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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-hour 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.

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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 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 are not the only device 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 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); 70 dB measurement range; noise floor 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 (Figure 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 90 hours and noise thresholds 65-70 dBA. Only one unit, the Larson Davis Spark 706RC, had an advertised runtime >100 hours 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: Audio Tools 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-hour 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 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. The SLMs datalogged noise levels at 5-min intervals, had a nominal 27-118 dBA measurement range, and used a slow (1 sec) 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 hours, 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 sec) response time to evaluate the effects of these settings. The Audio Tools 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-sec 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 calibration could not be adjusted, but we securely coupled the housing surface around the slightly recessed microphone on the iPod Touch devices to the port of the CAL150 calibrator and documented pre- and post-measurement responses of the iPod Touch devices at two calibrator stimulus levels (94 and 114 dB). Note

that this procedure differed substantially from that of the dosimeters and SLMs, which involved insertion of the microphone into the calibrator port, rather than the contact coupling between the entrance of the calibrator port and the surface surrounding the iPod Touch microphones.

2.1.4. Device runtime testing—We evaluated device runtimes by repeatedly testing time to failure using battery power. The SLMs ran for an average of 27 hours (1.1 days) on internal batteries, and an average of 236 hours (9.8 days) on the external battery in the measurement case. The dosimeters ran for about 120 hours (5 days) on internal alkaline batteries, and 168 hours (7 days) with internal lithium batteries. The iPod Touch 4 and 5 devices ran for about 8 hours on internal batteries. Based on these results, the SLMs (using external batteries) and dosimeters (using lithium batteries) met our 7-day measurement target, while the iPod Touch devices required AC power to operate continuously over this period.

2.1.5. Device side-by-side semi-controlled noise measurement comparison—

The SLMs, dosimeters, and iPod Touch devices with AudioTools-SPL Graph app were tested for 96 hours in semi-controlled scenarios in secure office environments to assess instrument performance. In each scenario, we took measures to reduce the likelihood of tampering or inadvertent interference with the instruments. The dosimeters and SLMs were secured inside locked carrying cases, and the iPod Touch devices and SLM and dosimeter microphones were secured to the masts on the carrying cases. The cases themselves were placed adjacent to (but not in contact with) walls and surrounded by signs indicating that an experiment was being conducted and that people should not approach the instruments. The cases served to isolate the instruments from floor vibration. Microphone height was 1 m from the floor in all but one scenario (number 5); this height was chosen to represent the height of a 36-month old child.

Table 1 summarizes the details of the seven test scenarios. Briefly, these were:

1. Evaluation of side-by-side SLMs to assess inter-device differences.
2. Evaluation of side-by-side iPod Touch 4 devices to assess inter-device differences.
3. Evaluation of side-by-side iPod Touch 5 devices to assess inter-device differences.
4. Evaluation of side-by-side dosimeters with different settings to assess inter-device and settings-induced differences.
5. Evaluation of SLMs and dosimeters with different heights and distances from walls to assess the effects of alternative microphone mounting approaches (Figure 1a).
6. Evaluation of side-by-side SLMs, dosimeters, and iPod Touch 4 devices prior to in-home measurements (Figures 1b).
7. Evaluation of side-by-side SLMs, dosimeters, and iPod Touch 4 and unused iPod Touch 5 devices following in-home measurements (Figure 1b).

In all scenarios but number 5, the SLM and dosimeter microphones were attached to the mast on the carrying case, while the units themselves were placed in the case. The iPod

Touch devices were secured to the mast using a clamp and rubberized gasket band. The SLMs and dosimeters were powered by external and internal batteries, respectively, and the iPod Touch units were run from AC power. When the carrying case and mast were assembled against the wall the microphones were about 1 m off the floor and 0.6 m away from the wall. After all devices were turned on, the electronic keypads were locked, and the case was secured with zip ties, a strap, and a cable to stabilize it and prevent it from being opened (Figure 1c).

