▶**RESEARCH**

Temperature and Relative Humidity Inside an ITE Hearing Instrument

By Jeremy Agnew, PhD

The reliability and longevity of electronic devices is often linked to the environmental conditions in which they operate. Typically, the higher the ambient temperature and relative humidity (RH), the shorter the operating life. Hearing instruments are no exception. The conventional assumption is that hearing instruments located in the ear operate at a temperature of 98.6°F and in an environment of high RH created by the body. The following study was performed to determine if this assumption is valid.

An accurate understanding of operating temperature and RH is of interest to a variety of individuals involved in the manufacture and distribution of hearing instruments. Circuit designers are interested in the operating temperature since the performance of electronic circuits at elevated temperature is often different than at room temperature. For example, the processing speed of digital signal processing (DSP) circuits generally decreases as temperature increases above room temperature. Thus, it is important to include circuit design compensation for temperature variations and to verify that circuits designed to operate at room temperature will also perform correctly at the higher temperatures encountered in the ear.

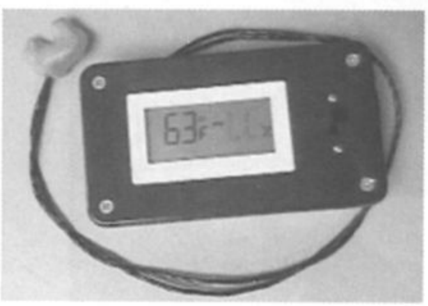

Fig. 1. *The test hearing aid connected to the temperature and relative humidity measuring device.*

Mechanical engineers and component suppliers are interested in environmental temperature and RH because high values of both conditions often accelerate failure modes, such as problems due to corrosion. Hearing care professionals are interested in environmental conditions, since elevated temperature and RH can promote failure for the user.

Battery manufacturers are also interested in operating conditions, since zinc-air button cells used to power modern hearing instruments change their characteristics and useful lifetime as temperature and RH change. For example, the mechanical and chemical composition of these cells are usually optimized for a specific range of RH. A cell exposed to higher or lower values of RH during operation may exhibit a shorter than normal service life.

Jeremy Agnew, PhD, is director of product development for Starkey Laboratories, Eden Prairie, MN.

Conventional Assumptions About Temperature and RH

A temperature of approximately 98°F is often assumed to be the operating temperature of a hearing instrument in the ear, since 98.6°F is usually considered to be body temperature for a healthy person. In reality, 98.6° is the average oral temperature of the human body. The temperature of core visceral organs, such as the liver, may be as high as 105°F. Except under extreme conditions, core body temperature stays essentially constant, even with varying environmental temperature. In contrast, the extremities and peripheral structures found at the surface of the body, such as the external ear, typically exhibit lower temperatures that vary with ambient temperature. For example, the temperature of the feet can drop to 77°F if the external environmental temperature drops to 73°F.[1]

A common assumption is that the ear is very humid due to the ceruminous glands inside the ear canal, which are essentially the same as the apocrine sweat glands of the armpit.[2] In reality, the unoccluded ear canal allows free interchange of air with the ambient environment and allows perspiration to evaporate.

Standard ambient temperature conditions for testing of a hearing instrument are specified to be 73° +/- 9°F (25° +/- 5°C). Figures commonly reported for relative humidity indicate the amount of water vapor in the air, as compared to that amount necessary to completely saturate the atmosphere. This RH figure is given as a percentage. ANSI (1996)[3] specifies an RH range of 0-80%, whereas IEC (1983)[4] specifies an RH range of 40-80%. These measurement conditions are part of standardized manufacturing quality control specifications and are not necessarily representative of operating conditions in the ear.

Relative Humidity

The atmosphere always contains some moisture in the form of an invisible vapor. Moisture evaporates into the atmosphere from water sources until the air can contain no more. At this point, the air is fully saturated with water vapor, and no more water can be

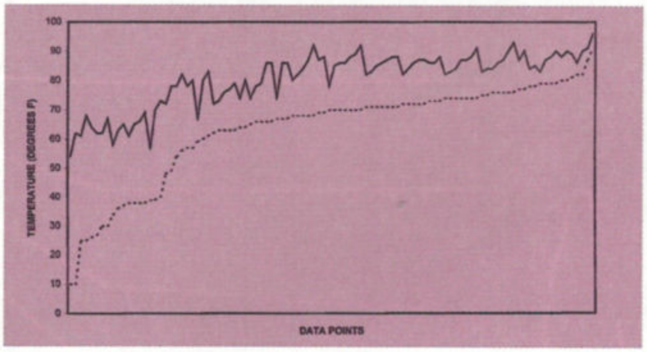

Fig. 2. *Readings of ambient and hearing instrument internal temperatures, arranged on the horizontal scale from the lowest to highest ambient temperature. Dashed line is ambient temperature; solid line is the corresponding temperature inside the hearing instrument.*

