



Noise dosimeter for monitoring exposure to impulse noise

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Abstract

Commercially available noise dosimeters do not perform properly in impulsive noise environments because they suffer from instrumentation limitations and lack metrics that characterize impulse noise. In this paper, a design concept is proposed for an impulse noise monitoring dosimeter that addresses the current dosimeter's limited capabilities and describes the various parameters that can appropriately be used to measure and evaluate exposure to impulse noise. The design concept is based on the accurate acquisition and storage of the original impulse waveform. For data analysis (using MATLAB) and calculation of "impulse noise metrics," National Institute for Occupational Safety and Health (NIOSH) used a prototype impulse noise dosimeter system that consisted of a Bruel&Kjaer 4136 microphone and a Panasonic Digital Audio Tape Recorder. The proposed instrument would enable collection of data for validation of presently defined and yet to be defined metrics quantifying noise-induced permanent threshold shifts (NIPTS) resulting from impulse/impact exposures. It will also enable occupational safety and health professionals to make accurate measurements of ultimately approved metrics. © 2005 Elsevier Ltd. All rights reserved.

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1. Introduction

Noise dosimeters have been used extensively over the past two decades to document personal exposures and assure compliance with rules and regulations. Such dosimeters are required to comply with the American National Standards Institute (ANSI) Specification for Personal Noise Dosimeters S1.25-1991 (R1997), which states that dosimeters should be suitable for measurement of impulsive, intermittent, and continuous noise [1]. The Occupational Safety and Health Administration (OSHA) established standards and the National Institute for Occupational Safety and Health (NIOSH) recommended guidelines state that no unprotected impulse noise exposure should be permitted above 140 decibels peak sound pressure level (dB SPL) [2,3]. As a result, contemporary dosimeters designed to comply with regulations are required to operate properly up to 140 dB. Although current standards provide no guidance for evaluating impulse noise above 140 dB, dosimeters continue to be employed for measurements of noise levels (e.g., gunfire and construction) that substantially exceed their intended range of operation.

Investigations conducted at NIOSH found that presently available noise dosimeters have inherent limitations and are susceptible to producing erroneous results when they are used in predominantly impulsive noise environments [4]. These standard noise dosimeters suffer from instrumentation limitations and lack measurement parameters that have been associated with characterizing impulse noise and its effect on noise-induced hearing loss (NIHL).

Currently, no universally accepted standard defines impulse noise accurately nor does a standard method exist to measure impulses. In addition, current impulse damage risk criteria suffer from a lack of empirical data needed to quantify impulse noise exposures and assess potential damage to hearing [5,6]. A new design concept for an impulse noise dosimeter is introduced here that should address the limitation issues of the existing instrumentation, as well as define impulse measurement parameters, which can be incorporated into the design of new dosimeters. A prototype impulse noise dosimeter was constructed using a B&K 4136 1/4" microphone, powered by a B&K 2807 power supply. The output was recorded on a Panasonic Digital Audio Tape Recorder (DAT). Analysis of the acquired impulse signals was conducted using custom software routines developed by the authors in MATLAB. Impulse data collected from three different weapons—the Beretta .40 caliber pistol, the Remington 12 gauge shotgun, and the M4 .223 caliber assault rifle were used to highlight the relevancy of these parameters and showed how they could be better used to evaluate the hazards of impulsive noise.

2. Existing dosimeter limitations

Contemporary noise dosimeters face three major problems when used in impulsive noise environments. First, microphones and circuitry in current dosimeters have been designed to satisfy prevailing regulatory practices and guidelines for monitoring hazardous exposures to limited ranges of noise waveforms and magnitudes. The

second problem relates to the uncertainty associated with the dose–response relationship in an impulse noise environment. The third problem arises from the existing measurement parameters such as time-weighted average (TWA) and resultant dose calculations that cannot properly describe an impulsive event.

