Trevor W. Jerome

Hearing risk of referee whistles

Physics 492R Capstone Report Project

Advisor: Dr. Kent Gee

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Abstract

Referee whistles output high-level short duration noise that has not been thoroughly studied. Damage risk criteria (DRC) exist to quantify the overall risk of sound exposure for continuous noise (OSHA, 1981; NIOSH, 1998) and other DRCs are intended for use with impulse noise (MIL-STD-1474D, 1991; Price, 2007). The noise from whistles is similar to impulse noise and the impulse DRC of equivalent A-weighted 8-hour energy (L_{eqA8}), MIL-STD-1474D, Pfander, Smoorenburg, and the AHAAH model are used to analyze recordings of whistle-blows from a trained referee in a controlled environment. Recording locations were at the ear and one meter in front of the referee. Computational analysis shows that using some of the DRC, allowable exposures for referees during a sports match range from 18 to 118 exposures. Hearing protection is recommended for officials, especially for those who are exposed to other loud situations on the same day.

Introduction

Background

An impulse noise is defined by a rise time constant of at most 35 milliseconds and an asymptotic decay constant of 1.5 seconds (Earshen, 2003). Rise time is the time taken to get from the noise floor to the maximum of the impulse peak. The whistle tweets analyzed had a sharp jump to an initial peak, and eventually oscillated to a greater peak. While time from the noise floor to the first peak is 5ms (±10ms), time to the global maximum of the whistle noise is 100ms (±20ms). This type of noise does not qualify as impulse noise. However, with mean B-duration of 219ms (13 to 629ms) and mean C-durations of 80 ms (23 to 148ms), the whistles can be impulsive in that they are more similar to impulse noise than they are to continuous noise.

Many referees are exposed to several tweets each time they are on the job. According to the National Institute for Occupational Safety and Health, Exposures to continuous noise at levels above A-weighted, time-weighted average (TWA) 85 dB for 8 hours per day, 5 days per week, 50 weeks per year and a 40 year working career presents a significant increase in the risk of developing material hearing impairment (average hearing loss > 25 dB in both ears at 1- 4 kHz), for an 8-hour exposure, can be damaging for a time-weighted average (TWA) of 85 dB SPL re 20 µPa on an A-weighted scale (NIOSH, 1998; Prince, Smith, & Gilbert, 1996). Continuous occupational noise exposure standards have been implemented in the United States by the Occupational Safety and Health Administration (OSHA). Studies for the OSHA standards are performed by The National Institute of Occupational Safety and Health (NIOSH), which has published its own recommendations for continuous noise. Because a whistle tweet has such short duration time, it is analyzed as an impulse.

