# AN INVESTIGATION INTO THE EFFECT OF SWEAT AND MOISTURE ON THE PERFORMANCE OF IN-EAR MONITORS

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## 1 INTRODUCTION

In-ear monitors (IEMs) have become increasingly used in the live events industry due to numerous benefits over traditional stage monitors. Research has been carried out into the performance of IEMs and how they affect hearing, but to the authors' knowledge little to no research has been done into how IEM performance could be affected by moisture or sweat.

Live music events are often in hot and humid environments, increasing the likelihood of sound engineers and performers sweating whilst wearing IEMs. Not only can sweat be produced through body temperature regulation, but stress and pressure can also lead to emotional sweating. Once this sweat gets into the ears how does this change the perceived output of the IEMs and what level of moisture do changes start to be seen? This paper will investigate these scenarios.

The paper begins in Section 2 with background information on issues related to IEMs in live event settings as well as relevant fundamentals of fluid dynamics. Section 3 presents the adopted methods for the four experiments conducted as part of this work, where results and accompanying analyses are given in Section 4. The paper is concluded in Section 5, including recommendations for further research in this area.

## 2 IN-EAR MONITORS

### 2.1 Usage at live events

After long periods of wearing IEMs, as is often the case at live events, a build-up of moisture is possible, where the two main causes of IEM faults are wax and sweat[1]. With a wax build-up in the ear, the loudspeaker port can get clogged, resulting in lower quality audio delivery. When using universal IEMs that have foam tips, the moisture from sweating is absorbed, causing them to fall out of the wearer's ears[2].

Whilst custom IEMs offer an air-tight fit, this is not always the case. Custom molds have a lifespan of two years. They can shrink and the size and shape of a person's ear can change over time[2]. Once that tight seal has been lost, this gives an opportunity for more moisture to enter the person's ear. A wearer may also not have the IEMs inserted for the whole duration of the event, regularly taking them in and out of their ears in instances such as conversation. The ear canal can also be altered through jaw movement, creating opportunities for moisture to enter the ear during the occasions when the IEMs are not worn or sealed correctly[3].

The above scenarios illustrate the challenge of using IEMs at live events: with so many ways for moisture to enter a user's ear, it can be difficult to ensure a consistent listening experience, which has the potential to negatively impact a performance.

## 2.2 Sound propagation in liquids

Sound struggles to transfer between the air into a liquid due to a mismatch in acoustic impedance between the two mediums. When sound waves hit the surface of the liquid most get reflected[4]. The human ear is designed to hear sounds in air and is not as efficient in liquids. Vibrations can bypass the eardrum due to the head containing tissues that contain liquid, altering the perceived output of the sound[5]. In the context of IEMs, the introduction of moisture to the hearing system is likely to result in alterations to the frequency response of the IEMs, due to the complicated interaction between air-borne sound and moisture.

## 2.3 Capillary action

Capillary action is the result of cohesion and adhesion which results in a liquid moving along the surface of another material[6]. Cohesion is the attraction of molecules of the same type, while adhesion is the attraction of molecules of different types. Capillary action occurs with some liquids but not all; only when adhesive forces are stronger than the cohesive forces which become a surface tension[7]. Water is better at capillary action than most liquids. When a straw is placed into a cup of water, the water particles are attracted to the particles of the straw forming a meniscus[8]. Through cohesive forces, the attracted molecules will pull other water molecules along, resulting in the water rising inside the straw to a higher level than inside the cup, acting against gravitational forces[9].

Capillary action also occurs on the outside of the straw, but due to the narrower diameter inside the straw, the cohesive forces are stronger. The narrower the tube, the greater the effect of the capillary action[10]. In narrower tubes, the liquid rises to a higher level. An increase in temperature will also increase the capillary action[7]. An example of capillary action with organic tissue is in the eye, the lacrimal ducts are narrow tubes that transport moisture, or tears, from the surface of the eye to the nasal cavity[11].

Regarding the use of IEMs, which typically contain narrow tubes or ports leading to the transducers, the introduction of moisture to the system is likely to experience capillary action. This will result in the moisture drawing up the tubes/ports of the IEM, potentially reaching the transducer(s) and causing a degraded response and potentially failure.