2.1. Microphone and electronic circuitry limitations

The principal limitation of using current noise dosimeters to measure impulse noise lies in the ability of the microphone and electronic circuitry to respond accurately to the pressure pulse. The microphones used in current noise dosimeters are rated Type 2 and have a limited frequency response that significantly deteriorates above 3 kHz. The limited bandwidth also means the instrument is not capable of responding to impulses with fast rise time. Current dosimeters have a limited peak detector dynamic range, usually around 63 dB, and an 80–146 dB SPL dynamic measurement range [7,8]. Although this range may be adequate for some impact noise environments encountered in industrial situations, it limits the capability of the dosimeter to measure impulses that are produced by weapons and certain construction equipment. The responses of several noise dosimeters to impulse noise were examined in the laboratory and during a noise assessment at an indoor firing range. Peak noise levels greater than the range (80–146 dB) of the instrument were “clipped” and treated as if they were at the maximum level [9].

Most noise damage risk criteria rely on the accurate measurements of true peak pressure levels to predict hearing damage risk from impulse noise. Any measurement system that clips the impulsive noise cannot yield accurate data above the clipping level. In addition, the correct computation of dose and TWA rely on the accurate reporting of the A-weighted, equivalent sound level. Because true peak levels above 146 dB SPL were clipped, the dose and TWA were also be in error.

2.2. Impulse dose–response relationship limitation

The dose–response relationship in contemporary dosimeters is based on the assumption that halving the exposure time would create the same degree of hazard as reducing the noise level by 3 dB (NIOSH, ACGIH, ISO) or 5 dB (OSHA). While this might hold true for continuous noise over a specific dynamic range, there have not been sufficient well-controlled studies to conclusively evaluate the equal energy hypothesis with humans when the noise contains impulsive components.

For example, noise dose calculation under NIOSH guidelines is based on the following equation:

$$D = [C_1/T_1 + C_2/T_2 + \dots + C_N/T_N],$$

where C_N is the total time of exposure at a specified noise level, and T_N is the exposure duration for which noise at this level becomes hazardous and given by the following equation: $T_N = 8/2^{(L_{AS}-85)/3}$, where L_{AS} is A-weighted *slow* sound level. T_N is well defined for continuous noise levels under 130–140 dB(A). However, it has not been scientifically validated for impulsive noise. For instance, a single shot from a

shotgun measured inside a firing range had peak level of 163 dB ($L_A = 126$ dBA), T_N calculates to 2.2 s. Durations C_N were 456–676 μ s. According to the above equation, a single shot contributes a minimal 0.02–0.03% to the daily allowable dose. To achieve 100% of the daily dose, the formula suggests a person can be exposed up to 5000 shots safely. However, studies have shown that the energy necessary to cause noise induced hearing loss is approximately 140+ dB for humans [10]. A recent study of exposure to weapons noise in the Finnish Forces showed acoustic trauma in 65 out of 113 patients (57.5%) resulting from exposure to a single gunshot [11]. The above example demonstrates that the dosimeter dose calculation becomes meaningless and not representative of the actual auditory hazard in an environment that contains impulsive noise levels above 140 dB SPL.

2.3. Lack of impulse noise parameters

Current noise dosimeters report noise levels (average, maximum, minimum and peak), dose and projected dose, and the sound exposure level. However, these parameters are not suitable to describe an impulsive noise environment. Impulsive noise is characterized by a different set of parameters. The Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) suggested in 1992 that to evaluate fully the effect of impulse noise on the auditory system, specific parameters should be considered such as peak pressure, durations, rise time, energy, spectral content, number and mixture of impulses, and temporal spacing [12]. Ear modeling algorithms developed by Price and Kalb to model the response of the auditory periphery to impulsive and continuous noise in order to assess the potential Auditory Hazard to such exposures [13]. Johnson and Patterson showed no significant temporary threshold shift (TTS) in 95% of their subjects, and that current military exposure limits may be over-protective for humans wearing hearing protection [14]. The French Committee for Weapons Noises advocates the use of the *A*-weighted energy concept in the form of LAeq8 (8-h, equivalent *A*-weighted sound exposure level) with a limit of 85 dB for unprotected ears [15,16].

