Using Smart Devices to Measure Intermittent Noise in the Workplace

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Abstract

Purpose: To determine the accuracy of smart devices (iPods) to measure intermittent noise and integrate a noise dose in the workplace.

Materials and Methods: In experiment 1, four iPods were each paired with a Larson Davis Spark dosimeter and exposed to randomly fluctuating pink noise in a reverberant sound chamber. Descriptive statistics and the mean difference between the iPod and its paired dosimeter were calculated for the 1-s data logged measurements. The calculated time weighted average (TWA) was also compared between the devices. In experiment 2, 15 maintenance workers and 14 office workers wore an iPod and dosimeter during their work-shift for a maximum of five workdays. A mixed effects linear regression model was used to control for repeated measures and to determine the effect of the device type on the projected 8-h TWA.

Results: In experiment 1, a total of 315,306 1-s data logged measurements were made. The interquartile range of the mean difference fell within ±2.0 A-weighted decibels (dBA), which is the standard used by the American National Standards Institute to classify a type 2 sound level meter. The mean difference of the calculated TWA was within ±0.5 dBA except for one outlier. In experiment 2, the results of the mixed effects model found that, on average, iPods measured an 8-h TWA 1.7 dBA higher than their paired dosimeters.

Conclusion: This study shows that iPods have the ability to make reasonably accurate noise measurements in the workplace, but they are not as accurate as traditional noise dosimeters.

Keywords: Exposure assessment, industrial hygiene, noise exposure, smart devices

INTRODUCTION

Hearing loss is the third most common chronic condition in the United States, and noise-induced hearing loss (NIHL) is the most common work-related illness. Noise is the single greatest preventable cause of hearing loss and one of the most common occupational hazards. The National Institute of Occupational Safety and Health (NIOSH) estimates that over 22 million American workers are exposed to hazardous noise >85 A-weighted decibels (dBA). NIHL prevalence can vary widely depending on the industry. Workers in traditionally noisy industries (mining, construction, manufacturing, and transportation) have a prevalence of NIHL ranging from 9.5 to 34.8%, and in these industries, there is considerable information available regarding noise exposures. There is much less information about noise exposure available in the service industry, healthcare, and the wholesale and retail trade despite a prevalence of any hearing impairment ranging from 7.8 to 16.7%, that is, not much below that of industries traditionally perceived as “noisy.” Many companies in these industry sectors do not have formal occupational health departments that can monitor a worker’s exposure to noise.

Collecting exposure information in these industries requires the use of noise dosimeters or sound level meters, which are expensive and require trained individuals to operate and interpret the results. By contrast, smart devices (phones, tablets, and other devices) have the ability to utilize applications (apps) that can make noise measurements in a very straightforward and simple manner. A study by Nast et al. in 2014 found that the measurements made by a variety of apps on an iPhone 4S were subject to significant error and were considered unsuitable to measure noise.

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laboratory study by Murphy and King[7] in 2016 found that varying levels of accuracy in measuring noise. Another laboratory study by Murphy and King[7] in 2016 found that iOS apps were generally superior to Android apps, but that the app used, phone model, and the age of the device could all affect the measurement accuracy. We conducted a study in 2016 that examined the effect of several commercially available microphones, the MicW i436 and the Dayton Audio iMM-6, on the accuracy of noise measurements in the reverberant sound chamber. Using a similar method to Kardous and Shaw, measurements were taken using the different generations of iOS devices running three different apps while using the external microphones. We found that both external microphones substantially increased the accuracy and precision of noise measurements and reduced the measurement variability introduced by different iOS devices and apps.[8]

All of the previous studies were conducted in a controlled laboratory setting and were focused on assessing the accuracy of smart devices when measuring steady state (i.e., non-time-varying) noise. However, in the workplace, such stable exposure conditions are uncommon. In addition, most of the contemporary noise measurement apps have the ability to datalog and integrate a noise dose over a workday, but such measurements have never been compared to the measurements from traditional noise dosimeters. This study aimed to address these knowledge gaps in two ways. The first (experiment 1) was to determine how accurately smart devices measured intermittent noise in a laboratory setting by comparing measurements made by a noise dosimeter to those made by smart devices. The second (experiment 2) was to compare the real-world accuracy of smart device noise measurements to those made with noise dosimeters in two worker populations with different exposure profiles.