# 3 METHODOLOGY

## 3.1 Artificial sweat solution

A solution for artificial sweat was synthesized in three equal parts, consisting of distilled water, sodium chloride (NaCl) 20 g/l, and ammonium chloride (NH4Cl) 17.5 g/l[12]. Ammonium chloride is a hazardous substance due to being an irritant to the skin, eyes, and lungs and may affect the kidneys if swallowed[13]. Due to these hazards, the artificial sweat substance was created in a controlled lab environment located at the University of Derby which was also the location where experiments were conducted.

To determine the measurement increments for the introduction of moisture to the IEM/ear system, research into the volume of a bead of sweat was conducted. Unfortunately, this information was unable to be obtained. An investigation was made to overcome this issue, in which a human test subject was put through physical activity until sweat started to form around the face and ears. Using a pipette, sweat was extracted with the aim of obtaining a measurement for one drop with enough volume to start running down the face and ultimately entering the ear. The pipette used had a measurement resolution of 0.01 ml and, therefore, six beads of sweat had to be collected before this minimum measurement was reached. The sweat formed around the forehead, the side of the face and the ears, running down the side of the face and gathering in the hair allowing the sweat to enter the ear from various routes.

## 3.2 Ear model and IEMs

The ear model was constructed by taking an impression of a test subject's pinna and ear canal by inserting silicone into the ear with a syringe. The silicone was left inside the ear to set, before being removed and 3D scanned into a computer. From these scans, a model of the test subject's ear was 3D printed with the ear canal extended to be 25 mm long with an 8 mm diameter, representing the approximate measurements of an ear canal[14]. The measurements also allow for an Earthworks M30BX measurement microphone to be placed inside the ear canal and to reduce the possibility of external noise affecting results. The impressions were taken at Cosmic Ears and the model and IEMs were manufactured on-site. The IEMs used in the experiment were the Cosmic Ears CE3P, which have a bandwidth of 18 Hz – 18 kHz[15] and were constructed based on the scans of the test subject's impressions, fitting snugly into the artificial ear.

## 3.3 Data acquisition

A four-second sweep was created in the digital audio workstation, Reaper, with a sampling rate of 48 kHz using the ReaVerb plugin. Connecting the IEMs to a computer via a Focusrite Scarlett 2i2 USB audio interface, the sweep outputted through the left IEM which was placed into the artificial ear. Outputted soundwaves travelled through the ear canal and were captured on-axis by the measurement microphone, placed inside the ear canal opening at the rear of the model. The microphone was connected via the Focusrite audio interface and recorded the measured signal into Reaper on a separate track. The captured sweep was deconvolved through the ReaVerb plug-in. This process consists of inverting the originally generated sweep and subtracting it from the captured sweep, the inverse filter, resulting in an impulse response[16].

This process was repeated after increasing the amount of moisture using the constructed artificial sweat solution. Initially a test was done with no moisture to provide baseline results. Using a pipette, 0.01 ml of the artificial sweat solution was inserted into the top of the pinna of the model, given four seconds to allow the solution to run down into the ear before placing the IEMs back into the model and measured. This process continued until a total of 30 trials were conducted equalling a total of 0.29 ml applied to the artificial ear. Between trials, the microphone was removed and wiped to ensure moisture did not enter the device causing any malfunctions.

After ensuring the 3D model had thoroughly dried out, a second test (Test 2) was conducted, where this time the solution, in 0.01 ml increments, was inserted into the ear canal via the rear of the model. This method of testing does not accurately represent how sweat would enter the ear but ensures all of the moisture is inside of the ear canal to show how the increased moisture volume affects the measured IEM response. During the first test (Test 1), it is difficult to say what volume of moisture ran down into the inner ear before the IEMs were reinserted and could have also escaped as the IEMs were removed. Test 2 avoids this uncertainty while also not requiring the constant reseating of the IEMs in the artificial ear. A total of 51 trails were conducted in Test 2, resulting in 0.50 ml of artificial sweat being inserted into the ear canal.

A third test (Test 3) consisted of applying 0.01 ml increments of the artificial sweat solution into the top of the pinna (as in Test 1) with a longer delay (10 minutes) before inserting the IEMs taking a measurement. This was carried out over a two-hour period which resulted in 13 trials and 0.12 ml of artificial sweat solution applied.

