Heat and humidity buildup under earmuff-type hearing protectors

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Abstract

A major barrier to effective wear of hearing protection is comfort. This study examined several comfort indicators in the earmuff-type hearing protectors. Twenty subjects wore hearing protectors instrumented with two different temperature/humidity measurement systems (Omega and iButton) while walking a corridor for about 25 min. The instruments recorded the temperature and humidity every 10 s and their results were compared. In addition, skin surface pH was measured at the ear canal entrance before and after the task. Finally, the subject indicated earmuff comfort at the beginning and end of the session. Earmuff comfort decreased significantly over the course of the walking task. Ear canal pH became slightly less acidic, but the change was not statistically significant. The two temperature/humidity systems provided comparable results. Heat increased at about 0.3°F while humidity built up at about 0.5%/min. However, the study found some limitations on the instrumentation. The complexity of the electrical connections and equipment in the Omega probe system led to loss of three subject's data. The iButton device was more robust, but provided only 256 gradations of temperature and relative humidity. Even with its limitations, the iButton device would be a valuable tool for field studies. The present study showed that the buildup of heat and humidity can be modeled using linear equations. The present study demonstrates that relatively inexpensive tools and a low-exertion task can provide important information about the under-earmuff environment, which can inform assumptions about comfort during use.

Keywords: *Comfort, hearing protection, personal protective equipment*

Introduction

Workers typically voice two major objections to wearing hearing protectors: comfort and communications. Generally, earplugs are more popular than earmuffs, at least in part because earmuffs are perceived as building up more heat and humidity than earplugs (for a review of hearing protector comfort see Davis, 2008).[1] Workers judge earmuffs to be more cumbersome in tight quarters, and they cannot be worn with glasses.

The advantages of earmuffs have been previously described. Inexperienced and experienced workers alike can don a pair of earmuffs and obtain more predictable and repeatable attenuation than with earplugs.[2] With current technology, earmuffs can be electronically outfitted to produce full physical attenuation in noisy environments, while producing no attenuation or even amplification in quiet environments. Earmuffs can be fitted with electronics that actively cancel external noises to increase their low-frequency attenuation. In addition, earmuffs can effectively be worn over hearing aids.[3]

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Only one parametric study of hearing protector heat and humidity buildup has been reported in the literature. An extended abstract by Ivarsson *et al*.[4] reported on what appears to be a single subject wearing earmuff hearing protectors while pedaling a stationary bicycle for 1 h at 40% load. Skin temperature behind the ear, relative humidity and ambient temperature under the muff were measured, although no details of instrumentation were given. In addition, perspiration and condensation were collected in an absorbent material in the earmuff. The results are contained in three graphs and the following information comes from reading data off of those graphs. The outside skin temperature rose from 94.5º to 98.6ºF over about 30 min when it neared asymptote. Temperature under the muff rose from 75º to about 91.4ºF over the first 30 min, then slowly rose another degree over the next 30 min. The relative humidity quickly rose from 47% to 65% over the first 5 min, then slowly continued to increase during the rest of the 60-min session.

The present study was undertaken for two reasons. The first reason was to characterize several parameters of comfort under the earmuffs in a relatively low-effort working environment in a larger sample than used by Ivarsson. The second reason was to compare two systems for measuring heat and humidity under the earmuff cup. One system was rather bulky and required modifying the hearing protector ear cup; the other system used a single instrument about the size of a U.S. nickel. Our goal was to determine whether the iButton might be a useful field instrument.

Methods

Subjects

All procedures were approved by the NIOSH Human Subjects Review Board. Twenty subjects were recruited (14 male and six female). Subjects were offered $25 for participating in the experiment. Subjects under the age of 18 years were required to obtain parental consent in order to participate. Subject ages ranged from 16 to 56 years, with an average age of 38.45 years (standard deviation = 14.3 years).

Equipment

Three earmuffs were used: a Peltor H7A (Noise Reduction Rating [NRR] = 27), the Howard Leight Leightning (NRR = 31) and the Moldex M1 (NRR = 29). The style of all the earmuffs was similar; each consisted of hard plastic earcups with a foam lining and soft vinyl cushions. In each protector, a technician drilled a hole through the plastic and the foam lining of one of the earcups of each set and inserted a rubber bushing. The right-angle measurement probe of a RH411 high-performance digital thermohygrometer (Omega Technologies Ltd., Stamford, CT, USA) was pushed through the rubber bushing and was held in place by friction. The sensor opening was positioned to be about in the center of the cup while not touching the subject's pinna [Figure 1]. The RH411 system has an accuracy of ±1ºF and ±3–5% RH. (This system will be referred to as the "Omega" system.) The Omega system is considered the "gold standard" in this experiment.