Material and Methods

Experiment 1

For experiment 1, a 4-h sample of random pink noise was generated in MATLAB version 8.5 (Natick, MA) using the “Pink Noise Generation with MATLAB Implementation” software package (Hristo Zhivomirov 2013). The noise was exported as a .wav file and loaded into the REATPLus software (ViAcoustics, Austin, TX) and transduced through three JBL XRX715 two-way loud speakers inside a reverberant sound chamber located at the NIOSH acoustic testing laboratory in Cincinnati, OH [see Figure 1 for an example of the equipment used].[8] The reverberant sound chamber allowed for the generation of a sound field with equal energy throughout the chamber, which negated the influence of microphone location on the noise measurement.

Figure 1: The paired dosimeters and devices mounted on a stand in the reverberant sound chamber prior to testing in experiment 1

Noise was measured using four Spark Model 706 dosimeters (Larson Davis, Depew, NY), each of which was paired with a 5th generation iPod (Apple, Cupertino, CA) running iOS version 9.3.2 with the SoundMeter app (Faber Acoustical, LLC) and a MicW i436 external microphone (Beijing, China). The application and microphone were chosen, because they provided the most accurate measurements in our previous study.[8] In addition, the MicW i436 claims that it meets the International Electrotechnical Commission’s standard for a class 2 microphone.[9,10] The clocks on all of the instruments were synchronized, and each pair of devices was started at the same time and set to log noise measurements at 1-s intervals for the duration of the experiment. Both the dosimeter and the iPod were set with a threshold of 40 dB, exchange rate (ER) of 3 dB, and a criterion level of 85 dB. This was performed to ensure that the full range of noise levels presented in the chamber was integrated into the noise dose measured by both the devices. All of the devices were calibrated at 114 dB using a Larson Davis Cal 150B SLM calibrator before and after the experiment. Each pair of devices was exposed to random pink noise for between 15 and 240 min over 11 different trials; this allowed for the evaluation of the effects of different runtimes on agreement of the paired devices. Because this experiment was comparing paired devices, the results from all the trials were combined into one dataset for analysis. Descriptive statistics and the mean difference were calculated for each device pair for both the 1-sec data logged measurements and the time-weighted average (TWA) calculated for each measurement by both devices.

Experiment 2

Experiment 2, which involved human participants, was approved by the institutional review board at the University of Michigan (HUM00100764). Fifteen volunteer maintenance workers at the University of Michigan were recruited and provided informed consent to participate in the study. The
maintenance workers were chosen, because we believed that they would be exposed to the high levels of intermittent noise given their work activities. Each was followed for a maximum of five consecutive workdays. Fourteen volunteer office workers at the university with no occupational noise exposure were also recruited and followed for a maximum of five consecutive workdays. During their work-shifts, which were all 8 h in duration, all workers wore a 3M Edge eg-5 (3M, Maplewood, MN) and a 5th generation Apple iPod Touch inside a protective case running iOS version 9.3.2 with the SoundMeter app, and connected to a MicW i436 external microphone. The microphones for both devices were placed side-by-side on the dominant hand shoulder of the participant [see Figure 2 for an example] for the duration of each measured work-shift. In the event that the iPod failed to record a measurement, the paired dosimeter measurement was also excluded from the analysis.

Both the dosimeter and smart device were set to measure noise using the method specified by NIOSH with an ER of 3 dB, a criterion level of 85 dB, and a threshold of 80 dB. All devices were pre- and post-calibrated at 1000 Hz and 114 dB using a Larson Davis Cal 150B SLM calibrator before and after data collection. Measurements from devices with a post-calibration <113.5 and >114.5 dB were excluded. The exposure profiles of all workers were visually examined using the 3M Detection Management Software (3M, Maplewood, MN). Descriptive statistics were calculated for the 8-h TWA for each group of workers in STATA 14 (College Station, TX). A mixed effects linear regression model was developed to compare the difference in measurements between the dosimeter and smart device while accounting for repeated measurements. This model is displayed in Eq. (1), where \( Y_{it} \) indicates the 8-h TWA, \( \beta_1 \) and \( \beta_2 \) are indicator variables for what type of device was used and from which group the worker came, \( b_1 \) is the random intercept for the worker, and \( b_2 \) is the random intercept for day nested in the worker.

\[
Y_{it} = \alpha + \beta_1 \text{device} + \beta_2 \text{group} + b_1 + b_2 + \epsilon_{it}
\]

Eq. (1) is the general equation for the linear mixed model used in experiment 2.

