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Impulse noise generated by starter pistols

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Abstract

Objective—This study describes signals generated by .22 and .32 caliber starter pistols in the context of noise-induced hearing loss risk for sports officials and athletes.

Design—Acoustic comparison of impulses generated from typical .22 and .32 caliber starter pistols firing blanks were made to impulses generated from comparable firearms firing both blanks and live rounds. Acoustic characteristics are described in terms of directionality and distance from the shooter in a simulated outdoor running track. Metrics include peak sound pressure levels (SPL), A-weighted equivalent 8-hour level (L_{eqA8}), and maximum permissible number of individual shots, or *maximum permissible exposures* (MPE) for the unprotected ear.

Results—Starter pistols produce peak SPLs above 140 dB. The numbers of MPEs are as few as five for the .22-caliber starter pistol, and somewhat higher (≤25) for the .32-caliber pistol.

Conclusion—The impulsive sounds produced by starter pistols correspond to MPE numbers that are unacceptably small for unprotected officials and others in the immediate vicinity of the shooter. At the distances included in this study, the risk to athletes appears to be low (when referencing exposure criteria for adults), but the sound associated with the starter pistol will contribute to the athlete's overall noise exposure.

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Keywords

Impulse noise; starter pistol; noise level; noise exposure; noise-induced hearing loss; sports injury; occupational health and safety; track and field

Athletic events have historically been started by using loud acoustic signals (e.g. track and field races). A trumpet blow was used by officials of the ancient Olympic Games beginning in the sixth century B.C. to start the Stadion (running race). Eventually, firearms replaced the trumpet as the acoustic signal source for a variety of sporting events (e.g. track and field, swimming, speed skating, horse racing). Prior to the widespread ability to rapidly transmit signals through wired or wireless networks, the sound produced by a firearm blast provided a recognizable and brief signal that traveled rapidly for great distances. The signal is purposely chosen to be loud and audible to the athletes, officials, and audience.

The common use of firearms for the purpose of starting sporting events eventually led to the development of starter pistols, a signaling device that replicates the general shape of a handgun but uses only “blank” cartridges (i.e. cartridges containing only combustible material or containing a combination of combustible and non-combustible materials, but no bullet or projectile). The black powder produces smoke that signals the race officials to trigger manual timing devices. The starter pistol has also found use in other contexts where a facsimile and sound of a handgun is desired, such as in television programs, movies, historical reenactments, theatre performances, dog training, and sport dog competitions. A recent search of retail internet sites revealed that more than 55 starter pistol models are available for purchase.

Present day starter pistols are typically designed as a revolver and are fired to start athletic activities such as track and field events, or less commonly, at competitive swimming or speed-skating races. A neon orange plastic barrel tip or handle may be used to visually differentiate a starter pistol from a real firearm. Starter pistols used for athletic events are typically a .22 or .32 caliber. The term “caliber” refers to the size of the internal diameter of the barrel bore or the diameter of the cartridge stated as a proportion of an inch. A starter pistol fires a charged cartridge (blank) and typically has a blocked barrel that prevents firing a projectile (bullet or shot). The explosive material is typically black powder or nitrocellulose. The “go” shot is fired by the athletic official who is instructed to hold the pistol extended at arm’s length above the head. Often a bright protective cloth sleeve is worn for visibility at a distance and to shield the arm from discharged residue.

The U.S. Bureau of Labor Statistics (Department of Labor, 2011) reported 15,630 individuals are employed as “umpires, referees, and other sports officials.” However, these numbers would largely reflect the numbers of people who reported that their primary occupation was to be a sports official. The officials at most amateur sporting events normally perform their duties as a secondary occupation or volunteer. The National Association of Sports Officials (NASO) reports 19,000 members worldwide. Neither the Department of Labor (DOL) nor the NASO can provide a numerical breakout by sport. As one of the top four states for sports official employment, the Colorado High School Activities Association (CHSAA) reported a total of 5215 officials state-wide; 272 officials for track and field and 131 for swimming sports (M. Tillman, personal communication, May 23, 2012). In comparison, Wisconsin has 463 track and field sports officials (P. Murphy, personal communication, June 4, 2012) and is the state with the second highest sports official employment rates after California.

Since the acoustic signal is subject to the physical laws of nature (i.e. the speed of sound), the reaction time of the athletes is influenced by the signal timing and intensity arriving at the ear of the athlete. Quicker reaction times (RT) are advantageous in highly competitive running sports. Brown et al (2007) investigated the relationship between the “go” signal intensity and reaction time in the 2004 Olympic Games and experimentally in 16 college athletes during a sprint start. Olympic reaction times for the sprint events were obtained from the International Association of Athletics Federations (IAAF) archives and analysed as a function of lane 1–8 position. Runners in lane 1 had significantly lower RT (150± 26 ms) compared to all other lanes (range, 171–185 ms). In order to investigate the influence of signal intensity on reaction time, a controlled experiment was conducted with collegiate sprint runners. A microphone was placed beside a trumpet horn and used to record the onset time of the “ go ” signal. Strain gauges were placed in series behind the starting blocks and peak horizontal force calculated for the period between the “set” and “go” signal and for the period after the “go” signal. RT was calculated as the difference in time between the two peak horizontal force measurements. The “go” signal intensity was experimentally increased from 80–100–120 dB and RT decreased from 138±30 ms to 128±25 to 120±20 ms, respectively. Brown et al were able to demonstrate that runners positioned closest to the starters received a higher intensity “go” signal and had significantly shorter reaction times than those further away, thus providing an unfair advantage for some athletes as a function of lane position for the start of the race.

Today’s Olympic officials utilize a modern “starting pistol” that is plugged directly into the timing system and initiates the electronic timing chain when the trigger is pulled. The gunshot sound is routed to loudspeakers behind each athlete to ensure an equal opportunity to hear the start signal. For non-Olympic sports venues, electronic start systems are available. These battery-operated devices are wired to a megaphone and broadcast the starting signal to the athletes. These devices also produce a red strobe flash for visual timing. Specifications for at least one commercial product used for swim sports indicate a loudspeaker output of “120 decibels” (International Sports Timing, Grand Rapids, USA).

