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Pilot study of methods and equipment for in-home noise level measurements

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ABSTRACT

Knowledge of the auditory and non-auditory effects of noise has increased dramatically over the past decade, but indoor noise exposure measurement methods have not advanced appreciably, despite the introduction of applicable new technologies. This study evaluated various conventional and smart devices for exposure assessment in the National Children's Study. Three devices were tested: a sound level meter (SLM), a dosimeter, and a smart device with a noise measurement application installed. Instrument performance was evaluated in a series of semi-controlled tests in office environments over 96-h periods, followed by measurements made continuously in two rooms (a child's bedroom and a most used room) in nine participating homes over a 7-day period with subsequent computation of a range of noise metrics. The SLMs and dosimeters yielded similar A-weighted average noise levels. Levels measured by the smart devices often differed substantially (showing both positive and negative bias, depending on the metric) from those measured via SLM and dosimeter, and demonstrated attenuation in some frequency bands in spectral analysis compared to SLM results. Virtually all measurements exceeded the Environmental Protection Agency's 45 dBA day–night limit for indoor residential exposures. The measurement protocol developed here can be employed in homes, demonstrates the possibility of measuring long-term noise exposures in homes with technologies beyond traditional SLMs, and highlights potential pitfalls associated with measurements made by smart devices.

1. Introduction

Noise exposure is one of the most prevalent environmental exposures in the United States (US) and globally [1,2]. It is linked to a wide range of health effects beyond the classically-recognized noise-induced hearing loss (NIHL), including hypertension, myocardial infarction, stress, and sleep disturbance [3–5], annoyance [6,7], adverse learning and communication effects [8–11], and mental health issues [12]. A recent study suggests that noise exposures may have a public health burden of the same magnitude as environmental hazards with greater recognition, such as radon and secondhand smoke [13].

Some countries, notably those in Europe, have made great strides in the past decade in evaluating public exposures to noise [14,15], conducting measurements of sound pressure level (SPL) at fixed outdoor locations in urban environments (often at the external façade of residential structures) [16–18], using these to develop outdoor exposure estimation models for residential locations [19], and in some cases implementing measures to reduce exposures [20,21]. With a few exceptions [22,23], available US data rely on estimates that are nearly 40 years old [24], and do not include spectral analysis. US noise exposure assessments have historically been conducted to evaluate risk of NIHL from high levels of noise in occupational settings. However, recent research suggests that speech intelligibility reduction and non-auditory effects of noise may occur at substantially lower levels (e.g., 45–55 dBA) than those necessary to cause NIHL (e.g., >70 dBA) [3,25,26], and that different frequency spectra may lead to different health outcomes [27]. This situation suggests that additional noise measurement data, collected with contemporary and standardized protocols and equipment, are needed.

In-home measurements are essential to understand the relationship between noise and various health outcomes; outdoor measurements or qualitative exposure estimates cannot accurately

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account for additional noise produced by activities inside the home [28]. SLMs are considered the gold standard device for measurements of residential noise exposures [29,30], but they are not the only devices capable of such measurements. Several studies have used smart devices and noise measurement applications ("apps") to measure noise levels in laboratory settings [31–33], and a handful have compared them to conventional devices [34–36]. However, the paucity of data on the performance of smart devices and apps makes it difficult to draw conclusions on the appropriateness of such devices to estimate long-term average indoor noise exposures or to evaluate spectral differences in noise exposure frequencies.

Our study had two objectives, both designed to assess the feasibility of in-home noise measurements for large-scale children's health studies [37]. Our first objective was to evaluate the performance of SLMs, personal noise dosimeters, and smart devices and apps through side-by-side experimental comparisons in a semi-controlled environment. Our second objective was to develop and evaluate measurement approaches for seven days of continuous, unobtrusive in-home monitoring of noise levels using a number of different exposure metrics measured with both conventional and smart devices.

2. Methods

Our study involved two research elements: selection and evaluation of conventional and smart sound measurement devices under semi-controlled conditions; and subsequent pilot in-home assessment of noise in homes with these devices. The semi-controlled study procedures did not involve human subjects, while the in-home study procedures did involve human subjects and were approved by the Westat Institutional Review Board prior to collection of data.

2.1. Device selection and evaluation under semi-controlled conditions

2.1.1. Selection of SLM, personal dosimeter, and smart device app

We evaluated a variety of SLMs and noise dosimeters for inclusion in the in-home study. Our inclusion criteria for SLMs and personal dosimeters were: ability to A-weight measured decibel (dB) levels to mimic the frequency sensitivity of the human ear; ability to average noise levels over time; ability to log time history data; runtime of $\geqslant$7 days on internal or external power; computation of the equivalent continuous average exposure level (L_{EQ}), L_{90} (the level exceeded 90% of the measured time, a measure of background noise), and L_{10} (the level exceeded 10% of the measured time); $\geqslant$70 dB measurement range; noise floor $\leqslant$40 dBA; and ability to secure the monitor keypad to prevent tampering. We further required SLMs and dosimeters to meet American National Standards Institute (ANSI) Type 2 accuracy or better, and SLMs and smart devices to have octave band frequency analysis capability over a minimum range of 250–8000 Hz.

