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COMPARISON OF APPLE WATCH TO A COMMERCIAL NOISE DOSIMETER

Anna Barrett, James Mainolfi, Joshua Trice
Cape Fox Federal Integrators

Benjamin Roberts
Cardno ChemRisk

Chucri Kardous
NIOSH

Marc Lejeune
88 AMDS/SGPB

Daniel Cowan
UES, Inc.

Taylor Ellestad, David R. Mattie
711 HPW/RHB

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AIR FORCE RESEARCH LABORATORY
711TH HUMAN PERFORMANCE WING,
AIRMAN SYSTEMS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

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DAVID R. MATTIE, PhD, DABT
Exposure Health Team Lead
Product Development Branch

//signature//

DIRK YAMAMOTO, DR-III, PhD, CIH, CSP, PE
Chief, Force Health Protection Section
Product Development Branch
Airman Biosciences Division

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Anna Barrett[1], James Mainolfi[1], Joshua Trice[1], Benjamin Roberts[2], Chucri Kardous[3], Marc Lejeune[4], Daniel Cowan[5], Taylor Ellestad[6], David R. Mattie[6]

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
[1]Cape Fox Federal Integrators, 7050 Infantry Ridge Rd, Manassas, VA 20109
[2]Cardno ChemRisk, 235 Pine St. Ste. 2300, San Francisco, CA 94104
[3]NIOSH, 1090 Tusculum Avenue, Cincinnati, OH 45226
[4]88 OMRS/SGXB, Wright-Patterson AFB, OH 45433
[5]UES, Inc., 4401 Dayton Xenia Rd, Dayton, OH 45432

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14. ABSTRACT

Noise-induced hearing loss, a workplace injury, is a serious impairment that critically reduces military readiness, effectiveness, safety, and fitness for duty. This study measured accuracy and feasibility of Series 5 Apple Watches microphone and Apple Health app in capturing noise exposures, as compared against two reference systems: Larson Davis (LD) Model 2559 random incidence microphone and LD Model 831 Type 1 sound level meter (SLM). Testing was conducted with 8 smartwatches in a reverberant chamber at NIOSH's acoustical laboratory in Cincinnati, OH, using a pink noise, octave bands, and recorded sound. Apple Watch collects sound levels at 30-second intervals and an Air Force-developed Noise Export app was used to extract data to compare with measurements from reference systems. Results indicated Apple Watches measured 3.4 dB(A) lower than SLMs when exposed to pink noise, 0.1 dB(A) lower for recorded transportation noise, and 1.3 dB(A) lower for recorded factory noise. Higher precision was seen during octave band analysis. Results indicate the Apple Watch Series 5 provides reliable noise measurements, but may be less accurate in quieter, and inherently less risky, environments and when measuring low frequency sounds. A second phase of the study with field measurements will be provided as a separate report. The approach used in this study may be useful as a template for future studies of similar devices.

15. SUBJECT TERMS
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1.0 SUMMARY

Noise-induced hearing loss, a workplace injury, is a serious impairment that critically reduces military readiness, effectiveness, safety, and fitness for duty. Currently, all workplace noise exposure assessments for the United States Air Force (USAF) are conducted by Bioenvironmental Engineering (BE) technicians using one of the two main noise measurement instruments, sound level meter (SLM) or noise dosimeters. This project, developed in collaboration with the National Institute for Occupational Safety and Health (NIOSH), aimed to determine if the Apple Watch's noise exposure capability and its built-in microphone are an adequate substitute in cases where professional noise measurement instruments are not readily accessible or as a screening mechanism prior to a complete noise assessment using sound level meters or noise dosimeters. The intent of the study is not to recommend a replacement for professional sound level meters or noise dosimeters or professional BE expertise in the field. This report describes the first phase of testing which was conducted in a laboratory setting, while the second phase was conducted in the field with military personnel recruited by BE technicians and will be reported at a future date.