The temperature and relative humidity analog outputs of the subject's RH411 were routed through three wires to two VOLT101 voltage data loggers (input range: -1 to +16 VDC) (MadgeTech, Warner, NH, USA). These data loggers read each analog output signal every 10 s. The data loggers were programmed and data were retrieved by MadgeTech software and saved in a standard Microsoft Excel spreadsheet format. The data loggers were attached to the RH411 by Velcro® squares. The RH411 was secured to the subject's belt to allow for unimpeded walking.

A second Omega RH411 system displayed lab-ambient temperature and relative humidity. Data loggers were not used with this stand-alone system.

The second measurement system consisted of a model DS1923 iButton (Maxim Integrated Products, Sunnyvale, CA, USA) relative humidity and temperature recorder. (This will be referred to as the "iButton" system.) The iButtons were programmed and the data were read using a universal serial bus (USB) to 1-Wire/iButton adapter and iButton Viewer Software and were saved as a comma-delimited file. The iButton recorders were programmed to record and store values every 10 s. According to the online data sheet, the accuracy of the iButton is about ±0.9ºF and about ±0.64% RH. The iButton was attached to the foam inside the ear cup opposite the Omega system by a Velcro® square [Figure 2]. The Omega and iButton systems therefore recorded the same session in opposite ear cups.

Figure 1: Omega temperature and humidity probe in a Peltor ear cup

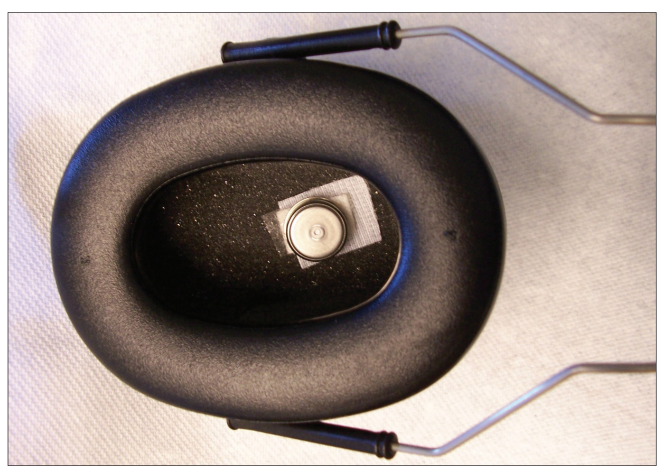

Figure 2: iButton temperature and relative humidity sensor attached to a Peltor ear cup with velcro squares

Skin surface pH was measured by a MSC 100 Mobile Skin Center with a Skin-pH-Meter probe (Courage and Khazaka Electronics, Köln, Germany). Measurements were recorded to the 1/10 pH unit. The probe tip was stored in the supplied buffer between the measurements. Before and after making a measurement, the probe was rinsed with a flow of distilled water.

Procedure

To ensure consistency, the session was scripted. Subjects were greeted and provided with an oral summary of the experiment. If 18 years of age or over, they were provided with the consent form. Those under 18 years of age were given 24 h to obtain consent from their parents. Cold bottled drinking water was available.

The three ear muffs were rotated between the subjects. Each subject wore only one earmuff set.

Subjects were seated and a pH reading was taken in the concha of the pinna just below and to the rear of the ear canal opening.

Subjects then placed the earmuff into position and the experimenter checked for proper placement. Subjects were asked to indicate on a paper scale (1–5, with 1 labeled very uncomfortable and 5 labeled very comfortable) the current feeling of hearing protector comfort at that moment. This value was recorded. An electronic timer was started and subjects were asked to return to the lab room in about 25 min.

Subjects walked at their own chosen pace up and down a 96-m, level, air-conditioned corridor for about 30 min.

Upon the expiration of the timer, subjects returned to the lab. They were again asked to point to the scale indicating the level of comfort for the earmuffs. The earmuffs were then removed and the subjects were seated. A second pH reading was taken at the same place on their pinna. At that time, any additional questions were answered. Payment was made and the subject was released.

The data from the data loggers and from the iButton were downloaded to a laptop computer. Temperatures were recorded in Fahrenheit and relative humidity was recorded in per cent.

