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ANALYSIS OF THERMAL GRADIENTS WITHIN HUMAN TEMPORAL BONES

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Abstract—The inner ear contains three mutually perpendicular bony ducts, called semicircular canals, which are the major transducers of angular head movements. During rotation of the head, relative motion of the fluid results in stimulation of sensory cells within the duct. When a temperature gradient is established across the bony duct, density changes in the fluid also result in a pressure difference across these sensory cells. This method of stimulation is used clinically as a test of the vestibular function. The test consists of introducing an irrigating medium at a non-body temperature into the external ear canal. The transient heat transfer processes in the temporal bone and the resulting pressure changes in the semicircular canal were analytically and experimentally studied.

NOMENCLATURE

a, $= k/\rho c$, thermal diffusivity;
A_i, amplitude of step change in temperature at time b_i, equation (6);
b_i, time of step change in temperature, equation (6);
B_i, $h/\omega' k$, a Biot modulus;
C, specific heat (constant pressure);
D, distance from external auditory canal to center of semicircular duct;
g, acceleration due to gravity;
h, heat-transfer coefficient;
$I(t-b_i)$, Heaviside unit function $= \begin{cases} 1 & t > b_i \\ 0 & t < b_i, \end{cases}$ see equation (6);
J, energy [J];
k, thermal conductivity;
m, meters;
N, newtons;
P, pressure;
r, cross sectional radius of semicircular duct;
R, radius of semicircular duct;
t, time;
t^*, $(t-b_i)I(t-b_i)$;
T, temperature;
W, watts;
X, spacial coordinate.

Greek symbols

α, $(\omega' x + \delta)$ phase lag;
β, coefficient of thermal expansion;
δ, Arctan $(B_i + 1)^{-1}$;
η, integration variable;
ϕ, angle—see Fig. 3b;
ρ, density;
θ, $T - T_\infty$;
ω, frequency;
ω', $(\omega/2a)^{1/2}$.

Subscripts

a, irrigating medium;
e, endolymph;
i, index;
m, maximum amplitude;
∞, at $x = \infty$.

INTRODUCTION

THE VESTIBULAR portion of the inner ear contains three mutually perpendicular bony ducts, usually called semicircular canals. These fluid filled ducts are the major biological transducers of angular head movements. During angular head rotation, relative motion of the fluid with respect to the duct results in stimulation of sensory cells located within the duct. These sensory cells can be artificially stimulated by establishing a temperature gradient across the bony duct when the plane of the duct is non-horizontal. The temperature gradient causes density changes of the fluid and thereby a pressure difference across the sensory cells. This method of stimulation is used clinically as a major test of vestibular function and is called caloric testing. The test consists of introducing an irrigating medium at a non-body temperature into the external ear canal, thereby imposing a temperature gradient across the semicircular canals. The resulting eye movements are recorded as an indication of a vestibular response.

Although many attempts have been made to improve caloric testing, the test remains essentially qualitative and time-consuming. One of the major reasons for this is a lack of knowledge concerning the unnatural thermal stimulus and its effect on vestibular receptors. The present study was undertaken in an attempt to provide insights into the various factors influencing the caloric response. Better understanding of the various thermal, biophysical and physiological events occurring during thermal stimulation can be expected to increase the efficiency and diagnostic value of the test.

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ANATOMY

Figure 1 is a schematic representation of one of the three semicircular canals located within the inner ear. Each canal originates from a common sac (utricular sac), forms a rough semicircle and returns to the utricular sac. An enlarged portion of the duct—the ampulla—contains specialized sensory hair cells which project into the lumen of the ampulla. These sensory cells are located on the crista ampullaris. Overlying the sensory cells is a gelatinous substance called the cupula. The canals are filled with a fluid (endolymph) whose density and viscosity are approximately equal to that of water. The cupula has a similar density.

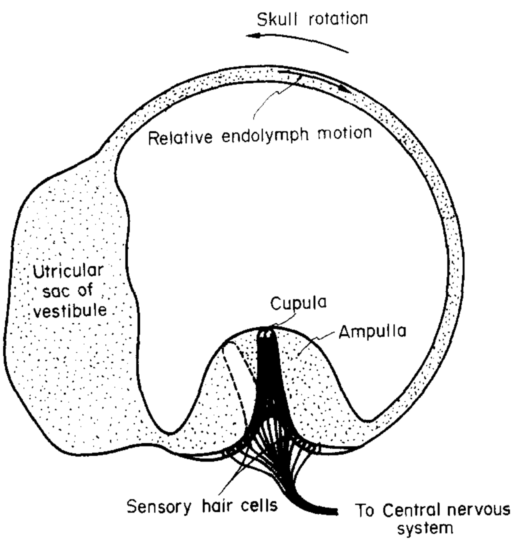

FIG. 1. Schematic representation of semicircular duct.