Various organizations generate the rules governing the start of track and field races including the National Federation of State High School Associations (NFHS), the National Collegiate Athletic Association (NCAA), and the IAAF. The NFHS rules state that indoor and outdoor meets using fully automatic timing (FAT) may be started by a .32 or .22 caliber starter pistol (closed-barrel) or an electronic (gunless) device for record purposes (NFHS, 2011). A .32 caliber pistol is recommended for outdoor venues and a .22 caliber is recommended for indoor venues. There are no pre-assigned start positions for starters and assistant starters at NFHS events. The starters are required “…to position themselves to fairly observe the start of each race. Positioning should minimize the exposure of competitors, officials, and spectators to the report of the starting device” (p. 79). Starter pistols may also be fired at other times during high school track and field events and by more than one individual (recall starters). The official may fire the pistol to signal the last lap for the runners or to stop and recall a race. In these instances, the starter may be in the middle of the track and potentially positioned closer to the athletes if they are running past the shooter at that point in time.

For 2011/2012 NCAA track events:

> All races shall be started as a result of the starter activating a simultaneous audible and visible signal. The report of a pistol that can be cocked, not less than .32 caliber, or an electronic tone of at least 112 dB at 15 feet, together with the flash/smoke generated by the pistol, or an electronic flash/strobe, clearly visible to the timers, shall be used. A misfire shall not be a start. A .22-caliber pistol may be used at indoor events (NCAA, 2010, p. 70).

The IAAF rules state that “All races shall be started by the report of the Starter’s gun held upwards” (IAAF, 2012, p. 144). The “gun” in this case may refer to either a traditional starter pistol or an approved electronic starter.

Impulse Sound Generation

The propellant is the primary source of the sound impulse generation from firearms. When a propellant is ignited, a three-step transformation of chemical energy occurs: (1) a chemical propellant converts to a gas, (2) a thermodynamic driven motive-power (heat to mechanical energy) is released, and (3) then physical energy in the form of hot gases pushes the projectile which releases energy that produces torque and recoil due to the reactive force and friction between the barrel and the projectile (Rinker, 2005). As the hot gases expand in the chamber, increased pressure pushes the projectile down the barrel and out of the muzzle. Multiple acoustic events may occur; the primer ignites the powder behind the projectile, the powder ignition produces the muzzle blast in the chamber and as the gases expand out of the muzzle; supersonic projectiles produce a shockwave with a characteristic N-wave heard as a sharp audible “crack.” A number of variables can impact the impulse acoustic characteristics including firearm make and model, ammunition type, barrel length, and muzzle brakes or ports. In the case of starter pistols, a blocked barrel eliminates the muzzle blast sound source from an open barrel and requires the high-pressure gases to find alternative routes of escape. Additionally, there is no projectile and therefore the supersonic source is also eliminated.

Risk of Injury

The terms *hazard* and *risk* are often used interchangeably, but they refer to different concepts. For the purpose of this paper, the term *hazard* is used to indicate a sound that is a potential source of auditory system damage. The term *risk* was used to quantify the likelihood of harm. Knowledge of the risk posed by a hazard informs the development of *damage-risk criteria*, (DRC) which are used to derive the limits of exposure necessary to reduce the probability of a noise-induced hearing loss of a given magnitude (e.g. a 25 dB permanent threshold shift) for a specified proportion of the population (e.g. the least susceptible 95%), with a known certainty (e.g. 95%). For brief signals such as starter pistol impulses, the DRC permit the transformation of signal parameters into a number of individual shots or maximum permissible exposures, or MPE. MPEs represent the limits beyond which a greater amount of hearing loss, in a portion of the adult population, or in instances of less than 95%, certainty would be expected.

Handgun weapons firing blanks are often presumed to be inherently harmless and eliminate the risk of injury and/or death from a bullet or other projectile. Starter pistols are largely unrestricted in terms of sale and carry for adults over the age of 18 years (Giese et al, 2002); however, local regulations may vary. In reality, blank cartridge handguns fired at a close distance are capable of inflicting serious or lethal injury (Buyuk et al, 2009; Jacob et al, 1990; Giese et al, 2002; Rothschild et al, 1998b; Rothschild & Vendura, 1999). In addition, acute acoustic trauma as a result of impulse noise exposure from weapons firing blanks has been reported (Fleischer et al, 2003; Savolainen et al, 1997). U.S. President and well-known movie actor, Ronald Reagan, provided a televised public service announcement in 1990 discussing his hearing loss as a result of acoustic trauma from firing blanks with a firearm (without wearing hearing protection) while acting in a movie production.

The auditory hazard is seldom recognized for the starter pistol operator and people nearby as compared to an open barrel “real” firearm of the same caliber and barrel length. However, there is a potential for a starter pistol to produce more sound pressure (and therefore more auditory hazard) than a real firearm with the same dimensions and combustible material. This is because none of the energy released through combustion is converted into the kinetic energy of a projectile, which accounts for approximately 3–40% of the chemical energy contained in the propellant (Warlow, 2005). In addition, sound levels may also be increased due to the use of plugged barrels, short barrels and open chambers/cylinders in starter pistols.