A fourth and final test (Test 4) consisted of applying three 0.01 ml drops of the sweat solution to the top of the pinna. This was done after a baseline test with no moisture was captured. After the three drops of artificial sweat were added, the IEMs were inserted into the model and measured at various intervals over an hour. With this test, the moisture level did not increase beyond the original 0.03 ml.

It must be noted that Tests 1 and 3 required the IEM and the microphone to be removed and reseated within the 3D printed model. Whilst best efforts were made to place both components back into the same position, slight differences in positioning may have affected the results. During Test 2, inserting the moisture into the rear of the model, the IEMs were only removed and reinserted once after the baseline test, to apply the artificial sweat solution. The microphone did need to be removed and best efforts were made to place this back to the same position, but this is another potential source of error.

The final test only required the microphone and IEM position to be altered once after the first baseline test, once the artificial sweat had been applied. As the position and angle of each component were consistent, the results were only affected by the moisture movement inside of the model, where no solution was observed to escape the model during the hour of testing.

# 4 RESULTS AND ANALYSIS

## 4.1 Test 1

Results from Test 1 show a significant change in the low frequency response of the IEM. After the final increment of the solution was applied, results show the highest output levels, averaging 7 dB above baseline below 1 kHz. After 25 drops of moisture were applied, a considerable reduction in level can be observed, where at 220 Hz this is 13 dB. All trials with moisture introduced to the system show a sharp attenuation around 6 kHz of approximately 23 dB, indicating potential capillary action within the IEM. Above 6 kHz, the magnitude responses show a consistent gain, peaking around 9 kHz, at 7 dB above baseline. Overall, the results from Test 1 indicate that the frequency response of the IEM under test varied considerably with the introduction of moisture, where trials showed the most variation in the low frequency range (below 1 kHz). The observed behaviour wasn’t linear. Instead, the observed level relative to baseline alternate between being above and below the dry measurement. This could be due to the reseating of the IEMs and microphone required between trails and will be inspected in the remaining test results.

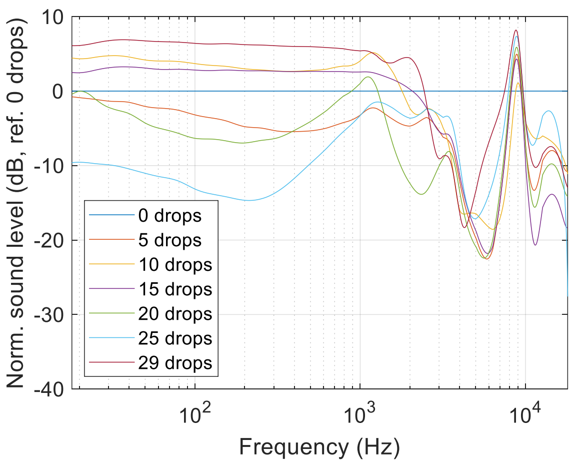


Figure 1. Test 1 results. Moisture applied to pinna in 0.01 ml drops, 4-second intervals.

## 4.2 Test 2

The impulse responses captured from Test 2 display more consistency compared to Test 1. With the IEMs staying in the same position for all trials, this source of error seen in Test 1 was removed. There are similarities, however, shown in these results as compared to Test 1, with the sound levels of the low frequencies showing significant nonlinear variation between trials.

The method of Test 2 allowed the observation of the solution gathering between each trial. As the moisture was applied, evidence of capillary action was directly observed, and as moisture continued to gather at the same point where it was applied, a meniscus formed as the artificial sweat solution began to rise the sides of the ear canal. The volume of solution continued to rise in this same manner until 0.37ml of moisture had been introduced. Before this point, increased low-frequency is observed from 0.21 ml onwards, in which the gap between air and moisture for the sound to travel through decreases as the moisture increases. Once the volume is sufficiently saturated with moisture (at 0.37

ml) the solution was observed to spread throughout the ear canal, potentially explaining the decrease in low frequencies, as the sound has significant interactions with the liquid.

