

# Estimation of sound pressure level exposures from sound power level measurements of powered hand-tools<sup>1)</sup>

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As part of a long-term goal to reduce noise-induced hearing loss in the construction industry, the National Institute for Occupational Safety and Health (NIOSH) estimated the A-weighted sound pressure level at the operator's ear ( $L_{pA,est}$ ) from the A-weighted sound power ( $L_{WA}$ ) measurements of 118 various model powered hand tools using the diffuse-field point source model Eyring theory.  $L_{pA,est}$  from the model are compared to sound pressure measurements ( $L_{pA,meas}$ ) acquired from a microphone located in the nominal hearing zone of a simulated powered hand tool operator. This paper provides a basis for the direct substitution of  $L_{WA}$  for  $L_{pA,meas}$  and a comparison of  $L_{pA,est}$  to  $L_{pA,meas}$ . The magnitude of  $L_{WA}$  is found to be a reasonable predictor of the magnitude of sound pressure level exposure, or  $L_{pA,meas}$ , that a powered hand tool operator might experience across a variety of acoustical environments. As such,  $L_{WA}$  can be used directly to select appropriate hearing protection and estimate worker's noise exposure.  $L_{WA}$  can be measured for all power tools with appropriate loading conditions; however, measuring the sound pressure levels for all combinations of powered hand tools and acoustical environments in the construction industry is not feasible. Purchasers and users of those tools deserve a viable method of estimating noise exposure. © 2007 Institute of Noise Control Engineering.

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## 1 INTRODUCTION

As part of a long-term goal to reduce noise-induced hearing loss (NIHL) in the construction industry, the National Institute for Occupational Safety and Health (NIOSH) instituted a program to estimate the A-weighted sound pressure level at the operator's ear ( $L_{pA,est}$ ) from the A-weighted sound power ( $L_{WA}$ ) measurements of powered hand tools. The A-weighted sound power level is used by engineers to characterize the tools, while the A-weighted sound pressure level is used by audiologists to characterize hearing loss potential. Understanding the relationship between sound power and sound pressure at the operator's ears will help engineers and hearing conservationists to relate the engineering characterization of power tool noise

with the audiological assessment of hearing loss potential.

A number of studies have shown that A-weighted sound pressure level exposures to construction workers from portable power tools range from 81 dB to 113 dB<sup>1-4</sup>. Although, these previous studies focused on personal, task-based, and area sound level measurements they did show that power tools were a major contributor to construction site noise. Figure 1 ranks the percentage of abnormal hearing by construction occupation. Power-tool-use-intensive construction occupations—such as plumbers, ironworkers, carpenters, and electricians show higher rates of abnormal hearing as compared with occupations that are less dependent on power tools, such as painters<sup>5</sup>. Lastly, a linear relationship between a power tool's sound power level and an operator's noise exposure has been shown<sup>2</sup>.

Studies conducted at the University of Washington found that 40% of the noise exposure measurements made on carpenters and laborers were over the state of Washington's Permissible Exposure Limit (PEL) of an equivalent A-weighted sound pressure level of 85 dB for 8 hours<sup>3</sup>. Twenty-four percent of the measurements made on those who work in the so-called "quiet"

<sup>1)</sup> The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH).

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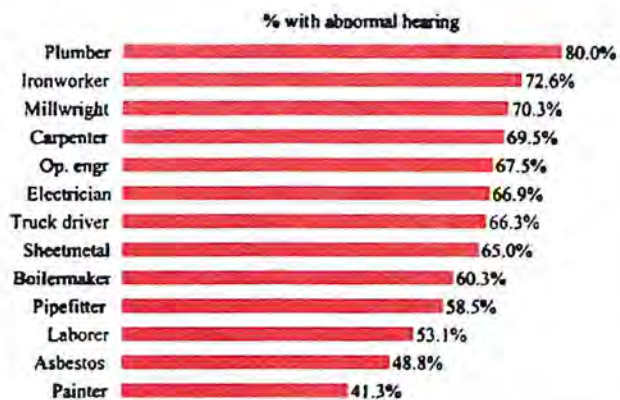


Fig. 1—Percentage of workers having abnormal hearing for various construction occupations. The occupations with greater dependence on power tools (i.e., carpenters, plumbers, ironworkers) have a higher percentage of abnormal hearing than occupations with less dependence on power tools (i.e., painters)<sup>5</sup>.

trades, such as electricians, were also over this PEL<sup>1</sup>.

Regulation of noise exposure in the construction industry currently falls under Occupational Safety and Health Administration's (OSHA) 29 CFR 1926.52. This regulation does not have the stringent requirements promulgated for other industries (OSHA 29 CFR 1910.95) to reduce noise exposure. For example, in fiscal year 2005, fines levied under 1926.52 (Occupational Noise Exposure) on the construction industry by federal OSHA inspectors amounted to 0.03% of total construction industry fines, while manufacturing industries made up 1.7% of total fines. In fiscal year 2005, 49,214 construction inspections by federal OSHA resulted in only 29 citations for noise totaling \$20,122 in fines despite the well-documented existence of high noise exposure and high rates of NIHL in the construction industry<sup>6,7</sup>.

As there is no regulatory requirement in the construction industry to have a hearing conservation program (HCP) in place, the construction industry is among the least likely across all industries to provide audiograms and monitor their employee's hearing. The low prevalence of HCPs in the construction sector necessitates providing, among other things, noise level information that can be readily used by powered hand tool users to reduce their own risk of suffering from NIHL. The professional standard for describing noise emissions from equipment and machinery is sound power level (reported in Watts or dBA ref 10<sup>-12</sup> Watts). In Europe, smaller outdoor equipment and machinery are mandated to be labeled with either a sound power

level label or a sound pressure label whichever is more appropriate for each type of equipment<sup>8</sup>. In the US, there is an unenforced EPA regulation requiring similar labeling of equipment and machinery<sup>9</sup>. In anticipation of more restrictive noise level requirements on construction sites and the enforcement of existing labeling regulations in the US, this project examines an analytical model by which A-weighted sound power level is related directly to A-weighted sound pressure level.