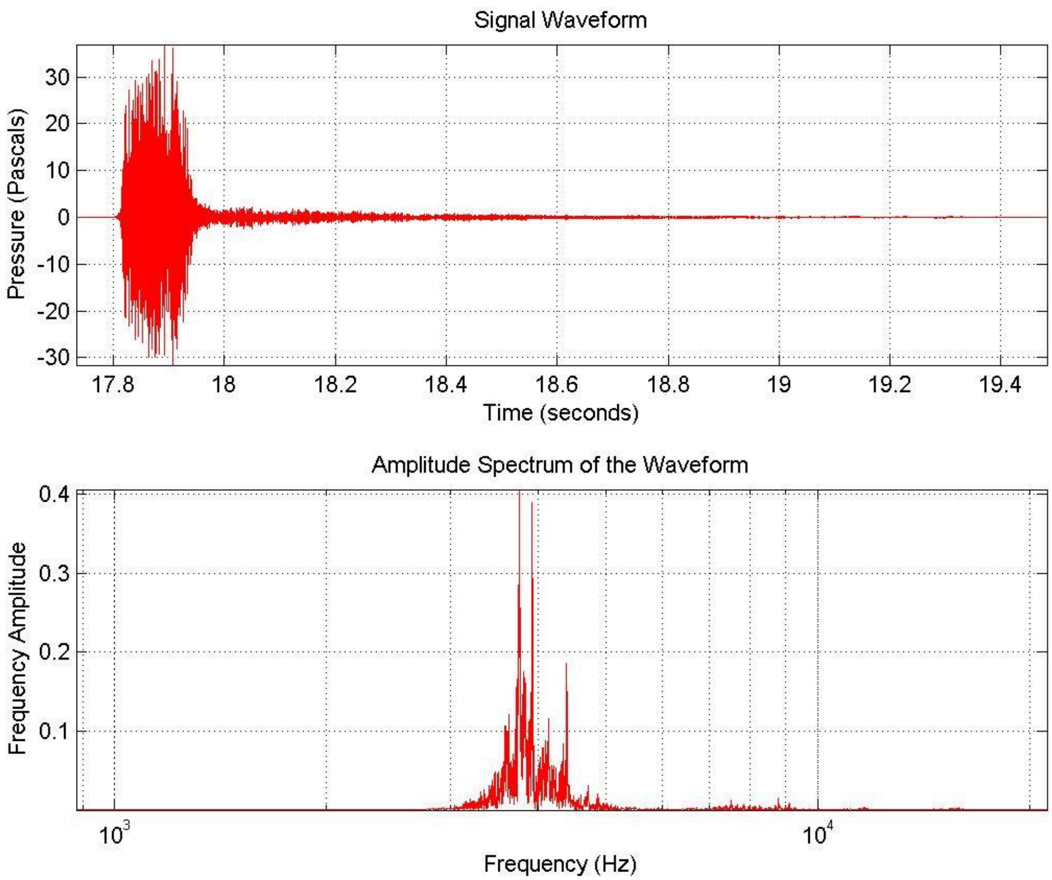

Figure 1: Waveform and Spectrum of a typical whistle tweet from this study

Only a single, ubiquitous standard exists from both OSHA and NIOSH for impulse noise, which derives from the National Academy of Science-National Research Council Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) (Ward, 1966). Kryter et al. (1966) established that exposures above 140 dB peak SPL re 20 µPa present a significant potential for causing permanent hearing damage in the absence of hearing protection. Sound pressure level is measured on a logarithmic scale (in dB), and referenced to the threshold of hearing at 20 µPa. It is converted from a linear scale (Pascals) to dB with a logarithmic function of base 10, as shown in the following equation:

$$SPL\ re\ p_{ref} = 20 * Log_{10}(\frac{p}{p_{ref}})$$

Various federal agencies (OSHA, MSHA, NIOSH, and EPA) and consensus standard committees (ANSI S3.44-1996, 1996; ISO 1999, 1990) have established 140 dB peak SPL as the maximum occupational exposure limit for impulses. In the absence of hearing protection, this 140 dB has been generally accepted as the threshold of hearing damage (ISO 1999, 1990). This impulse regulation takes neither duration nor number of exposures into consideration.

Preliminary analysis of whistle blows reveals that peak sound pressure levels within one meter of the referee are between 112 and 126 dB re 20 µPa. At the ear, the levels are between 120 and 135 dB. Figure 1 shows a typical waveform from the analyzed data with its spectral content found through Fourier analysis. While these levels are below the 140 dB limit for impulse noise, a maximum permissible number of these exposures per game may help officials understand the danger that can come from too much noise exposure. Despite the existence of the several DRC, no global standard exists for assessing risk of impulse noise (Starck, Toppila, & Pyykko, 2003) below the 140 dB limit. Very few studies have been done on the long-term hearing loss of referees. Jiang (Jiang, 1997) and Nigro & Warrick (Nigro & Warrick, 1996) have reported that referee whistles can be dangerous to hearing, but do not supply any specific limits. Flamme and Williams (Flamme & Williams, 2013) examined in detail the status of sports officials' hearing due to whistle use. A third publication goes into depth about the status of sports officials' hearing status due to whistle use, but recommended acceptable exposure levels are only estimated based on answers to a questionnaire. (Flamme & Williams, 2013). Since we do not have much documentation of how much damage is occurring to referees' hearing, damage risk criteria are applied to the noise to quantify the potential risk involved in prolonged whistle use.

Three types of DRC for impulse noise exist: parameter-based, energy-based, and theoretical ear model-based (Flamme, Liebe, & Wong, 2009). Preliminary calculations, many of which are necessary for some of the DRC that will be implemented, are A, B, C, and D durations; peak levels; octave band spectrum; rise time; and kurtosis. The DRC use different parameters to integrate the effective reverberant contributions (Pfander, Bongartz, Brinkmann, & Kietz, 1980; Pfander, 1994; Smoorenburg, 1982).