For the first phase of testing, eight Apple Watch Series 5 smartwatches were placed on a stand approximately 4 feet off the floor inside the reverberant chamber at the NIOSH acoustical laboratory in Cincinnati, OH. The watches were exposed to two types of noises, broadband (pink) and narrow band, as well as recorded transportation and factory noise generated from speakers placed in the chamber. Reference sound level measurements were obtained using both a Larson Davis (LD) microphone and a Type 1 SLM. The second phase of testing, which will be reported separately, consisted of 27 participants recruited to wear both an Apple Watch and a Type 2 LD noise dosimeter. For both phases, the timestamps of noise levels were logged by each watch and matched to the timestamps of noise levels from the sound level meter or a matched dosimeter. The noise exposure feature built into the Apple Watch collects data every 30 seconds and saves it to the iPhone's Health application (app). However, the LD sound level meter and noise dosimeters used in the study assess environmental noise data in one-second intervals. To address this discrepancy and compare data based on the same interval, we developed the Noise Exporter app to read sound levels from the microphone in the watch every second and save it to the iPhone's Health data.

Evaluation of the data from the laboratory testing consisted of three parts. The first part consisted of calculating the mean and standard deviation of the difference between each watch's measured sound level and that of the reference system. The second part evaluated the difference between each watch's measured sound level and reference system for each sound pressure level at various octave band frequencies. The final part evaluated the difference in measurement of the watch and the reference system for various industrial and transportation noise recordings. On average, the watches measured 3.4 decibels A-weighted [dB(A)] lower than the reference system (including the type 1 sound level meter) when exposed to broadband or 'pink' noise. A high level of measurement precision from the watches was demonstrated during the octave band analysis. In addition, the watches measured 0.1 dB(A) lower than the reference system for recorded transportation noise, but 1.3 dB(A) lower for recorded factory noise. Results indicate the Apple Watch Series 5 provides reliable noise measurements, but may be less accurate in quieter, and inherently less risky, environments and when measuring low frequency sounds. Based on this

limited evaluation, it appears that the watches do not meet the requirements for a Type 2 sound level meter or noise dosimeter if the noise environment consisted of broadband-type noise environments. But, the watches performed better for narrowband type noise environments, as indicated by the octave band results. Additional studies and evaluations would be required to establish the efficacy of the watches as a quick assessment noise tool, but one main finding from this study shows that the watches are overall consistently precise but may not be as accurate as would be needed in order to replace professional instruments. However, they can serve, along with the Noise Exporter app, as a simple preliminary assessment (i.e., screening) tool.

2.0 INTRODUCTION

The Apple Watch study was initially developed under what the USAF called the "Total Exposure Health" program. During a team meeting, the idea of using the Apple Watch's built-in microphone to measure noise levels in the environment for Air Force use was proposed. The study would address knowledge of current sensor capabilities and requirements of data collection to support data analysis. The idea of the study was similar to an on-going study conducted by the University of Michigan, to utilize data collected by smart technology to provide insight into health, wellness, and disease (Roberts, Kardous and Neitzel, 2016).

To assist in evaluating the efficacy of the Apple Watch to measure noise exposure, NIOSH researchers from the Noise and Bioacoustics team in Cincinnati, OH were contacted to collaborate with the USAF/Apple Watch study, based on their previous research with smartphones and smartphone noise apps (Kardous and Shaw, 2016). The original goal of the USAF Apple Watch study was to investigate if the Series 5 or later microphone and health app could be used as a substitute for commercially-available Type 2 occupational noise dosimeters. This study was designed to measure the accuracy and feasibility of the Apple Watch's microphone, and its ability to capture occupational noise exposure against professional instruments, such as the LD noise dosimeters, and to look at the applicability of using the Apple Watch for environmental noise measurements. NIOSH agreed to support the study through a data sharing agreement with the 711 HPW/RH. NIOSH would examine the accuracy and precision of noise measurements of the Apple Watch at their acoustical laboratory according to standard testing protocols using reference sounds. The data collected by the watches would be compared to the LD noise dosimeters. Cardno ChemRisk, a collaborator of NIOSH, was also added to the project under a data sharing agreement with the 711 HPW/RH, helped with analysis of noise data from the Apple Watch and LD noise dosimeters.

In its current form, the built-in Apple noise exposure feature collects data every 30 seconds and saves it to the Apple iPhone's Heath data. New software, the Noise Export app, was developed to access environmental noise data from the Apple Watch at one-second intervals, similar to that of commercially-available occupational noise dosimeters, and saves it to the iPhone's Health data.

