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Infrared ear thermometry, sometimes incorrectly referred to as *tympanic thermometry,* has compelling advantages over traditional methods of thermometry, including extraordinary speed, safety, comfort, lower cost, and potentially greater accuracy.

The issue of accuracy is the most important. The accuracy of an infrared thermometer can be specified with great precision when tested with a device known as a blackbody (Figure 1). A blackbody is a specially configured cavity which emits a precise quantity of radiation corresponding to its temperature. It is called a blackbody because the cavity reflects nothing and indeed looks black.

An accurate infrared thermometer will produce a temperature indication matching the blackbody temperature to within a small tolerance — i.e., 0.22°F (0.1°C) — over a specified range of blackbody temperatures and ambient temperatures. In a simplistic analysis, the ear canal seems to be a good blackbody, and thus an IR thermometer which can measure blackbodies accurately should be able to measure ear canals accurately. However, *the ear canal is not a good blackbody because it is not uniform in temperature,* which is a requirement for the physics and mathematics of a blackbody to apply.

Ear canal temperature also is not the same as core body temperatures of interest. Despite its proximity, ear canal temperature is not even the same as tympanic membrane (TM) temperature, since there is a significant temperature gradient from the insulated deep location of the tympanic membrane to the open distal end of the ear canal, which loses heat to the environment. Variability errors of more than 5°F (3°C) can result from this cooling effect alone, which would render the method seriously suspect when compared to conventional methods.

Accordingly, this article will present the underlying quantitative thermal physics for the method of infrared thermal heat balance, extending earlier work,[3'4] how the method improves overall accuracy, and how it is implemented in the design of the infrared thermometer employing the method of arterial heat balance via the ear canal (AHBE).

EAR ANATOMY

Anatomical texts traditionally present a sectional view of the ear as an anterior aspect of a complex plane through the ear, which tends to show the ear canal as a slightly curved tube connecting the ear opening to the TM (Figure 2A). A more informative view, which more accurately presents the structural details influencing the ear's thermal physics, is a view of the superior aspect of a transverse plane through the ear (Figure 2B). Such views are not found in most anatomy texts, but may be most conveniently observed from three dimensional castings with transparent materials.

The striking feature of the superior aspect view is the right angle bend in the ear canal, which occurs between the flexible cartilage of the auricle and the rigid osseous portion of the ear canal. This bend divides the canal into two distinct areas: the deep tissue which is optically closed to the outside, and the superficial tissue which is optically open to the outside. The optically open and closed conditions provide the thermal driving force differences that produce the variations in temperature gradient.

The dominant method of thermal loss by the warm ear canal tissue to the cooler environment is radiation, which is more than ten times greater in magnitude than thermal loss via conduction through the stationary air in the ear canal. Accordingly, the importance of the optical characteristics is clear since radiation heat exchange follows the same physics as visible light optics: *heat radiation travels in straight lines.*

From an efficiency perspective, the ear is extraordinarily well-designed thermally (Figure 3). The TM is maintained at arterial temperature since it simply assumes the temperature of its blood supplied via the carotid artery, which in turn is at the temperature of the arterial supply — the most useful definition of "core" temperature. By optically closing off the open end of the ear canal, the cartilage provides optical insulation for the TM and thus provides a closely uniform temperature from the TM to the end of the osseous portion of the ear canal.

The optically open cartilage section, however, is losing heat energy to the cooler ambient at a rate many times greater than the TM, and thus its temperature is considerably cooler and more variable than arterial temperature — up to several degrees cooler (Figure 4). In addition, since much of the blood supply to the ear cartilage is derived from arteries superficial to the skull, it is further subject to the cooling effects of ambient temperature.

Accordingly, the optically open external ear canal, that which can be seen from outside without manipulation of the cartilage, is cooler than arterial temperature due to radiated loss of heat energy to ambient. If a subject's head were placed in an ambient environment which was at the same temperature as arterial, the thermal loss would be zero, and the outer ear canal would be at the same temperature as the TM and aorta.

The anatomical observations above can be confirmed with a volunteer and a penlight. By shining the penlight into an ear, you will not be able to view the TM, only the optically open portion of the ear canal. If the ear canal is straightened by manipulation of the external cartilage, as in an otoscopic examination, the TM will come partially into view. If an otoscope is inserted into the canal past the bend, then the TM can be viewed fully.