Impulses from firearms are often described in terms of instantaneous peak sound pressure levels (SPL). In order to prevent cochlear damage and resultant noise-induced hearing loss (NIHL) from impulse sounds, the World Health Organization (WHO) recommends an unprotected limit of 140 dB peak SPL for adults and 120 dB SPL for children (WHO, 1999). Multiple U.S. government agencies, including the National Institute for Occupational Safety and Health (NIOSH, 1998), the Occupational Safety and Health Administration (OSHA, 1983), the Mine Safety and Health Administration (MSHA, 1999), the Federal Railroad Administration (FRA, 2007), and the Department of Defense (MIL-STD-1474D,1997) reference a limit of 140 dB peak SPL for adults. The European Union Directive 2003/10/EC (2008) also limits exposure at 140 dB C-weighted. Internationally, 120–140 dB peak SPL limits (weighted or unweighted) are referenced in the international occupational noise exposure standards for Australia, Brazil, Chile, Columbia, India, Israel, Netherlands, New Zealand, United Kingdom, and Venezuela (Suter, 2007). Peak levels from firearms shooting projectiles usually exceed these limits for both the shooter and the bystander (Flamme et al, 2009b, 2011; Kardous et al, 2003; Murphy & Tubbs, 2007; Odess, 1972, Ylikoski et al, 1995, and the current authors’ unpublished data, 2012). In recent studies, mean peak levels for firearm impulses ranged from 141–167 dB SPL at the shooter’s ear and at a bystander position to the left of the shooter for a subset of civilian firearms and ammunition, (Flamme et al, 2009b, 2011). Rothschild et al (1998a) reported the peak sound pressure levels from 15 different models of starter pistols at four azimuths (0° shooting direction, 45°, 90°, and

180°) and four distances from the muzzle (25 cm, 50 cm, 100 cm, and 200 cm). All weapons exceeded 160 dB peak SPL at a distance of 1 meter and in the 0° shooting azimuth.

An alternative equivalent-energy approach may also be used to describe the sound hazard from impulse noise in terms of L_{eqA8} (Atherley & Martin, 1971). This criterion is based upon filtering the acoustic signal to approximate the transfer function of the human ear at 40 phons and integrating the energy over time. Most regulatory agencies utilize this approach for establishing the 85 or 90 dBA time-weighted average (TWA) permissible noise exposure limits for both continuous and impulsive noise sources in the workplace (NIOSH, 1998; OSHA, 1983). There is no specific DRC developed for application to children.

Motivation for the current study came from an inquiry from a high-school track and field official advocating for the use of safer means of starting races than the traditional starter pistols. This official was interested in addressing concerns expressed by the physician director of the state-level athletic association, and the lack of peer-reviewed evidence indicating that starter pistols are potentially hazardous to the official and/or student athlete. A series of three experiments were conducted to further explore the acoustic properties and risk of NIHL from starter pistols. Specifically, (1) acoustic directionality was measured for two .22 caliber starter pistols; (2) acoustic comparisons of the impulses generated from typical .22 and .32 caliber starter pistols firing blanks were made to impulses generated from comparable caliber revolvers firing both blanks and standard-velocity live ammunition and (3) a simulated track and field measurement for both a .22 and .32 caliber starter pistol.

One purpose of this research effort was to evaluate the sound levels produced by starter pistols and assess potential auditory hazard to the shooter or to people near the sound source. A variety of procedures are available for examining auditory risk (i.e. the probability of harm resulting from a hazardous exposure), ranging from early methods relying on the empirical relationship between changes in human hearing and (1) the fine structure of the impulse stimulus (e.g. Coles et al, 1967), (2) the overall (i.e. integrated) impulsive sound energy (e.g. Dancer, 1982; Smoorenburg, 2003), and (3) models estimating the type and degree of mechanical motion produced by the impulse (e.g. Price, 2007). Based on recent evaluations of a variety of DRC for impulsive noise (Murphy et al, 2009, 2011) and based on the observation of strong correlations among the DRCs (Flamme et al, 2009b), the study adopted the use of integrated impulsive sound energy as our metric of auditory risk for the purposes of this paper. The maximum allowable level used for this paper is 85 dBA L_{eq} in accordance with a well-known standard of this type (Direction Technique de Armements Terrestres (DTAT), 1983). Interested readers may wish to consult Flamme et al (2009a) for further explanation of the various DRCs as applied to adult subjects.

Methods

Design

Firearms—A total of five pistols (revolver style) were used for the various experiments; three blocked-barrel starter pistols and two comparable open barrel pistols. The three models of starter pistols were the .22 caliber Precise International "Champion", the .22 caliber Kimar Model 314, and the .32 caliber Harrington & Richardson (H&R). The two open-barrel pistols were the .22 caliber Smith & Wesson K-22 Masterpiece and the .32 caliber H&R. The ammunition used is noted within each experimental description. The shooter and researchers utilized hearing protection while conducting the impulse measurements.

Instrumentation—For these experiments, impulse recordings were made using 0.125-inch prepolarized pressure calibrated microphones (G.R.A.S. Type 40 DD or Type 40 DP) with an approximate sensitivity of 1 mV/Pa and oriented at grazing incidence to the sound source. These microphones offer a useable frequency range up to 140 kHz and a dynamic range extending to 186 dB peak SPL. The microphones were equipped with 0.25-inch preamplifiers (G.R.A.S. Type 26AC) capable of carrying the potentially large signals without overload or slew rate limitations. The power to the front end equipment was supplied by two 2-channel constant voltage power modules (G.R.A.S. Type 12AA) with adjustable gain (+20, 0, −20, and −40 dB) and providing a dynamic range of ±42 V. Finally, a National Instruments data acquisition system based on the PXI-6120 module permitted simultaneous sampling data acquistion for each channel. This module allowed simultaneous 4-channel data recording with 800 kHz sampling rate, with data stored in a 64 Msample on-board data buffer that was set-up to record 50 msec of data before the trigger with a total data length of 0.5 sec. The data were sampled with 16 bit resolution, giving a 90-dB spurious-free dynamic range. The data acquisition process was controlled by a custom LabView program with an integrated calibration routine and trigger control. The data were saved in text files for post-processing and analysis in MATLAB.

Three experiments were conducted using the same equipment; yet slightly different methodology was employed for each. The three experiments were designed to (1) explore the directionality of the .22 caliber starter pistols shooting blanks, (2) compare the .22 and .32 starter pistols with .22 or .32 open barrel revolvers, and (3) describe the sound levels when measured from selected positions for a simulated sprint track event.