2.1 Occupational Noise Exposures

Occupational and general-purpose sound level measurements are conducted using Type 1 (accuracy ± 1 dB(A)) or Type 2 (accuracy ± 2 dB(A)) sound measurement instruments that must meet the requirements of American National Standards Institute (ANSI) S1.4-1983 (R2007), Specifications for Sound Level Meters [ANSI, 1983 (R2007)]. ANSI S1.4 states the following: "the expected total allowable error for a SLM measuring steady broad dB(A) and noise in a reverberant sound field is approximately ± 1.5 dB(A) for a Type 1 instrument and ± 2.3 dB(A) for a Type 2 instrument." For compliance with occupational and environmental noise requirements, standards and regulations in the United States require that instruments meet ANSI Type 2 specifications. The Occupational Safety and Health Administration (OSHA) noise standard [29 CFR 1910.95] considers Type 2 instruments to have an accuracy of ± 2 dB(A).

In order to examine the efficacy of any new (or smart) instrument or app to measure sound levels accurately, studies must compare the results of such sound level measurements against a reference Type 1 or Type 2 sound measurement instrument as specified by standards and required by regulations. This study compares measurements obtained by the Apple Watch against a Type 1 'reference' sound measurement system which includes a Type 1 SLM.

3.0 METHODS

3.1 Materials and Methods in the Laboratory Evaluation

3.1.1 Laboratory Testing System

A total of 8 Apple Watch Series 5 smartwatches were used for the laboratory evaluation at the NIOSH acoustical testing facility. The smartwatches were placed on a stand approximately 4 feet high inside a reverberant noise chamber with access to microphones/speakers that can be monitored from a control room. The chamber ensures that a diffuse (uniform noise) sound field is generated within the chamber, so orientation or size of the smartwatches do not influence the results of the study. The reverberant chamber is shown in Figure 1.

Figure 1. The NIOSH acoustic testing laboratory showing reverberation room and control equipment.

For the experimental setup, pink noise was generated with a 20 hertz (Hz) – 20,000 Hz frequency range, at levels from 65 dB(A) to 95 dB(A) in 5-dB(A) increments (7 different noise levels). The measurement range was chosen to reflect the majority of typical occupational noise exposures encountered in the workplace today. Noise generation and acquisition were performed using the Trident Multi-Channel Acoustic Analyzer software (VIAcoustics, Austin, TX). Noise was generated through three JBL XRX715 two-way loudspeakers oriented to provide maximum (max) sound diffusivity inside the chamber. Reference sound level measurements were obtained using a reference system that consisted of a ½-inch LD (DePew, NY) model 2559 random incidence microphone, and a National Instruments PXIe 4464 Data Acquisition Board (National Instruments, Austin, TX). Additionally, an LD Model 831 Type 1 SLM was used to verify sound pressure levels obtained by the reference system. Both systems were calibrated to produce results within a fraction of a decibel and, in this study, the use of the 'reference system' indicates readings from either of those systems. The microphone and SLM were calibrated before and after each measurement using G.R.A.S. (Holte, Denmark) model 42AP pistonphone. All the reference measurement instrumentation used in this study underwent annual calibration at a National Institute of Standards and Technology-accredited laboratory. The experimental setup is shown in Figure 2.