Currently, there are models for estimating sound pressure level,  $L_{pA,est}$ , at the operator's position from a noise source located at some distance from the operator's ear<sup>10-12</sup>. The model used in ISO standard 11203 shown by Eqn. (1) uses the sound power  $L_{WA}$  ref. 10<sup>-12</sup> Watts and the quantity  $Q$ .  $Q$  is either determined experimentally or calculated from a measurement surface surrounding the tool or equipment under test.

$$L_{pA,est} = L_{WA} - Q \text{ (dB)}, \quad (1)$$

where  $Q$  will vary with the directionality of the tool/equipment under test, the acoustical environment, and the distance from the source to the operator's ears. Equation (1) assumes an omnidirectional source, a reflective acoustical environment, and a relatively steady distance between the source and receiver. The ISO standard 11203 does provide a range of  $Q$  values from 4 to 12 dB for hand-held machines. Note the parameters  $L_{pA,est}$  and  $L_{WA}$  use dBA ref. 20  $\mu$ Pa and dBA ref. 10<sup>-12</sup> Watts respectively.

Guidance for predicting sound pressure levels from sound power measurements throughout a workroom is contained in ISO 11690-3. ISO 11690 does not provide any equations or rules of thumb for predicting sound pressure levels. Unfortunately the graphs contained in ISO 11690-3 are limited to distances greater than 1 m from a power tool, which is outside the nominal hearing zone. Consequently, ISO 11690-3 is not relevant to power tool operators; however, it is useful in predicting sound pressure levels at the positions of other workers in workrooms<sup>11</sup>.

The Australian government noise control guide provides a flowchart which gives<sup>12</sup>

$$L_{pA,est} = L_{WA} - 8 + (6 \text{ or } 0) \text{ (dB)}, \quad (2)$$

where 6 dB is added if the sound power level measurement was taken in a highly reverberant acoustical environment or the age or loading of the machine is not representative of the conditions when the measurement was taken (i.e., the tool was new when tested but may now have many hours of wear or the tool is tested in the unloaded condition). This model does not specifically take into consideration source directivity, distance of

Table 1— $L_{rp}$  increases with the number of reflecting planes that the sound source is near (within 1/3 wavelength). The presence of reflective surfaces does not increase the sound power level in Eqn. (3).

Number of reflective planes	Geometric description of reflector	Measurement Surface	Increase to	
			$L_{rp}$ (dB)	$L_{pa}$ (dB)
0	No reflective surfaces	Sphere	0	0
1	Floor, wall, or hard ceiling	Hemisphere	3	0 to 3
2	Interior Edge	Half a Hemisphere	6	0 to 6
3	Interior Corner	Quarter Hemisphere	9	0 to 9

the source to the operator's ear, or the effects of nearby reflective planes.

## 2 THEORETICAL MODEL

A model for estimating noise exposure from portable powered hand tools should consider the tool's sound characteristics, the environmental sound characteristics, and the proximity of the noise source to the operator's ears. These considerations are accounted for in the diffuse-field, point source Eyring theory model<sup>13-15</sup>. The diffuse-field point source model Eyring theory provides:

$$L_{pA,est} = L_{WA} + 10 \log_{10} \left( \frac{Q_{\theta}}{4\pi r^2} + \frac{4}{R} \right), \quad (3)$$

where  $Q_{\theta}$  is the tool or machine's directivity factor,  $r$  (m) is the radial distance between the sound source (the tool/machine) and the receiver (the tool operator's ears), and  $R$  (m<sup>2</sup>) is the room constant. Eyring theory approximates the sound source as a point source having directivity, located in a room having a diffuse sound field at some distance from the receiver.

The first term inside the parenthesis of Eqn. (3) represents the effect of the direct sound field. The second term inside the parenthesis represents the effect of the reverberant sound field. Equation (3) can be rearranged to more easily show the direct and reverberant sound field's effect on the sound level. Moving  $L_{WA}$  to the left side of the equation yields,

$$L_{pA,est} - L_{WA} = 10 \log_{10} \left( \frac{Q_{\theta}}{4\pi r^2} + \frac{4}{R} \right). \quad (4)$$

Now the left side term,  $(L_{pA,est} - L_{WA})$ , provides a convenient way to view the relationship between the difference in estimated sound pressure level and measured sound power level, and the right side consists of the direct and reverberant sound fields. A description of each of the direct and reverberant sound level variables,  $Q_{\theta}$ ,  $r$ , and  $R$  and their effect on the estimation of  $L_{pA,est} - L_{WA}$  is detailed below.

### 2.1 Directivity Factor $Q_{\theta}$

The sound source directivity of a powered hand tool is characterized by its directivity factor. This factor describes the tool's changing noise emission levels relative to the angle about the tool. For comparison, a tool not under the influence of reflecting planes and acting as an omnidirectional or monopole source would have  $Q_{\theta} = 1$ . A sound source with a high directivity factor will have large variations of sound levels as the angle about the tool changes. In effect,  $L_{pA,est}$  will vary with the angle between the tool and the operator's ear. Note that directivity does not affect the  $L_{WA}$  measurement. The directivity factor is a dimensionless quantity defined as:

$$Q_{\theta} = 10^{DI_{\theta}/10}, \quad (5)$$

where the directivity index is

$$DI_{\theta} = L_{pA\theta} - \overline{L_{pA}} + L_{rp}(\text{dBA}), \quad (6)$$

and  $L_{pA\theta}$  is the sound pressure level measured at distance  $r$  and at angle  $\theta$  from the source,  $\overline{L_{pA}}$  is the level of space-averaged mean-square sound pressure level determined over the test hemisphere of area  $2\pi r^2$  ( $8\pi$  in the case of this paper as  $r=2$  meters in the hemi-anechoic chamber) surrounding the source, and  $L_{rp}$  is the sound pressure level correction factor to account for the sound source's location near reflecting planes.