3. New impulse noise dosimeter concept

While it is beyond the scope of this paper to address the specific hardware or software implementations needed to achieve the new instrument, but rather, the rationale for a new impulse dosimeter design is presented. A prototype impulse dosimeter based on a B&K 4136 microphone attached to a DAT recorder was used to capture impulse waveforms generated from gunfire, and software to calculate the various parameters associated with characterizing impulse noise exposure. Fig. 1 shows the prototype dosimeter as used for measurements of impulse noise from gunfire.

3.1. Microphones and front-end circuitry

A microphone is a transducer that generates an electrical signal that is supposed to be proportional to the sound pressure impinging at its diaphragm. Since most

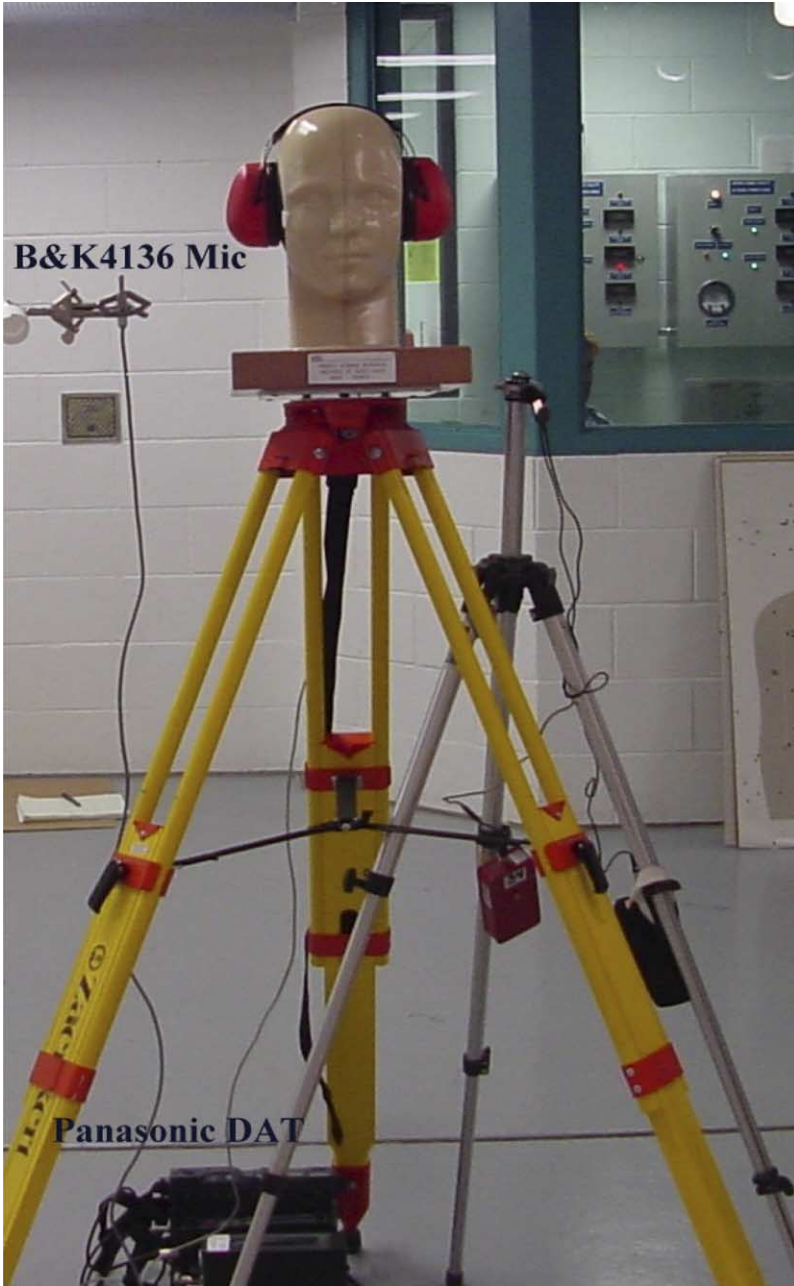


Fig. 1. Prototype impulse noise dosimeter used to measure gunfire. Prototype dosimeter consisted of B&K 4136 1/4" microphone, B&K 2807 power supply, and Panasonic Digital Audio Tape Recorder.