MIL-STD-1474D is the current DRC used by the US military to gauge impulse risk, such as weapons fire. MIL-STD-1474D uses the peak impulse level and reverberant decay (B-duration) to determine the permissible number of impulses to which a soldier may be exposed. This DRC was computed with the following formula:

$$N_{exposures} = \frac{time\ alloted}{impulse\ time} = \frac{480_{minutes} * 2^{(85\ - Peak\ Level)/3})}{t_{b_{seconds}} * \frac{1_{minute}}{60_{seconds}}}$$

Here, duration is in the form t_b, and is another method used for capturing the time duration of the impulse. Codes used to compute time durations were supplied by Edward Zechmann from NIOSH, and are available on MATLAB Central File Exchange (Zechmann, 2009). Single and double hearing protection, as well as no protection, can be accommodated in the calculation. Two other parameter-based DRC are used in Europe, developed by Pfander and Smoorenburg. They derived equations for finding the number of allowable exposures that differ only by the type of duration of the impulse. The levels associated with each impulse is used with a Pfander level of for N impulses. (Murphy & Kardous, 2012). Pfander uses C-duration, and Smoorenburg uses D-duration in the following formulas:

$$Pfander\ Level = L_{Peak} + 10Log_{10}(c - duration) + 10Log_{10}(N)$$

$$Smoorenburg\ Level = L_{Peak} + 10Log_{10}(d - duration)\ + 10Log_{10}(N)$$

C-duration is the time-duration from when the level reaches -10 dB prior to the peak of the pulse until it reaches 10 dB again on the decline from the peak. D-duration is the time from the beginning of the impulse until the level drops to within 10 dB of the peak (Brinkmann, 2000). MIL-STD-1474D uses the 20 dB decay of impulse level from the maximum peak sound pressure level, Pfander uses a 10-dB reduction and computes the time that the signal is within 10-dB of the peak level to estimate the C-duration, T_{c}.. Like MIL-STD-1474D, Smoorenburg computes the duration of the impulse envelope that is within 10 dB of the peak level.

The second DRC type is based on the hypothesis that equal amounts of sound energy will produce equal amounts of hearing impairment, regardless of how the sound energy is distributed in time (Atherley & Martin, 1971). The energy-based DRC is a measurement of the equal energy in an 8-hour exposure of continuous noise, notated as L_{eqA8} (Dancer & Franke, 1995; Amrein & Letowski, 2012). The L_{eqA8} figures dictate a level of energy that is permissible for an 8-hour exposure of equivalent continuous noise. Some offices in the United States (such as OSHA) use an 85 dB threshold with a 5 dB exchange rate, but this exchange rate starts to break down at higher frequencies. For 1-3 kHz, 5 dB relates to an average TTS of 15 dB, where frequencies within the 4-6 kHz range follow a 3 dB exchange rate more closely (Smoorenburg, 2003, pp. 1-6). Table 1 shows the acceptable dosage amounts per day. Exceeding 110 dB of equivalent energy in impulse noise for more than 15 minutes over the period of a game will likely bring hearing loss. Given that the

Daily Exposure Limit (Hours)	**L_{eqA} (dB)**
8	85
6	87
4	90
3	92
2	95
1.5	97
1	100
0.5	105
<0.25	110

Table 1: Equivalent Level permissible per hours of exposure (Smoorenburg, 2003).

pulses have durations on the order of a half-second, that would suggest that at a level of 110 dB, 30 pulses would be a limit before hearing trouble would occur. L_{eqA8} has been widely established in the United States and Europe. One equation for the computation of these levels is

$$L_{eqA8} = 10\log_{10}\left(\frac{N_{samples}}{sample\ rate_{samples/second} * 8_{hours} * 3600_{secons/hour}}\right) + 10\log_{10}\left(\frac{\sqrt{\sum p^2}}{\sqrt{N} * {p_{ref}}^2}\right)$$

where N is the number of samples, p_{ref} is 20 µPa, and p is each sample's pressure in Pascals.