A peak at 5 kHz is seen after moisture is applied, There is a considerable boost of 15dB after 0.3ml of moisture which remains constant at 0.4 ml of moisture despite being the point where the moisture dispersed throughout the ear canal. By the final trial this peak had increased even further. This pattern can also be observed between 2 kHz and 3 kHz. After 0.10 ml, the sound level shows minimal difference and only a 2 dB increase after 0.2 ml. At 0.3 ml and 0.4 ml this increase further to 10 dB and again to 12 dB after 0.5 ml. The significant attenuation at 6 kHz in Test 1 isn't observed in this test, indicating that the observation from Test 1 can be attributed to the moisture preventing a good seal when the IEM was reseated in the ear.

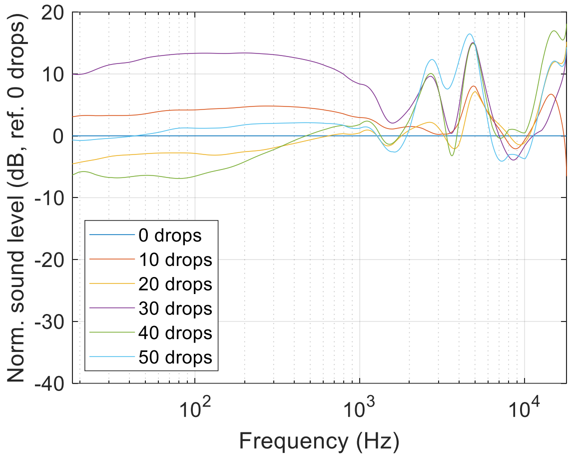


Figure 2. Test 2 results. Moisture applied to rear ear canal in 0.01 ml drops, 4-second intervals.

## 4.3 Test 3

Test 3 reveals significant variation in the low-frequency response due to the introduction of moisture to the system under test. 0.12 ml shows the highest increase in low frequency energy. The lowest observed low frequency level is seen after 0.1 ml with an attenuation of 10 dB. As with Test 2, a high frequency peak is observed after moisture is applied, at a slightly higher frequency of 6 kHz instead of 5 kHz in Test 2. The results from this test are largely aligned with those of Test 1, aside from the omission of the null at 6 kHz. Due to the longer delay between measurements (10 minutes instead of 4 seconds), it is likely that the IEM was able to make a better seal with the ear after being reseated as the pinna had more time to dry as the moisture dripped into the ear canal.

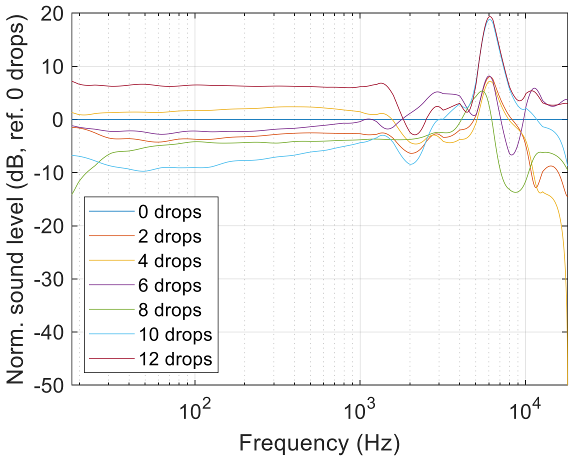


*Figure 3. Test 3 results. Moisture to pinna in 0.01 ml drops, 10-minute intervals.*

## 4.4 Test 4

Test 4 displays the most consistent results throughout the four tests, with a consistent magnitude response difference observed between baseline and measurements after the 0.03 ml of moisture was introduced. No further moisture was introduced to the system, where measurements were taken at three minute intervals over one hour. While the responses are largely consistent over time, at the 40-minute mark frequencies below 2.5 kHz show around 0.5 dB attenuation, along with the further attenuation at 6 kHz. This is likely the moment when capillary action starts to occur, where a higher volume of moisture has moved from the pinna into the ear canal, affecting the acoustical output.