2.2. Pilot assessment of in-home noise

2.2.1. Selection of participants—In-home study participants were recruited by an advertisement posted on a Westat intranet site and administered a screening questionnaire to interested volunteers to determine eligibility. Given that the study was designed to inform measurement approaches being considered for the National Children's Study, eligibility criteria were: 1 child ages 24–48 months in the home; household occupied for 5 days of the 7-day sampling period; and home located within a one-hour driving distance from the Westat office in Rockville, Maryland. Selected volunteers received a brochure explaining the purposes and procedures of the study, provided informed consent, were enrolled, and scheduled their setup and pick-up visits. Participants who completed seven days of monitoring received \$50, and an additional \$25 if they also completed a daily time activity diary reporting aspects of the home on an hourly basis, including occupancy level and noisy activities (the results of which are not described here).

2.2.2. Measurements—Pre-calibration of SLMs, dosimeters, and iPod Touch 4 devices was conducted as described in section 2.1.3. During the setup visit, research staff placed two matched sets of equipment (one set pictured in Figure 1c) in participants' homes in the configuration used in semi-controlled test scenario 6. One set was configured in the room where the home's child(ren) spent most of the time while awake (the “most-used room”), and the second set was placed in the room where the child(ren) typically slept (the “bedroom”). To minimize the influence of reflected sound, microphones were placed 1 m above the floor, and at least 0.6 m away from any walls when possible (Figure 1c). Distances from the microphone to the floor and closest walls were recorded, as were set-up date and time and various other aspects of the home.

After seven days of continuous measurement, the equipment sets were recovered by research staff. Prior to disassembly, the location and placement of the equipment sets was reviewed for possible changes or damage. All devices were post-calibrated, and all data were compiled into an electronic database for analysis.

2.3. Data manipulation and analysis

The data from the SLM, dosimeter and iPod Touch units were logged at 5-min, 1-min, and 1-sec intervals, respectively. Data from all three sources were synchronized by time stamp. The 1-min dosimeter L_{EQ} data were logarithmically collapsed to 5-min intervals to match the SLM data:

$$L_{EQ,T} = 10 \log_{10} \left[\frac{1}{T} \sum t_i \times 10^{L_{EQ_i}/10} \right] \quad (1)$$

where $L_{EQ,T}$ is the average L_{EQ} in dBA for a 5-min interval T and t_i represents the i th 1-min monitoring interval. Similarly, iPod Touch data were logarithmically collapsed from 1-sec to 1-min intervals, and then further collapsed to 5-min intervals to match the SLM and dosimeter data.

The measured noise levels from each of the devices were used to compute various exposure metrics. Equation 1 was modified slightly to determine the 24-hour equivalent continuous average exposure ($L_{EQ(24)}$), where T represented 24 hours instead of 5 mins. L_{EQ} levels (in dB) were similarly computed for each of the octave bands measured by the SLMs and iPod Touch units.

Frequency distributions were assessed to determine L_{10} and L_{90} levels in dBA for each measurement. These values were then used to compute a ratio of exposure variability (L_{10}/L_{90T}) analogous to measures used in previous studies [40–42]:

$$L_{10}/L_{90T} = \log_{10} \left[\frac{1}{T} \sum \frac{10^{L_{10_i}/10}}{10^{L_{90_i}/10}} \right] \quad (3)$$

where T is the total duration of exposure across all 5-min intervals into which the L_{10} and L_{90} metrics were collapsed, as described above. These metrics have been used in occupational settings, but have not been used previously for analyzing in-home noise measurement data.

We computed descriptive statistics for the L_{EQ} levels measured during the semi-controlled test scenarios, and for each of the four metrics ($L_{EQ(24)}$, L_{10} , L_{90} , and L_{10}/L_{90}) by day and device type for each of the nine homes in the in-home assessments. We used analysis of variance (ANOVA) to evaluate possible differences in noise exposures measured within instrument type (semi-controlled test scenarios 1-4), as well as between instrument type (test scenarios 6-7 and in-home measurements), and also by measurement location (test scenario 5 and in-home measurements).