The last DRC type is an electric-acoustic model of the human auditory system, and is called the Auditory Hazard Assessment Algorithm for Humans (AHAAH) (Prince & Kalb, 1991). The auditory system has two unique features that may provide some protection against hearing loss when loud sounds occur. One feature of protection is the nonlinearity in the annular suspension of the stapes footplate. Another is the middle ear muscle contraction (MEMC), an autonomic reflex that tightens the muscles of the middle ear (Tensor Tympani and Stapedius muscles).

The auditory system is protected by the annular ligament suspension of the stapes footplate. The stapes connects to the cochlea at the oval window, and the annular ligament connects the stapes footplate to the otic capsule of the cochlea. The ligament acts as a linear spring for small amplitude displacements of the stapes. However, for high-level impulses such as gunshots or explosions, the motion of the stapes becomes nonlinear and the ligament is stretched to its full extent, about 20 microns (Prince & Kalb, 1991).

The second feature of the auditory system is the MEMC, which affects the stiffness of the ossicular chain and reduces the amount of high frequency energy that is transmitted to the cochlea (Pang & Peake, 1986, pp. 36-43). The MEMC is a protective mechanism of the ear, and defends against harmful sound. It is not an instantaneous activation, however, because it takes between 60 and 290 milliseconds after the onset of an impulse to engage (Sułkowski, 1980). In a "warned" condition, this contraction of inner-ear muscles has been engaged prior to the onset of noise, constricting the displacement of the oscillatory bones. The amplitude of displacement is thus decreased for loud noises, resulting in less transmittance to the cochlea, and a reduction in risk of hearing loss when compared to an "unwarned" state. The MEMC theoretically provides up to 30 dB SPL re 20 µPa of protection, and occurs with a force proportional to the sound intensity it receives (Dallos, 1964). However, Fletcher identified that the MEMC may provide only about 10 dB of protection for exposures below 1000 Hz (Fletcher, 1960). According to Price, the referee's middle ear muscles may become conditioned to contract prior to the act of blowing the whistle (Price, 2007).

The AHAAH software package requires that the exposed ear be considered to be in either the unwarned or warned state, to allow for the MEMC (Price & Kalb, 1998). For the exposures due to referee whistles, the nonlinearity of the annular ligament is not expected to come into play. However, the MEMC activates for transient impulses above about 100 to 110 dB, which justifies the application of MEMC in the analyses. The AHAAH model has a mode of analysis for both the warned and unwarned conditions, representing states where the MEMC is or is not engaged prior to the onset of the impulse, respectively. For this model, the neural conduction is allowed 9 ms, followed by 11.7 ms as the contraction rises to its full strength. The equation for AHAAH calculation is compiled in an executable file that allows the user to choose between warned and unwarned states. The program returns a value in Auditory Hazard Units (AHU). For the 5% top most sensitive ear, 500 AHU is the allowable exposure daily limit. The person with median hearing sensitivity (50^{th} percentile) has a limit of 5000 AHU. MATLAB code used to verify the results from the provided AHAAH software. The difference between the results computed with the program provided by the authors of the model and the results from the MATLAB code I executed disagreed by less than 0.257 AHU.

Each DRC presents its own advantages and disadvantages. MIL-STD-1474D specifies a maximum number of daily impulse exposures for various levels, but is criticized as being too conservative, being based on assumptions that lack validation, and building upon an incomplete biomedical database (Amrein & Letowski, 2012; Chan, Ho, Kan, & Stuhmiller, 2011; Leibrecht & Patterson, 1986; Smoorenburg, 2003). Critics of L_{eqA8} say that this method does not account for the shape of the impulse or its spectral content, and thus cannot account for a wide enough range of hazardous exposure conditions (Hamernik, Qiu, & Davis, 2003). The ear-model DRC, AHAAH, is criticized for being less accurate at frequencies greater than 5 kHz. It uses an implementation of adjusting computations for the MEMC in warned subjects, which often leads to conflicting results. While the model claims that the MEMC adjustments have been repeatedly validated, a there are assumptions used within the model are questioned. Limits for safe exposure under AHAAH are based upon the integrated basilar membrane displacement instead of hair cell damage, which is currently believed to be a more important factor in hearing loss. The model has been inconsistent in its computations across several platforms (Davis, Johnson, Talmadge, & Holthouser, 2001). Flamme (2009) sums up the dilemma:

> Some differences between DRC were expected. The Coles-CHABA DRC tends to overestimate auditory risk from exposure to impulses from large-caliber weapons, and the Price-Kalb model was developed in part to explain and correct this error. So relative to Coles-CHABA, the Price-Kalb model was expected to permit more exposures than the Coles-CHABA model. However, the Price-Kalb model showed the opposite effect for

many impulses in this study, indicating greater auditory risk than Coles-CHABA, often by many orders of magnitude.