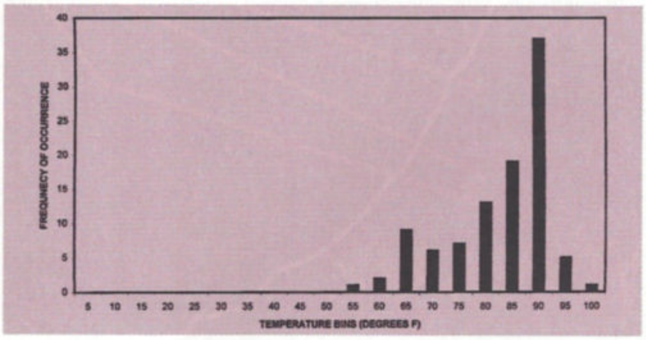

Fig. 3. *Histogram showing the distribution of temperature readings inside the hearing instrument.*

absorbed—evaporation stops. This situation becomes unpleasant for humans during hot weather, since perspiration can no longer evaporate and provide its intended cooling effect for the body. This condition is called *high relative humidity*.

The amount of moisture necessary to saturate the air varies with the ambient temperature. For a given amount of moisture, the percentage of RH decreases when the temperature of the atmosphere rises. Conversely, for a given amount of moisture in the air, decreased temperature results in a higher RH figure. If the temperature is lowered sufficiently within a short period of time, the atmosphere becomes oversaturated and the excess water vapor starts to condense, forming either fog or dew.

Extremes in RH can cause a particular problem for hearing aid batteries. Zinc-air cells have small air holes in their cases to allow the entrance of oxygen which drives the internal chemical reaction that ultimately produces energy. The rate of this chemical reaction is partially governed by the transfer of oxygen through the holes and through a diffusion membrane that is located inside the cell at the surface of the cathode.[5] This membrane also allows water vapor to transfer in and out of the cell. Under conditions of very low ambient RH, water in the electrolyte evaporates and moves outside the cell through the air holes. Under continued exposure to conditions of low RH, the electrolyte will dry out more rapidly than intended, and the anticipated service life of the cell may be shortened. Conversely, if the external RH is very high, water vapor from the air may be absorbed into the electrolyte, causing it to swell and increase in volume. Under extreme conditions of absorption, this expanded electrolyte may even leak out of the air holes.

Variations in RH from the cell design norm may be encountered by dispensers both in very dry parts of the country, such as the western U.S. desert states during the summer and fall, or in very humid areas, such as the southern Atlantic seacoast during the summer. The obvious solution is to decrease the size of the air holes so that transport of water vapor in and out of the cell becomes slower. However, this is not necessarily an appropriate solution, since the holes determine the rate of oxygen entry and a high rate of oxygen diffusion into the cell may be periodically necessary to allow the cell to deliver peaks of current to the circuit when required.

Study Methods

This study was performed using a custom ITE hearing instrument fitted to the author's right ear. It was recognized that the data gathered has the limitation of measurements made in only one ear, but it also has the advantage of consistency of ear environment over a wide variety of locations and measurement conditions. Useful data would also be gained from measuring a variety of ears in controlled situations in order to compare different ear environments.

The hearing instrument configuration was an ITE with a medium canal length. No external vent was provided in the shell in order to create the worst test condition for the potential build-up of moisture on the canal portion. The hearing instrument contained a battery drawer, amplifier, volume control, microphone and receiver. Subminiature electronic probes for sensing temperature and RH were located in the center of the hearing instrument and were attached via thin, flexible cables to an external portable electronic processor and display. Fig. 1 shows the configuration of the test hearing instrument and measurement device.