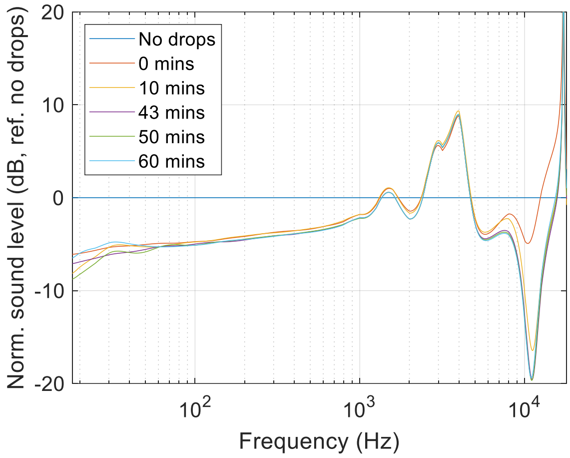


Figure 4. Test 4 results. 0.03 ml of moisture applied to pinna at t = 0 minutes.

## 4.5 Subjective investigation

Following the experiments with the 3D model, an informal investigation was conducted. For safety reasons 0.03 ml of water was used instead of the synthetic sweat solution. The water was inserted into the pinna of the author's left ear followed by the IEMs used in the previous tests. Music was outputted through the IEMs for one hour, with any audible changes or experiences noted.

Water was instantly felt entering the ear canal as the IEMs were inserted and a noticeable difference in sound could be heard between the left and right outputs with the left sounding dull and quieter. After one minute, the movement of moisture was heard, and the output of the left IEM became subjectively worse. After four minutes a further movement of moisture was heard although the perceived output did not change. At 15 minutes a small amount of moisture was felt escaping at the bottom of the outer ear and at 17 minutes movement of moisture could be felt at the top of the pinna. No further changes were noticed until 42 minutes when the movement of moisture was again heard in the ear canal and the perceived output changed, becoming less muffled, although still at a much lower SPL compared to the right ear. This continued until 58 minutes when moisture movement was again heard, and the output returned to the previous dull experience. On removal of the left IEM after 60 minutes, moisture was quickly felt exiting the ear and was also observed on the IEM.

# 5 CONCLUSIONS

Observations from the four conducted tests give evidence of moisture affecting the performance of IEMs. Test 2 and Test 4 justify this more so with the controlled test methods (avoiding the need to reseat the IEM for every trial). Tests 2 and 4 also display evidence of capillary action. Test 2 allowed visual inspection of the ear canal and correlated to the measurements when the volume of moisture distributed throughout the ear canal (and resulting meniscus) became significant. Capillary action in Test 4 could not be observed visually, but the captured responses provide evidence of this occurring between 30 and 40 minutes, resulting in changes to the frequency response.

The research conducted into the volume of a bead of sweat and the moisture levels used in the experiments demonstrates what could occur in certain live event conditions. After conducting Test 4 in which the IEMs and microphone remained in the same position throughout the experiment, further testing using this method with different volumes of moisture would have been worthwhile. By testing with smaller volumes than the 0.03 ml used, results may have shown how little amount of sweat it takes for IEMs to be affected. The time of 40 minutes in which major changes to the output were observed, could also occur at a different time with different moisture levels. Unfortunately, due to time restraints further testing could not be carried out.

The lab in which experiments were taking place was kept as quiet as possible during all tests, some background noise could be heard at times and could have been picked up during the measurements, although these would have been minimal and it is not thought results were negatively affected by this. If the experiments were to be conducted again, ideally, they would be done in a semi-anechoic chamber. For this experiment, it was felt that the benefits received from conducting the tests outside of the lab were not worth the risk of moving the hazardous substance. In between tests, the model was thoroughly dried and placed into a bag containing silica gel bags to absorb any remaining moisture. A hygrometer was attempted to be obtained to test the moisture level before each test, but a suitable device could not be acquired in which further testing would benefit.

Further research into the conditions of live events and observations on IEMs would add to the findings of this research. Professionals were contacted and their feedback was a valuable part of the research conducted. By being on-site at a live event, notes can be made regarding the conditions such as average temperature. At what point during the event do the artists and engineers wearing IEMs start to show evidence of sweating? How often are the IEMs removed and reinserted into the ears? The subjective investigation can also be expanded, by increasing the number of test subjects and recording their experiences, different volumes of moisture would also be used.