impulse noise events are unique and typically not reproducible, appropriate selection of microphones or pressure transducers with sufficient dynamic range, frequency bandwidth, and maximum peak response is imperative. The microphone should have a linear response that is independent of frequency (flat) response to at least 50 kHz. To measure impulses that can range as high as 170–175 dB, pressure transducers, having the smallest possible outer diameter and membrane surface should be balanced against the dynamic range in excess of 90 dB [17]. For extreme impulsive environments, dynamic pressure sensors can be used. These sensors use piezoelectric transducer or other sensing technology and feature extremely fast rise times, typically less than 1 s, because of their inherent stiffness.

The front-end circuitry should be capable of providing adequate frequency bandwidth and a large dynamic range (100 dB) to allow for the accurate capture of peak levels over ambient noise levels and fast rise time. Analog-to-Digital (A/D) converters should have 20–24 bit resolution to allow for such measurements. The digital sampling rate of the waveform will need to be performed at 200 kHz to allow the accurate capture of impulses that can have a fast rise time as low as 5 μ s.

3.2. *Impulse noise exposure parameters*

Presently, no universally accepted measurement parameters exist to quantify impulse noise and its potential for contributing to NIHL. The design concept addresses the various impulse noise parameters that have been associated with characterizing an impulsive event. Fig. 2 shows a screen shot of the software platform built to analyze the parameters such as peak level, L_{eq} , kurtosis, number of impulses, B-duration, temporal spacing, peak range. The figure shows graphics representation of time and frequency domain response as well as octave and 1/3-octave response. In addition, the platform calculates exposure limits based on the most common damage risk criteria in use today— L_{Aeq8} , the MIL-STD-1474D, and Auditory Hazard Units (AHU) based on Price-Kalb ear model.

3.2.1. *Peak pressure level*

Peak sound pressure is the maximum instantaneous sound pressure that occurs during a given time period. Peak sound pressure should be measured without any frequency-weighting. Peak pressure level is one of the most commonly used parameters for the characterization of the auditory damage from impulse noise. However, as previously presented, many contemporary dosimeters typically saturate for peak pressure levels above 140 dB. The new dosimeter should be capable of accurately measuring peak pressure levels to 170–175 dB without distortion or clipping limitation.

3.2.2. *Impulse time duration and rise time*

The most widely used time durations are the A-duration and B-duration. Fig. 3 illustrates the time durations and rise time of the impulse waveform [18]. A-duration is the time from the beginning of the impulse until the first zero crossing after the drop from peak pressure. B-duration is also called the “pressure envelope” duration