Statistical analysis

In order to describe and compare measurement activity in the Omega and iButton systems, the generalized estimating equations approach[5] was used, with all the temperature data represented in one model and all the relative humidity data represented in another model. Starting with temperature, the model estimates the mean temperature, T_{ij}, for subject i at measurement j with (1):

$$T_{ij} = \beta_0 + \beta_1\ \text{system}_{ij} + \beta_2\ \text{testtime}_{ij} + \beta_3\ \text{testtime}_{ij}^2 + \beta_4\ \text{system}_{ij}\text{xtesttime}_{ij} + \beta_5\ \text{system}_{ij}\text{xtesttime}_{ij}^2 \quad \text{...(Eq.1)}$$

in which, system_{ij} represents the type of measurement system being used (0 = Omega and 1 = iButton) and testtime_{ij} is the length of exposure time in minutes that has passed for subject i at measurement j. The parameters have the following meanings:

- β_0 = intercept for the Omega system,
- β_1 = difference between the intercepts for the Omega system and for the iButton system,
- β_2 = coefficient for length of exposure time for the Omega system,
- β_3 = coefficient for the square of length of exposure time for the Omega system,
- β_4 = difference between the coefficients for length of exposure time for the two measurement systems,
- β_5 = difference between the coefficients for the square of length of exposure time for the two measurement systems.

The model uses an identity link, meaning that g (μ_{ij}) = μ_{ij}, and standard errors obtained using the sandwich estimator.[5] Correlation was modeled as exchangeable. We used essentially the same model for relative humidity, for which the mean relative humidity for subject i at measurement j, RH_{ij}, is:

$$RH_{ij} = \beta_0 + \beta_1\ \text{system}_{ij} + \beta_2\ \text{testtime}_{ij} + \beta_3\ \text{testtime}_{ij}^2 + \beta_4\ \text{system}_{ij}\text{xtesttime}_{ij} + \beta_5\ \text{system}_{ij}\text{xtesttime}_{ij}^2 \quad \text{...(Eq. 2)}$$

Analyses were conducted using the *xtgee* procedure in *Stata.*[6]

Results

The average pH changed from 7.2 (standard deviation = 0.4) at the beginning of the session to 7.36 (standard deviation = 0.35) at the end of the session. A paired t-test of the pH change was not statistically significant (df = 19, P = 0.072).

The comfort rating declined from 4.1 out of 5 (standard deviation = 0.79) at the beginning of the session to 3.5 (standard deviation = 0.94) at the end of the session. This reduction of comfort rating was statistically significant (paired t-test, df = 19, P = 0.00048).

In two sessions, the relative humidity data were lost by the Omega system when interconnections between the meter and the data logger came loose. One session of both relative humidity and temperature data ended prematurely when the Omega meter went into sleep mode after 20 min. No data were lost in the iButton recordings. Generally, both systems measured a rapid increase in temperature and relative humidity under the muff. Regression lines for the individual subjects are presented in Figure 3. The results of modeling the temperature data with equation 1 are shown in Table 1 and relative humidity data with equation 2 are shown in Table 2. Thus, from Table 1, we see that the two measurement systems differ significantly from each other with respect to the intercept, linear term and