Three commercially-available SLMs met our study requirements. Based on the straightforward hardware and software design, cost, and availability of an off-the-shelf combination carrying case/deployment stand, we selected the Larson Davis Soundtrack LxT SLM (Depew, NY), with added datalogging capability and a low range preamplifier, PRMLxT2L, along with an off-the-shelf Larson Davis carrying case/deployment stand (EPS-030-LXT) that housed a 12 V sealed dry cell battery and a detachable mast for the microphone-preamplifier that placed the microphone about 1 m above the floor. We then added to the detachable measurement mast on the case (Fig. 1) a laboratory clamp holder and a three-prong extension clamp to allow attachment of up to two microphones and a smart device.

Our assessment of commercially-available dosimeters found nearly all units to have runtimes $\leqslant$90 h and noise thresholds $\geqslant$65–70 dBA. Only one unit, the Larson Davis Spark 706RC, had an advertised runtime >100 h and a noise threshold of 40 dBA. We therefore selected this unit for the study.

We explored a variety of smart devices and eventually selected 4th- and 5th-generation Apple (Cupertino, CA) iPod Touch devices, referred to hereafter as iPod Touch 4 and 5, respectively. These devices use the same operating system (iOS) as Apple iPhones without contract costs for cellular service. More than 20 iPod Touch noise measurement apps were considered. Given our requirements (e.g., measurement of L_{EQ}, L_{90}, and L_{10}, octave band frequency analysis, measurement range and floor, datalogging capability, and security requirements), we identified one suitable app: AudioTools with SPL Graph software (Studio Six Digital, Boulder, CO). We utilized the internal microphone of the iPod Touch devices in order to evaluate the simplest possible measurement configuration.

2.1.2. Choice of daily exposure metrics

In addition to the L_{EQ}, L_{10}, and L_{90} described above, other metrics are used in the US to assess exposure to noise over a given period. These include $L_{EQ(T)}$ (the L_{EQ} measured over time T; for example, $L_{EQ(24)}$ represents a 24-h average L_{EQ}) and the day–night noise level (L_{DN}, an $L_{EQ(24)}$ with a 10 dB penalty applied to levels between 10 PM and 7 AM to account for potential sleep disruption during those hours). While use of the L_{DN} is specified in various US noise regulations and guidelines, particularly for assessment of community noise annoyance [38], for this pilot study we focused on measurement methodologies which did not evaluate any health effects and we elected to measure $L_{EQ(24)}$, which is the underlying metric for nearly all daily metrics for noise in the US and globally, and from which a number of metrics, including L_{DN}, can be computed *post hoc* as desired.

2.1.3. Device settings and calibration

We acquired five units of each of the three selected devices for configuration and testing. All were configured to use A-weighting (Table 1). The SLMs datalogged noise levels at 5-min intervals, had a nominal 27–118 dBA measurement range, and used a slow (1 s) response time. The dosimeters datalogged at 1-min intervals, and were configured to measure noise according to the exposure limit recommended by the Environmental Protection Agency [39], e.g., criterion time of 8 h, criterion level of 75 dBA (the level equivalent to 100% of the allowable noise dose over the criterion duration), 0 dB threshold, and 3 dB time-intensity exchange rate (meaning that for every increase or decrease of 3 dB in an average exposure level, the allowable exposure duration is halved or doubled, respectively). Several dosimeters were configured with conventional occupational measurement ranges (70–140 dBA) and slow response time, while others were configured with a lower measurement range (40–110 dBA) or a fast (0.125 s) response time to evaluate the effects of these settings. The AudioTools app on the iPod Touch units were set to use microphone compensation filters to compensate for the high-pass band filter in the Apple iOS, and used a low measurement range (noise threshold of 30 dBA and measurement range of 30–100 dBA with the internal iPod Touch microphone), and 1-s measurement intervals. The AudioTools app supported different versions on the 4th and 5th generation iPod Touches; however, the settings used on the two versions were identical for this study.

The SLMs and dosimeters were calibrated pre- and post-measurement using a Larson Davis CAL150 calibrator with a 114 dB stimulus tone. Per the manufacturers' specifications, the devices were considered to be within calibration if measured levels were within ±0.5 dB of the calibration value. The iPod Touch unit