RESULTS

Experiment 1

Table 1 presents a summary of the measurements made by each device in experiment 1. On average, each device made 39,413 measurements across all the trials. Measured noise levels ranged between 34.8 and 98.0 dBA with a mean of 75.0 dBA and a standard deviation of 4.5 dBA. The difference in 1-s data logged measurements for each pair of devices is displayed in Figure 3. A value of 0 indicates perfect agreement between the devices while values further away from 0 indicate less agreement. The interquartile range of the differences between the iPod and dosimeter fall within or very close to the ±2.0 dBA range, which is the criteria used by the American National Standards Institute (ANSI) to classify type-2 microphones. Similarly, Figure 4 shows that the difference in the calculated 8-h TWA

![Figure 2: An example of the noise dosimeter and iPhone microphone placed on a worker in experiment 2](image)

Table 1: Summary statistics for noise exposure (in dBA) for experiment 1

|          | Mean | SD  | Min  | Max  | Avg. | Total N |
|----------|------|-----|------|------|------|---------|
| Total    | 75.0 | 4.5 | 34.8 | 98.0 | 28.664| 315,306 |
| Pair 1   |      |     |      |      |      |         |
| iPod     | 74.7 | 4.9 | 35.7 | 88.9 | 3585  | 39,430  |
| Dosimeter| 74.9 | 4.1 | 37.1 | 88.3 | 3585  | 39,430  |
| Pair 2   |      |     |      |      |      |         |
| iPod     | 75.7 | 5.0 | 34.8 | 89.5 | 3582  | 39,400  |
| Dosimeter| 75.8 | 3.9 | 40.4 | 87.6 | 3582  | 39,400  |
| Pair 3   |      |     |      |      |      |         |
| iPod     | 74.8 | 4.8 | 36.6 | 89.3 | 3583  | 39,409  |
| Dosimeter| 75.1 | 4.2 | 36.6 | 98.0 | 3583  | 39,409  |
| Pair 4   |      |     |      |      |      |         |
| iPod     | 74.5 | 4.8 | 36.4 | 90.2 | 3583  | 39,414  |
| Dosimeter| 74.6 | 4.0 | 37.9 | 88.1 | 3583  | 39,414  |

There were a total of 11 trials conducted for each pair in experiment 1.
between the dosimeter and iPod pairs is typically ±0.5 dB, with the exception of one outlier. Figure 4 also suggests that the iPods tend to produce measurements that are slightly higher than the dosimeters.

**Experiment 2**

Descriptive statistics for both occupational groups are presented in Table 2. A total of 54 iPod and dosimeter measurements were collected from the maintenance workers while 50 iPod and dosimeter measurements were collected from the office workers. The results from the first day of monitoring the maintenance workers were discarded because of the widespread failure of the iPods. This resulted in only 4 days of data from the maintenance workers cohort. Despite the fact that the office worker cohort was monitored for an additional day (i.e., 5 days vs. 4), many of the office workers had work obligations that required them to miss a day or more of the study. This resulted in the office worker cohort having fewer samples than the maintenance workers. As would be expected, the maintenance workers had on average higher levels of noise exposure compared to the office workers. However, office workers had a larger standard deviation, suggesting that there is a greater variability in the 8-h TWA measurements for the office workers than the maintenance workers. For both the groups of workers, the iPods on average produced higher measurements than the noise dosimeters. Table 3 shows that the mean difference between the measurements made by the dosimeters and the iPods ranged between −0.2 and −4.4 dBA for the maintenance workers and −1.6 to 0.6 dBA for the office workers, depending on the measurement day.

Results from the mixed effects regression model are presented in Table 4. By including a random intercept for each participant and each day nested within participant, the measurements from the iPod and dosimeter are centered for each person and day. This made it possible to determine that the iPods systematically measured noise exposure 1.7 dBA higher than the noise dosimeters. On average, noise exposure for the maintenance workers was 22.8 dBA higher than the office workers. Approximately 76.9% of the variance in the model was explained by the random effect for worker and day nested within worker. This implies that only 23.1% of the variance between measurements made by the iPods and dosimeters could not be explained by the model.