All of the aforementioned DRC ignore bone conduction, which can intensify hearing damage from low-frequency noise.

Motivation

While soccer, ice hockey, and wrestling use referees with whistles during matches, basketball, volleyball, and football may be of greater concern because these sports may be greater in frequency of whistle use and/or whistle sound intensity required to overcome generally larger crowd nose. Flamme and Williams (2013) found that referee whistles in sport settings produce a-weighted sound pressure levels of up to 116 dB, which is within the range of peak pressure levels found in this study. In order to combat potential loss of hearing, knowledge of the risk related to using whistles will help officials, their supervisors, and people in the vicinity of officials during play. A study at The Pennsylvania State University showed that levels at a football game can reach 110 dB when averaged over intervals of over one second (Mountz, 2007). With already loud levels from crowd noise and sports interactions, additional risk comes from whistle use. As persons involved in whistle use are better informed of the risk of hearing loss due to whistles, improvements can be made to help prevent the loss.

Context

The findings from this study are compared with what is practical and what is known about referees. For example, adding the 15.6 average fouls per game per team for the past season's top 50 college basketball teams (NCAA.com, 2012) with all the many other reasons for starting or stopping play, one could estimate that a whistle sounds over 50 times in a game.

Volleyball matches use two referees and require whistles for starting a rally; ending a rally; substitutions; net, rotation or line violations; and other infractions. Some games have several hundred whistle blows. Several referees have reported hearing loss, but qualitative loss and the impact of whistles on their hearing is not known (Flamme & Williams, 2013).

Methods

A trained basketball referee was given a standard refereeing whistle in a closed, mostly empty high school gymnasium. He was instructed to do short, intense tweets, simulating whistle tweets from a real basketball game. One microphone was placed just over the right ear of the referee, and another microphone was placed 1 meter away, directly in front of the referee. The referee gave 5 short whistle blows about 2 seconds apart for each saved audio file. Twenty-six of these files were recorded at a sampling rate of 44100 Hz and saved in WAV file format. To prevent aliasing errors, the Nyquist frequency (half of the sampling rate) provides a frequency limit for the bulk of the data. Spectral analysis shows that the bulk of the content is between 3 and 5 kHz, well below 22.05 kHz, and for this reason waveform analysis was justified.

The audio files were processed using appropriate formulas for each DRC, Each impulse recording was trimmed to have a uniform starting point relative to a set threshold level before the peak, and the resulting segments were saved as new files. The files were converted from Volts/Pascal to Pascals using the conversion factors supplied by the recorded calibration tone and its level. Ultimately, the data were interpreted in terms of dB SPL, using the standard 20 μPa reference point for 0 dB SPL. Visual inspection and variance calculation of each file would ensure that the variation of calculated DRC between each set of data is low.

Each DRC was applied to each file separately, and the results were saved into a spreadsheet for ease of comparison. 130 independent pieces were analyzed using two separate channels, giving 260 whistle tweets. The number of exposures allowed by each DRC was independently computed for each impulse. For the AHAAH model, the analysis was conducted for the individual impulses and for the collective set of five tweets. In this model, the MEMC is activated when the threshold is reached, but does not disengage as it might in a real ear. In a set of five tweets, the first would be considered unwarned and the rest are analyzed in the warned condition.

Results & Discussion

As shown in Figure 1, the waveform for a typical whistle tweet from the data set is about one second long. The bulk of the content in the tweet happens in the sustained segment of the whistle blow, which in the waveform shown is about 0.15 seconds long. The fast Fourier transform of the data show that the frequency content lies in the 3-5 kHz range. The results from the recording and computation are given in Table 2. Each DRC gives its own range of allowed exposure to the whistle. Mean peak SPL for each channel is given in the first rows of the table.