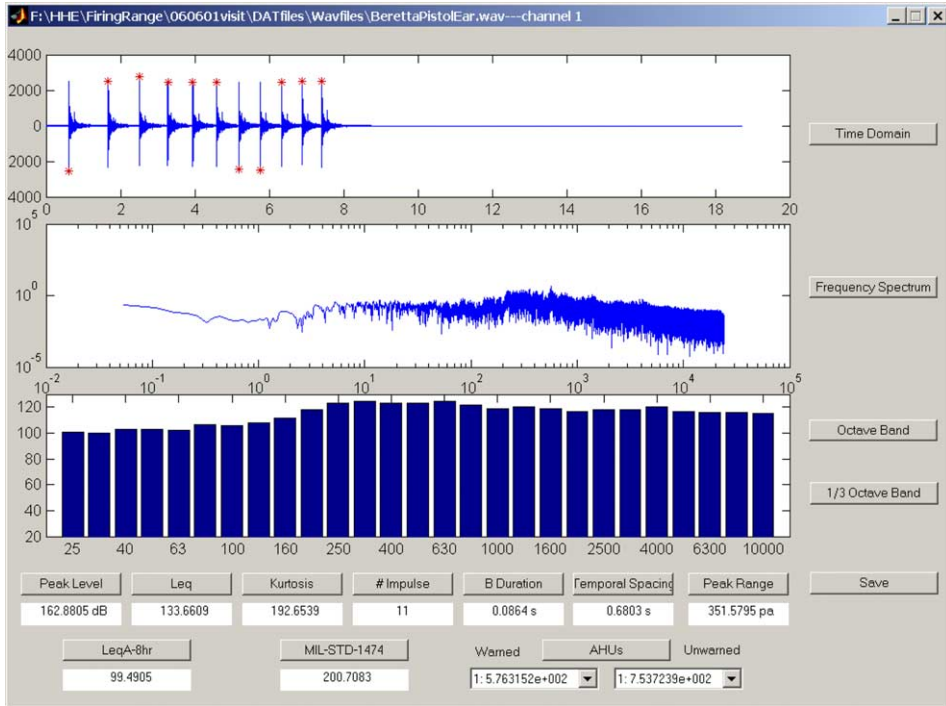


Fig. 2. NIOSH impulse noise measurement software. Screen snapshot shows the various parameters buttons and the graphical display of the time and frequency domain waveforms.

and it is the time interval that encompasses the “envelope of pressure fluctuations” (positive and negative) within 20 dB of the peak pressure level. Two other durations are described in the literature: The German C-duration is defined as the time duration from -10 dB before the peak to -10 dB after the peak. D-duration, used in the Netherlands, is defined as the time from the beginning of impulse noise until the drop of one envelope, around the pressure-time diagram, to a value of 10 dB below maximum. Table 1 shows time durations and rise time for three different firearms obtained with the prototype impulse noise instrument.

3.2.3. Spectral distribution

The CHABA damage risk criterion for impulse noise, based on the work of Coles et al. [19], did not give any consideration to the spectral characteristics of the impulse. Coles implied that this was due to the instrumentation limitations at the time. Price was among the first to emphasize the importance of the spectral distribution of impulse noise for damage-risk estimates [20]. Patterson found that impulses having different spectra but the same peak levels produce different amounts of hearing loss [21,22]. The new dosimeter should be capable of retaining the original impulse waveform for the performance of spectral analysis.

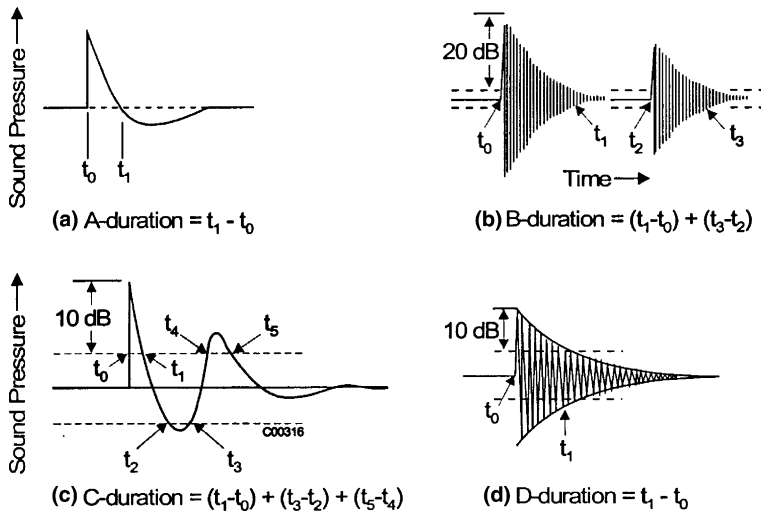


Fig. 3. Illustration of various time durations. A-duration is the time from the beginning of the impulse until the first zero crossing after the drop from peak pressure. B-duration is the time interval that encompasses the “envelope of pressure fluctuations” (positive and negative) within 20 dB of the peak pressure level. C-duration is defined as the time duration from -10 dB before the peak to -10 dB after the peak. D-duration is the time from the beginning of impulse noise until the drop of one envelope, around the pressure-time diagram, to a value of 10 dB below maximum.