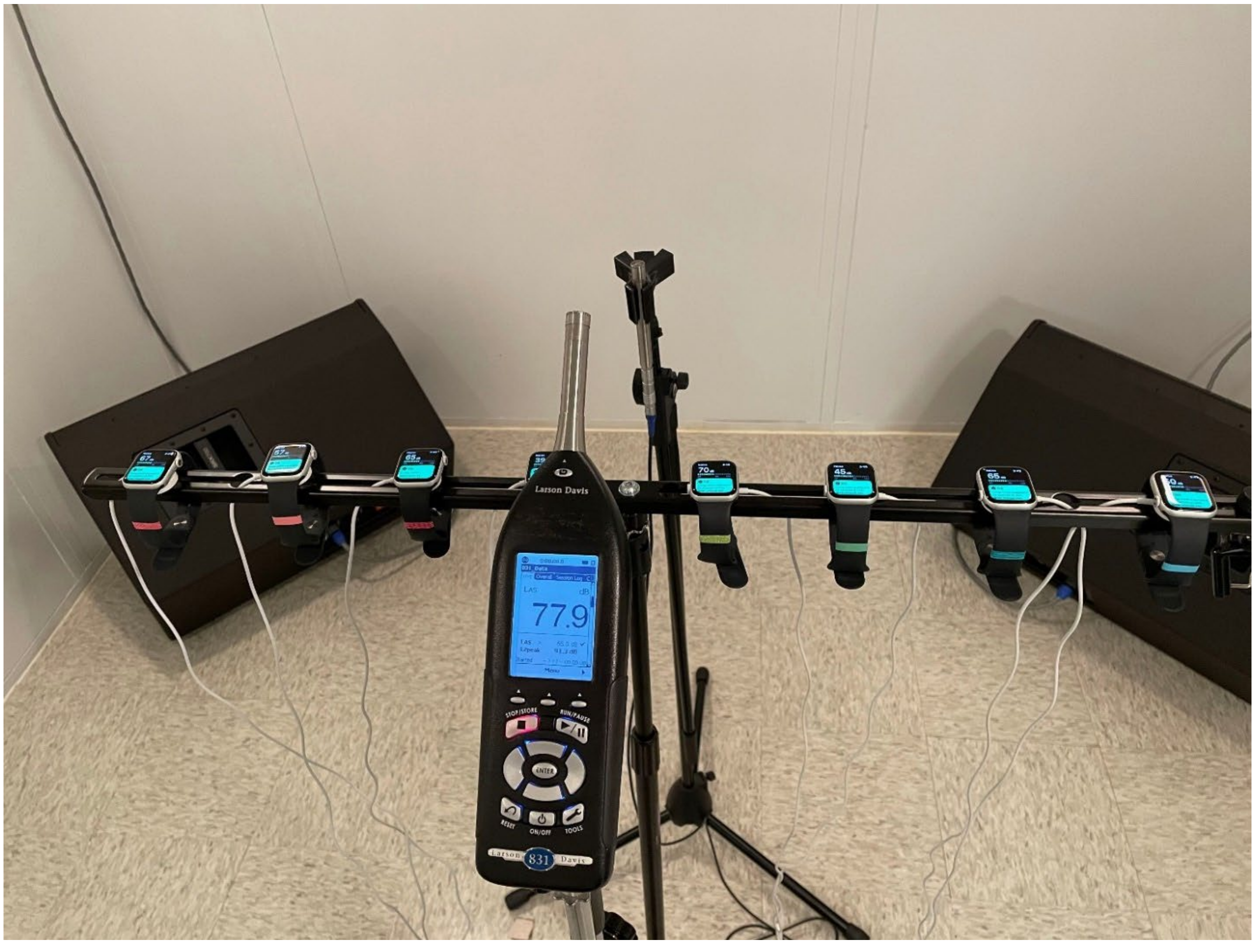

Figure 2. The testing apparatus consisting of a smartwatch stand, reference microphone and reference system and sound level meter. Noise generation speakers shown in background.

3.1.2 Test Conditions

To assess the accuracy of the Apple Watch, different types of noise were selected to simulate the response of typical sound measurement instruments over a wide range of sound levels, frequency bands, and real-life noises recorded in the field.

3.1.3 Broadband Sound Level Analysis

Eight watches were exposed to broadband (pink) noise in the reverberant chamber in 5-dB(A) increments from 65 to 95 dB(A). The measured noise levels were logged by each watch and subsequently extracted using the Air Force-developed Noise Exporter app. The timestamps on the measurements extracted from the Noise Exporter app were matched to the timestamps on the SLM. The mean and standard deviation (SD) of the difference between each watch's measured sound level and the reference system were calculated, along with the minimum (min) and max difference. Simple linear regression was used to determine whether differences among the measurements made by each watch were statistically significant ($p < 0.05$).

3.1.4 Octave-Band Analysis

The watches were evaluated based on the accuracy of their measurements to noise at various frequencies (1/1 Octave Bands: 125, 250, 500, 1000, 2000, 4000, and 8000 Hz). Sound was generated at 70, 80, 90 dB(A) at each of the octave bands. The results were shown graphically by constructing a boxplot of the difference in measurements between each watch and the reference microphone for each sound pressure level at each octave band.

3.1.5 Representative Occupational Noise Recordings

Two recordings of real-life transportation (more variable) and factory (less variable) noises were used in the evaluation. The recordings were played at an average equivalent sound level of 85 dB(A) to represent real-world occupational environments. The data were tabulated and compared across the different devices. A boxplot was used to assess the distribution of the difference in measurements between the reference system(s) and watches.