TYMPANIC VERSUS EAR THERMOMETRY VERSUS ARTERIAL HEAT BALANCE

There are three types of infrared thermometers used to measure temperature at the ear: tympanic, ear, and AHBE. True tympanic thermometers (Figure 5) provide an uncorrected, direct reading of the TM temperature, which correlates with pulmonary artery (PA) temperature. Like PA, TM temperature is not subject to artifactual errors that can affect oral, rectal, axillary, and ear temperatures. Ear thermometers6 provide biased readings of the generally cooler distal ear canal, and are subject to artifactual errors due to the severe thermal gradients of the distal ear canal. AHBE thermometers measure specific distal ear canal tissue and calculate arterial temperature via heat balance, while maintaining the convenience and comfort of ear thermometers but without the artifactual errors.

It has become common practice to refer to any infrared thermometer making a temperature measurement at the ear as a tympanic thermometer. While a misnomer, the interchange of words is analogous to the use of more familiar words like *Kleenex, Xerox copy,* or *Scotch tape.* Although the terms tympanic and ear are used interchangeably, they actually describe quite different measurements.

Tympanic temperature is the temperature of the TM and surrounding deep tissue of the osseous portion of the ear canal. Both areas are at arterial temperature due to the efficiency of optical insulation described previously. No corrections are required, since the temperature measured is interchangeable with arterial temperature.

There is much historical data on the efficacy of tympanic thermometry using contact thermocouples, stemming originally from the work of the Benzingers and others nearly thirty years ago.[7,8,9,10,11] However, the thermocouple method never gained wide acceptance due to the risk of injury to the delicate TM. More recently, the advent of infrared devices has made the measurement of TM temperature possible by noncontact means, thus eliminating risk of injury to the TM. scan the canal to assure seeing the TM, similar to the technique employed when conducting an otoscopic examination.

In order to measure TM temperature, it is necessary to actually view the TM with the infrared device. To accomplish this, the canal must be straightened, the instrument inserted far enough into the canal to see around the dog-leg bend, and the instrument must scan the canal to assure seeing the TM, similar to the technique employed when conducting an otoscopic examination.

This requirement places constraints on both device and clinician since: (a) the device must have a narrow field of view, be shaped such that it is capable of being positioned past the bend in the ear canal, and be capable of scanning; and (b) nursing staff may not be proficient with otoscopic technique, nor wish to subject the patient to the required ear manipulation or discomfort.

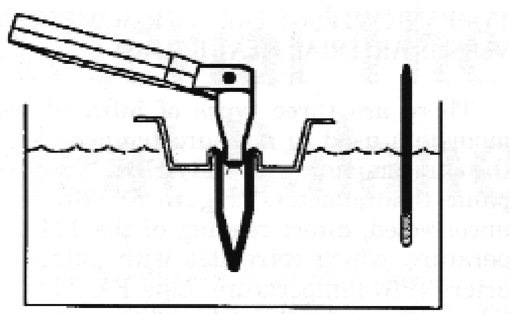

FIGURE 1. Floating blackbody calibration verification.[1]

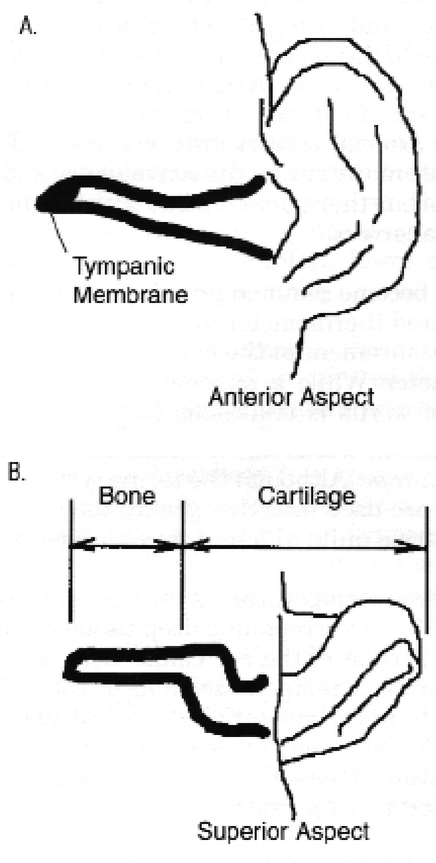

FIGURE 2. Ear canal cross-sectional views.