3. Results

3.1. Device evaluation under semi-controlled conditions

Deviations of measured values from the calibration stimulus levels varied widely across devices (Table 2). The dosimeters had the smallest calibration deviations, followed closely by the SLMs, while the iPod Touch units had largest deviations. For the 4th generation units, the bias at the 94 dB stimulus level was only a fraction of a decibel and an order of magnitude smaller than the bias at 114 dB, while for the 5th generation units, the bias was nearly 15 dB at both calibrator stimulus levels. While a portion of the bias for both iPod Touch units was undoubtedly due to the non-optimal coupling between the iPod Touch units and the calibrator, the small bias at 94 dB suggests that this coupling could result in nearly

unbiased measurements at some stimulus levels with the iPod Touch – 4th generation units. By comparison, the much larger negative bias in the iPod Touch – 5th generation units suggests other potential sources of bias, including microphone configuration and software parameters.

The results of 72 hours of side-by-side testing of the various devices in an office setting are shown in Figure 2. Four SLMs were in nearly all instances within 1 dB of a fifth reference SLM in position one of the cluster of tested SLMs (test scenario 1, Figure 2a), while four iPod Touch 4 units were in nearly all instances within 2 dB of a fifth reference iPod Touch 4 (test scenario 2, Figure 2b) at the center of the cluster of tested iPods. Note the consistent ordering of the responses of the iPod Touch 4 units compared to the reference unit, which suggests that iPod Touch microphones may be more directional than those used in the SLMs due to the microphone's design and its slightly recessed location within the housing of the device. The results of the five dosimeters tested side-by-side over this period (test scenario 4) are shown in Figure 2c. Although this figure shows substantially more variation across units than Figures 2a (SLMs) and iPod Touch units (Figure 2b), this variation is primarily due to the different measurement settings used. Dosimeters with identical settings yielded similar measurements; for example, dosimeters 1 and 2 (with conventional occupational measurement range of 70-140 dB and conventional slow response time) differed by 1-2 dB, and dosimeter 4 was generally within 1-3 dB of the reference dosimeter (both of these instruments used a 70-140 dBA range but fast response time to reduce attenuation of variability in measured levels). Dosimeter 5, which used a low measurement range and the conventional slow response time, yielded the highest measured levels (since it measured and logged levels down to 40 dBA, rather than logging measured levels of <70 dBA as 0 dBA, as all other dosimeters did) and differed by 2-11 dBA from the reference dosimeter. The settings from dosimeter 5, which eliminated the data censoring associated with conventional occupational dosimeter settings for levels between 40-70 dBA, were carried forward into the in-home measurements.

Figure 3 shows the results of the dosimeter and SLM microphone location evaluation (test scenario 5). The levels measured by the three dosimeters were generally within 2-3 dBA of one another regardless of a wall mounting height of 1m or 1.52 m, and consistently tracked the levels measured by the SLMs. However, these levels were 2-10 dBA higher than those measured by the SLMs at 1m height and 0.6 m away from the wall, suggesting that wall mounting resulted in positive bias.

Table 3 shows the results from test scenarios 6 and 7. In both test scenarios, the iPod Touch 4 devices had higher mean $L_{EQ(24)}$, L_{10} and L_{90} levels compared to the SLMs and dosimeters, but lower mean L_{10}/L_{90} ratio values. ANOVA analyses indicated that the mean levels measured by the dosimeters, SLMs, and iPod Touch 4 devices in scenario 6 were significantly different for all four metrics in both experimental periods. In scenario 7, L_{10} and L_{90} levels from the iPod Touch 5 devices were nearly 10 dB lower than the 4th generation devices and roughly 5 dB lower than the mean values from the dosimeters and the SLMs. The difference in mean values between the iPod Touch 4 and 5 devices was significant (Student's t test, $p < 0.05$), and, as with scenario 6, ANOVA analyses indicated that

the mean levels measured by the dosimeters, SLMs, and iPod Touch 4 and 5 devices were significantly different for all four metrics in both experimental periods.