3.2 App Development

The watch sound level feature provided by Apple displays decibel levels every second and saves data every 30 seconds to Apple HealthKit data storage. HealthKit provides a central repository for health and fitness data on the iPhone and Apple Watch. With the user's permission, apps communicate with the HealthKit store to access and share this data. Previously, the raw data was not able to be extracted, and only a 30-minute averages of data was extracted. The Apple HealthKit was evaluated and a way to extract the 30 second raw data points was discovered. Coauthors developed an iPhone app called the Noise Exporter to read the 1-second exposure data from HealthKit, display it to the user, and export it to a comma-separated values file (.csv) for easier comparisons to professional sound measuring instruments. The app was designed to be easy to use, with a simple user interface that shows summary statistics and, has easy access to the export function and full sample details, if needed. The app has been deployed to the app store for beta testing through Apple's TestFlight.

4.0 RESULTS

4.1 Results and Data Analysis for the Laboratory Evaluation

4.1.1 A-Weighted Sound Level Analysis

Overall, a total of 11,441 measurements were collected through the Noise Export app. The average difference between each watch and the reference system is presented in Table 1. On average the watches measured 3.4 dB(A) lower than the reference sound levels. The min and max are the overall minimum and maximum across the dataset. The mean and SD are also calculated across the entire dataset. The "max" differences shown in the table are extreme outliers that are likely due to the desynchronization between the watches when the stimulus test stop (i.e., one would still be measuring while others stopped). Figure 3 illustrates the estimated mean and corresponding 95% confidence interval of the difference in noise level between each watch and the reference measurement. The overlapping confidence intervals indicate that the difference in measurements between each watch and the SLM were not significantly different.

Table 1. A-Weighted Analysis: Difference between the SLM and each Apple Watch (dB(A))

Device	**N**	**Min**	**Mean**	**SD**	**Max**
A1	1,427	-2.8	3.2	6.7	59.7
A2	1,430	-3.4	3.1	8.2	64.4
A3	1,432	-3.1	3.3	7.8	63.4
A4	1,431	-2.7	3.9	8.2	64.3
A5	1,432	-3.0	3.2	7.2	59.2
A6	1,429	-3.1	3.4	8.1	64.3
A7	1,432	-2.6	3.6	7.0	59.0
A8	1,428	-3.0	3.4	8.0	64.2
Total	**11,441**	**-3.4**	**3.4**	**7.7**	**64.4**

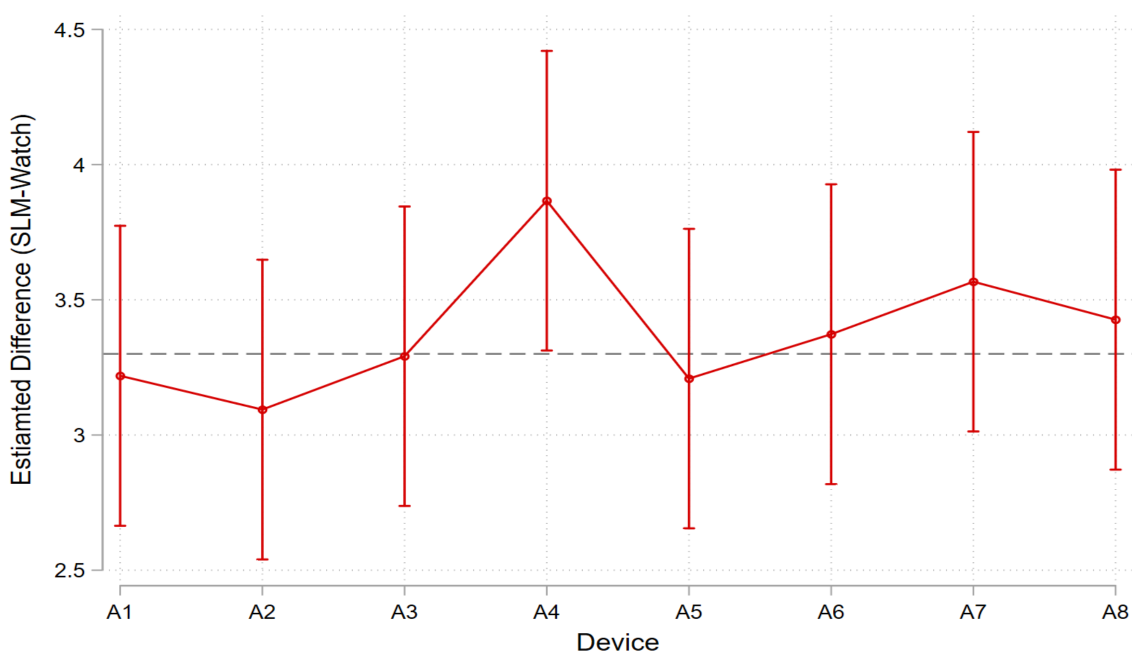

Figure 3. Plot of the estimated mean and corresponding 95% confidence interval of the difference in sound levels between watches and the reference.