Directionality experiment

The directionality of the noise emitted from the .22 caliber Kimar Model 314 and the .22 caliber Precise International “Champion” starter pistol was measured by placing four microphones equidistant in a 50 cm radius circle around the tip of the blocked barrel at a height of 1.6 metres from the ground. Five shots were fired with the firearm held horizontally with only the shooter’s arm extending into the measurement circle (see Figure 1). The ammunition was .22 Winchester short black powder blanks.

Comparison experiment

This experiment evaluated the differences in peak SPL and L_{eqA8} at various spatial locations for the .22 and .32 caliber starter pistols shooting blanks, as compared to equivalent caliber open barrel revolvers shooting blanks and live round ammunition. The primary microphone location was the shooter’s left ear. The remaining three microphone locations were at 10 cm adjacent to the left of the chamber, 10 cm adjacent to the left of the muzzle, and 10 cm adjacent to the left but 1.5 m downrange from the muzzle. The end of the blocked barrel of the starter pistol is referred to as “muzzle” in subsequent text for ease of reference with open-barreled firearms.

The four firearms utilized in this experiment were the .22 caliber Kimar Model 314 starter pistol, the .22 caliber Smith & Wesson K-22 Masterpiece revolver, the .32 caliber H&R starter pistol, and matched revolver. The blank ammunition consisted of .22 caliber Winchester SuperX Short Blank Black Powder X225B or .32 Smith & Wesson Blank Black Powder 32BL2P as appropriate for the respective firearm. The K-22 Masterpiece was fired with three types of ammunition; the same .22 caliber Winchester SuperX Short Black Powder blank cartridge as used in the starter pistol and two bullets (.22 CCI long rifle and .22 Winchester short). The .32 caliber H&R was fired with two types of ammunition; the same .32 caliber Smith & Wesson Blank Black Powder cartridge as used in the starter pistol and Winchester SuperX Smith & Wesson 85 Grain Lead Round Nose. Five shots were fired for each of the firearm/ ammunition combinations.

Simulated athletic sprint track experiment

Microphones were placed at the standing shooter's right ear (right handed shooter) and the lane center equivalent of lanes numbered 1, 4, and 8 of a regulation sized running track. Track microphones were at a height of 65 cm to correspond with ear-level of a runner in the traditional sprint start position. The shooter was placed at three locations to simulate starter/ recall positions for high school sprint events (see Figure 5, positions A and B) and provided acoustical comparison for distance variation. Shooter position A was located 10 m in front of the runners and 0.5 m from the track edge. Shooter position B was located in line with the runners and 3 m from lane 1 inside edge. A third shooter (see Figure 5, position C) was created to evaluate the sound levels for a position 10 m towards the inside of the track oval at a greater distance from the athletes. The shooter's ear microphone was positioned at ear-level at a height of 1.67 m. Two calibers of starter pistols were utilized. The .22 Kimar Model 314 was fired with 22 Winchester SuperX Short Blank Black Powder X225B blank ammunition. The .32 H&R starter pistol fired .32 Smith & Wesson Blank Black Powder 32BL2P blanks.

Analysis

The impulse text data were post-processed afterward in National Instruments DIAdem software with subequent transfer and scaling into Pascal (Pa) units using MATLAB software routines originally developed in the NIOSH Taft Laboratories (Zechmann, 2012). Peak sound pressure levels and dB L_{eqA8} were calculated and reported as the mean of the five shots for each measurement condition. Maximum permissible exposures were determined using an 85 dB L_{eqA8} criterion (DTAT, 1983) via the following equation:

$$\mathrm{MPE}=10^{\frac{(85-\mathrm{dBL}_{\mathrm{eqA8}})}{10}}$$

where MPE represents the maximum number of permissible exposures (unprotected), and dB L_{eqA8} represents the mean level produced in the measurement condition. Non-integer MPE values were converted to integer values via truncation.

Results

Directionality

The peak SPL results of the directionality experiment for the two .22 caliber starter pistols (Precise International "Champion" and Kimar Model 314) are summarized in Figure 1. Peak levels exceed 164 dB SPL for both firearms at all measurement positions. Peak levels for the .22 Precise International "Champion" starter pistol were higher than the .22 Kimar Model 314 for all azimuths with the exception of the 0° or muzzle direction. There appeared to be negligible directionality effect for the .22 Kimar Model 314 as all peak SPL values were within 1.4 dB. Some directionality was evident for the .22 Precise International "Champion" starter pistol; peak SPL measurements to the rear and left were ~5.6 dB higher than the muzzle forward position.

Comparison experiment results

Sound pressure levels at the shooter's ear are most relevant in terms of risk of acute acoustic trauma. For comparative and illustrative purposes, one representative shot from each .22 caliber firearm and ammunition condition recorded at the shooter's left ear microphone is presented in Figure 2 (A–D). All axes in this figure are scaled identically to simplify comparison. The .22 starter pistol shooting blanks generated the highest peak pressure at 166.4 dB peak SPL (Figure 2, A) and the .22 K-22 Masterpiece revolver firing the same blank cartridge has the lowest peak pressure at 146.5 peak SPL (Figure 2, B). Peak pressures ranged from (≈154–157 dB peak SPL) when live ammunition was fired from the .22 revolver.

The peak SPL measured at the chamber/cylinder microphone was 22.5 dB higher for the .22 starter pistol shooting blanks than for the .22 revolver firing the same ammunition (Table 1). The blocked-barrel design of the .22 starter pistol may contribute to this substantial difference since the explosive gases are released at angles somewhat perpendicular to the direction the starter pistol is pointed, and this moves the sound source closer to the shooter's ears and allows the resulting acoustic wave to reach the person's ears with less diffraction required. At the shooter's ear position, sound levels are 16.9 dB higher for the starter pistol shooting blanks as compared to the K-22 revolver shooting the same blank ammunition. When shooting two different types of .22 caliber ammunitions, the peak SPLs do not vary more than 3.6 dB. At a position 1.5 metres ahead of the muzzle, peak SPLs ranged from 154.0 to 158.9 dB and were approximately 3–5 dB higher for blank cartridges than for the .22 CCI long rifle and Winchester shorts. The SPLs were as much as 5.1 dB higher at the muzzle for the starter pistol when compared to the K-22 revolver shooting blanks or live rounds. For live .22 ammunition, peak SPL differences ranged between 0.7 to 3.6 dB depending upon measurement location.