During the angular acceleration in the plane of the canal, the endolymph lags behind the bony canal wall thereby causing displacement of the cupula and stimulation of the sensory cells. Figure 1 illustrates the relative displacement of endolymph and the cupula resulting from a counter-clockwise rotation of the head. In general the Reynold's number of the endolymph flow is quite small, because of the small inertial and large viscous forces acting, with the result that the cupular position is approximately proportional to angular head velocity. The sensory cell responses are approximately proportional to cupular displacement and therefore angular head velocity. Neural signals from the sensory cells ultimately cause eye movements in the same plane as the endolymph movement. The compensatory eye movements are known as nystagmus. This reflex action is essential for stabilization of the retinal image during angular head movements. Consider the following illustration. During a counterclockwise head rotation, the vestibular system senses the direction and magnitude of the head movement and causes the eyes to move in a clockwise direction with a velocity approximately equal to the velocity of the head movement, thereby keeping the visual image fixed on the retina. By recording the velocity of these compensatory eye movements, one can obtain an indication of the vestibular response.

The effect of a thermal gradient upon a semicircular canal can also be illustrated by considering Fig. 1. If the fluid within the utricular sac is warmer than the fluid within the thin portion of the duct, endolymphatic convection currents will cause deflection of the cupula towards the utricular sac as shown. This cupular deflection will result in compensatory eye movements just as if the head were rotated.

PROCEDURE

A system engineering analysis approach was taken, which required development of an analytical description of the interrelated series of events occurring during caloric stimulation. To accomplish this, the caloric test was divided into a series of time-related events which were analyzed individually using the appropriate heat-transfer, biophysical and applied physiological principles. This division of the caloric test into a series of time-related events is shown in Fig. 2. The analysis begins with an examination of the thermal events

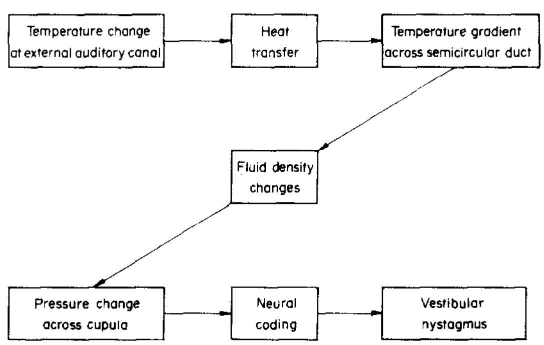

FIG. 2. Sequence of events in caloric testing.

occurring during caloric stimulation. Heat-transfer pathways and the thermal properties of temporal bone were studied in cadaver specimens in order to verify a proposed thermal model describing the heat-transfer process. To predict the thermally induced pressure changes within the duct, the duct was approximated by a rigid toroid, and fluid density was assumed to be a linear function of temperature. Using these approximations and the above mentioned model for heat transfer, fluid pressure changes were calculated for various temperature changes at the external auditory canal. The effect of the pressure changes on the sensory cells are described in detail elsewhere [1, 2]. Finally, the predictions of the heat-transfer and pressure models are compared to caloric nystagmus data obtained from human subjects.

MODELS

Heat transfer

Three heat-transfer pathways are possible from the external auditory canal to the horizontal semicircular canal (the semicircular canal which is subjected to the largest temperature gradient during caloric stimulation): (1) Along a bony bridge connecting the external ear canal and the horizontal semicircular canal. (2)

Across the middle ear space. (3) Along the ossicular chain (malleus, incus and stapes).

In view of the small size of the ossicular chain and the fact that the middle ear is filled with air, one might expect the bony bridge to be the major heat-transfer pathway. This is in agreement with the majority of the previous studies [3–5].

In an attempt to derive a general description of the thermal events associated with caloric stimulation, it was assumed that the heat transfer in the bony bridge could be approximated by one dimensional heat conduction through a homogeneous semi-infinite solid with forced convective heat transfer at the boundary, as represented in Fig. 3(a).

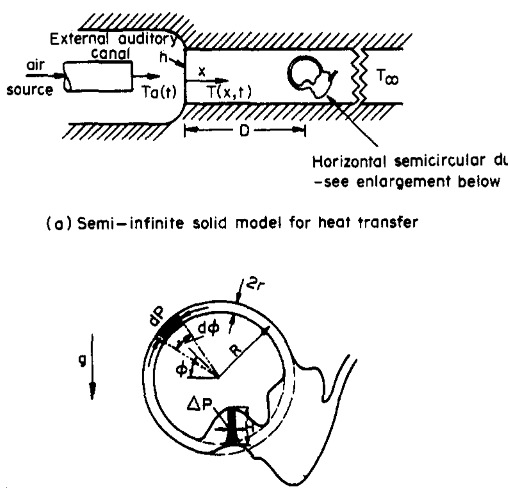

FIG. 3. Models for computation of pressure difference within semicircular duct.