4.1.2 Octave Band Analysis

A total of 18,449 measurements of octave band noises were collected. For each 1/1 (i.e., "full") octave band, 2,635 measurements were made. Figure 4 displays the difference in measurements between the watches and the reference system at each octave-band. The boxes represent the 25th to 75th percentile of the difference (i.e., the interquartile range, IQR), while the line in the box represents the 50th percentile (median). The boxplot whiskers represent all data points within 1.5 IQR of the nearest quartile. Individual markers outside the range of the whiskers represent statistical outliers from the distribution. All the watches measured lower than the reference microphone from the 125 Hz to 1000 Hz octave bands, with the agreement between the watches and reference steadily improving up to the 2,000 Hz octave band, where the watches and reference microphone had the best agreement. At the 4,000 Hz octave band, the watches measured higher sound pressure levels than the reference microphone, but when evaluated at the 8,000 Hz octave band, the watches again measured lower than the reference microphone. Similar to the A-weighted results, the watches demonstrated a high level of measurement precision as each watch consistently reported the same difference with the reference system.

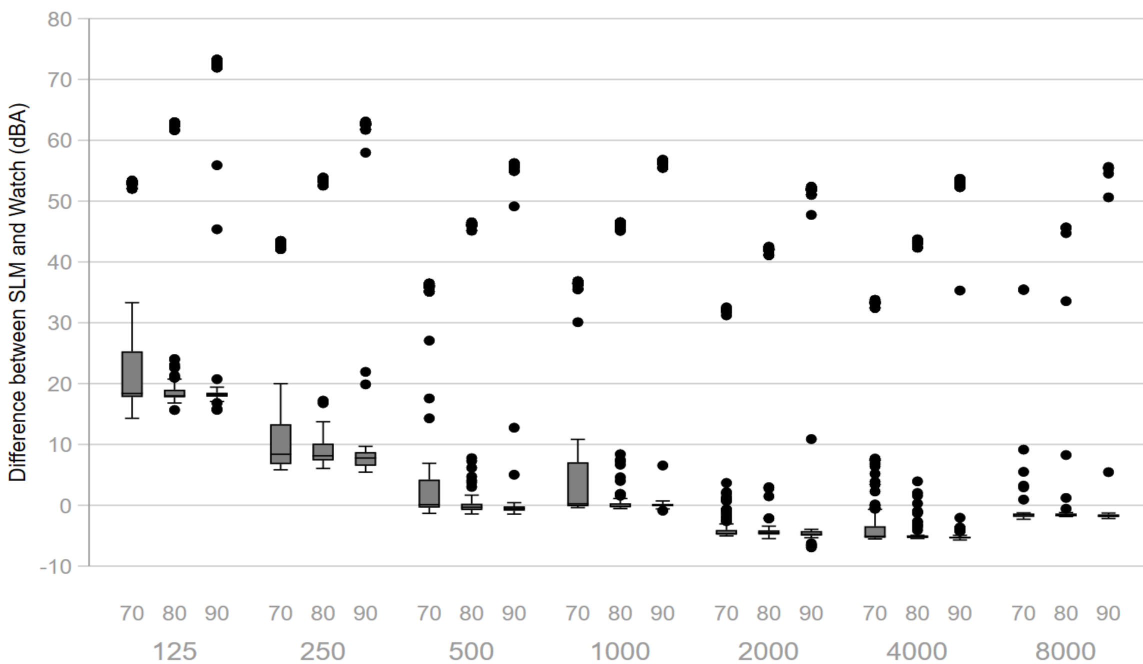

Figure 4. The difference in measured sound levels between the watches and the reference.

4.1.3 Occupational Noise Recordings Analysis

The difference in measurements between the reference system(s) and each watch are provided in Table 2. On average, the watches measured 0.1 dB(A) lower than the SLM for the recorded transportation noise compared to an average difference of 1.3 dB(A) lower for recorded factory noise. However, when the individual points are graphed out as a boxplot (Figure 5) it becomes apparent that even though on average the watches had better agreement with the reference system (s) when measuring transportation noise, there was far more variance in the level of agreement between the watches and the reference system(s) when measuring the recorded factory noise.