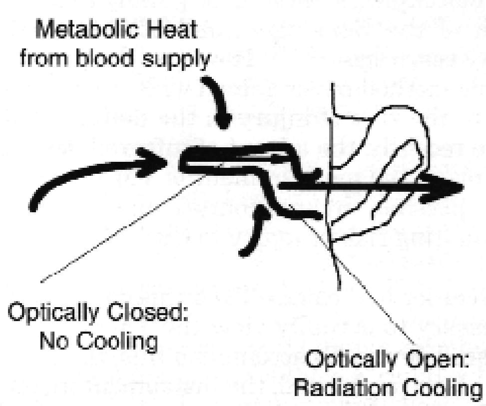

FIGURE 3. Thermal physics of the ear canal.

For routine clinical use, ear thermometry has been preferred by nursing as a simpler, faster, and more convenient alternative to true infrared tympanic thermometry. The distal ear canal is easily accessible, free of bodily fluids, and cannot easily be influenced by the patient. The absolute temperature of this site, however, is lower and more variable than arterial temperature because of the cooling effect resulting from the heat radiated to the environment, and a heat balance method is required in order to produce the requisite accuracy.

THE THERMAL PHYSICS OF HEAT BALANCE AT THE EAR

The heat loss of the external ear canal to the environment can be calculated with the following well-known equation:

$$q = hA\,(T_e - T_a) \qquad (1)$$

where q is heat flow, A is surface area, T_e and T_a the ear canal and ambient temperatures, respectively, and h is an empirically determined coefficient which includes a radiation view factor between the ear tissue and ambient. The equation takes the linear form for simplicity. Although the exact form of the equation is fourth-power due to the radiation exchange, the linearized form provides excellent accuracy over the range of interest.

Heat flow from the core arterial source to the distal ear canal is via the circulation, which is many times more effective than tissue conduction. Thermal transport via the circulation can be described with the following equation:

$$q = wc\,(T_c - T_e) \qquad (2)$$

where q again is heat flow, w is blood mass flow rate, c is blood specific heat, and T_c and T_e are core and ear temperatures, respectively.

Accordingly, the distal ear canal can be viewed thermally as tissue being warmed by its blood supply as governed by Equation 2, balanced by radiating heat to ambient as governed by Equation 1 (Figure 6).

Equating:

$$hA\,(T_e - T_a) = wc\,(T_c - T_e) \qquad (3)$$

Simplifying by dividing by A:

$$h\,(T_e - T_a) = pc\,(T_c - T_e) \qquad (4)$$

where ρ is blood flow per unit area, also termed *perfusion rate.*

Equation 4 then provides a method to calculate core temperature T_c when ear temperature T_e and ambient temperature T_a are known, and the coefficients (or their ratio) have been empirically determined.

Solving for T_c:

$$T_c = (h/\rho c)(T_e - T_a) + T_e \qquad (5)$$

and $h/\rho c$ is empirically determined on a statistical basis over a range of patients and clinical situations.

An alternative method of calculation is to employ an electrical analog technique, since Equations 1 and 2 have the identical form of a simple voltage/current relationship. The method employs the convention that electrical current is analogous to heat flow and voltage differential analogous to temperature differential.

Accordingly, Equations 1 and 2 may be written as:

$$q = (1/R_1)(T_e - T_a) \qquad (6)$$

$$q = (1/R_2)(T_c - T_e) \qquad (7)$$

and the electrical circuit can be drawn, with T_c and T_e as constant temperature (voltage) reservoirs (Figure 7). A third equation with a more convenient form can be written as:

$$q = (1/(R_1 + R_2))(T_c - T_a) \qquad (8)$$

Using Equations 6 and 8 and solving for T_c:

$$T_c = ((R_1 + R_2)/R_1)(T_e - T_a)+T_a \qquad (9)$$

and finally:

$$T_c = k(T_e - T_a)+T_a \qquad (10)$$

which is the precise form of the heat balance equation programmed into the AHBE instruments, with $(R_1+R_2)/R_1$ expressed as the *k-Factor.*

THE SCAN FUNCTION: LOCATING THE DEEPEST TISSUE THAT CAN STILL SEE OUT

The reliability of the heat balance is directly related to the reliability of the value of h, whose value is