3.2. In-home measurements

Over 25 interested and eligible volunteers responded to the study advertisement, and the first nine respondents were enrolled. Four homes were detached single-family dwellings, three were townhouses, and two were apartments; all were located within residential neighborhoods. Participants in all nine homes completed the home noise measurement and daily noise log for the full seven-day period. In two homes, iPod Touch 4 measurements were not obtained for all seven days because of potential tampering or because of device failure.

Table 4 shows the four noise metrics evaluated in homes using the three different devices. Regardless of the device used, noise levels were 5-10 dBA higher in the most used room than the child's bedroom, and the variability in levels was typically 1-2 times larger in the most used room compared to the bedroom. $L_{EQ(24)}$, L_{10} , and L_{90} noise levels measured by the iPod Touch 4 devices were higher than those measured by SLM or dosimeter, but, conversely, the iPod Touch 4 units demonstrating the smallest variability in measured noise (i.e., the smallest L_{10}/L_{90} ratio metric). Of the various metrics, only $L_{eq(24)}$ and L_{10} levels were not significantly different across the three devices. L_{90} differences are due at least in part to the measurement floor of 40 dBA for the dosimeter and 30 dBA or less for the SLM and iPod Touch units.

Figure 4 shows a boxplot of $L_{EQ(24)}$ values measured by the three devices on each day of the week in the bedroom and most used room. The iPod Touch 4 devices always produced the highest median noise level. Median noise levels were highest on Saturdays and lowest on Mondays and Fridays in both measured rooms. Within-day variability was similar between the child's most used room and their bedroom, while between-day variability was greater in bedrooms. There was no trend in measured noise levels by monitoring day, suggesting that the novelty of the devices on the first monitoring day did not result in significant differences in measured levels. Home 4 had consistently low measured levels due to long periods of non-occupancy on several of the monitored days.

Figure 5 shows a comparison of 24-hour average octave band noise levels measured in the bedroom and most used room via SLM or iPod Touch 4. Unlike the $L_{EQ(24)}$ levels, octave band noise levels were more variable in the most used room. For both device types, octave band noise levels in both rooms were greatest between 500 and 1000 Hz. However, compared to the SLM, the iPod Touch 4 units showed substantial attenuation in measured noise levels at frequencies below 125 Hz and augmentation above 4000 Hz.

4. Discussion

We developed and pilot tested a strategy for making seven-day measurements of in-home noise levels using a variety of devices to inform noise exposure assessment strategies for the National Children's Study. Noise levels have previously been measured in such settings; however, our comparison of the performance and utility of different instruments over an

extended measurement period is novel and adds to the small body of peer-reviewed literature [34–36] on contemporary measurement devices that can be used to evaluate in-home noise exposures. These devices also have the potential for use in validation of modeled noise exposures predicted from limited measurements taken at the outdoor façade of residences; such modeling approaches are commonly used in environmental noise assessment, but have not been sufficiently validated against in-home measurements.

The accuracy and performance of the SLM and dosimeter models evaluated here was comparable, and our results suggest that these or similarly-capable devices could be employed for in-home noise measurements, although only SLMs provide the capability for octave band analysis. In contrast, the iPod Touch 4 and 5 devices had much lower accuracy (when compared to SLM units and during calibration), and showed biases in different directions depending on the metric assessed (e.g., average vs. variability metrics). The selected SLM and dosimeter can operate continuously for seven days on battery power, while the iPod Touch devices required AC power for measurements longer than eight hours. While AC power is available in nearly all homes, the use of a subject's electricity may represent an undesirable burden and also introduces the possibility of instrument failure due to power outages. These issues can be avoided through the use of battery-powered devices.