If the tool is operated near reflecting surfaces (within 1/3 wavelength distances), those reflecting surfaces change the directivity index, which in turn changes the directivity factor. Table 1 specifies the values for  $L_{rp}$  for a powered hand tool under the influence of zero to three reflective surfaces<sup>15,16</sup>. The effect of directivity factor on  $L_{pA,est} - L_{WA}$  is shown in Fig. 2.

The top curve demonstrates maximum  $L_{pA,est} - L_{WA}$  being found in a highly reverberant environment having a short distance from the powered hand tool to the operator's ears. The bottom curve shows the effect on  $L_{pA,est} - L_{WA}$  from a highly absorptive environment having a long distance between the powered hand tool

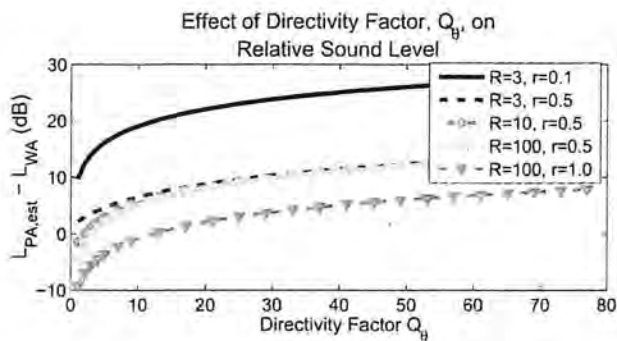


Fig. 2—This diagram shows the effect of the directivity factor  $Q_\theta$  on  $(L_{pA,est} - L_{WA})$  for five combinations of acoustical environment and distance from the powered hand tool to the operator's ears. The top curve is for a highly reverberant acoustical environment with a powered hand tool in close proximity to the operator's ears, the middle three curves are for a powered hand tool at 0.5 (m) from the operator's ears in acoustical environments ranging from reverberant to absorptive, and the bottom curve is for an absorptive environment with a powered hand tool a long distance from the operator's ears  $r=1.0$  m.  $L_{pA,est}$  (dBA ref.  $20 \mu\text{Pa}$ ) and  $L_{WA}$  (dBA ref.  $10^{-12}$  Watts).

and the operator's ears. The middle three curves have acoustical environments ranging from reverberant to absorptive with a typical distance from the powered hand tool to the operator's ears of  $r=0.5$  m.

The direct sound term dominates as  $Q_\theta$  increases. Values of a given  $R$  have little influence on  $L_{pA,est} - L_{WA}$  for  $Q_\theta > 10$  and  $r < 1$  m. A value of  $Q_\theta > 10$  can be the result of the source having high source directivity in combination with being in close proximity to several reflecting planes.

## 2.2 Distance from the Sound Source to the Operator's Ear, $r$

The distance from the powered hand tool to the operator's ears,  $r$ , greatly effects  $L_{pA,est} - L_{WA}$ . Figure 3 shows  $L_{pA,est} - L_{WA}$  for  $Q_\theta=2$ , in three acoustic environments (reverberant  $R=1$ , intermediate  $R=10$ , and absorptive  $R=100$   $\text{m}^2$ ) as  $r$  varies from 0.03 m to 1 m. As  $r$  approaches 0, the direct sound field dominates and  $L_{pA,est} - L_{WA}$  becomes greater than 20 dB.  $L_{pA,est} - L_{WA}$  changes less than 10 dB for conditions of  $r > 0.5$  m,  $R > 10$   $\text{m}^2$ , and  $Q_\theta=2$  which are conditions typical of tool operations.

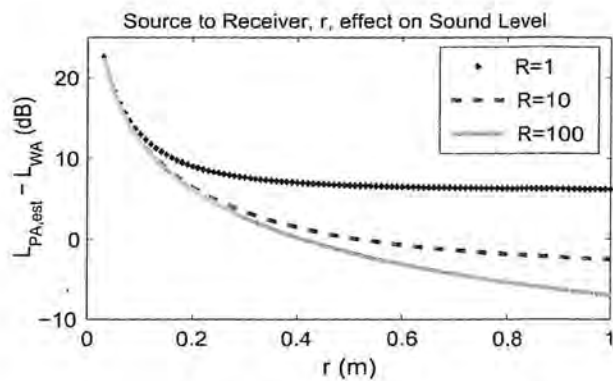


Fig. 3— $(L_{pA,est} - L_{WA})$  is calculated from Equation (4) as the distance from operator's ears to the powered hand tool is varied from 0.03 to 1 m.  $Q_\theta=2$  and three values of  $R$  representing three different acoustical environments are used in the calculation.

## 2.3 Room Constant, $R$

The room constant,  $R$ , describes both surface area and sound absorption characteristics of a room or volume. The Eyring theory formula for  $R$  is applicable to enclosed rooms having an average surface absorption, a simple geometry, and a diffuse sound field. Neglecting air absorption, the formula for the room constant is:

$$R = \frac{-S \ln(1 - \bar{\alpha})}{1 - \bar{\alpha}} \quad (7)$$

where  $S$  is the total surface area of the room and  $\bar{\alpha}$  is the average absorption coefficient of the room<sup>14</sup>.

Table 2 lists room constants calculated using Eqn. (7) for various sizes of architectural spaces. A power tool and its operator will not typically be working inside a small volume such as a cabinet or small closet, consequently values for  $R \leq 3$   $\text{m}^2$  are presented here strictly for comparative purposes. For general consideration, the range of  $R > 3$   $\text{m}^2$  is used as the applicable range of room constants for establishing  $L_{pA,est}$  with the point source model.