While the research detailed in this paper is likely to suffer from certain unavoidable sources of error, the results provide evidence to the fact that the introduction of moisture to the outer ear of a performer wearing IEMs during a live event has the potential to significantly affect the listening experience. The observed effects of the moisture don’t appear to behave in a linear fashion over time. Instead, certain critical amounts of moisture cause a discontinuity in the IEMs behaviour, resulting in relatively sudden changes in frequency response. It is the hope of the authors that this work provides a starting point for others to consider this practical issue in the live event industry to work towards methods for minimizing the impact of moisture on IEM performance.

# 6 REFERENCES


1. Make Life Click (2022) in-ear monitors #1 beginners guide to understanding IEMs, Make Life Click. Available at https://makelifeclick.com/beginners-guide-in-ear-monitors-custom-universal/ (Accessed: 24 October 2022).
2. Electronic Musician (2020) How to get the most out of in-ear monitors, MusicRadar. Available at: https://www.musicradar.com/how-to/how-to-get-the-most-out-of-in-ear-monitors (Accessed: 24 October 2022).
3. Gordon, K. (2008) In-Ear Monitors: Tips of the Trade, AudiologyOnline. Available at: https://www.audiologyonline.com/articles/in-ear-monitors-tips-trade-902 (Accessed: 13 November 2022).
4. Baird, Dr.C.S. (2013) How does sound going slower in water make it hard to talk to someone underwater?, Science Questions with Surprising Answers. Available at: https://wtamu.edu/~cbaird/sq/2013/11/12/how-does-sound-going-slower-in-water-make-it-hard-to-talk-to-someone-underwater/ (Accessed: 13 November 2022).
5. De Brabandere, S. (2019) What Do You Hear Underwater?, Scientific American. Available at: https://www.scientificamerican.com/article/what-do-you-hear-underwater/ (Accessed: 13 November 2022)

6. Study.com (2022) Capillary Action in Plants: Concept & Importance, Study.com. Available at: https://study.com/learn/lesson/capillary-action-plants-concept-importance.html (Accessed: 27 November 2022).
7. Peiris, A. and Stein, B. (2020) Capillary Action, Chemistry LibreTexts. Available at: https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Physical_Properties_of_Matter/States_of_Matter/Properties_of_Liquids/Capillary_Action (Accessed: 27 November 2022).
8. Water Science School (2018) Capillary Action and Water, US Geological Survey. Available at: https://www.usgs.gov/special-topics/water-science-school/science/capillary-action-and-water (Accessed: 27 November 2022).
9. Helmenstine, A.M. (2020) Capillary Action: Definition and Examples, ThoughtCo. Available at: https://www.thoughtco.com/definition-of-capillary-action-604866 (Accessed: 13 November 2022).
10. Study.com (2021) What is Capillary Action?, Study.com. Available at: https://study.com/learn/lesson/capillary-action.html (Accessed: 27 November 2022).
11. Ducker, L. and Rivera, R.Y. (2022) ‘Anatomy, Head and Neck, Eye Lacrimal Duct’, in StatPearls. Treasure Island (FL): StatPearls Publishing. Available at: http://www.ncbi.nlm.nih.gov/books/NBK531487/ (Accessed: 27 November 2022).
12. British Standards Institution (BSI) (2015) BS ISO 3160-2:2015 Watch-cases and accessories - Gold alloy coverings. Available at: https://bsol-bsigroup-com.ezproxy.derby.ac.uk/PdfViewer/Viewer?pid=000000000030298697 (Accessed: 29 January 2023).
13. New Jersey Department of Health (2016) ‘Hazardous Substance Fact Sheet - Ammonium Chloride’. New Jersey Department of Health. Available at: https://www.nj.gov/health/eoh/rtkweb/documents/fs/0093.pdf (Accessed: 25 April 2023).
14. Areias, B. et al. (2016) ‘Finite element modelling of sound transmission from outer to inner ear’, Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine, 230(11), pp. 999–1007. Available at: https://doi.org/10.1177/0954411916666109.
15. Cosmic Ears (no date a) CE3P, Cosmic Ears. Available at: https://www.cosmicears.com/products/starburst/sb-ce3p/ (Accessed: 1 May 2023).
16. Francis, G. (2016) ‘Supplement to REAPER User Guide The REAPER Cockos Effects Summary Guide’. Available at: https://www.reaper.fm/guides/ReaEffectsGuide.pdf (Accessed: 1 May 2023).