For the .32 starter pistol, the peak SPL values were lower than the values obtained for the .22 starter pistol at the shooter's ear, essentially equivalent at the side of chamber location and downrange from the muzzle, and higher for the left of muzzle location. Peak levels at the shooter's ear were 6.4 dB higher for starter pistol impulses compared to the .32 revolver shooting identical blank ammunition. At the position 10 cm to the left of the chamber, the .

32 starter pistol had a peak SPL 13.0 dB higher than the same position for the .32 revolver shooting the same blank ammunition. A 0.5 to 4.5 dB difference was evident for the two different types of live .32 caliber ammunition across all measurement locations.

The potential for the higher peak SPLs at the shooter's ear and to the side of the chamber for starter pistols can be appreciated by closely examining the design differences between the firearm types in Figure 3 and the gas escape patterns in Figure 4. Note the gap between the cylinder and the barrel for the .22 Kimar Model 314 starter pistol in the top panel and the essentially "open" cylinder for the .32 H&R starter pistol in the middle panel as compared to the tight cylinder design for the .32 H&R revolver in the bottom in panel. The open cylinder, closed barrel designs result in gas (and sound) radiation to the side and back as opposed to the front for an open barrel design.

Integrated A-weighted levels were 77.3 dB L_{eqA8} for the Kimar .22 starter pistol and 73.0 dB L_{eqA8} for the .32 Starter pistol at the shooter's ear (Table 2). The L_{eqA8} was highest for the Kimar .22 when measured 10 cm to the side of the chamber (91.6 dB) and lowest in front of the muzzle (69.6 dB). For the .32 Starter pistol, the L_{eqA8} was highest for the 10 cm to the side of the muzzle position (93.2 dB) and lowest in front of the muzzle (71.2 dB). The .22 and .32 starter pistols shooting blanks had L_{eqA8} levels that exceeded the same condition when shooting open-barreled firearms with either blanks or live ammunition. Levels (dB L_{eqA8}) near the chamber were greatest, followed by the levels at the muzzle, the shooter's ear, and those observed 1.5 m downrange.

The MPEs near the sound source for the same experimental conditions are summarized in Table 3. It becomes apparent that MPEs are reduced for exposures to the side of the chamber and muzzle and greatest for the shooter's ear, with the exception of both the .22 and .32 starter pistols. In some conditions the MPE is zero and no unprotected exposure should occur.

Sprint track simulation

The sprint track setup experiment results are summarized in Figure 5. These findings suggest that with the shooter at an acceptable NFHS appointed start or recall position, both the shooter and the nearest athlete positions exceeded impulse noise limits as specified by NIOSH (140 dB SPL_{peak}) and all positions exceeded the WHO (120 dB SPL_{peak}) limit for children. Peak levels are highest for the sports official positions (Figure 5, A–C). Minimal differences (<3 dB) are evident when comparing the .22 and .32 starter pistol peak levels regardless of measurement location.

Analyses of the equivalent continuous levels at the athlete positions identified in Figure 5 revealed levels ranging between 46 and 60.5 dB L_{eqA8}, with greater levels observed at athlete positions nearer the sound source (Table 4). Using an 85 dBL_{eqA8} maximum allowable exposure level, the numbers of MPEs ranged between 283 (position B, lane 1) and 7943 (position C, lane 8) and are summarized in Table 5. Shooter ear-levels ranged from 70.71 to 73.88 dB L_{eqA8} and remained generally consistent across firearms and track positions. For the starting official position A, unprotected MPEs ranged between 12 and 26 shots. More shots are permitted when firing the .32 caliber starter pistol as compared to the .22 caliber starter pistol.

Discussion

This study was conducted to evaluate the assumption that starter pistols are intrinsically safe for users (sports officials), spectators, and athletes in sporting events. Starter pistols (.22 and .32 caliber) were examined with respect to the directional characteristics of the impulse noise they generate when fired (Experiment 1), their sound emissions relative to comparable firearms (Experiment 2), and the degree of exposure produced for the shooter and athletes at three shooter positions on a simulated sprint track (Experiment 3).

The two starter pistols used in the directionality experiment exhibited similar characteristics. When measurements were centered on the apparent muzzle end of the starter pistol barrel, it appeared that more sound was directed back toward the shooter. However, if peak levels were adjusted for the distance between the muzzle and the lateral end of the firing cylinder (centered on the firearm), the levels observed would likely be similar in all directions—and might suggest essentially spherical propagation at distances of 50 cm and beyond. The small difference in length between the tip of the barrel and the physical “center” of the pistol are significant when measuring levels in the near-field. Figure 6 illustrates the orientation of the starter pistol during starter official firing and the elevation of the pistol above and angled away from the athletes provides for the sound source escaping from the chamber area and radiating back towards the shooter’s ear.

Starter pistols produce more sound at the shooter’s ear than normal open-barrel guns firing either live ammunition or blanks. The magnitude of the difference varied with caliber, with a greater difference and level at the shooter’s ear for .22 caliber cartridges. However, the levels 1.5 m downrange and beside the exit chambers were nearly identical across calibers of starter pistols. While the differences between these starter pistols is likely due to the design characteristics of the individual models used in this study, these findings suggest that lower sound levels should not necessarily be expected from smaller-caliber starter pistols. This is important when considering the suggested use of .22 caliber starter pistols for indoor sporting events.