## 3 METHODS

The sound power level  $L_{WA}$  for 118 powered hand tools was measured using sound pressure level ( $L_{pA}$ ) data gathered from a 10-microphone array over a hemispherical measurement surface, in accordance with ISO 3744. All of the measurements in this study were conducted in a hemi-anechoic chamber. The hemi-anechoic chamber, measurement setup, and data processing, analysis, and presentation of  $L_{pA}$ ,  $L_{WA}$ , and  $L_{pA,meas}$  are described in detail in the project's study protocol, searchable website database, and other subse-

Table 2—Room constants for various sizes and surface treatments of enclosed architectural spaces. Room constants greater than 3 m<sup>2</sup> are generally applicable to establishing  $L_{pA,est}$  levels

Room Type	Acoustical Surface Type	$R$ (m <sup>2</sup> )	$S$ (m <sup>2</sup> )	$\bar{\alpha}$ (0-1)	Room Size L × W × H (m <sup>3</sup> )
Small Cabinet	Concrete	0.1	1.5	0.05	0.5 × 0.5 × 0.5
Small Cabinet	Hard	0.2	1.5	0.1	0.5 × 0.5 × 0.5
Large Cabinet	Concrete	0.3	6	0.05	1 × 1 × 1
Large Cabinet	Hard	0.7	6	0.1	1 × 1 × 1
Closet	Concrete	1.3	24	0.05	2 × 1.3 × 2.85
Closet	Soft	6.7	24	0.2	2 × 1.3 × 2.85
Small Room	Hard	6.1	52	0.1	3 × 3 × 2.85
Small Room	Soft	15	52	0.2	3 × 3 × 2.85
Small Office	Hard	13	110	0.1	6.7 × 3.8 × 2.85
Small Office	Soft	30	110	0.2	6.7 × 3.8 × 2.85
Conference Room	Hard	30	260	0.1	8 × 10 × 2.85
Conference Room	Soft	130	260	0.3	8 × 10 × 2.85
Ball Room	Hard	350	3000	0.1	30 × 30 × 10
Ball Room	Soft	840	3000	0.2	30 × 30 × 10
Hemi Anechoic Chamber	Absorptive Surfaces, Reflective Floor	1180	800	0.513	8 × 4 × 3
Open-Field	Hard Ground	∞	∞	1.0	∞

quent documents<sup>17-21</sup>. The determination of the values of  $Q_\theta$ ,  $r$ , and  $R$  for the tests are detailed below. Note that an 11<sup>th</sup> microphone was positioned in the tool operator's hearing zone.  $L_{pA,meas}$  was measured using this 11<sup>th</sup> microphone and likewise,  $r$  was measured from the 11<sup>th</sup> microphone to the powered hand tool.

Each powered hand tool of similar type was oriented in the same direction for each of the measurements so that the directivity could be compared within powered hand tool types.  $Q_\theta$  was calculated at an angle passing through the operator's ears over one reflecting plane using the sound pressure data from the 10-microphone array and Eqn. (5); the measured source directivities were smooth and amenable to linear interpolation and cubic spline methods to calculate  $Q_\theta$ . Influences on directivity due to the powered hand tool direct noise emissions and the indirect emissions resulting from the reflecting plane are included in calculating  $Q_\theta$  (see Eqns. (5) and (6)).

A total of 236 sound power level tests were conducted with a variation in the loading conditions and the distance,  $r$ , between the powered hand tool and an 11<sup>th</sup> microphone. 129 tests were conducted with  $r = 0.89$  m (100 unloaded, 29 loaded) and 107 tests were conducted with  $r = 0.50$  m (18 unloaded, 89 loaded). The use of two different distances,  $r$ , provided a variation of that parameter for the purpose of validating its effect on the model. The loading condition was in accordance with ANSI S12.15<sup>20</sup>; moreover, all tools were tested in both the loaded and unloaded conditions. The loaded and unloaded tool data were gathered to

study of the effects of loading conditions on sound power level and do not change the relationship between  $L_{WA}$  and  $L_{pA}$ <sup>22</sup>.

The value of  $R$  in the hemi-anechoic chamber was calculated using Eqn. (7).  $S$  was obtained by measuring the surface area of the reflective floor and the outer surface area of the acoustical wedges on the walls and ceiling. The average sound absorption coefficient,  $\bar{\alpha}$ , was estimated by measuring the reverberation time and applying the results to Eqn. (8):

$$\bar{\alpha} = 1 - e^{\left(\frac{4mV}{S} - \frac{55.3V}{cT_{60}S}\right)} \quad (8)$$

where  $T_{60}$  (s) is the reverberation time,  $V$  (m<sup>3</sup>) is the volume of the hemi-anechoic chamber,  $c$  (m/s) is the speed of sound,  $2m$  (Np/m) is the energy air absorption exponent, and  $S$  (m<sup>2</sup>) is the total surface area<sup>14</sup>. The reverberation time was obtained by discharging a cap gun in the chamber and measuring the time for sound pressure level to decay by 60 dB in the hemi-anechoic chamber.

#### 4 DATA ANALYSIS

For each of the 2036 test runs, the respective  $L_{WA}$ ,  $Q_\theta$ ,  $r$ , and  $R$  was applied to Eqn. (4) to obtain the  $L_{pA,est}$  calculation. The resulting value of  $L_{pA,est}$  was then compared to  $L_{pA,meas}$ . The  $L_{pA,est} - L_{pA,meas}$  difference was calculated for each tool in the loaded and unloaded condition. The mean, standard deviation, and confidence interval of the difference were calculated

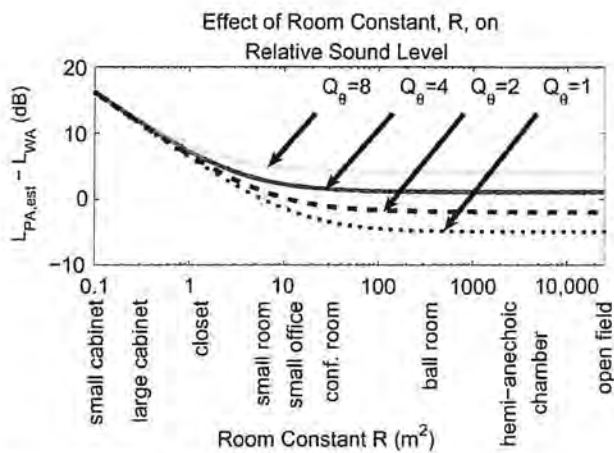


Fig. 4—From Eqn. (4),  $(L_{pA,est} - L_{WA})$  is calculated as the Room Constant,  $R$ , is varied from 0.1 to 25,000  $m^2$ ,  $Q_\theta = 1, 2, 4,$  and  $8$ , and  $r = 0.5$  m.  $L_{pA,est}$  (dBA ref.  $20 \mu Pa$ ) and  $L_{WA}$  (dBA ref.  $10^{-12}$  Watts).

for each tool type. Similarly, the difference and statistical analysis were performed on the same data set for  $L_{WA} - L_{pA,meas}$ .