Our semi-controlled experimental results generally agree with the few other peer-reviewed studies of the performance of noise measurement apps running on smart devices. A study by the National Institute for Occupational Safety and Health (NIOSH) [35] evaluated 130 apps for iPhones and 62 for Android devices, and found only 10 and 4 apps for the two platforms, respectively, that met the criteria for inclusion in the study, which were similar to those used here, e.g., ability to measure average noise levels over time, to datalog noise levels, and to measure noise using the A-weighting network. The AudioTools app used here was not evaluated by NIOSH. The NIOSH investigators conducted their short-term measurements in a reverberant sound chamber and found that none of the Android-based apps provided sufficient functionality or accuracy for use in personal noise measurement. Four of the ten iPhone-based apps provided accuracy to within ± 2 dB or dBA of the reference SLM, which agrees with our conclusion that apps can provide results similar to a reference SLM under semi-controlled conditions (Figure 2b). However, in contrast to our findings, the majority of the iPhone-based apps displayed substantial negative biases in measured noise levels compared to the reference SLM. Although the app we selected did not allow for adjustment of internal calibration values, use of apps with that capability could address this limitation.

Another study by Nast et al. [36] that evaluated app performance on 4th generation iPhones found that virtually all of the tested noise measurement apps were biased high compared to a reference SLM for measurements made over short periods. This agrees with our own observations, though, as with the NIOSH study, the AudioTools app evaluated here was not evaluated by Nast et al. Our study supports the findings of other similar studies and suggests that the use of smart devices for short-term noise measurements may be a plausible approach for future studies, but that additional research on the accuracy and functionality of the apps used on such devices is needed, particularly for applications where extended measurement durations are desired in homes.

A large number of studies have measured short-term noise levels at the external façade of homes, particularly homes in European cities [43,44]. However, there are only two previous studies that appear to have assessed noise exposures via in-home measurements in homes with children, and both of these did so via broadband measurements that did not assess frequency spectra. Pujol and colleagues [28] assessed noise levels in the homes of urban schoolchildren in France using SLMs and measurement approaches similar to those used here. $L_{EQ(24)}$ levels were not reported, but L_{EQday} levels (reflective of the period from 6 AM to 6 PM) averaged 48.2 dBA in children's bedrooms and 55.2 dBA in the main room of the home – levels that agree quite well with the $L_{EQ(24)}$ levels measured here of 48.7 and 56.2 dBA, respectively (Table 4). In another analysis of these data, Pujol et al [44] noted the complex relationship between indoor and outdoor L_{EQ} noise levels at children's homes, further reinforcing the need for indoor noise measurements to supplement model-based external façade noise estimates.

Based on our market assessment, only a fraction of commercially-available noise measurement devices are appropriate for extended in-home measurements of noise. In particular, the ability to conduct spectral analysis over time eliminates the vast majority of SLMs, dosimeters, and smart device apps from consideration. Given the potential importance of variations in noise exposure frequency spectra from an annoyance perspective [45] and the poorly-understood relationships and mechanisms associated with noise exposure and non-auditory health effects such as cardiovascular disease and stress [3], the ability to capture spectral information could add substantial additional benefit to noise measurements. While certain apps on smart devices provide octave band analysis capabilities, the limitations of the inexpensive microphones in these devices (as evidenced by the attenuation in low frequency levels and amplification of higher frequency levels measured by the iPod Touch devices vs. the SLMs in Figure 5) must be accounted for in any future assessment, possibly through normalization of measured levels to a specific frequency (e.g., 1000 Hz).

In several homes we encountered bedrooms and most used rooms that were so small and/or cluttered that the microphone measurement stand was deployed <0.6 m from the nearest wall. Our data suggest that this kind of situation can influence measurement results (Figure 3) and highlight the importance of documenting the configuration and location of instruments.