As expected, based on the comments of Warlow (2005), sound levels downrange of open-barreled guns were lower when a projectile (i.e. bullet) was fired because of the energy expended to accelerate the projectile. However, sound levels at the shooter’s ear and to the side of both the cylinder and muzzle tended to be higher when live ammunition was used. It is possible that this finding stems from the exclusive use of revolvers in this study. The projectile is accelerated due to the pressure differential across the bullet. As the rear end of the projectile passes through the gap between the cylinder and barrel in the revolver, the pressure might be more easily able to escape through the gap than to continue propelling the projectile down the barrel, and this could lead to greater sound levels to the side of the firearm. However, it is possible that this result will not be observed in firearms without a cylinder gap (e.g. single-shot or semi-automatic action firearms).

The numbers of maximum permissible exposures (without protection) near the shooter (Tables 3 and 5) confirmed that unprotected ears of a shooter firing a starter pistol are likely to be at an elevated risk of noise-induced hearing impairment. At the shooter's ear, a maximum of five to twelve unprotected .22 caliber starter pistol exposures per day would be allowable. This number of permissible shots could be exceeded during routine track and field events at both the high school and collegiate level. Track events with a larger number of races and a greater number of heats would create a more hazardous exposure condition for the official. False starts or timing recalls would further increase the auditory risk for an unprotected official.

Peak sound pressure levels measured at athlete positions exceed the WHO criteria of 120 dB for both the .22 and .32 caliber starter pistols. When measured outdoors, the numbers of maximum permissible adult exposures in the simulated track experiment suggest that athletes are at a low risk for NIHL at the static starter locations included in this experimental design. However, spectators near the starter are at a substantially elevated risk for hearing loss if hearing protection is not used. Athlete risk may also be different depending on their position relative to the pistol when fired for last lap or recall signals. Clinical reports of hearing loss as a result of a single impulse exposure from a firearm shooting blanks have been reported in the literature; however, none of these reports involved exposure at an athletic event (Fleischer et al, 2003; Savolainen et al, 1995). It may also be worth considering that the MPE calculations are based upon research outcomes with adult subjects and were not designed with specific application to ears of younger children. There are no impulse DRC developed specifically for the young ear. Recent animal research with non-impulsive noise suggests that a young noise-exposed group may demonstrate accelerated "age-related" hearing loss in later life when compared to a non-noise exposed group (Kujawa & Liberman, 2006). The amount of "material" hearing impairment may also differ when considering adult versus child listeners. Consequently, it is difficult to ascertain an absolute safe level for impulse exposure for youth and a more conservative approach may be warranted.

Officials using starter pistols are advised to utilize hearing protection in both ears while firing the pistol. Electronic and newer designs of non-linear attenuation hearing protection may be advantageous for persons firing starter pistols and for individuals positioned near the official. Non-linear devices, such as the E·A·R® Combat Arms, are advantageous in terms of enabling communication while affording protection from impulse signals (Murphy et al, 2012). Electronic hearing protectors may also be used with radio communication systems via a direct input jack. School systems or other employers of sports officials may be obligated to provide a comprehensive hearing conservation program including noise measurement, noise control, employee training, hearing testing, and hearing protection program components per OSHA 29 CFR 1910.94 or European Union Directive 2003/10/EC (note: other international regulations may also be relevant). Officials using starter pistols are advised to have their hearing routinely monitored and their hearing protectors fit-tested to assure adequate and on-going protection from impulse noise.

The sound pressure levels produced by starter pistols measured in this study are excessive for the purpose of signaling the start of a sporting event. The level recorded at Position A

(Figure 5) for the .32 caliber H&R starter pistol shooting blank ammunition was 165.0 dB peak SPL at the shooter's ear. Based on the inverse square law, the athlete would have to be 90 metres away from the starter in order for the peak levels to be <120 dB SPL and avoid exceeding the WHO impulse exposure limit for children. Adult support staffand bystanders would need to be 8 metres away from the starter in order for peak levels to be <140 dB SPL and avoid exceeding the WHO impulse exposure limit for adults.

The study results confirm that there is a need for hearing protection for the starters as recommended by the NCAA (Kleeman, 2008; Zemper, 2009). However, these findings illustrate that the need for hearing protection extends to people situated within 8 metres (adults) or 90 metres (youth). These distances would be impractical in terms of establishing a perimeter around a starter for a typical athletic event attended by persons of all ages. Additionally, the use of open-barreled pistols as suggested by Zemper (2009) does not eliminate the risk of acoustic trauma and creates additional challenges in terms of weapons permits and the physical presence of a firearm on school properties. Therefore, the use of alternative starting devices may be warranted to minimize the risk to the shooter, athletes, and nearby bystanders during athletic events.

The measurements made in these experiments were conducted outdoors in an environment having no significant reflective surfaces except the ground. While the peak SPL values would be expected to remain similar in an indoor environment, the integrated energy levels (dB L_{eqA8}) can be expected to increase, and therefore the numbers of permissible exposures can be expected to decrease. Given the sound levels produced by starter pistols, their use for indoor events or when there are acoustically reflective surfaces nearby is of particular concern. Additional research in indoor athletic venues is needed.

Summary

The impulsive sounds produced by starter pistols are hazardous to the shooter and others in the immediate vicinity of the shooter. The maximum permissible number of individual shots or MPE are unacceptably few for an unprotected official (shooter). Binaural hearing protection is recommended for the shooter and any nearby event staff. The hearing protection device should afford audibility and provide adequate attenuation for impulse noise. Although the starter pistol can be hazardous and the sounds they produce are excessive for the intended purpose of signaling the start of an event, it does not appear likely that people more than 3 m from the starter would be exposed to enough impulses to exceed the MPE (for adults) used in this study (dB L_{eqA8}). At the distances included in this study, the risk to athletes appears to be low (when referencing adult MPE criterion), but the sound exposure associated with the starter will contribute to the athlete's overall noise exposure. The peak levels of starter pistol impulses exceed the 120 dB peak level limit advocated by the WHO for youth when measured at the simulated athlete positions. The use of starting devices with lower level signaling would be necessary to avoid exceeding the 120 dB WHO limit for impulse noise for youth.