In some instances as noted in the results section, the measured sound pressure level was adjusted to a more reverberant acoustical environment  $R = 10 m^2$  and closer proximity of the tool to the operator's ears  $r = 0.5$  m. These adjusted conditions are more comparable to conditions found on construction sites. The adjustment causes  $L_{pA,est} - L_{WA}$  to be closer to zero (as can be seen in Fig. 4 by translating from  $R = 1180 m^2$  to  $R = 10 m^2$  along  $Q_\theta = 2$ ). The purpose of the adjustment

is to compare  $L_{pA,est}$  and  $L_{WA}$  in a harsher acoustical environment, because the hemi-anechoic chamber measurements do not have any reverberant field and are therefore unrealistically forgiving. While all calculations for estimated and adjusted  $L_{pA}$  used the  $Q_\theta$  calculated for that particular tool relative to the 11<sup>th</sup> microphone position, the overall  $Q_\theta$  was approximately 2. The adjustment is made by:

$$L_{pA,meas}(Adjusted) = L_{pA,meas} + 10 \log \left( \frac{Q_\theta}{4\pi(0.5)^2} + \frac{4}{1180} \right) - 10 \log \left( \frac{Q_\theta}{4\pi(r_{used\ in\ test})^2} + \frac{4}{1180} \right) \quad (9)$$

Recall that the hemi-anechoic environment had  $R = 1180 m^2$  and it is more likely the construction site environment will have some  $R$  considerably less than  $1180 m^2$ . The  $L_{WA} - L_{pA,meas}(Adjusted)$  data set were analyzed in a similar fashion to the  $L_{WA} - L_{pA,meas}$  data.

## 5 RESULTS

The following tables and figures present the measured, adjusted, and comparative data. Table 3 shows the amount of variation between the loaded and unloaded  $L_{WA}$  test data. Figures 5–7 compare  $L_{pA,est} - L_{pA,meas}$ ,  $L_{WA} - L_{pA,meas}$ , and  $L_{WA} - L_{pA,meas}(Adjusted)$  respectively. The parameters,  $r$ ,  $R$  and  $Q_\theta$  were calculated for each figure. Exact values of  $Q_\theta$  were used in all calculations and had a small effect of the results.  $Q_\theta$  for the powered hand tools tested in the unloaded

Table 3—The mean of the standard deviation, and mean of the confidence interval of the measured sound power levels for tools tested in the loaded and unloaded condition. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type.

$L_{WA}$ (dB) Tool Type (number tested)	Loaded test condition		Unloaded test condition	
	Mean Standard Deviation	Mean Confidence Interval	Mean Standard Deviation	Mean Confidence Interval
Circular Saw (28)	0.86	0.49	0.12	0.10
Drill (14)	0.66	0.32	0.09	0.14
Grinder (18)	0.96	0.35	0.71	0.11
Hammer Drill (12)	0.66	0.33	0.06	0.06
Jig Saw (5)	0.28	0.26	0.07	0.07
Miter Saw (6)	1.11	0.43	0.04	0.05
Orbital Sander (17)	0.23	0.24	0.17	0.18
Reciprocating Saw (14)	0.98	0.56	0.55	0.08
Screw Driver (4)	1.00	0.38	0.08	0.08

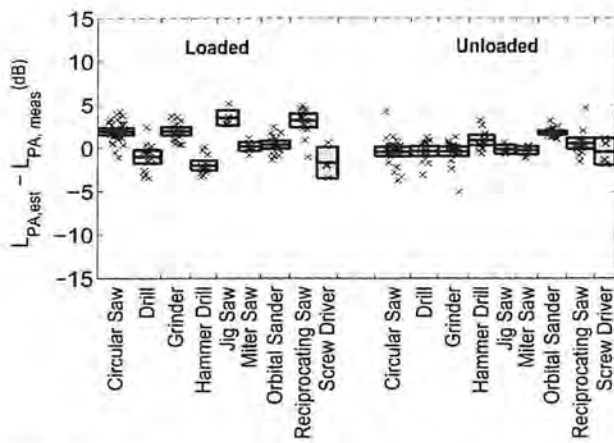


Fig. 5—The difference between the estimated sound pressure level calculated from the model and actual measured sound pressure level is typically between 6 dB and -4 dB for both the loaded and unloaded condition. Note that this figure is not comparing loaded vs. unloaded, it is simply comparing the  $L_{pA,est}$  for a particular tool and loading condition with the  $L_{pA,meas}$  for that same exact tool and loading condition. Each "x" on the graph denotes the comparative result for the particular tool noted directly below on the x axis.