One-hundred measurements were made at different sites across the U.S. The measurements were made over a period of nine months (July 1998-March 1999) in order to account for variations during different seasons. Measurements were made both indoors and outside. Outside measurements were made in a variety of weather conditions that included sun, rain, overcast, wind, still air and snow on the ground. Locations included the East Coast, West Coast, Midwest, Desert Southwest, both oceans and both high-altitude and sea-level elevations. Tests were repeated to confirm repeatability of measurements. Measurements included varying levels of exertion in order to create effects due to perspiration. Some measurements were made under deliberately humid conditions, such as in a steamy bathroom after a hot shower in order to create a wet ear environment, and also shortly afterwards in a cooler environment where the lower temperature affected the RH measurement. Some measurements were made with the canal of the hearing instrument case being wet to the touch in order to try and simulate a hearing instrument user with a "wet" ear.

Results and Discussion

Fig. 2 graphically summarizes all the temperature measurements, compiled on the x-axis from the lowest ambient temperature measurement to the highest. The dashed line is a compilation of the ambient temperatures, while the solid line represents the corresponding hearing instrument temperatures. All the measurements are included on one graph since the intent of the study was to give an overall view of hearing instrument temperatures that might be encountered under a variety of conditions. Data could also be extracted and categorized under various specific conditions, but this approach did not meet the intent of this study.

One reason that the hearing instrument temperature curve is not smooth was the occurrence of localized

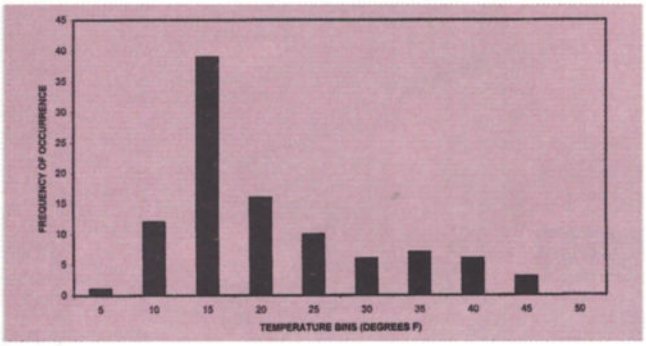

Fig. 4. *Histogram showing the distribution of temperature readings from inside the hearing instrument below average "normal" oral temperature of 98.6°F.*

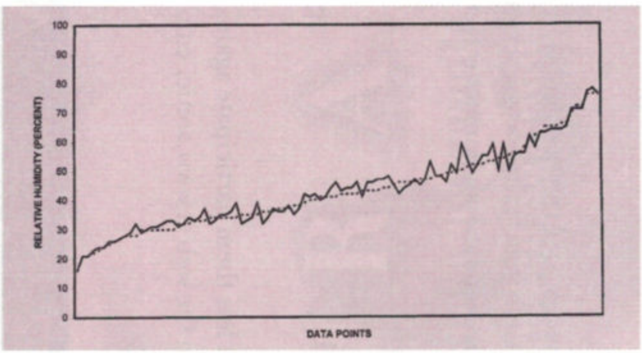

Fig. 5. *Readings of ambient and hearing instrument internal RH values, arranged on the horizontal scale from the lowest to the highest ambient RH. The dashed line is the ambient reading; the solid line is the corresponding internal hearing instrument reading.*

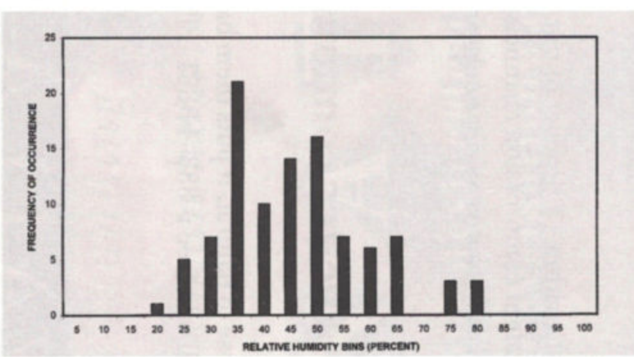

Fig. 6. *Histogram showing the distribution of readings of relative humidity inside the hearing instrument.*

variations when making the measurements. For example, wearing a wool hat that extended down over the ear in some of the winter measurements increased the temperature inside the hearing instrument by 4-5°F, as compared to the measurement without a hat. There was also a difference in hearing instrument temperature depending on whether the measurement ear was on the sunny side of the head or in shade, conditions which created typical temperature differences of about 4-7°F. Some of the temperature variations seen in the curve were due to varying degrees of physical exertion during different measurements.