While our analyses primarily focused on L_{EQ} noise levels, we modified equation 1 to include a 10 dB penalty for noise levels measured between 11 PM and 7 AM and computed L_{DN} values for each monitored day across all nine participant homes (data not shown). The mean and SD bedroom L_{DN} levels were 54.7 ± 2.8 , 55.0 ± 2.3 , and 57.1 ± 2.7 dBA for the SLM, dosimeter, and iPod Touch 4 devices, respectively. The values for the most used room were higher: 58.5 ± 2.9 , 58.9 ± 2.8 , and 60.9 ± 3.0 dBA for the SLM, dosimeter, and iPod Touch 4 devices, respectively. The higher observed values in the most used room compared to the bedroom are not unexpected, as noisy play and loud group activities are more likely to occur in common areas than in bedroom settings. The higher levels measured by the iPod Touch devices compared to the dosimeters and SLMs are likely due at least in part to the amplification of noise in octave bands >250 Hz in the iPod Touch devices (Figure 4); these

frequencies are emphasized when A-weighting is applied, and therefore have a more profound effect on differences in A-weighted levels between devices than the attenuation of octave band frequencies 250 Hz seen in the iPod Touch devices, since these lower frequencies are heavily discounted using A-weighting.

The EPA recommends that L_{DN} levels not exceed 45 dBA to permit 100% intelligibility of speech [39]. Bedroom L_{DN} levels exceeded this recommended limit in 96%, 85%, and 100% of daily periods when measured by SLM, dosimeter, and iPod Touch, respectively, while for the most used room these exceedance fractions were 100%, 87% and 100%, respectively. These results highlight the need for further evaluation of in-home noise exposures in the US, as L_{DN} levels of this magnitude are associated with adverse health outcomes [3].

5. Conclusions

Both the SLM and the dosimeter evaluated here are appropriate for use in evaluating average A-weighted in-home noise levels continuously for up to seven days, although the dosimetry results highlight the importance of proper selection of measurement range and response time for in-home noise exposures. While there is an emerging interest in using smart devices for assessment of a range of environmental exposures, the iPod Touch 4 and 5 devices evaluated here cannot be recommended for use in extended in-home monitoring at this time. They consistently demonstrated bias in average and variability noise metrics compared to both the SLM and dosimeter units, cannot make measurements for more than a fraction of a day without AC power, and failed during several attempted measurements. Smart devices represent a promising future mechanism by which to collect in-home measurements, but successful use of these devices for this purpose will require additional evaluation and validation, as well as development of calibration curves across a range of devices and apps.

The noise measurement protocol we developed and assessed here demonstrates the relative ease with which environmental noise exposures can be assessed in home settings. Our pilot measurements demonstrating exposures potentially high enough (e.g., >45 dBA L_{DN}) to result in non-auditory health effects highlight the need for additional research. While both the SLM and dosimeter evaluated here may be used to measure average noise levels, and the dosimeter offers relatively low logistical hurdles, only the SLM can also measure the frequency spectra of noise. Given the emerging literature which suggests that simple broadband (i.e., A-weighted) measurements of noise may not be sufficient to explain the range of performance [45] and non-auditory [3] effects increasingly associated with noise exposure, SLMs comparable to the units evaluated here – i.e., with a large measurement range, low noise threshold, and datalogging and octave band analysis capabilities, represent the optimal exposure assessment tool for directly assessing noise levels in homes or validating statistically modeled noise exposures.

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a. Testing of placement and height of dosimeter microphones (test scenario 5)*

b. Testing of five side-by-side sets of iPod Touch 4 and 5 units following in-home measurements (test scenario 7)

c. Monitoring set installed in a home (distance to nearest horizontal surface 0.6 m)

Figure 1. Data collection setup for noise measurements

*Dosimeter microphones placed at heights of 1.5 m and 1 m on the wall and dosimeter and SLM microphones on a case 0.6 m from the wall and 1 m off the floor in an office lobby (in front of a kitchenette)

a. Scenario 1: Five SLMs, 72 hours; reference was SLM 3. Identical settings across units.