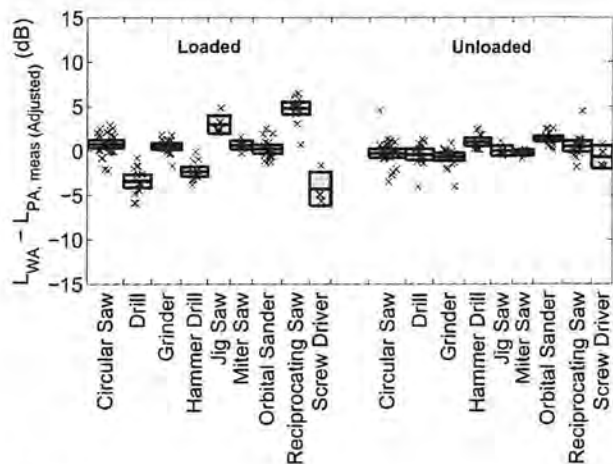


Fig. 7—The difference between the magnitude of the sound power level and the measured sound pressure level was adjusted for  $R = 10 \text{ m}^2$  and  $r = 0.5 \text{ m}$ . The graph demonstrates that sound power level magnitude may be a useful metric for estimating the sound pressure level exposures to operators of powered hand tools. Each "x" on the graph denotes the comparative result for the particular tool noted directly below on the x axis.

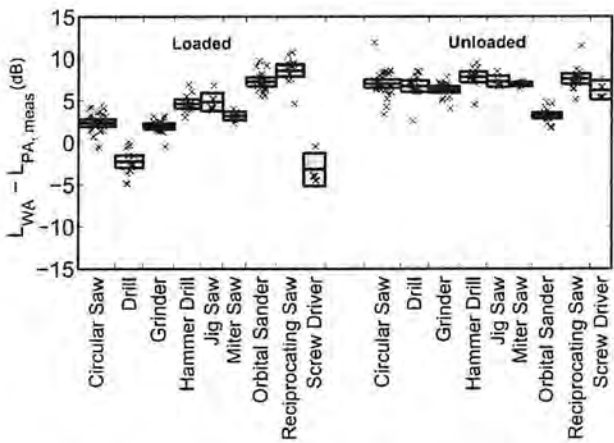


Fig. 6—The difference between the magnitude of the sound power level and the measured sound pressure level at the operator's ears is compared across different tool types and loading conditions. Each "x" on the graph denotes the comparative result for the particular tool noted directly below on the x-axis.

condition had an average of  $1.98 \pm 0.17$  (0.90, 2.88).  $Q_{\theta}$  for tools tested in the loaded condition had an average of  $2.30 \pm 0.55$  (0.79, 3.82). The values for  $R$  and  $r$  used during the measurements in the hemi-anechoic chamber (i.e.,  $R = 1180 \text{ m}^2$ ,  $r = 0.89 \text{ m}$ , and  $r = 0.50 \text{ m}$ ) are used in Figs. 5 and 6. Figure 7, uses the adjusted values  $R$  and  $r$  (i.e.,  $R = 10 \text{ m}^2$  and  $r = 0.5 \text{ m}$ ).

## 6 DISCUSSION

For each power tool,  $L_{WA}$  was measured several times in both the loaded and unloaded conditions, and the standard deviation and confidence intervals were calculated. The standard deviations and confidence intervals were then averaged across tool types. Table 3 shows that the average standard deviation and average confidence intervals are greater for the loaded condition than for the unloaded condition. The greater variability when testing tools in the loaded condition may be expected since there are many more conditions that change as the tool cuts material. This would also be true for gathering data in the field, further exemplifying the need to make broad-based noise exposure assessments using  $L_{WA}$  instead of archiving a limited library of field sound pressure level measurements and consequently using that archive to estimate noise exposures

*Table 4—The mean, standard deviation, and confidence interval of the difference between estimated sound pressure level and measured sound pressure level for tools tested in the loaded and unloaded condition. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type. The CI provides the upper and lower bound for the mean with 95% confidence for the entire set of particular tool type tested.*

$L_{pA,est} - L_{pA,meas}$ (dB)	Loaded test condition	Unloaded test condition
Tool Type (number tested)	Mean±Stand. Dev. (dB) (Confidence Interval)	Mean±Stand. Dev. (dB) (Confidence Interval)
Circular Saw (28)	1.94±1.30 (1.52, 2.36)	-0.41±1.67 (-0.95, 0.13)
Drill (14)	-0.99±1.65 (-1.77, -0.22)	-0.35±1.23 (-0.93, 0.23)
Grinder (18)	1.98±1.17 (1.50, 2.46)	-0.37±1.39 (-0.92, 0.18)
Hammer Drill (12)	-2.00±1.14 (-2.59, -1.41)	0.93±1.18(0.32, 1.54)
Jig Saw (5)	3.52±0.98 (2.63, 4.41)	-0.14±0.57 (-0.66, 0.38)
Miter Saw (6)	0.20±0.65 (-0.31, 0.71)	-0.24±0.58 (-0.70, 0.22)
Orbital Sander (17)	0.39±1.06 (-0.06, 0.84)	1.81±0.57 (1.57, 2.05)
Reciprocating Saw (14)	3.21±1.70 (2.41, 4.01)	0.55±1.42 (-0.09, 1.19)
Screw Driver (4)	-1.68±1.67 (-3.47, 0.11)	-0.40±1.47 (-1.97, 1.17)

across an entire population of tools, acoustical environments, and tool operators.

Figure 5 shows the difference between  $L_{pA,est}$  calculated using the model from Eqn. (4) and  $L_{pA,meas}$ . The graph separates the loaded and unloaded test conditions and groups the models according to tool types. A value

of zero dB on the y-axis coincides with the sound pressure model perfectly estimating the actual sound pressure level exposure error. Points below zero dB on the y-axis indicate areas where the model underestimates  $L_{pA,est}$  and points above zero indicate an overestimation. The data shown in Fig. 5,  $L_{pA,est} - L_{pA,meas}$ ,

*Table 5—The mean, standard deviation, and confidence interval of the difference between the sound power level and the measured sound pressure level for tools tested in the loaded and unloaded condition. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type. The CI provides the upper and lower bound for the mean with 95% confidence for the entire set of particular tool type tested.*