Fig. 2 shows that the hearing instrument temperature stayed at a fairly constant level above the ambient temperature down to an ambient temperature of about 60°F. Below this ambient temperature, the two tended to diverge, with the hearing instrument staying at a temperature that was higher than the ambient temperature. These results should be expected, since the hearing instrument is in contact with a peripheral body organ (the ear) which would be expected to generally be at a lower temperature than core body temperature. It also makes intuitive sense that, as the environment gets colder, the difference between the ambient and hearing instrument temperatures should increase, because the instrument's contact with the ear will act as a thermal reservoir and keep the it warm at low temperatures.

A histogram showing the distribution of temperature measurements inside the hearing instrument is shown in Fig. 3. Most of the readings occurred between 85-90°F, with the highest grouping occurring between 80-85°F. Fig. 4 shows the same data from a different perspective. This is a histogram showing the distribution of temperature readings inside the hearing instrument below the average oral temperature of 98.6°F. The highest number of readings occurred in the range of 10-15°F below "normal" oral temperature. Analyzed statistically, the mean temperature below normal oral temperature was 19°F. Probably of more significance for generalizing the results was that the median of these measurements was 15°F and the mode was 13°F. In inside environments, the mean was 13°F below "normal" oral temperature.

Fig. 5 shows a compilation of the readings of ambient RH and hearing instrument internal RH. In general, the RH inside the hearing instrument tracked the ambient RH. The variations between the measurement pairs seen on the graph were attributed to additional environmental factors, such as high levels of exertion and forced conditions such as a steamy bathroom or wet ear canal.

In general, a decrease in RH of 1-3% as compared to the ambient measurement was observed in the ear, as might be expected from a temperature increase with a constant vapor pressure. Under the deliberately wet conditions, such as outside in the rain or with the ear wet from a shower or near ocean spray, the RH increased about 3-5% when measured in the ear as compared to the ambient measurement. However, upon statistical analysis of the data group as a whole, it was found that the mean difference between the ambient and in-the-ear measurements was 1%, and the median and modal differences were zero.

This result was initially unexpected, since it was presumed that the location of the hearing instrument in the ear would raise the internal RH. If anything, it had been assumed that the higher temperature of the hearing instrument in the ear would result in a consistently lower RH than the ambient RH, since RH decreases as temperature rises for a given constant environmental vapor pressure. It can be conjectured that these results were obtained because the canal portion of the hearing instrument case may have provided a good enough seal to the ear cavity to trap any moisture from perspiration inside the canal and did not allow large amounts of moisture to penetrate the inside of the hearing instrument. At the same time, on the faceplate side of the hearing instrument, there may have been enough air flow in and out of the hearing instrument case through leakage channels (e.g., battery door) that the inside of the hearing instrument continually stayed in equilibrium with the external environment.

Fig. 6 is a histogram showing the distribution of RH measurements inside the hearing instrument. It can be seen that there was a large cluster of measurements in the 30-40% range, with a large number of measurements also falling between 40-50% RH.

The measurements made during this study tended to confirm earlier findings described by Bailey and Valente[6], which were collected primarily in the greater Cleveland and St. Louis metropolitan areas, whereas this study contains a wider geographical range of measurements made across the

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U.S. The majority of the temperatures that they measured fell between 80-100°F. Sixty-nine percent of the measurements reported here were between 75-90°F.

Bailey and Valente[6] commented that the medical literature reported canal humidity to be greater than 60%; however, they found that 63% of their measurements of RH inside the hearing instruments were between 30-50%. Similar findings were observed in the data reported here: 61% of measurements of RH were between 30-50%. They also observed that the RH of the hearing instrument increased with the ambient RH, which is also corroborated here by Fig. 5.

Conclusions

The majority of temperature readings inside the test hearing aid in this study fell between 80°F and 90°F, thus occurring 10°F–20°F below "normal" body temperature. The most common operating temperature was about 15°F below body temperature, or 85°F. The main conclusion from this is that the circuit inside an ITE hearing instrument often operates at a lower temperature than that which has been previously assumed. From the hearing instrument standpoint, then, this is helpful in reducing failures induced by elevated temperatures inside the device.