**DISCUSSION**

We have successfully evaluated the performance of smart devices used to measure intermittent noise exposures in

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**Table 2: Descriptive statistics for experiment 2, 8-h TWA noise measurements (dBA) made using an iPod and noise dosimeter**

| Occupational group     | Device | iPod | Dosimeter |
|------------------------|--------|------|-----------|
| Maintenance workers    | N      | 54   | 54        |
|                        | Mean   | 84.1 | 81.6      |
|                        | SD     | 5.5  | 6.3       |
| Office workers         | N      | 50   | 50        |
|                        | Mean   | 65.9 | 65.2      |
|                        | SD     | 9.6  | 9.2       |

**Table 3: Mean difference in experiment 2 between the 8-h TWA measurements (dBA) made by the iPod and dosimeter**

| Group               | Day 1 | 2 | 3 | 4 | 5 | Total |
|---------------------|-------|---|---|---|---|-------|
| Maintenance workers | Mean  | −3.8| −4.4| −0.2| −1.5| −2.5  |
|                     | SD    | 7.7 | 9.6 | 2.8 | 2.3 | 6.4   |
|                     | N     | 12  | 14 | 13 | 15 | 54    |
| Office workers      | Mean  | −0.3| −0.9| 0.6 | −1.6| −1.3  |
|                     | SD    | 2.4 | 6.7 | 4.2 | 2.5 | 4.4   |
|                     | N     | 7   | 11 | 11 | 10 | 50    |

*Day 1 measurements were not included because of the widespread failure of the iPods.
comparison to gold-standard measurement instruments. The results from experiment 1 add to the growing body of evidence that low-cost external microphones can be used by a smart device to collect noise measurements that approach the accuracy of conventional instruments. The median for the difference between 1-s logged measurements was close to 0 dBA for all the pairs of devices [Figure 1]. However, there are a number of measurements in which the difference in measurements between the two devices is >2.0 dBA. Each pair of devices was started manually; while care was taken to start and stop the measurements at the same time, it is likely that each dosimeter/iPod pair was recording slightly different 1-s intervals, which may account for some differences. Traditional noise dosimeters are built for a singular purpose while even factory-new iPods in so-called “airplane mode” (i.e., with communication functions disabled) are running numerous processes that could impact the performance of the application recording noise measurements. We had no way to detect or account for this possible difference during our analysis. Despite these potential sources of error, Figure 2 shows that the 8-h TWA calculated by the iPods was generally within 0.5 dB of the TWA calculated by the matched dosimeters. Previous studies have shown that smart devices can make very accurate measurements when exposed to continuous noise and compared to results from a sound level meter. However, this is the first study that examined the accuracy of smart devices in measuring intermittent noise and compared the calculated 8-h TWA to results from a noise dosimeter.

Experiment 2 represented a field test of smart devices to determine how well they performed in a “real world” scenario and determine how durable the devices were in the workplace. The two occupational groups were chosen because we expected them to have dissimilar exposure profiles. As shown in Table 1, maintenance workers were indeed exposed to higher levels of noise, though the office workers had a larger standard deviation in their mean 8-h TWA. The mean difference in 8-h TWAs between smart devices and noise dosimeters was smaller for office workers than for maintenance workers [Table 2]. This is likely due to the fact that office workers are not routinely exposed to the levels of noise that exceed the threshold setting on the dosimeter. This was to be expected and suggests that the smart devices are not incorrectly measuring subthreshold noise as above the threshold, which would contribute to an artificial increase in a worker’s 8-h TWA. Unlike office workers, maintenance workers were regularly exposed to noise levels exceeding the threshold setting of the devices. As expected, the results from the laboratory portion of this study showed better agreement between the devices than the results from the field test. The descriptive statistics presented in Table 3 suggests that this difference is due in large part to the cohort of maintenance workers. The visual examination of the graphical output from the dosimeter software indicated that the maintenance workers were generally exposed to more rapidly fluctuating levels of noise than the office workers, which likely contributed in the lower agreement between the dosimeters and iPods. While we attempted to simulate rapidly fluctuating noise in experiment 1, the system we used can only generate noise levels up to 100 dBA and the rate at which the noise levels change do not occur as quickly as would be encountered in the workplace; therefore, the results from the field test should be considered a better assessment of how well these devices measure noise under “real world” conditions. This suggests that smart device apps may be less accurate in measuring rapidly fluctuating noise levels and should not be used to measure peak or maximum noise levels.