$L_{WA} - L_{pA,meas(adjusted)}$ (dB)	Loaded test condition	Unloaded test condition
Tool Type (number tested)	Mean ± Stand. Dev. (dB) (Confidence Interval)	Mean ± Stand. Dev. (dB) (Confidence Interval)
Circular Saw (28)	2.35±1.35 (1.92, 2.78)	7.01±1.59 (6.50, 7.52)
Drill (14)	-2.28±1.60 (-3.04, -1.52)	6.71±1.48 (6.01, 7.41)
Grinder (18)	1.95±0.87 (1.60, 2.30)	6.32±0.96 (5.94, 6.70)
Hammer Drill (12)	4.60±1.09 (4.04, 5.16)	7.80±1.28 (7.14, 8.46)
Jig Saw (5)	4.82±1.23 (3.72, 5.92)	7.28±0.74 (6.61, 7.95)
Miter Saw (6)	3.17±0.63 (2.67, 3.67)	6.93±0.33(6.67, 7.19)
Orbital Sander (17)	7.25±1.29 (6.71, 7.79)	3.21±0.84 (2.86, 3.56)
Reciprocating Saw (14)	8.59±1.53 (7.87, 9.31)	7.59±1.40 (6.96, 8.22)
Screw Driver (4)	-3.23±1.84 (-5.19, -1.27)	6.23±1.09 (5.07, 7.39)

Table 6—The mean, standard deviation, and confidence interval (CI) of the difference between sound power level and adjusted measured sound pressure level for tools tested in the loaded and unloaded condition show that the sound power level can estimate the noise exposure in the loaded and unloaded conditions within 5 dB on average. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type. The CI provides the upper and lower bound for the mean with 95% confidence for the entire set of particular tool type tested.

$L_{WA} - L_{pA,meas(adjusted)}$ (dB)	Loaded test condition	Unloaded test condition
	Mean $\pm$ Stand. Dev. (dB) (Confidence Interval)	Mean $\pm$ Stand. Dev. (dB) (Confidence Interval)
Tool Type (number tested)		
Circular Saw (28)	0.77 $\pm$ 1.31 (0.35, 1.19)	-0.28 $\pm$ 1.56 (-0.78, 0.38)
Drill (14)	-3.42 $\pm$ 1.57 (-4.16, -2.68)	-0.41 $\pm$ 1.38 (-1.06, 0.24)
Grinder (18)	0.49 $\pm$ 0.87 (0.13, 0.85)	-0.67 $\pm$ 1.11 (-1.11, 1.11)
Hammer Drill (12)	-2.35 $\pm$ 1.09 (-2.91, -1.79)	0.99 $\pm$ 0.88 (0.54, 1.53)
Jig Saw (5)	2.96 $\pm$ 1.14 (1.94, 3.98)	0.02 $\pm$ 0.65 (-0.57, 0.61)
Miter Saw (6)	0.64 $\pm$ 0.61 (0.16, 1.12)	-0.23 $\pm$ 0.42 (-0.56, 0.10)
Orbital Sander (17)	0.20 $\pm$ 1.18 (-0.30, 0.70)	1.30 $\pm$ 0.70 (1.00, 1.60)
Reciprocating Saw (14)	4.79 $\pm$ 1.48 (4.09, 5.49)	0.47 $\pm$ 1.38 (-0.16, 1.10)
Screw Driver (4)	-4.29 $\pm$ 1.79 (-6.20, -2.38)	-0.73 $\pm$ 1.22 (-2.03, 0.57)

were analyzed by tool type and loading condition; the resulting mean, standard deviation, and confidence interval are shown in Table 4.

Figure 6 illustrates the relative difference between the  $L_{WA}$  and the  $L_{pA,meas}$  as gathered in the hemi-anechoic environment. The figure shows the difference before any adjustment is made to  $L_{pA,meas}$ . Using  $L_{WA}$  to estimate  $L_{pA,meas}$  results in an underestimation of noise exposure (i.e., values below zero on the y-axis). Conversely, all values above zero represent an overestimation of noise exposure. Table 5 shows the relative difference between the  $L_{WA}$  and the  $L_{pA,meas}$  before adjustments. It can be argued that using the magnitude of  $L_{WA}$  directly to estimate  $L_{pA,meas}$  and consequently, choosing appropriate hearing protection, would result in overprotecting the worker. However, considering the data used to evaluate the Eyring theory model were taken in a highly sound absorptive environment, which caused the measured sound pressure levels,  $L_{pA,meas}$  to be lower and consequently the model underestimated a worker's real-world noise exposure. If all powered hand tool use occurred in an open-field environment over a reflecting plane the unadjusted model would be sufficient. However, that environment minimizes the reverberant sound field, the typical acoustical environment of a construction site would be a more enclosed and reverberant environment. There-

fore,  $L_{pA,meas}$  is adjusted as described above to provide a more conservative and realistic estimate of a worker's noise exposure when operating powered hand tools.

Figure 7 shows the difference between the  $L_{WA}$  and the  $L_{pA,meas(Adjusted)}$ , where  $L_{W,d}$  is an estimate of the adjusted sound pressure level at the operator's ears  $L_{pA,meas(Adjusted)}$ . As in Fig. 6, values below zero on the y-axis underestimate a worker's exposure and values above zero overestimate exposure. However, in Fig. 7, overestimation becomes less likely since the adjustment typically increases the sound pressure levels in order to better model the acoustical environment of a construction site. Table 6 shows that the mean of the difference in sound levels after the adjustment, which is closer to 0 dB than Table 5. These results demonstrate that the magnitude of  $L_{WA}$  can be used to estimate noise exposures of tool operators.