3.2.4. Number of impulses

Once the damage risk from a single impulse is well-defined, it may be possible to establish a trading relationship between intensity and the number of impulses. Coles suggested a 10-dB correction factor for going from 100 impulses to a single one. Patterson found a linear energy-trading rule between intensity and the number of impulses over a 15-dB range of peak levels from 131 to 147 dB SPL [23]. Since there are an infinite number of variations in exposures to differing amounts of impulses, a verified trading relation between permissible noise exposure and number of impulses is essential to the establishment of damage risk criteria. The new dosimeter should have the capability to calculate the number of impulses in an exposure event.

3.2.5. Temporal spacing

Research has found that when impulses follow each other so rapidly that the acoustic reflex is maintained, the hazard is considerably reduced. Perkins et al.,

Table 1
Durations and rise time calculations from three different firearms^a

Firearm	A-duration (μ s)	B-duration (ms)	Rise time (μ s)
Remington 12 ga. Shotgun	456	676	146
M-16 Rifle	340	458	88
Beretta 9 mm Pistol	258	366	72

^a Calculated from prototype noise dosimeter using MATLAB.

reported that beyond 10 s, TTS and permanent threshold shift (PTS) will be reduced as the interval increases [24]. In a similar manner for accounting for the number of impulses, a correction factor may be used to account for the interstimulus interval between impulses. A new dosimeter should be capable of calculating the temporal spacing between impulses.

3.2.6. Kurtosis

Erdreich [25] and Hamernik et al. [26] have suggested that a simple *A*-weighted L_{eq} is not a sufficient measure of the hearing damage risk from impulse noise. They advocated using kurtosis as a parameter to describe the impulsiveness and the spectral composition of a noise environment. Kurtosis is a statistical measure defined as the ratio of the fourth moment to the squared second moment of a distribution:

$$\beta(t) = m_4 / (m_2)^2 = \frac{\sum(x_i - \bar{x})^4}{[\sum(x_i - \bar{x})^2]^2}.$$

It gives a relative measure for peakedness or flatness of a noise distribution. Kurtosis accounts for the difference between peak and background or ambient noise levels. The kurtosis of a normally distributed white Gaussian signal is 3.0. Table 2 shows kurtosis $\beta(t)$ calculations obtained from the prototype dosimeter for three different firearms at an indoor firing range. Lei et al. [27] suggested that a metric based upon $\beta(t)$ in conjunction with an L_{eq} may be useful in predicting hearing damage.

3.2.7. Energy

Patterson suggested that the energy expressed as unweighted sound exposure level (SEL) is a better predictor than peak pressure of both the threshold of hearing loss and the extent of hearing loss [15]. Acoustic energy per unit area is defined as:

$$E = \frac{1}{Z_0} \int_0^T p^2(t) dt,$$

where Z_0 is the acoustic impedance of the air in $N\ s/m^3$ and $p(t)$ is the instantaneous acoustic pressure in Pa or N/m^2 . $Z_0 = 413\ N\ s/m^3$ at 20 °C and air density of 1.2 kg/m^3 according to the *Guidelines for the Measurements of Impulse Noise from Weapons*. [28] The French criterion advocates the use of energy in the form of *A*-weighted, 8-h, equivalent level as a predictor of NIHL. The attractiveness of *A*-weighted energy lies in its simplicity and the ability to integrate continuous and intermittent noise. However, using energy alone as the sole determinant of hazard has shown negative

Table 2
Kurtosis calculations from three different firearms^a

Firearm/area	Kurtosis $\beta(t)$
Beretta 9 mm Pistol	195.65
Remington 12 ga. Shotgun	179.23
M16 Rifle	68.81

^a Calculated from prototype noise dosimeter using MATLAB.