The governing differential equation is:

$$\frac{\partial \theta}{\partial t} = a\frac{\partial^2 \theta}{\partial X^2} \tag{1}$$

with initial and boundary conditions:

$$\theta(X, 0) = 0 \tag{2}$$

$$\theta(\infty, t) = 0 \tag{3}$$

$$-\frac{\partial \theta(0, t)}{\partial X} + \frac{h}{k}[\theta(0, t) - \theta_a(t)] = 0. \tag{4}$$

The solutions of equations (1–4) are of interest here for two cases of the time-varying temperature of the irrigating media $\theta_a(t)$:

The periodic harmonic variation

$$\theta_a(t) = \theta_{am}\sin(\omega t). \tag{5}$$

The arbitrary variation, expressed in terms of n finite steps by

$$\theta_a(t) = \sum_{i=1}^{n} A_i I(t - b_i) \tag{6}$$

The solution for the periodic variation, equation (5), is well known [6] and can be placed in the form:

$$\frac{\theta(X, t)}{\theta_{am}} = \frac{B_i}{[(B_i+1)^2+1]^{1/2}} e^{-\omega' X}\sin(\omega t - \omega' X - \delta) + \frac{B_i}{\pi}\int_0^{\infty} \frac{(\eta\cos\eta\omega' X + B_i \sin\eta\omega' X)}{(\eta^4/4+1)(B_i^2+\eta^2)} \times e^{-(\omega/2)\eta^2 t}\,\eta\, d\eta. \tag{7}$$

The first term on the right side in equation (7) is the steady periodic solution, and the amplitude of the sinusoidal temperature variation for this case is given by:

$$\frac{\theta_{max}(X)}{\theta_{am}} = \frac{B_i}{[(B_i+1)^2+1]^{1/2}} e^{-\omega' X} \tag{8}$$

The phase difference between the periodic irrigating medium temperature $\theta_a(t)$ and the steady periodic temperature response $\theta(x, t)$ is:

$$\alpha = \omega' x + \delta. \tag{9}$$

If the semi-infinite solid is a reasonable representation of the heat transfer from the external ear canal to the horizontal semicircular duct, then the temperature changes within the bony bridge connecting these points not only should be periodic as well, but the amplitude of the temperature should decrease exponentially with distance from the external canal, and the phase lag should increase linearly with this distance. Furthermore, measurements of the amplitudes and the phase lags could be used to calculate the thermal diffusivity of the temporal bone, and the thermal conductivity as well if the heat-transfer coefficient at the external ear canal is known or can be estimated.

The solution for the stepwise arbitrary variation of the irrigating media, equation (6), can be written, using the principle of superposition (6, 7):

$$\theta(X, t) = \sum_{i=1}^{n} A_i\left[\operatorname{erfc}\left(\frac{X}{2\sqrt{(at^*)}}\right) - e^{\left(\frac{hX}{k} + \frac{h^2}{k^2}at^*\right)}\operatorname{erfc}\left(\frac{X}{2\sqrt{(at^*)}} + \frac{h}{k}\sqrt{(at^*)}\right)\right]. \tag{10}$$

The computed transient temperatures will be compared with measured temperatures, and will also be used to compute pressure differences across the cupula.

Pressure

To estimate the pressure difference across the cupula as a result of thermal stimulation, the horizontal semicircular duct is approximated by a rigid toroid with large radius R and cross-sectional radius r, as shown in Fig. 3(b). It is assumed that the temperature of the fluid within the toroid is uniform at a given cross-section, and therefore is a function of R and ϕ only. This assumption appears reasonable since the ratio R/r for man is 15·9 [8]. Using the semi-infinite solid model of Fig. 3(a) the temperature at any point within the toroid can be computed with the transformation $X = D - R(\cos\phi)$. The thermal transient processes are sufficiently slow that the pressures can be calculated assuming a quasi-static process.

With the plane of the toroid vertical, the differential pressure dP across an element of fluid $d\phi$ in the duct, shown in Fig. 3(b), is given by

$$dP = -\rho_e(T) g R \cos\phi \, d\phi. \tag{11}$$

The density of the endolymph ρ_e is assumed to be a linear function of temperature over the range of interest, and may be expressed in terms of the coefficient of thermal expansion β.

Substituting the expression for density in equation (11) and integrating over the entire toroid gives the pressure difference ΔP across the cupula:

$$\Delta P = 2\rho_{e\infty} \beta g R \int_0^{\pi} T(\phi) \cos\phi \, d\phi. \tag{12}$$

Since $T(\phi) = T(x, t)$ is a function of time, ΔP is also a function of time. It will then be possible to compare the transient pressure difference across the cupula as predicted from the measured transient irrigation temperature $T_a(t)$ with the measured physiological result of the cupula deflection, the nystagmus (compensatory eye motion).

EXPERIMENTS

Thermal measurements

Human half skulls without the calvarium were obtained at autopsy and mounted in casting resin. X-rays were taken of the imbedded bones to determine the relative position of inner ear structures. Using coordinates obtained from the X-rays, vertical holes 1 mm in dia. were drilled through the floor of the middle cranial fossa into the vestibule, lateral portion of the horizontal semicircular canal and middle ear space. After placing thermistors in these holes and obtaining temperature measurements at the three locations, additional holes were drilled and temperature measurements obtained along the bony bridge connecting the posterior osseous canal wall to the horizontal semicircular canal. The imbedded bones were then dissected to verify the anatomical location of each measurement.