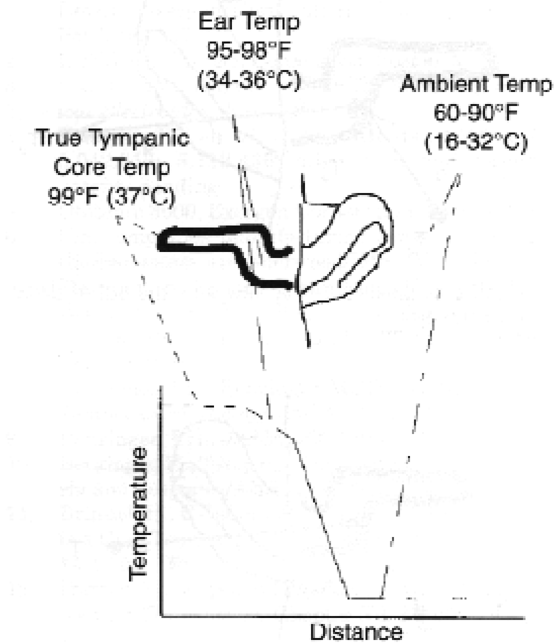

FIGURE 4. Temperature profile of the ear.

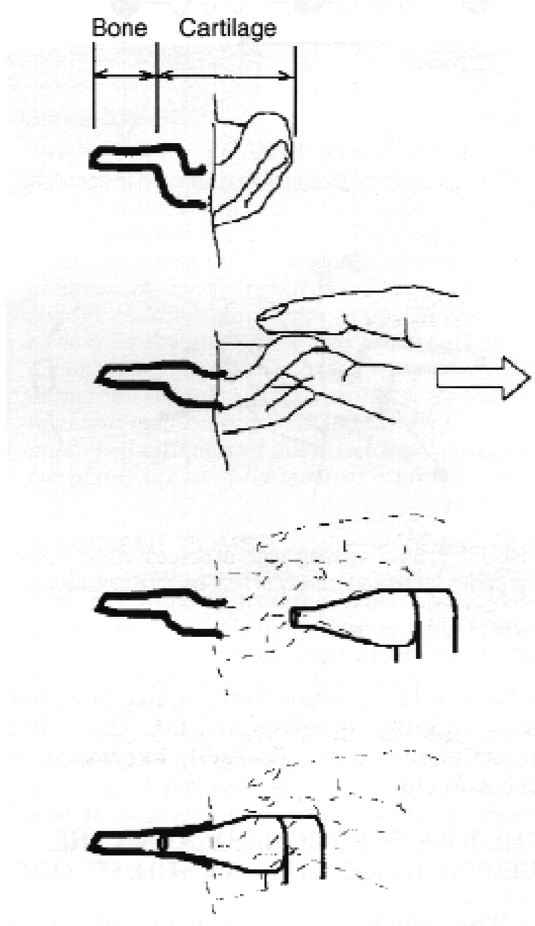

FIGURE 5. Tympanic Membrane Thermometer: using otoscopic technique to measure true tympanic temperature.[5]

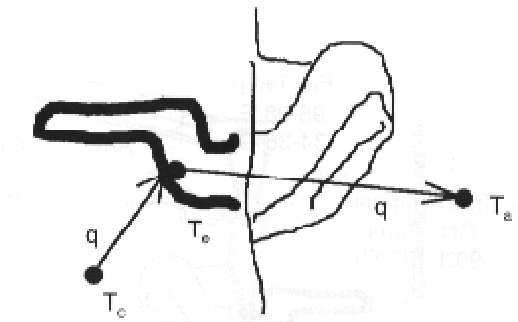

FIGURE 6. Balancing heat flow into and out of distal ear canal tissue.

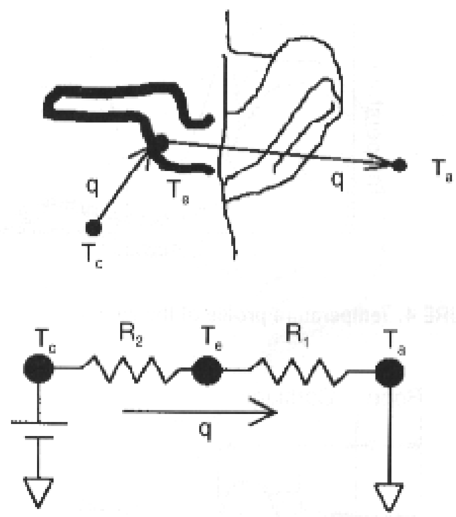

FIGURE 7. Electrical analog of heat flow and temperature.