b. Scenario 2: Five iPod 4s, 72 hours; reference was POD 3. Identical settings across units.

c. Scenario 4: Five dosimeters, 72 hours; reference was dosimeter 3.*

Figure 2. Test scenarios evaluating deviations in measured L_{EQ} noise levels (dB) in office lobby and hall settings among different types of devices making simultaneous side-by-side measurements compared to a reference instrument of the same type

*DM 1 and 2: 70-140 dBA measurement range, slow response time

DM 3 and 4: 70-140 dBA measurement range, fast response time; fast response used to reduce attenuation of variability in measured levels

DM 5: 40-110 dBA measurement range, slow response time

Figure 3.

Comparison of two dosimeters (“DM”) mounted on a wall (“Wall”) with a dosimeter (“Case”) and two SLMs (“Case”) placed in a measurement case 0.6 m from the wall (Test scenario 6). “High” denotes 1.5 m height, “Low” denotes 1 m height, and “Case” denotes mounting on case 0.6 m from the wall at a height of 1 m.

a. Noise levels in bedroom

b. Noise levels in most used room

Figure 4.

Comparison of $LEQ(24)$ noise levels measured in-home with three types of devices in bedroom and most used room over a 7-day measurement period (n=9 homes). Lower and upper edges of boxes indicate 25 and 75th percentile values, respectively, and line in box represents median level. Circles and stars indicate outliers and are numbered by home site.

a. Octave band noise levels in bedroom **b. Octave band noise levels in most used room**

Figure 5. Comparison of 24-hour LEQ octave band noise levels measured in-home with SLMs and iPod Touch units over a 7-day measurement period (n=9 homes)

* t-test, $P < 0.05$ for difference between SLM and iPod Touch

** t-test, $P < 0.01$ for difference between SLM and iPod Touch

Table 1
Summary of instrument settings, microphone (“mic”) location, and test scenarios; all units in all scenarios used A weighting network

Scenario		Instruments and settings		
No.	Description	SLM/unit number (5 min datalog intervals)	iPod Touch/unit number (1 sec datalog intervals)	Dosimeter/unit number (1 min datalog intervals)
1	Side-by-side, prior to in-home measurements	<i>All units:</i> 27-118 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	--	--
2	Side-by-side, prior to in-home measurements	--	<i>All 4th generation units:</i> 30-100 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	--
3	Side-by-side, prior to in-home measurements	--	<i>All 5th generation units:</i> 30-100 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	--
4	Side-by-side, prior to in-home measurements	--	--	<i>All units:</i> mic 0.6 m from wall, 1 m height <i>Units 1 and 2:</i> 70-140 dBA range, SLOW response <i>Units 3 and 4:</i> 70-140 dBA range, FAST response <i>Unit 5:</i> 40-110 dBA range, SLOW response
5	Variable height and location, prior to in-home measurements	<i>All units:</i> 27-118 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	--	<i>All units:</i> 70-140 dBA range, SLOW response <i>Unit 1:</i> mic on wall, 1.5 m height <i>Unit 2:</i> mic on wall, 1 m height <i>Unit 3:</i> mic 0.6 m from wall, 1 m height
6	Side-by-side, prior to in-home measurements	<i>All units:</i> 27-118 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	<i>All 4th generation units:</i> 30-100 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	<i>All units:</i> 70-140 dBA range, SLOW response, mic 0.6 m from wall, 1 m height
7	Side-by-side, after in-home measurements	<i>All units:</i> 27-118 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	<i>All 4th generation units:</i> 30-100 dBA range, SLOW response, mic 0.6 m from wall, 1 m height <i>All 5th generation units:</i> 30-100 dBA range, SLOW response, mic 0.6 m from wall, 1 m height	<i>All units:</i> 70-140 dBA range, SLOW response, mic 0.6 m from wall, 1 m height

Table 2
Deviations from calibration value (bias) across all test scenarios by instrument type