Using a mixed effects linear regression model, we were able to account for the repeated measure design of this study and evaluate the systematic difference in measurements made by the iPods compared to the traditional noise dosimeters. Overall, the iPod produced an 8-h TWA that was 1.7 dBA higher than the noise dosimeter. While the overall mean difference falls within the 2 dB tolerance limit ANSI uses to define a type 2 SLM, when the model was run stratified by occupational group, the iPod produced an 8-h TWA that was 2.6 and 0.7 dBA higher than a dosimeter in the maintenance and office workers, respectively. This suggests that smart devices should not be used in place of dosimeters for compliance measurements, especially for

Table 4: Fixed and random effects for the mixed effects linear regression model for experiment 2

| Coefficient (dBA) | SE  | P-value | 95% CI (dBA) |
|-------------------|-----|---------|-------------|
| Intercept         | 86.4| 1.6     | <0.001 83.3 89.5 |
| Device<sup>a</sup> | -1.7| 0.6     | 0.004 -2.9 -0.6  |
| Group<sup>b</sup> | -22.8| 1.7     | <0.001 -26.0 -19.5 |

Random effects

| Subject: random intercept | 40.3 | 14.7 | 19.7 | 82.5 |
| Day: random intercept    | 16.2 | 4.4  | 9.5  | 27.6 |
| Residual                | 16.9 | 2.4  | 12.8 | 22.3 |

<sup>a</sup>0 = iPod, 1 = dosimeter. <sup>b</sup>0 = maintenance workers, 1 = office workers.
workers who are exposed to the variable levels of noise throughout the workday. Therefore, these results should not be interpreted as an indication that smart devices with an external microphone are equivalent to a type-2 SLM. It is also important to consider that there are a large number of noise measurement apps available. This study only used one app (SoundMeter) based on previous data that showed this app performed the better than several other apps that were available. It is unknown how well other apps would perform, because they have not been evaluated to the same extent that SoundMeter was here in our previous study or in Kardous and Shaw. Additionally, there are many other models of external microphones available; however, there has been little research conducted on the quality of these microphones.

In addition to the quantitative results, we were able to make several observations about the durability and the feasibility of using smart devices to measure noise in the workplace. The first observation is that many smart devices will automatically turn off when exposed to temperatures that exceed the devices’ safe operating parameters. When this happens, the noise measurement app is closed, and no measurements are made. Additionally, using an external microphone necessitates attaching the microphone to a 3.5 mm extension cord so that the microphone can be mounted in the hearing zone of the measured subject while the smart device is placed in a pocket. The smart device could theoretically be mounted in a worker’s hearing zone, but the design and fragility of smart devices makes this infeasible in practice. If the external microphone is disconnected from the device, the app will either stop recording measurements or continue recording measurements using the internal microphone, which has been found to be highly inaccurate in some cases. This occurred during the first day of sampling the maintenance workers and resulted in the discarding of all of the first day’s measurements. This issue was resolved by purchasing several protective cases for the iPods. Among office workers, it can be difficult for a person without pockets to wear an iPod for their entire work-shift. This can be alleviated by using armbands to mount the device and using a short 3.5 mm extension cord to mount the microphone in the hearing zone.

**Conclusion**

Despite these drawbacks, we have shown that commercially available iOS apps paired with an external microphone can make reasonably accurate full-shift noise measurements. The high prevalence of smart phone use in the United States and around the world means that with an external microphone and app, it is possible for lay individuals to make accurate noise level measurements at work or in the general environment. While smart devices and apps are not accurate enough to replace traditional noise dosimeters at this time, they do have the potential to reduce the cost and difficulty of identifying worker who need further monitoring or should be enrolled in a hearing protection program, particularly in industries with limited occupational health and safety resources. These devices can also empower workers to make their own measurements and lobby their employer for additional noise monitoring or the implementation of noise controls. In situations wherein traditional noise dosimeters are not available, such as small businesses, smart devices can be used to gather reliable noise exposure data. The quality of the collected data is still dependent on the user, making it imperative that these apps provide some basic measurement instructions on how to effectively collect noise measurements. However, the use of smart devices provides an opportunity for workers and occupational health professionals to better characterize noise exposure in the workplace that can then be used to make decisions on how to best protect a worker’s hearing.

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**Conflicts of interest**

There are no conflicts of interest.

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