The measurements of RH inside the test hearing aid closely tracked the ambient RH, with the majority falling between 40% and 50%. Subsequent on-going measurements appear to confirm the supposition that, if the canal of the hearing instrument is sealed well to the ear, the RH inside the instrument will be closer to the ambient RH than the ear canal RH. Measurements made inside a hearing instrument with a vent through the case to the inside of the instrument from the ear canal resulted in RH measurements that were 17%–23% higher than ambient RH. This leads to the conclusion that, if the hearing instrument is sealed well to the ear canal, deleterious effects due to moisture penetration will be lower than had previously been supposed. Thus, the operating environment inside an ITE hearing instrument that fits well in the ear appears to be not as extreme as has previously been assumed. ◆

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Correspondence can be addressed to HR or Jeremy Agnew, PhD, Starkey Laboratories, Inc., Colorado Research Center, 4920 Centennial Blvd., Suite 100, Colorado Springs, CO 80919; e-mail: jerry_agnew@starkey.com.

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A Field Study on the Effect of Relative Humidity on Hearing Aid Receivers

Observations and RH measurements on patients

BY C. MIKE HALL, AuD, AND CARL CROUTCH, AuD

The basic components of hearing devices are the microphone, receiver, amplifier, and power source. As hearing amplification systems have progressed, many of these components have become smaller and more complex. We have learned that the receiver is the component that is most prone to malfunction. We also touch upon some of the remedies that have been proposed to ameliorate or eliminate receiver failure.

Based on observations, articles, and discussions with colleagues, there appears to be a correlation between the amount of relative humidity (RH) and proximity of the hearing aid receiver to the tympanic membrane with the incidence of receiver problems. This is true with custom devices such as the in-the-ear (ITE), in-the-canal (ITC), completely-in-the-canal (CIC), and the newer types of devices that are positioned adjacent to the tympanic membrane. As hearing devices have decreased in size, receiver fragility has become an issue.

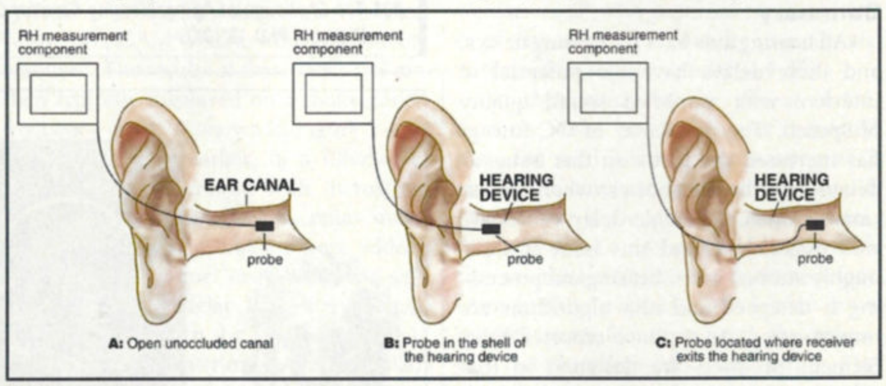

FIGURE 1. Schematic showing three different methods for placement of a probe for measuring relative humidity (RH).

Previous research. To date, there have been relatively few studies regarding RH measurements of the ear in general, or that specifically examined the RH in a patient's ear as it would apply to hearing aids.[1-4] Bailey and Valente,[4] with the help of three assistants, collected data on temperature and RH data occurring inside the shells of ITEs and ITCs they wore. They found that most (77%) of the temperature readings were between 80 and 99°F and most (63%) of the RH readings were between 30% and 49%. Smaller hearing aids (with a smaller mass) like ITCs tended to be slightly warmer, and they noted that exercise and even head gear worn can have some influence on both temperature and RH.

Agnew[2] reported similar findings wearing a custom ITE with the temperature and RH measured inside the shell of the device. He found that the RH inside the shell closely tracked the RH of the ambient environment (usually between 40% and 50% RH).

Gray et al[3] conducted a study of RH on a group of patients, including those with no history of pathological middle ears including no perforations, otitis media, or middle ear drainage. Those with negative histories of middle-ear pathology had RHs of around 40%, whereas a separate group who had positive histories of past and current middle ear problems had RHs of around 70%. This problematic subgroup is that which had a well-documented history of moisture on the canal portion of the device when it was taken out of the ear or had frequent episodes of middle-ear pathology with possible surgical intervention.

However, all of these studies were conducted with the RH probe placed in an open ear[3] or in the middle of the hearing aid case[2,4] (Figures 1a-b). We feel a more valid method to assess the relationship of RH and *receiver problems* would be to place the humidity probe where the receiver

C. Mike Hall, AuD, is a clinical audiologist who lives in Walnut Creek, Calif, and is now retired from private practice. **Carl Croutch, AuD,** is an audiologist at Kaiser Permanente Hearing Center in Daly City, Calif.