Thermal stimuli consisted of a controlled temperature air stream introduced into the external auditory canal through a polyethylene tube 1·7 mm ID. Air stream temperature was monitored by an iron–constantan thermocouple 0·076 mm in diameter mounted at the end of the tubing. Temperature was controlled by a thermoelectric device [9] which employed two identical Peltier units mounted on both sides of a copper heat exchanger. The current flow in the Peltier units was electronically regulated to provide periodic or arbitrary air stream temperatures.

Temperature measurements within the bones were obtained with bead thermistors 0·36 mm in diameter which were mounted in hypodermic tubing assemblies 0·91 mm in diameter. A thermistor interface unit provided a constant current of 10^{-6} amperes and amplified the resulting voltage signal, which was then recorded. The thermistors were calibrated against a platinum resistance thermometer from 15 to 33°C to an accuracy of $\pm 0{\cdot}01$°C.

Human nystagmus recordings

Nine subjects between the ages of 18 and 35 and with no previous history of ear diseases, hearing loss or vestibular problems were administered clinical audiometric and neurological examinations before being tested with the air irrigation system. The neurological examination consisted of tests for spontaneous, positional and optokinetic nystagmus, as well as a series of conventional Cawthorne–Hallpike caloric tests using water.

Caloric testing was done with the head tilted back 60°, and the horizontal eye motion was recorded continuously with silver chloride electrodes placed on the outer canthi and glabella. The recording system was calibrated by having the subject fix on two light spots subtending 10 degrees of arc. All testing was performed in a dark room. The caloric responses as manifested by the slow phase velocity of the eyes were reduced by hand from the recordings.

The relationship between the predicted endolymphatic pressure change induced by the thermal gradients and the resulting vestibular nystagmus was determined by introducing a temperature-controlled air stream into the external auditory canal and recording the subsequent nystagmus. To permit accurate positioning of the air stream in the external canal, each subject was fitted with specially designed earmolds which had two tubes (1·7 mm ID) running down the center of the mold—one tube for air entering the ear canal and the other tube for air leaving. An iron–constantan thermocouple (0·076 mm in diameter) was mounted at the end of the inlet tube in the middle of the air stream for recording of the inlet air temperature. The inlet air stream temperature was controlled by the thermoelectric device described previously. The air flow rate was 4 l/min.

The nine test subjects were divided into two groups. One group of five subjects was given air calorics which approximated a 21°C step decrease in temperature measured at the external auditory canal. Irrigation durations of 30, 60 and 90 s were used. The caloric stimulus applied to the second group was a periodic modulation of the air stream temperature above and below normal body temperature.

More details of the experimental apparatus used are given in [1].

RESULTS

Thermal measurements

A preliminary study was carried out on three human temporal bones to examine the possible heat-transfer pathways from the external auditory canal to the horizontal semicircular canal. By observing temperature changes at various locations within the temporal bone it was concluded that, although temperature changes did occur in the middle ear space, earlier theories which stated that heat is conducted along the bony connection between the external auditory canal and the horizontal canal were probably the most realistic.

To verify this, temperature measurements were made

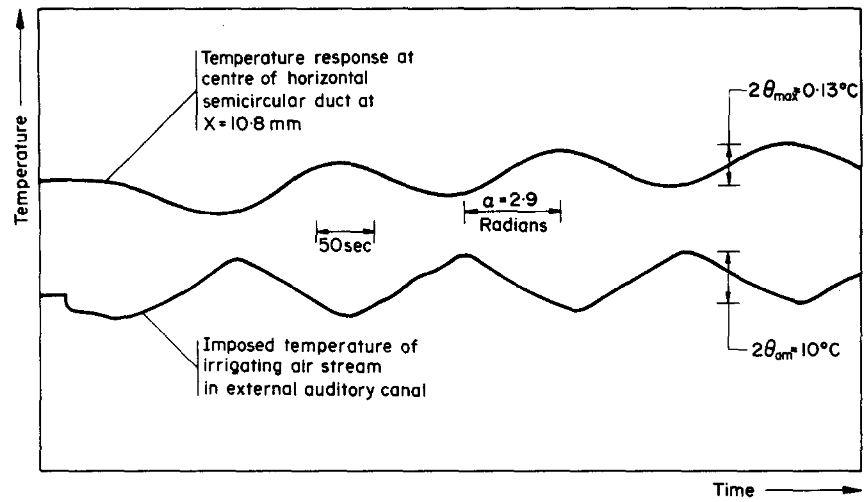

FIG. 4. Typical oscillatory temperature measurements in the middle ear. Bone 8.

along the bony bridge during caloric stimulation with a periodic air stream temperature. A typical result is shown in Fig. 4. The lower curve shows the periodic imposed temperature of the irrigating air stream in the external auditory canal. It is possible to compute the temperature response for this particular temperature variation by obtaining the Fourier components of the disturbance and using superposition. The higher harmonics, however, will be attenuated rapidly if their amplitudes are reasonably small. It was considered adequate here to use only the fundamental frequency for purposes of comparison. The upper curve in Fig. 4 shows the measured temperature within the bony bridge 10·8 mm from the external auditory canal, which corresponds to the center of the horizontal semicircular duct. The relatively large attenuation and phase shift from the periodic disturbance may be noted. Measurements of the maximum amplitudes and phase shifts were made for two different bones and for different locations within each bone, at least 300 s after the start of irrigation in order to allow for the establishment of the steady periodic process.