Table 3
Energy calculations at an indoor firing range^a

Signal/area	Energy flux E (J/m^2)
Calibration signal (124 dB SPL @250Hz)	2.4119
Firing range	2.9070
Observation tower	0.0042
Cleaning room	0.0032
Classroom	0.0017
Office	0.0015

^a Calculated from prototype noise dosimeter at an indoor firing range and its adjacent area during live-fire exercises.

results. Price reported that an A -weighted energy flux of $400 J/m^2$ from a Howitzer caused the same temporary threshold shift in cats (40 dB) as a $10 J/m^2$ from a rifle [29]. Table 3 shows an example of the energy flux calculations obtained from the prototype dosimeter during live-fire shooting sessions at an indoor firing range and adjacent areas where noise levels have dropped dramatically.

3.2.8. Auditory hazard units

The auditory hazard units (AHU) based on the mathematical model of the auditory periphery developed by Price and Kalb can be calculated using the Auditory Hazard Assessment Algorithm for Humans (AHA AH) program [30]. Although the program has not been validated independently for humans, it assumes a daily dose maximum of 500 AHUs [31]. The model takes into account the nonlinearities of the middle ear and explains studies that found more hazard from fewer energy impulses. Auditory hazard units were calculated using the AHA AH program for single impulses generated by the different firearms studied here and they ranged from 2500 to 5300 AHUs for unprotected ears.

If additional metrics are developed and linked to hearing loss from impulse noise, the new dosimeter's capability of archiving impulses would permit meta-analysis of the impulses with updated metrics. The different metrics highlighted in this section can be useful descriptors of hazards from impulse noise only when the dynamic transfer functions of the middle and outer ears are accurately defined. Only then will it be known what happens to the impulse waveform as it proceeds through the middle ear and enters the cochlea.

3.3. Instrumentation

Contemporary noise dosimeters do not retain the original waveform on which sound level and dose measurements are based. However, impulse noise measurements require the acquisition and storage of the original impulse waveform for post processing of the parameters cited previously. The new design concept addresses two major modifications to existing noise dosimeters. First, the state of the art allows us to take advantage of advances in storage and compression schemes to equip an impulse noise dosimeter with the capability to record and retain the actual impulses.

The application of audio compression schemes such as MPEG-1, layer 3 or MPEG-4 may prove feasible for capturing the essential impulse waveform time and frequency contents without substantial degradation. Portable music players currently provide up to 60 GB of hard drive (1000 h at 128 kbps MP3 encoding). Smart storage cards and removable media are also an option providing portability and added flexibility. Secondly, advances in microprocessor and digital signal processing technologies can be incorporated into the new design to allow for real-time calculation and measurement of impulse noise parameters, as well as implement modifications via software routines to adapt for changes in evolving damage risk criteria. These modifications can be performed using software algorithms that reside on computers that can be linked to the dosimeters via infrared ports or by any of the new emerging wireless protocols, such as Bluetooth or 802.11.

4. Conclusion

The principal problem with current impulse noise criteria is the lack of an empirical database to support exposure limits. The problem is compounded by the extremely broad variations of impulses that exist in industrial and military environments. A dosimeter that is capable of accurately measuring continuous and impulse noise will serve to advance the collection of data on which a new and reliable damage risk criterion can be established. This paper illustrates the current limitations of current noise dosimeters and proposes a new design concept for capturing or measuring a base of impulse noise parameters that are correlated with risk of hearing loss. Based on the impulse noise parameters measured with a prototype dosimeter, microphone element of a future dosimeter should have a maximum response of 170–175 dB, flat-test frequency response to sound to at least 50 kHz, and a linear response over a range of 100 decibels. The new instrument should be equipped with storage and archiving capabilities to retain the original impulse event. The new design should have the capability to modify existing parameters and include new parameter developments as more empirical data become available.

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