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Abbreviations

CHSAA	Activities Association
cm	Centimetre
dB	Decibel
dB L_{eqA8}	8-hour equivalent continuous level, A-weighted
DoD	Department of Defense
DOL	Department of Labor
DRC	Damage risk criteria
DTAT	Direction Technique de Armements Terrestres
EU	European Union
FAT	Fully automatic timing
FRA	Federal Railroad Administration
H&R	Harrington and Richardson
IAAF	International Association of Athletics Federations
L_{eq}	Level equivalent
L_{eqA8}	A-weighted equivalent 8-hour level
m	Metre
MPE	Maximum permissible exposure
ms	Millisecond
MSHA	Mine Safety and Health Administration
NASO	National Association of Sports Officials
NCAA	National Collegiate Athletic Association
NFHS	National Federation of High School Associations
NIHL	Noise-induced hearing loss
NIOSH	National Institute for Occupational Health and Safety
OSHA	Occupational Safety and Health Administration
Pa	Pascal
RT	Reaction time
SPL	Sound pressure level

WHO	World Health Organization
TWA	Time-weighted average

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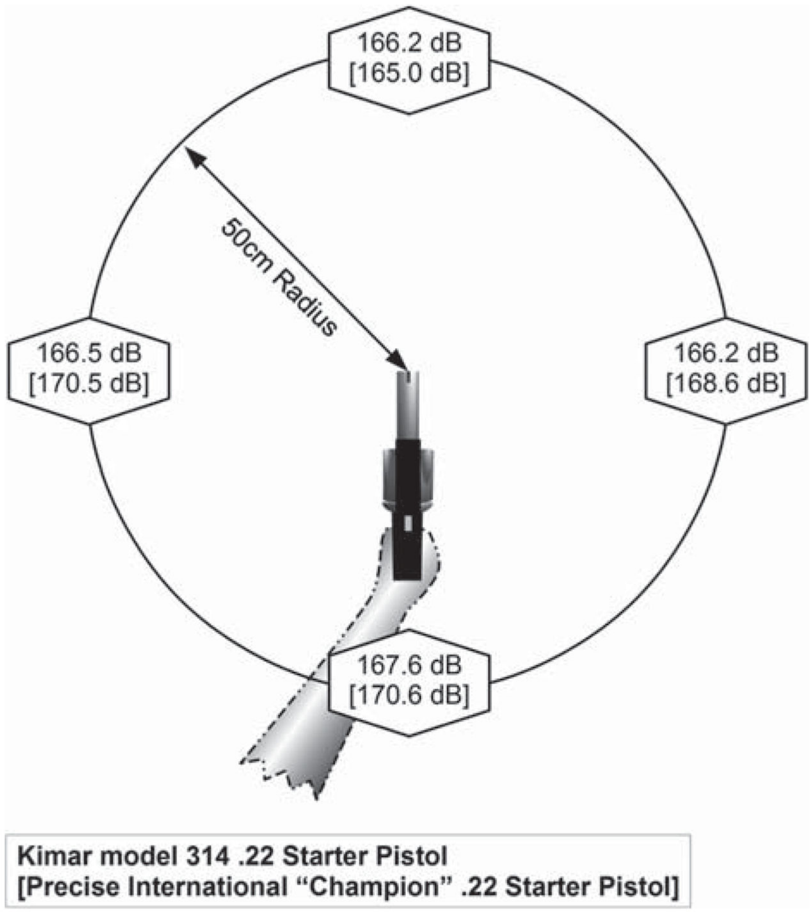

Figure 1.
Directionality experiment. Experimental setup and mean peak SPL results for two .22 starter pistols as viewed from above.

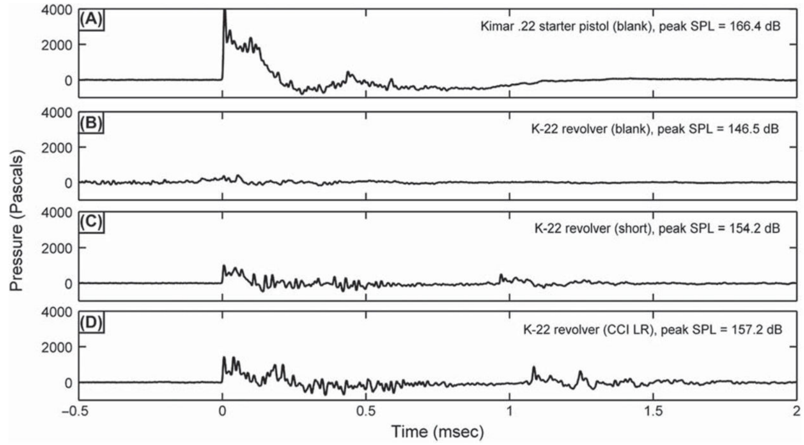

Figure 2.

Composite waveforms recorded from the shooter's left ear. Panel (A) Kimar .22 starter pistol firing Winchester blanks; (B) K-22 Masterpiece firing Winchester short blanks; (C) K-22 Masterpiece revolver firing Winchester shorts; and (D) K-22 Masterpiece revolver firing CCI Long Rifle ammunition, Sound pressure levels and L_{eqA8} are discussed in the text and summarized in Tables 1 and 2.

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Figure 3.

Side view of Kimar .22 starter pistol (top), H&R .32 starter pistol (middle), and H&R .32 revolver (bottom). Circled areas highlight the space between the cylinder and the barrel. In combination with a blocked barrel, the Kimar .22 and H&R .32 starter pistols have a significant gap between the cylinder and barrel, yielding a pathway for gasses to exhaust to the side. The H&R revolver has a very tight fit of the cylinder and the barrel, yielding negligible gap.