Instrument type	n	Bias (dBA)		
		Mean	SD	Range
SLM (114 dB)	41	-0.02	0.07	-0.1 to 0.1
Dosimeter (114 dB)	43	-0.002	0.09	-0.2 to 0.1
iPod – 4 th generation				
114 dB	36	-2.0	1.8	-0.9 to 8.6
94 dB	36	0.3	2.9	-8.4 to 4.9
iPod – 5 th generation *				
114 dB	10	-14.8	4.1	-20.2 to -8.9
94 dB	10	-14.4	3.6	-18.3 to -8.0

* iPod Touch 5 devices were not tested in homes and only used in testing at Westat offices. The iPod Touch 5 devices also had a different new version of the AudioTools-SPL Graph app than used on the iPod Touch 4 devices, but all settings were identical in both versions.

Table 3

Calculated L_{EQ} , L_{10} , L_{90} , and L_{10}/L_{90} ratio values. N= ten 24-hour measurement periods per device type in each scenario. Each 24-hour measurement period ran from 4 PM the first day to 4 PM the following day.

Test scenario/device	Experimental period days 1-3						Experimental period days 4-6					
	$L_{EQ(24)}$ (dBA)		L_{10} (dBA)		L_{90} (dBA)		$L_{EQ(24)}$ (dBA)		L_{10} (dBA)		L_{90} (dBA)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
<i>Test scenario 6, Pre in-home monitoring</i>												
SLM	59.2 [*]	0.2	62.9 [*]	0.2	51.5 [*]	0.2	59.2 [*]	0.2	62.4 [*]	0.1	51.4 [*]	0.3
Dosimeter	59.9 [*]	0.7	62.5 [*]	1.1	51.3 [*]	0.9	61.9 [*]	1.0	62.6 [*]	0.8	52.0 [*]	1.0
iPod Touch 4	61.5 [*]	0.9	65.3 [*]	1.3	54.9 [*]	1.0	63.2 [*]	1.1	65.5 [*]	1.3	54.8 [*]	1.0
<i>Test scenario 7, Post in-home monitoring</i>												
SLM	59.3 [*]	0.3	65.5 [*]	0.7	50.4 [*]	0.4	60.2 [*]	0.3	62.1 [*]	0.4	50.2 [*]	0.5
Dosimeter	59.2 [*]	0.2	62.9 [*]	0.2	50.6 [*]	0.3	60.4 [*]	0.3	62.3 [*]	0.3	50.4 [*]	0.2
iPod Touch												
4	61.4 [*]	0.9	65.0 [*]	1.3	54.8 [*]	1.0	61.9 [*]	1.0	65.7 [*]	1.4	54.1 [*]	1.4
5	54.1 [*]	0.7	57.5 [*]	0.5	44.2 [*]	0.3	55.2 [*]	0.6	56.7 [*]	0.7	43.8 [*]	0.7

^{*} ANOVA between devices, $p < 0.05$

Table 4
Calculated L_{EQ} , L_{10} , L_{90} , and L_{10}/L_{90} ratio values for in-home measurements over a 7-day measurement period (n=9 homes)

	$L_{EQ(24)}$				L_{10}				L_{90}				L_{10}/L_{90} ratio			
	$L_{EQ(24)}$		L_{10}		L_{90}		L_{10}/L_{90}		L_{90}		L_{10}/L_{90}		L_{10}/L_{90}		L_{10}/L_{90}	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SLM	48.7	2.9	56.2	5.1	49.5	3.9	58.4	5.6	30.8	3.7	35.1	9.4	21.6	5.4	25.2	6.9
Dosimeter	48.2	3.4	55.7	4.3	49.8	3.9	57.9	4.9	35.1	0.8	39.9	4.8	13.9	3.3	20.9	4.9
iPod Touch 4	51.3	1.7	57.9	2.8	50.2	1.7	54.5	6.1	37.5	2	43.1	5.6	10.8	4.4	17.2	5.2

* One-way ANOVA, $p < 0.05$