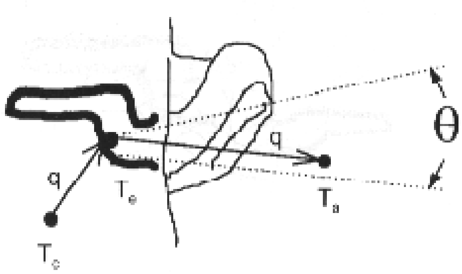

FIGURE 8. Small viewing angle of deepest visible tissue provides for reproducibility of heat balance calculations.

approximately proportional to the square of the viewing angle q (Figure 8). Accordingly, the physical interpretation is that the more superficial tissue has a greater and more variable radiation loss due to its greater θ.

The most reliable heat balance is obtained by viewing the deepest distal ear canal tissue, since it has the smallest value of θ, but is still able to "see out" and is thus at equilibrium with the environment. The location of this specific tissue is anatomically variable and thus cannot be located by positioning alone. However, since it has the smallest value for θ, *it is also the warmest.* It is this attribute that is used by the AHBE infrared devices to physically scan the ear canal for the highest temperature.

The scanning motion is produced by the user by gently pivoting the probe side-to-side to view the entire ear canal in order to find the highest temperature, which represents the deepest tissue that can still see out, thus producing a reliable heat balance measurement of arterial temperature.

The rounded probe is shaped similarly to a stethoscope ear piece, designed to comfortably seat at the ear canal opening, but does not actually enter the canal. The round shape facilitates the scan motion, and provides for consistent relative positioning from patient to patient.

To successfully scan the distal ear canal, the infrared measuring system must have a sufficiently narrow field of view to select the deepest tissue, and the necessary measurement speed to accurately record the temperature as the sensor sweeps the warmest tissue.

HEAT BALANCE IMPLEMENTATION

The AHBE infrared thermometer employs Equation 10 to calculate arterial temperature in its microprocessor. A temperature sensor in the instrument measures its own temperature as ambient, since it is at the same ambient as the patient. During each measurement, it scans the infrared radiation ten times per second and ambient temperature once per second. It solves Equation 10 ten times per second, selects the highest of the readings and discards all others. The final temperature displayed is the solution to Equation 10 which gives the maximum reading during a particular episode. This cycle can be repeated any time the ON button is pressed, and the measurements will continue at ten times per second as long as the button remains depressed.

Specific k-Factors programmed into AHBE instrument models vary depending on the site chosen for reference protocols, and are based on extensive published and unpublished clinical data. The calibration is not user accessible, in order to prevent accidental or unauthorized change.

RELATIONSHIP BETWEEN ARTERIAL, ORAL, AND RECTAL TEMPERATURE

Although arterial is strongly recommended as a display modality, there are certain circumstances in which clinicians may find it necessary to work in historically consistent terms — i.e., oral or rectal diagnostic equivalents. Since all body site temperatures of interest arise from the arterial temperature source, Equation 10 can be used at any site. Since Equation 10 is linear, a powerful theorem known as Thevenin Equivalence can be used to correct any two sites by a simple change in the site k-factor. Accordingly, oral and rectal diagnostic equivalents of arterial temperatures may be calculated by appropriate selection of k-Factor.

However, it should be noted that such temperatures may not be the same as actual oral or rectal taken simultaneously, since they are derived from arterial temperature without oral/rectal site artifacts. These artifacts (mouth breathing, placement, patient activity, lag time, etc.) render the actual site temperatures considerably less reliable than their arterial source, but are completely eliminated by using the heat balance method at the ear. For identification, an instrument calibrated to oral diagnostic standards is labeled as $\text{Arterial}_{\text{Oral}}$, indicating an oral reference standard based on arterial heat balance. Similarly, the rectal calibration is labeled as $\text{Arterial}_{\text{Rectal}}$.

ACID TEST: REPRODUCIBLE READINGS

The simplest and most direct method of testing an ear thermometer is reproducibility of readings on the same person: differences between the two ears should be clinically insignificant (<=0.3°C). With the AHBE instruments, this attribute is so reliable that nursing certification is based on this reproducibility of readings. The heat balance method, with the arterial calculations and scan function, is capable of delivering reliable arterial temperatures routinely and noninvasively.

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