The amplitude and phase lag from these measurements are plotted in Fig. 5 as a function of distance from the external auditory canal. To assist in orientation, the space occupied by the horizontal semicircular duct is indicated, and generally lies between 7·5 and 13·5 mm from the external auditory canal. Figure 5 shows that the amplitude follows the exponential attenuation reasonably well, as predicted by equation (8), and that the phase lag increases linearly, as predicted by equation (9).

It is possible to estimate the thermal diffusivity and thermal conductivity of the bony bridge from the data in Fig. 5. These data will be necessary to compute the pressure difference across the cupula from equation (12) later, using calculated temperatures from either equation (7) or equation (10). From equations (8) and (9), the slopes of the best fit straight lines give $\omega' = 0{\cdot}25\,mm^{-1}$. With the period of 200 s used this results in a thermal diffusivity $a = 0{\cdot}25\,mm^2/s$ for the temporal bone. The only other data available for this material was reported as $a = 0{\cdot}175\,mm^2/s$, in 1930 [10]. An approximate value for the Biot number can be determined from the intercept at $x = 0$ of θ_{max} in Fig. 5, and was calculated as $B_i = h/\omega' k = 0{\cdot}51$. Knowing ω' from above, then $h/k = 0{\cdot}128\,mm^{-1}$. By assuming that the average density of the temporal bone and its contained air spaces is that of water, and that the specific heat is the average between that of calcium and water, $C_p = 2{\cdot}5\,J/g\,C^{-1}$, the thermal conductivity is calculated for $a = 0{\cdot}25\,mm^2/s$ to be $k = 6{\cdot}25 \times 10^{-3}\,W/cm\,C^{-1}$. For comparison purposes, water at 100°F has a thermal

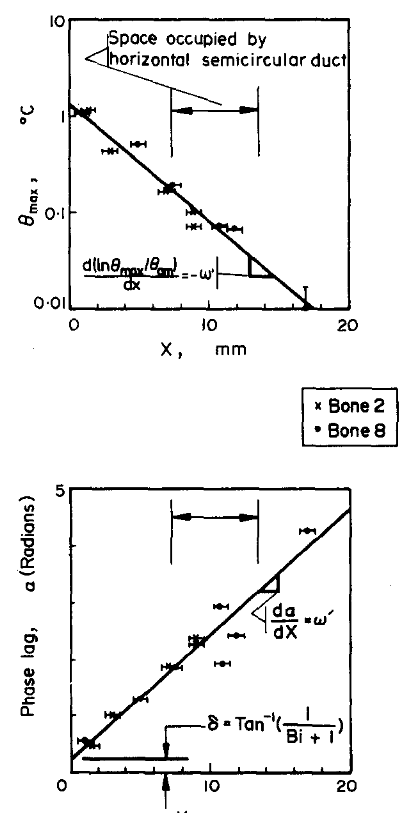

FIG. 5. Amplitude and phase lag of temperature within human temporal bones.

diffusivity $a = 0{\cdot}15\,\text{mm}^2/\text{s}$ and a thermal conductivity $k = 6{\cdot}32 \times 10^{-3}\,\text{W/cm}\,\text{C}^{-1}$.

In addition to the periodic air stream temperature stimuli on the temporal bones, tests were conducted in which air stream temperatures were to approximate step changes. An example of a measured air stream temperature is shown as $\theta_a(t)$ in the lower solid curve of Fig. 6. As can be seen, step changes in temperature were not possible, because of heat capacity effects in the heat exchanger. The corresponding transient temperature measured at the center of the horizontal semicircular duct is shown as the upper solid curve in Fig. 6. By approximating the air stream temperature

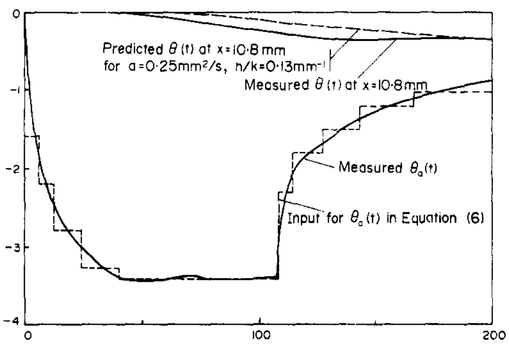

FIG. 6. Comparison of computed and measured temperatures in the middle ear.

by a series of steps as shown and using the properties "a" and "h/k" given above, the response at this point can be predicted with equation (10), and is shown as the upper dashed line in Fig. 6. Comparison shows that the response to the disturbance is more rapid in the measured case than as predicted, which indicates that inadequacies still exist in the one-dimensional model. The comparison could not be improved by making reasonable changes in the properties of the temporal bone.