The maximum level of all the tweets was 132.4 dB. Pfander and Smoorenburg values are drastically different than the rest. This is because those two methods are typically used with higher-level noise. Above 140 dB, the exposure allowances they provide are much closer to those given by equivalent energy, AHAAH model, and military standard measures. The mean value for the Pfander levels was 108.0 dB for the one meter location and 114.5 dB for the ear location. Smoorenburg mean values were 109.1 dB for the one meter microphone and 117.4 dB for the microphone at the ear. These values did not differ by much, which is expected, due to the

Damage Risk Criterion Name	Location	Mean (dB)	Min (dB)	Max (dB)		
Peak SPL re 20 μPa	1 m	119.3	112.8	125.6		
Peak SPL re 20 μPa	ear	125.5	120.2	132.4		
Damage Risk Criterion Name	**Location**	**Mean (dB)**	**Min (dB)**	**Max (dB)**	**Allowable Exposures – all subjects**	
L_{eqA8}	1 m	59.1	52.8	65.9	499.0	
L_{eqA8}	ear	65.4	57.7	73.3	118.0	
MIL-STD-1474D	1 m	119.5	112.5	126.3	61.9	
MIL-STD-1474D	ear	125.1	119.6	132.3	18.4	
Pfander	1 m	108.0	101.5	114.6	2,055,576.6	
Pfander	ear	114.5	107.1	112.5	46,039.6	
Smoorenburg	1 m	109.1	95.9	119.3	837,445.3	
Smoorenburg	ear	117.4	83.8	126.2	193,240.5	
Damage Risk Criterion Name	**Location**	**Mean (dB)**	**Min (dB)**	**Max (dB)**	**Allowable Exposures – median-susceptibility ear**	**Allowable Exposures – most susceptible 5%**
AHAAH Warned	1 m	75.2	10.8	288.8	66.5	6.6
AHAAH Warned	ear	94.0	10.8	521.0	53.2	5.3
AHAAH Unwarned	1 m	95.1	14.8	338.0	52.6	5.3
AHAAH Unwarned	ear	127.0	14.8	684.0	39.4	3.9

Table 2 – Mean, minimum, maximum and allowed exposures for each DRC at 1 meter in front of the official and at the ear

similarity of their equations. When Pfander and Smoorenburg DRC are applied, the allowed number of whistle tweets is high enough to suggest that there is little risk in using a whistle, MIL-STD-1474D, AHAAH, and L_{eqA8} give measures of exposures that may indicate the need for hearing protection.

The mean value for the one-meter location under MIL-STD-1474D is 119.5 dB and the ear location is 125.1 dB. Given these levels are correct, serious risk would come into play after about two to four minutes of whistle exposure. This is the criteria that is known for being more conservative, which explains why this is the more restrictive DRC of the energy-based criteria.

The mean AHU value for the population of impulses with the warned condition is 75.2 AHU for the position one meter in front of the referee, and 94.0 AHU for the position at the ear. The unwarned mean for the 1-meter value is 95.1 AHU, and the ear value is 127.0 AHU. Most referees will be in situations with crowd noise and other noise factors that will more than likely have already engaged the MEMC, and the more practical application here would be the warned state. In that condition, one tweet at 94.0 AHU is fairly high, relative to the 500 AHU limit. Since 25 dB threshold shift at any frequency is considered the limit of tolerable noise, the AHAAH model implies that after 6 whistle blows, the AHU limit for tolerable exposures would be exceeded and the most susceptible 5% of the referee population will experience over 25 dB compound threshold shift (CTS) (Price, 2007). The referee with the median amount of susceptibility will experience CTS after reaching 5000 AHU, or after 54 tweets. While there is not much data to support this conclusion, it seems reasonable. However, the different values presented by the L_{eqA8} DRC are also plausible.

The L_{eqA8} mean level for the microphone one meter away was 59.1 dB and for ear-level was 65.4 dB, which does not even break the threshold of 85 dB used by the other energy-based measurements. If the levels in Table 1 were extrapolated down to 60 dB, there would be 5 doublings of the eight hour threshold, rendering a theoretical total permissible whistle exposure number of 256 impulses. While the exposure limits are not meant to be extrapolated in this manner, the level clearly shows that it takes many more occurrences before hearing damage will likely occur vs. the AHAAH model. However, given that hundreds of whistle blows may occur in a game, it is not improbable for an official to use his whistle at several games in one day and reach or exceed 100 tweets. DRC of these last three types have shown that the risk of permanent hearing loss increases with increased used of whistles above the recommended number of exposures.