The applicable range of  $Q_\theta$ ,  $r$ , and  $R$  in the theoretical discussion contrasts the narrow range and specific values of  $Q_\theta$ ,  $r$ , and  $R$  chosen for the laboratory measurements and the expected values in actual field use.  $Q_\theta$  depends on the number of reflecting planes, (refer to Table 1 and Eqns. (5) and (6)). Given the average  $Q_\theta$  value, as calculated from the sound pressure levels of the 10 microphone array in the laboratory, equaled approximately 2 and that adding

additional reflecting planes near the power tool would cause  $Q_\theta$  to increase to 8, then the model would underestimate  $L_{pA,est} - L_{WA}$  by as much as 6 dB (or  $10 \log(2/8)$ ). The  $L_{pA,est}$  is adjusted to  $r=0.5$  m, and  $R=10$  m<sup>2</sup>. The adjustment of  $r$  to 0.5 m from 1 m increases  $L_{pA,meas(Adjusted)}$  by approximately 6 dB. The adjustment of  $R$  to 10 from 1180 m<sup>2</sup> is responsible for a 2 dB increase in  $L_{pA,meas(Adjusted)}$ . In the actual field usage the values of  $Q_\theta$ ,  $r$ , and  $R$  will vary beyond the specific values chosen for laboratory measurements and the adjusted values of  $Q_\theta$ ,  $r$ , and  $R$  chosen for realistic comparison. For a very wide range of  $Q_\theta$ ,  $r$ , and  $R$ , Figs. 2–4 give an indication of how  $L_{pA,est} - L_{WA}$  will behave in actual field usage.

In Figs. 2–4, the relative sound level  $L_{pA,est} - L_{WA}$  is plotted for the ranges of values of  $Q_\theta$ ,  $r$ , and  $R$ , which are theoretically applicable to a tool operator using a powered hand tool on a construction site. The entire ranges of all combinations of  $Q_\theta$ ,  $r$ , and  $R$  presented in these figures can theoretically be produced, yet gathering  $L_{pA,meas}$  for each of these combinations is cost prohibitive if not logistically impossible. From Figs. 2–4, the variation of  $L_{pA,est} - L_{WA}$  due to different combinations of  $Q_\theta$ ,  $r$ , and  $R$  within the above stated applicable ranges are approximately +28 to –10 dB, +23 to –7 dB, and +6 to –5 dB respectively. The extreme values of  $L_{pA,est} - L_{WA}$  from the theoretical analysis are physically possible, but may occur infrequently in actual use of power tools for many construction workers. From Figs. 6 and 7, the variation in  $L_{pA,meas} - L_{WA}$  is +5 to –12 dB and +6 to –6.5 dB respectively. From Fig. 7, for each tool type the mean value of  $L_{pA,meas} - L_{WA}$  had a range of +5 to –5 dB, which may be more representative of actual field use on a construction site.

For an accurate prediction of the sound pressure at the operator's ears, the sound pressure should be estimated at a distance representative of the distance from the power tool to the operator's ears. The hearing zone only extends as far as the tool operator's arms can reach with a power tool. The operator's hearing zone is generally from  $0.03 < r < 1$  m,  $R > 10$  m<sup>2</sup>, and  $1 < Q < 80$ . In Fig. 8, the critical radius is the distance from the power tool to a surface where the direct field and reverberant field are equal. If the reverberant field dominates the sound pressure, then an accurate estimation of the sound pressure at the operator's ears can be made much further away from the power tool. If the direct field dominates, then the sound pressure level must be estimated at the operator's ears. The lower half of Fig. 8 represents the hearing zone; this area is generally dominated by the direct sound field; consequently, the sound pressure at the operator's ears is generally dominated by the direct field and measurements of

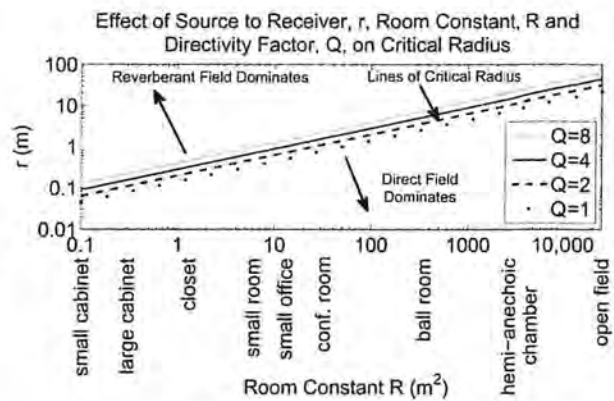


Fig. 8—The vertical axis is the distance from the power tool to the operator's ears. The critical radius is the distance from the power tool to the surface where the direct field and reverberant field are equal. The critical radius transitions from shorter than  $r$  to longer than  $r$  as the acoustical environment becomes by absorptive. The hearing zone extends approximately as far as the tool operator's arms can reach with a power tool; this area covers the lower half of the figure; consequently, the sound pressure at the operator's ears is generally dominated by the direct field.

noise exposure from power tools should be made at the operator's ears.

## 7 CONCLUSIONS

The theoretical and laboratory results show the two quantities  $L_{pA,est}$  and  $L_{WA}$  are nearly equal when consideration is given to the variety of acoustical environments for powered hand tools use.  $L_{WA}$  magnitude can be used directly to select appropriate hearing protection and estimate worker's noise exposure. Without this direct relationship it would be necessary to estimate sound pressure at the operator's ears for all combinations of power tools, acoustical environments, and proximity of tool to the operator's ears. It is much easier to make a database of sound power levels than such an extensive database of sound pressure levels. Tool purchasers and users of those tools deserve a viable method of estimating noise exposure from a label.

ISO standard 11203 (given here as Eqn. (1)) advocates subtracting 4 to 12 dB from measured sound power level to estimate sound pressure level exposures. Equation (2), the rule of thumb provided in the Australian government noise control guide<sup>12</sup>, subtracts 2 to 8 dB from measured sound power level to estimate

sound pressure level exposure. Using these methods will invariably underestimate the worker's noise exposure. If hearing protection is chosen accordingly, the worker may not be adequately protected from noise thereby increasing the risk of hearing loss.

Given a reasonable  $L_{PA,meas}$  estimator such as  $L_{WA}$ , it becomes feasible to provide the most comprehensive and economical noise exposure data set for powered hand tool operators. Of course, an accurate estimate is only viable where the  $L_{WA}$  magnitude is obtained appropriately and then made conveniently available to the tool user or safety professional through tool labeling or internet accessible database.

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