Human nystagmus recordings

Figure 7(a) shows the measured transient air temperature in the external auditory canal of a human subject. From this, the temperature response at the midpoint of the semicircular canal was computed using equation (10), and is shown in Fig. 7(b). $T(\phi)$ in equation (12) was also computed from equation (10), and the integral evaluated at different times to give the timewise variation of the pressure difference across the cupula, which is plotted in Fig. 7(c). The thermal properties of a and h/k measured with human cadaver bones were used in these computations. There is some evidence to suggest that no essential difference exists between living patients and the cadaver in this respect [11], but the validity of this assumption, which neglects the effect of blood flow in the temporal bone, must await further investigations. The value of the coefficient of thermal expansion used for the endolymph was $\beta = 4{\cdot}4 \times 10^{-4}\,°\text{C}^{-1}$ [12].

The measured slow phase eye velocities are plotted as Fig. 7(d), with each point representing the average

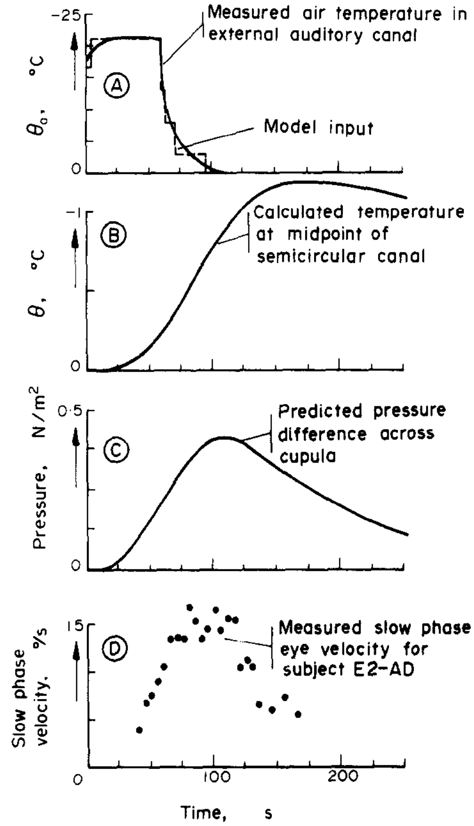

FIG. 7. Comparison of events accompanying a step change in temperature at the external auditory canal.

slow phase eye velocity per 5 s interval. Comparison of Figs. 7(c) and 7(d) suggests a somewhat similar profile for the calculated pressure difference and the resulting eye velocity. This can be seen more clearly in Fig. 8, where the normalized pressure and eye velocities of Fig. 7 are superimposed, along with data from two additional individuals. The stimuli were all the same as in Fig. 7(a). In all cases it appears that the slow phase eye velocity leads the predicted pressure difference somewhat on the increasing part, and considerably on the decreasing part. It might also be noted that the peak pressure difference in Fig. 7(c) leads the peak temperature at the center of the semicircular canal. This is to be expected, since the pressure difference is a function of the differences in temperature between the near and far sides of the semicircular duct.

Figure 9(a) shows the measured periodic temperature of the irrigating air stream in the external auditory canal of a human subject. The period used was 150 s. Both the starting transient and the steady periodic temperature response at the midpoint of the semicircular canal were computed using equation (7), and are plotted in Fig. 9(b). From the temperature calculations the pressure differences across the cupula were next computed with equation (12) for both the starting transient and steady case, and are plotted as Fig. 9(c). Although the temperature at the midpoint of the semicircular canal have not yet approached the steady periodic behavior by the end of the second cycle, the

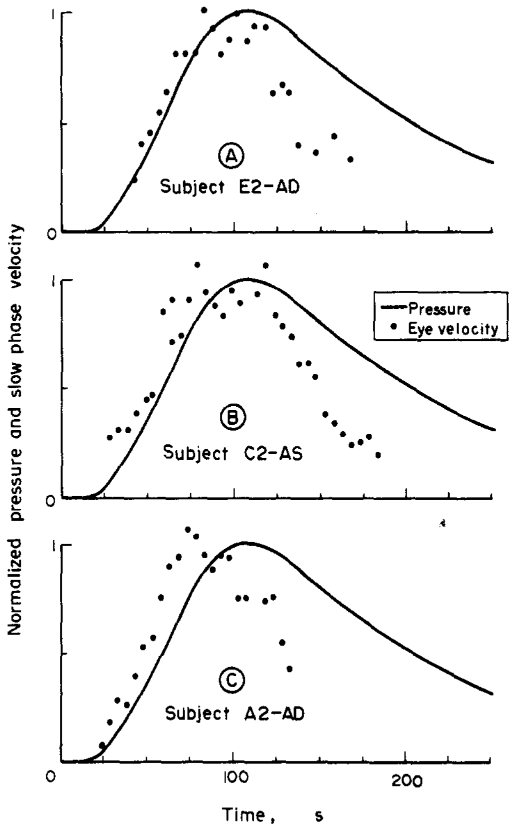

FIG. 8. Comparison of predicted cupula pressure differences with slow phase eye velocity for three subjects.