Table 2. Occupational Noise Analysis: Difference between the SLM and each watch (dB(A))

Factory Noise					
Device	**N**	**Min**	**Mean**	**SD**	**Max**
A1	46	-34.0	-2.2	6.2	20.0
A2	61	-10.0	-1.0	4.0	19.0
A3	58	-3.3	-0.4	5.5	21.0
A4	64	-3.3	-0.8	4.9	19.0
A5	66	-3.3	-0.5	5.6	20.0
A6	55	-10.0	-1.4	5.8	21.0
A7	74	-3.3	-1.7	2.6	19.0
A8	57	-36.0	-2.6	7.2	21.0
Total	**481**	**-36.0**	**-1.3**	**5.3**	**21.0**

Transportation Noise					
Device	**N**	**Min**	**Mean**	**SD**	**Max**
A1	98	-16.0	0.1	14.0	66.0
A2	138	-23.0	-0.6	12.0	66.0
A3	42	-24.0	2.6	21.0	65.0
A4	223	-24.0	-0.2	13.0	78.0
A5	90	-24.0	0.5	17.0	69.0
A6	256	-32.0	-0.5	13.0	68.0
A7	91	-23.0	-0.5	15.0	67.0
A8	213	-33.0	-0.1	12.0	74.0
Total	**1,151**	**-33.0**	**-0.1**	**14.0**	**78.0**

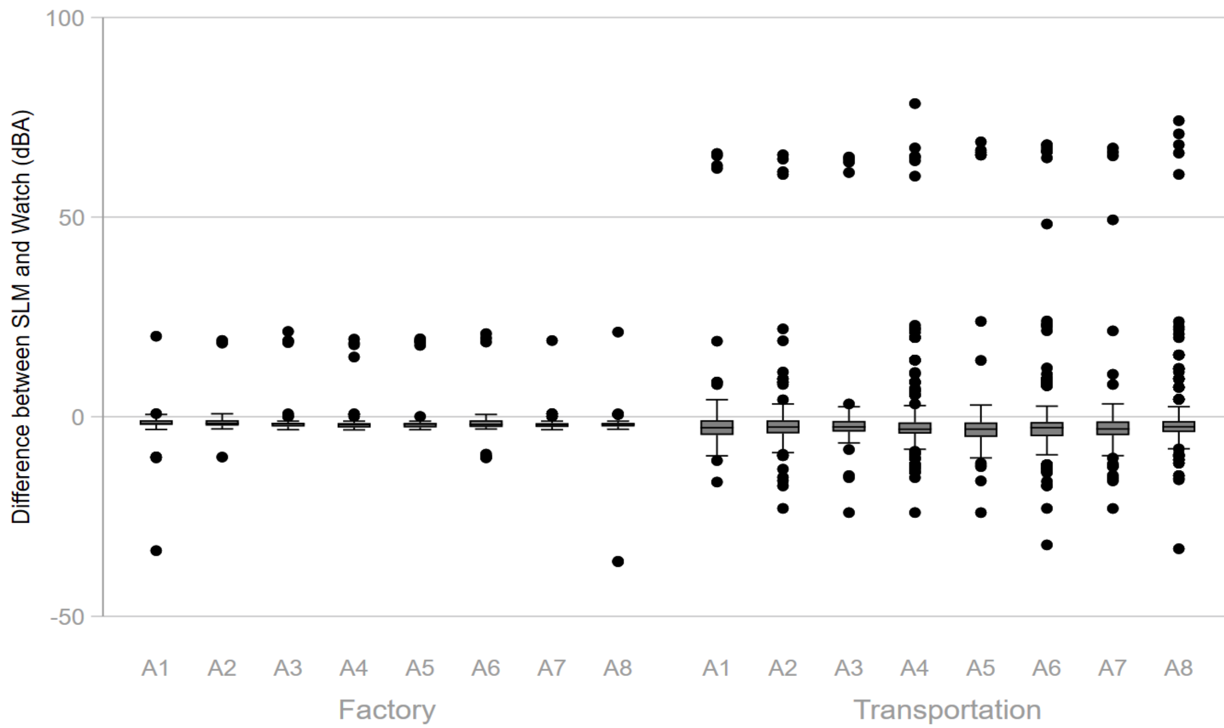

Figure 5. The difference in measured sound levels between the watches and the reference with two different types of recorded simulated noise.