Limitations

This study is valid for all users of a whistle without hearing protection. However, the ability to apply the findings found here decreases when other factors are considered. Since the tests were conducted in only one gymnasium, with one official, and only two microphone locations with a single orientation, the results will vary. Since the data were produced by human force, here can be negative effects on repeatability. There was one file that was much lower pressure than the other 259 files. For the purposes of this study in attempting to quantify the hearing damage risk of whistles, that file was not used in computing averages. Other limitations include factors relating to the emptiness of the gymnasium.

The facility was empty at the time of the recordings. In real game situations, crowds can number from a few hundred to a several thousand spectators. However, since the measurements were collected in the one-meter sphere around the referee's head, additional damping from the crowd will marginally affect the primary exposure that the referee receives whenever the whistle is blown. Crowd noise will be more of a factor than crowd dampening. Using the Penn State reference of 110 dB for football crowd noise on the field and the mean level from the whistle blow testing in this study of 125 dB, the contribution of a crowd noise to a whistle tweet becomes simple incoherent addition. First, the sound energy level of the crowd alone is given by:

$$pressure_{crowd}{}^2 = pressure_{reference}{}^2 * 10^{\frac{SPL_{crowd}}{10}} = 20\ \mu Pa^2 * 10^{\frac{110}{10}} = 40\ Pa^2$$

$$SIL_{crowd} = 10 * Log_{10}\left(\frac{Pressure^2}{I_{ref} * (\rho c)}\right) = 10 * Log_{10}\left(\frac{40\ Pa^2}{\frac{1pW}{m^2} * 415\frac{Pa\ s}{m}}\right) = 110\ dB$$

Adding the sound energy level by summing the squared pressures gives:

$$pressure_{whistle}{}^2 = pressure_{reference}{}^2 * 10^{\frac{SPL_{whistle}}{10}} = 20\ \mu Pa^2 * 10^{\frac{110}{10}} = 1265\ Pa^2$$

$$pressure_{crowd+whistle}{}^2 = pressure_{crowd}{}^2 + pressure_{whistle}{}^2 = 40 + 1265 = 1305\ Pa^2$$

$$SPL_{crowd+whistle} = 10 * Log_{10}\left(\frac{{pressure_{total}}^2}{{pressure_{reference}}^2}\right) = 10 * Log_{10}\left(\frac{1305\ Pa^2}{(20\ \mu Pa)^2}\right) = 125\ dB$$

$$SIL_{crowd+whistle} = 10 * Log_{10}\left(\frac{1305\ Pa^2}{\frac{1pW}{m^2} * 415\frac{Pa\ s}{m}}\right) = 125\ dB$$

On a logarithmic scale, an increase from 110 to 125 dB is more significant than it would be on a linear scale. As seen in the derivation, pressure went from $\sqrt{40} = 6.3\ Pa$ to $\sqrt{1305} = 36.1\ Pa$, which is nearly 600% increase in sound pressure.

An additional consideration of the study is that it is assumed that these levels contribute the only noise dosage for the day. Since many officials have additional occupations, especially those for high school events, damage risk increases if any outside exposure adds to the daily allotted levels. Officials will often work at several games a week, and sometimes multiple games per day. The data presented give best-case scenarios for risk of hearing loss.

Conclusions

Damage risk criteria do not agree on a number of impulses needed to produce permanent hearing loss in most people. The allowable number of exposures before permanent hearing loss is likely to occur due to whistle use according to each DRC is represented in Table 2. The results support the previous work done by Jiang, Nigro, and Flamme since all three articles predicted that hearing loss among officials is related to whistle use.

This capstone report contributes to the scientific communities by providing an application of theories to a type of data in a way that has never been recorded. The findings will help officials and those with whom they work better understand the amount of risk that the officials undertake on the job when they use whistles without hearing protection. Actions should be taken to promote hearing protection among referees using whistles.

Appendix

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