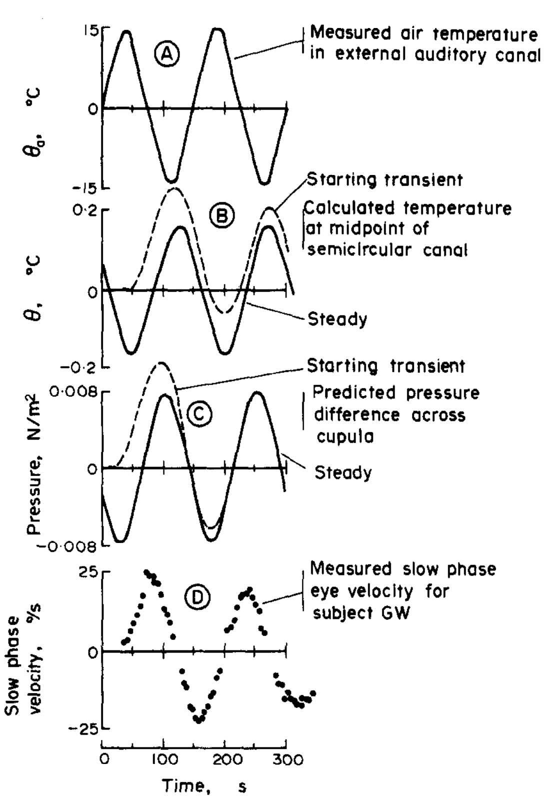

FIG. 9. Comparison of events accompanying a periodic variation in temperature at the external auditory canal.

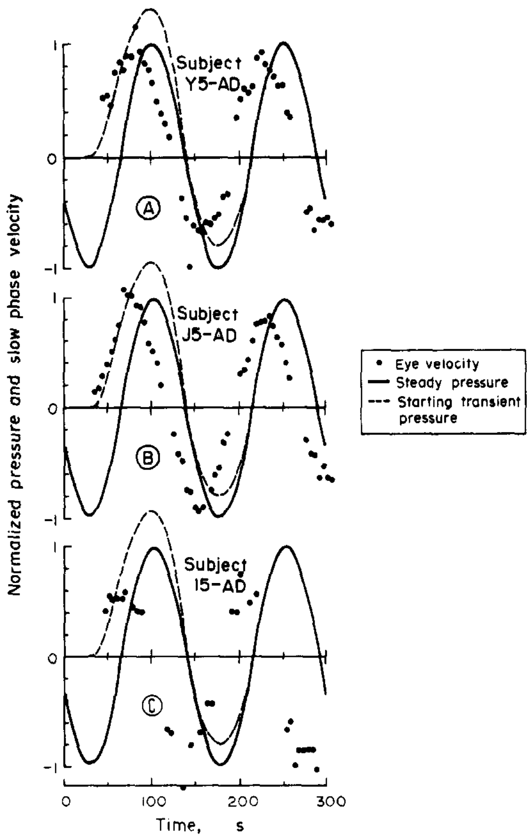

FIG. 10. Comparison of predicted cupula pressure differences with slow phase eye velocity for three subjects.

pressure difference across the cupula essentially has reached the steady periodic case. The measured slow phase eye velocities for one individual, corresponding to the disturbance of Fig. 9(a), are shown in Fig. 9(d). A comparison of Figs. 9(c) and 9(d) again suggest similar profiles between the calculated pressure difference and the resulting eye velocity, albeit with the measured eye velocity leading the pressure difference and decreasing in amplitude during the second cycle. A clearer comparison is possible when the pressure difference and slow phase eye velocities are normalized and superimposed, as in Figs. 10(a–c) for three individuals. This illustrates the variability possible among otherwise normal subjects. The stimuli were the same as in Fig. 9(a). Although the experiments on human subjects were begun from a static condition, it appears that a nearly steady periodic response is achieved on the second cycle.

DISCUSSION

Upon comparison of the measured transient temperature changes with the computed values in Fig. 6, and upon comparison of the computed pressure changes with the measured eye velocities in human subjects in Figs. 8 and 10, it appears that the measured responses lead the predicted values. The significant parameters having the greatest uncertainty are the heat transfer properties: (1) thermal diffusivity a, and (2) ratio of heat transfer coefficient to thermal conductivity