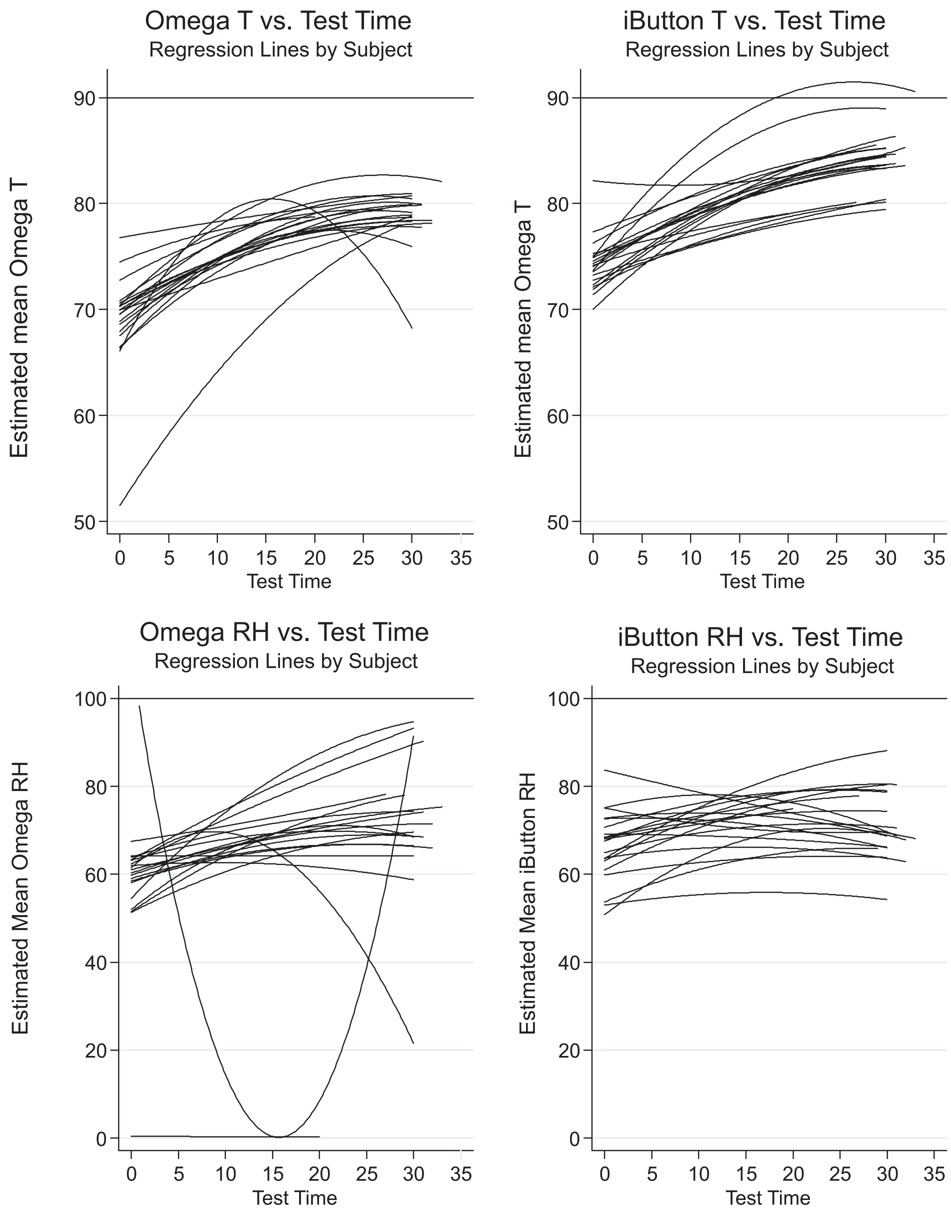

Figure 3: Regression lines fitted to raw data for temperature (top) and relative humidity (bottom). The left panels are for the Omega system and the right panels are for the iButton

Table 1: Results of analysis of temperature data using the GEE model given in equation 1

Independent variables and intercept	Coefficient estimate ($\hat{\beta}$)	Standard error	z	*P* > |z|	95% confidence interval
Intercept	69.1084 ($\hat{\beta}_0$)	1.1930	57.93	0.000	(66.7702, 71.4467)
System	5.1646 ($\hat{\beta}_1$)	1.2932	3.99	0.000	(2.6300, 7.6991)
Test time	0.7004 ($\hat{\beta}_2$)	0.0792	8.84	0.000	(0.5452, 0.8557)
(Test time)^2	-0.0121 ($\hat{\beta}_3$)	0.0016	-7.64	0.000	(-0.0152, -0.0090)
System X (test time)	-0.1673 ($\hat{\beta}_4$)	0.0854	-1.96	0.050	(-0.3347, 0.0000)
System X (test time)^2	0.0056 ($\hat{\beta}_5$)	0.0018	3.06	0.002	(0.0020, 0.0092)

quadratic term, and that all terms for both systems differ significantly from 0.0. Drawing on the results shown in Table 1, the model for the Omega system is:

$$T.Omega_{ij} = 69.1084 + 0.7004\ testtime_{ij} - 0.0121 testtime_{ij}^2 \quad \text{...(Eq. 3)}$$

The model for the iButton system is:

$$T.iButton_{ij} = (69.1084+5.1646) + (0.7004-0.1673)testtime_{ij} + (-0.0121+0.0056)testtime_{ij}^2 \quad \text{...(Eq. 4)}$$

$\Rightarrow$

$$T.iButton_{ij} = 74.2730 + 0.5331 testtime_{ij} - 0.0065 testtime_{ij}^2 \quad \text{...(Eq. 5)}$$

Thus, as shown in equation 3 and equation 5, the two measurement systems yield different models for predicting the mean temperature. The differences between the two models are statistically significant.