5.0 DISCUSSION

This study is an independent evaluation of a wearable consumer noise measurement device, the Apple Watch Series 5, conducted in a controlled laboratory environment. The results of the laboratory evaluation indicated that on average, the watches measured 3.4 dB(A) lower than the reference system(s) when exposed to pink noise generated in the laboratory. Although the Series 5 watches measured outside the 2.0 dB(A) tolerance stipulated by ANSI for Type 2 instruments (ANSI 2014), it is notable that the measurements were consistently lower than the reference system(s), and the measurements showed good precision. Further, as seen in Figure 3 and 4, the differences between the watches and the reference system(s) are consistent over the entire range of 65-95 dB(A), which suggests that microphone saturation does not occur, at least at levels below 100 dB(A). At sound levels greater than 80 dB(A), the watches measured, on average, 3.4 dB(A) lower. The octave band analysis found that the watches consistently measured lower sound pressure levels in the frequency bands less than 1,000 Hz when compared to the reference microphone. The watches had the best agreement at the 2,000 Hz frequency and overestimated sound pressure levels at the 4000 Hz frequency. This could be due to bandwidth restrictions associated with the sampling rate in the watches compared to dosimeters and SLMs, as power limitations in wearable devices likely warrant reduced sampling rates. It could also be due to the influence of the microphone port design on the watch, which may result in directionality-induced impacts on measured sound levels at specific frequencies. In addition, the results suggest that while the watches can make reasonably accurate measurements in recorded industrial noise, there is evidence that in fluctuating levels of noise recorded over a short duration, the watch may be less accurate than traditional instruments.

Results from the laboratory evaluation indicated that the watches provided more accurate measurements than most uncalibrated smartphone apps. In 2016, Kardous and Shaw found that the mean difference between ten different apps available on Apple or Android and a Type 1 SLM exposed to pink noise ranged between -13.2 dB(A) and 3.6 dB(A) (Kardous and Shaw, 2016). Subsequent evaluations similarly found that only one of the five Apple apps that was tested was within 5.0 dB of a calibrated SLM (Nast *et al*. 2014). A much larger study of seven apps across Apple and Android found that only one Apple app was within 1.0 dB of a reference microphone (Murphy and King, 2016).

Further laboratory and field studies should be conducted to assess the impact of the microphone location relative to the source of noise in real-life situations and the impact of personal protective equipment that covers the microphone on measurement accuracy. In addition, future occupational and environmental studies should compare the calculated 8-hour and 24-hour average noise levels as measured by the wearables to those calculated by a traditional dosimeter. Finally, different brands of wearables will need to be assessed as they become available.

6.0 CONCLUSIONS

This is the first known study to evaluate the accuracy of the noise measurements of the Apple Watch in a controlled laboratory environment and according to standard testing procedures. Our results indicate that the Apple Watch Series 5 provides reliable noise measurements, but may be less accurate in quieter (and inherently less-risky) environments and when measuring low frequency sounds. Furthermore, our approach can be used as a template for future studies of similar devices. While wearable consumer devices will not replace traditional noise dosimeters for compliance measurements, they are valuable tools, particularly when more expensive, dedicated sound measurement equipment is not available. Their ease of use makes these devices ideal for longitudinal studies of noise exposure. It is anticipated that devices like this will be used to generate a vast amount of exposure data that can be easily correlated with a time and location, and that these extremely large datasets will develop and employ new “big data” analysis approaches to better characterize human exposures to noise and associated health risks. The results may also give military health and safety experts the ability to utilize the device and technology to monitor noise levels throughout an installation or deployed location. Using the Apple Watch as a wearable sensor may possibly identify and prevent future noise induced hearing loss among Department of Defense personnel quickly and with less cost.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AFRL	Air Force Research Laboratory
ANSI	American National Standards Institute
app	application
BE	Bioenvironmental Engineering
dB(A)	decibels, A-weighted value of sound pressure level
Hz	hertz
IQR	interquartile range
LD	Larson Davis
min	minimum
max	maximum
NIOSH	National Institute for Occupational Safety and Health
SD	standard deviation
SLM	sound level meter
USAF	United States Air Force