h/k. These were determined from the periodic measurements as described earlier in connection with Fig. 5. Some inaccuracies exist in the determination of these properties from Fig. 5, and further work on the measurement of the thermal properties of temporal bones is necessary. In the present case, variations in the thermal diffusivity a as high as ± 50 per cent were attempted with little improvement. One could also adjust the value of (h/k) to make the results agree better. The value $h/k = 0{\cdot}128\,\mathrm{mm}^{-1}$ was used in computing the results presented here, but a value of $h/k = 0{\cdot}5\,\mathrm{mm}^{-1}$ was also tried with little improvement. To perceive the significance of these values for h/k, the heat-transfer coefficient h in the external auditory canal is computed to be $h = 8 \times 10^{-3}\,\mathrm{W/cm^2\,C^{-1}}$ for $(h/k) = 0{\cdot}128\,\mathrm{mm}^{-1}$ and for the thermal conductivity of the temporal bone taken as $k = 6{\cdot}25 \times 10^{-3}$ $\mathrm{W/cm\,C^{-1}}$, a reasonable value. This value of h can be compared with an order-of-magnitude approximation for forced convection heat transfer in a duct. With the air flow rate of 4 l/min used in the experiments and considering the external ear canal to be a duct 6 mm in dia, the flow Reynolds number is 2500. Assuming the asymptotic value of 3·66 for the Nusselt number with laminar flow in a tube results in $h = 1{\cdot}5 \times 10^{-3}$ $\mathrm{W/cm^2\,C}$, while by assuming turbulent flow in spite of the low Reynolds number, the Coburn equation predicts $h = 4{\cdot}3 \times 10^{-3}\,\mathrm{W/cm^2\,C}$. These are both reasonable order-of-magnitude comparisons with the value of 8×10^{-3} computed above. A value of $h/k = 0{\cdot}5\,\mathrm{mm}^{-1}$ for the same k, which gave little improvement, would require a flow Reynolds number of 12 500, which would correspond to an air velocity within the inner ear of over 35 m/s.

Since the discrepancies between the computed pressure changes and the measured eye velocities cannot be accounted for in terms of uncertainties in the thermal properties within the temporal bone, the conclusion would appear to be that the one dimensional model of heat conduction within the temporal bone is inadequate for the accurate representation of the heat-transfer process. The differences, however, may be a consequence of other effects such as the dynamic response of the cupula, neural properties, and cupula and neural adaptation, each of which require further investigation. In spite of the relative inaccuracy of the one dimensional model, it appears to result in a reasonable overall description of the process, and has the advantage of great simplicity over any multidimensional model which might be developed.

In using the caloric testing as a diagnostic tool, comparisons between individuals are still difficult because of the physiological variability between individuals. Additional measurements and statistical assessment may clarify this in the future. However, the test does permit a ready comparison between the two sides in a single individual. The periodic tests of Figs. 9 and 10 result in significant reductions in time required to administer the caloric tests when compared to the bithermal tests of Figs. 7 and 8, since it is not necessary to wait for equilibrium conditions to repeat the tests.

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ETUDE DES GRADIENTS THERMIQUES DANS LES OS TEMPORAUX HUMAINS

Résumé—L'oreille interne contient trois conduits osseux deux à deux perpendiculaires, appelés canaux semi-circulaires, qui sont les principaux transducteurs des mouvements angulaires de la tête. Pendant la rotation de la tête, le mouvement relatif du fluide a pour effet une stimulation des cellules sensitives à l'intérieur du conduit. Lorsqu'un gradient de température est établi d'un côté à l'autre du conduit osseux, les variations de densité du fluide provoquent également une différence de pression entre cellules sensitives. Cette méthode de stimulation est un procédé clinique utilisé comme test de la fonction vestibulaire. Le test consiste à introduire dans le conduit de l'oreille externe, un milieu d'irrigation à une température différente de celle du corps. Les processus transitoires de transfert thermique dans l'os temporal et les variations de pression qui en résultent dans le canal semi-circulaire ont été étudiés par voie analytique et expérimentale.

ANALYSE DER TEMPERATURGRADIENTEN IM MENSCHLICHEN SCHLÄFENBEIN

Zusammenfassung—Das innere Ohr enthält drei aufeinander senkrecht stehende Knochenkanäle, die Halbkreiskanäle, die die Hauptübertrager für Neigungen des Kopfes darstellen. Während der Drehung des Kopfes erfolgt eine Bewegung von Flüssigkeit in den Kanälen, die zur Anregung von Gefühlszellen führt. Bringt man einen Temperaturgradienten in den Knochenkanälen auf, so führen Dichteänderungen im Fluid ebenfalls zu einer Druckdifferenz an den Gefühlszellen. Diese Anregungsmethode wird klinisch als Test für die Vorhoffunktion benützt. Der Test besteht darin, eine Spülflüssigkeit von Nichtkörpertemperatur in den äusseren Ohrkanal einzuführen. Der instationäre Wärmetransportvorgang im Schläfenknochen und der sich ergebende Druckunterschied im Halbkreiskanal werden analytisch und experimentell untersucht.

АНАЛИЗ ТЕПЛОВЫХ ГРАДИЕНТОВ В ВИСОЧНЫХ КОСТЯХ

Аннотация — Внутреннее ухо содержит три взаимно перпендикулярных костных канала, называемых полукружными каналами, которые являются основными датчиками угловых движений головы. При повороте головы относительное перемещение жидкости вызывает возбуждение чувствительных элементов внутри канала. При установлении температурного градиента поперек костного канала изменение плотности жидкости вызывает также разность давлений поперек этих чувствительных элементов. Этот метод возбуждения клинически используется как проба вестибулярной функции, которая состоит во введении в наружный ушной канал орошающей среды, температура которой отлична от температуры тела. Проведено аналитическое и экспериментальное изучение нестационарных процессов теплообмена в височной кости и соответствующих изменений давления в полукружном канале.