For relative humidity, we see from Table 2 that for the Omega system the coefficients for time tested and (time tested)^2 did not differ significantly from 0.0. Thus, a valid model for relative humidity for the Omega system, based on the data from this study, would be

$$RH.Omega_{ij} = 56.5479 \quad \text{... (Eq. 6)}$$

To obtain a model for relative humidity based on the results of the iButton system, we can combine the coefficients for the Omega system with the differences between the Omega system and the iButton system, as shown in Table 2. The results of combining these effects are shown in Table 3. In the case of the iButton system, the coefficients for time tested and (time tested)^2 are clearly significantly different from 0.0. Thus, a model for relative humidity based on the iButton system is:

$$RH.iButton_{ij} = 66.0341 + 0.6288 testtime_{ij} - 0.0178 testtime_{ij}^2 \quad \text{...(Eq.7)}$$

Discussion

The present study confirms the data presented in the extended abstract of Ivaarson,[4] reflecting a buildup of heat and humidity under the earmuff. Temperature followed a quadratic model in both systems, while the relative humidity followed a quadratic model only in the iButton system.

We found that the model for relative humidity obtained from the iButton system, equation 7, is more useful than the one obtained from the Omega system, equation 6, because the iButton system effectively utilizes the data on length of exposure (time tested) and the Omega system does not.

The present study measured skin pH in the pinna before and after the task, because higher ear canal pH has been shown in patients to correlate with chronic otitis externa (outer ear infection).[7] Although the pH change was not statistically significant, our data indicate that wearing earmuff hearing protectors (and presumably ear plugs) increases the pH of the external ear canal and could increase the probability of a chronic outer ear infection in a susceptible worker. This observation deserves further exploration.

The present experiment demonstrates that a relatively low physical effort task can result in important physical and comfort data. This is valuable to know. For example, subjects in Park and Casali's[8] laboratory study were required to manipulate a wheel while wearing the HPD. They found similar results between their field study and their lab study. The present experiment shows that low physical effort tasks can result in valid comfort data.

The current study also showed that a simple device like the iButton can effectively measure heat and humidity buildup under an earmuff. The more complex Omega system resulted in some data loss due to experimenter error on three occasions. Because the Omega system is not designed to be portable nor maintain a history of the temperatures, it is not the best choice for monitoring workers in a field study. The iButton system would be preferred because it could be attached with Velcro or glue to the worker's current ear muff.

Conclusion

The current study found a significant buildup of heat and humidity under the cup of an earmuff hearing protector even in a low physical effort, environmentally controlled situation. Field studies of heat and humidity buildup can be effectively conducted using the iButton system. It appears to produce valid data with a minimum of equipment.

Table 2: Results of analysis of relative humidity data using the GEE model given in equation 2

Independent variables and intercept	Coefficient estimate ($\hat{\beta}$)	Standard error	z	$P > \lvert z \rvert$	95% confidence interval
Intercept	56.5479 ($\hat{\beta}_0$)	3.3494	16.88	0.000	(49.9832, 63.1126)
System	9.4863 ($\hat{\beta}_1$)	3.7262	2.55	0.011	(2.1830, 16.7896)
Test time	0.3577 ($\hat{\beta}_2$)	0.4996	0.72	0.474	(-0.6215, 1.3368)
(Test time)^2	0.0074 ($\hat{\beta}_3$)	0.0164	0.45	0.653	(-0.0248, 0.0396)
System X (test time)	0.2711 ($\hat{\beta}_4$)	0.5056	0.54	0.592	(-0.7199, 1.2622)
System X (test time)^2	-0.0251 ($\hat{\beta}_5$)	0.0177	-1.42	0.156	(-0.0599, 0.0096)

Table 3: Determining model for relative humidity as measured by the iButton system (equation 3)

Independent variables and intercept	Coefficient estimate	Standard error	z	$P > \lvert z \rvert$	95% confidence interval
Intercept	56.54786 + 9.48627 = 66.0341	1.7786	37.13	0.000	(62.5482, 69.5201)
Test time	0.35766 + 0.27111 = 0.6288	0.1239	5.08	0.000	(0.3860, 0.8716)
(Test time)^2	0.00737 - 0.02515 = -0.0178	0.0042	-4.25	0.000	(-0.0260, -0.0096)

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