Figure 4.
Picture of .32 H&R revolver (top panel) and .32 H&R starter pistol (bottom panel) both firing blank cartridges. The pattern of gas escape as evidenced by the black powder smoke is to the front for the open-barreled revolver and to the sides for the starter pistol. These images have been contrast-enhanced to increase visibility of the black powder smoke pattern.

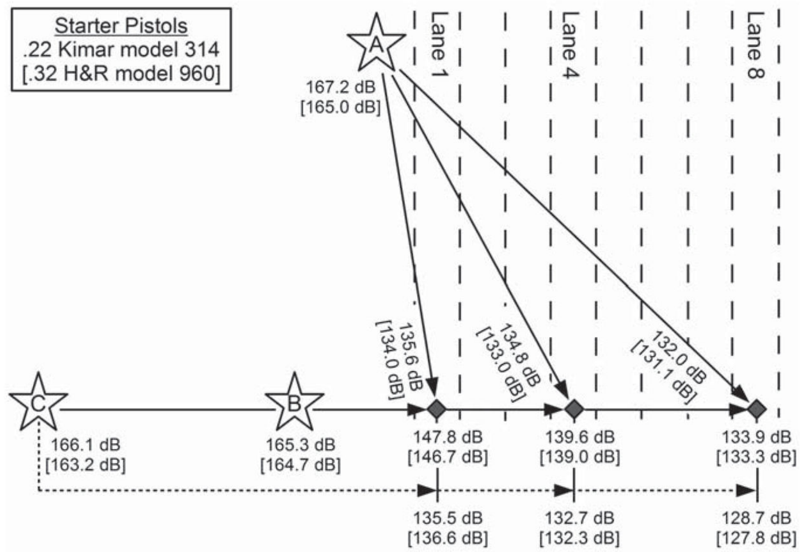

Figure 5.

Simulated athletic sprint track layout. Each lane is 1.2 metres in width. The shooter microphone positions are noted as stars A, B, and C. Athlete microphone positions are noted by the filled diamonds at the center of lanes 1, 4, and 8. Peak SPL measurements for the .22 Kimar Italian Model 314 and the .32 H&R starter pistols are noted for each microphone location as a function of shooter location.

Figure 6.

Typical firing position for official using a starter pistol with the firearm raised above the head and angled away from the athletes. Note the burning powder showering down after the weapon is fired. These particulates fall back onto the arm of the official and generally follow the path of the gas escape.

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Table 1

Mean peak SPL value for .22 and .32 caliber firearms.

	Impulse peak SPL (dB) at different measurement positions			
Pistol	**5 cm from shooter's ear**	**Chamber: 10 cm to side**	**Muzzle: 10 cm to side**	**Muzzle +1.5 m**
Kimar .22 starter pistol	164.8	179.8	177.1	157.1
K-22 revolver w/blanks	147.9	157.3	173.7	158.9
K-22 revolver w/CCI LR	158.1	180.7	174.9	154.0
K-22 revolver w/shorts	155.1	177.1	172.0	154.7
.32 starter pistol	157.6	179.3	182.0	157.4
.32 revolver w/blanks	151.2	166.3	174.3	161.7
.32 revolver w/W325	152.7	168.5	176.5	157.2

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Table 2

Mean L_{eqA8} values for .22 and .32 caliber firearms.

	L_{eqA8} (dB) at different measurement positions			
Pistol	**5 cm from shooter's ear**	**Chamber: 10 cm to side**	**Muzzle: 10 cm to side**	**Muzzle +1.5 m**
Kimar .22 starter pistol	77.3	**91.6**	**89.8**	69.6
K-22 revolver w/blanks	60.3	69.6	79.3	71.3
K-22 revolver w/CCI LR	70.2	**87.8**	83.8	70.1
K-22 revolver w/shorts	66.7	83.4	80.9	69.3
.32 starter pistol	73.0	**89.0**	**93.2**	71.2
.32 revolver w/blanks	67.0	76.7	84.6	74.7
.32 revolver w/W325	69.6	79.3	**86.9**	72.4

Note: bold text indicates values exceeding 85 dB L_{eqA8} criterion.

Table 3

Maximum permissible unprotected exposures near the sound source for .22 and .32 caliber pistols.

	Maximum permissible unprotected exposures (MPE) at different measurement positions			
Pistol	**5 cm from shooter's ear**	**Chamber: 10 cm to side**	**Muzzle: 10 cm to side**	**Muzzle +1.5m**
Kimar .22 starter pistol	5	0	0	34
K-22 revolver w/blanks	295	34	3	23
K-22 revolver w/CCI LR	30	0	1	30
K-22 revolver w/shorts	67	1	2	37
.32 starter pistol	15	0	0	23
.32 revolver w/blanks	63	6	1	10
.32 revolver w/W325	34	3	0	18

Table 4

Mean L_{eqA8} values for .22 and .32 caliber firearms in simulated sprint track setup.

		L_{eqA8}(dB) at different measurement positions			
Shooter position	**Source**	**Shooter's right ear**	**Lane 1**	**Lane 4**	**Lane 8**
Shooter position A	Kimar .22	73.88	53.32	51.66	48.52
	H&M .32	72.05	51.54	50.37	47.68
Shooter position B	Kimar .22	73.44	60.48	55.62	50.32
	H&M .32	72.30	59.48	54.75	49.49
Shooter position C	Kimar .22	72.52	53.13	50.96	46.92
	H&M .32	70.71	52.19	49.97	46.00

Table 5

Maximum permissible unprotected exposures in the simulated sprint track experiment for .22 and .32 caliber starter pistols.

	Maximum permissible unprotected exposures at simulated starter positions				
Shooter position	Source	Shooter's right ear	Lane 1	Lane 4	Lane 8
Shooter position A	Kimar .22	12	1472	2157	4446
	H&M .32	19	2218	2904	5395
Shooter position B	Kimar .22	14	283	866	2937
	H&M .32	18	356	1059	3556
Shooter position C	Kimar .22	17	1538	2535	6426
	H&M .32	26	1909	3184	7943