

BIOPHYSICAL EVALUATION OF THE
HUMAN VESTIBULAR SYSTEM

Second Semi-Annual Status Report on
NASA Grant NGR 22-009-156

January 1967

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MV-67-2

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ABSTRACT

The physical properties of the labyrinthine fluids and their variation with temperature were measured. A precision microviscometer was built and calibrated to measure viscosity of endolymph and perilymph. Progress in experiments and modeling of the vestibular caloric stimulation process is reported. Analytical efforts to establish a fluid dynamic model of the semicircular canals are discussed.

by Principal Investigators: J. L. Meiry
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I. PHYSICAL PROPERTIES OF THE LABYRINTHINE FLUIDS

In the last half of 1966 the construction and calibration of the micro-viscometer described in the First Semi-Annual Status Report (MV-66-2, June 1966) was completed, and the physical properties of density (ρ), coefficient of volume expansion ($\frac{1}{V} \frac{\partial V}{\partial T}$), viscosity (μ), and thermal coefficient of viscosity ($\frac{d\mu}{dT}$), have been measured for both cat and human perilymph, and human endolymph. These results and their error bounds are presented in table 1. The experimental methods used in the measurement of the properties of the labyrinthine fluids are described in the following paragraphs.

Density Measurements

The measurement of viscosity by the "rolling sphere" viscometer requires knowledge of the density of the fluid measured (see MV-66-2). However, since the tungsten carbide sphere used in our micro-viscometer has a density near 13, and the labyrinthine fluids have densities near 1, then the absolute accuracy of their differences is relatively insensitive to errors in the density measurement of the fluids. It is sufficient for this purpose to measure densities to an absolute accuracy of $\pm 2\%$.

Using a precision chemical balance to weigh a calibrated micropipette empty, filled with water, and filled with cat or human endolymph or perilymph, it was found that the labyrinthine fluids' density is indistinguishable from water, to an accuracy of $\pm 2\%$.

Thermal Coefficient of Expansion

To calculate the torque on the endolymph due to caloric stimulation it is necessary to know the change in density of endolymph due to variations in temperature. For this purpose it is convenient to recall that:

$$\frac{\partial V}{V \partial T} = \frac{-\partial \rho}{\rho \partial T}$$

where

V = volume

ρ = density

T = temperature.

The coefficient of expansion $(\frac{\partial V}{V \partial T})$ was obtained by measuring the change in length of a 0.500 inch column of fluid in a glass capillary. A microscope equipped with a micrometer adjustable table having a resolution of $.05 \times 10^{-3}$ in. was used for the readout instrument. By measuring the change in length for a 10°C change in temperature and taking into account

the expansion of the glass pipette, the coefficient of expansion was found to be $4.4 \times 10^{-4}/^{\circ}\text{C}$ for cat and human endolymph and perilymph. Error analysis bounds the measurement accuracy to $\pm 5\%$.

Coefficient of Thermal Conductivity

To evaluate analytically the thermal time constant of the caloric stimulation model which was presented in the First Semi-Annual Status Report (MV-66-2, June 1966), the thermal conductivity of endolymph and perilymph must be known.

A device to measure the thermal conductivity of 1μ samples is under construction. It measures the time constant of decay of the thermal gradient between two insulated bodies connected by a tube of fluid. It is expected that this measurement will be completed in the first quarter of 1967.

Modification of Proposed Viscometer Design

In practice it was found to be necessary to modify some of the original design features of the micro-viscometer. The first of two major changes was the inclusion of a closed loop temperature controller to maintain the sample within 0.1°C of the desired value. Secondly, it was found to be necessary to include an electrostatic shield in the design of the instrument to eliminate the effects of the electrostatic force field on the rolling sphere.

Modification of Sample Handling Techniques

Samples of human and cat labyrinthine fluids were obtained from Dr. Herbert Silverstein at the Massachusetts Eye and Ear Infirmary. These samples were the remainder of samples that had been used for chemical analysis, and although they were large enough for use in the viscometer, they contained small bits of paraffin, or glass, and all were sealed with mineral oil. It became necessary to centrifuge the samples to separate the foreign particles and to separate the droplets of oil from the tungsten carbide sphere.

The mineral oil serves both as a seal to prevent evaporation and contamination, and as a barrier which prevents the sphere from being caught in the surface tension of the fluid; thus the cap which had been specifically designed for those purposes, for the capillary tubes, was no longer needed. It was also found necessary to demagnetize the tungsten sphere after insertion in the sample tube.

Newtonian Behavior of the Labyrinthine Fluids

The viscosity of human endolymph was measured by the viscometer using two different angles of inclination of the plane of rolling (20° and 35°). It was found that the viscosities did not vary appreciably with the angle of tilt even though the terminal velocity of the sphere was nearly doubled. Similarly,

measurements indicate that when the sealed sample was left to set without disturbance for one day, and one week, there is no measurable change in viscosity within the 2% accuracy limitation of the instrument. Thus, it appears that the fluids do not change viscosity with "setting time" or increasing shear rates, and can therefore be considered as Newtonian Fluids. To further substantiate this claim, the chemical analysis of endolymph shows a low protien content whereas the non-Newtonian or "shear thinning" fluids, such as glycerine, have a high protien content.

II. VERIFICATION OF THE MODEL OF CALORIC STIMULATION

Utilizing the thermal lag model for caloric stimulation, as presented in MV-66-2 it can be shown that

$$\Theta_c(t) = A T_1 \int_0^{-1} \frac{1}{s(s + \frac{1}{\tau_1})(s + \frac{1}{\tau_2})(s + \frac{1}{\tau_3})}$$

where

$\Theta_c(t)$ = time history of cupular displacement due to
a step input of caloric irrigation

τ_1 = 25 sec. = thermal lag coefficient

τ_2 = 10 sec. = long time constant of lateral canal

τ_3 = .1 sec. = short time constant of lateral canal

A = system constant

T_1 = temperature above normal body temperature.

After expansion of the above equation and after performance of the Inverse Laplace Transformation:

$$(1) \quad \Theta(t) = A \tau_1 \tau_2 \tau_3 T_1 \left[1 - \frac{\tau_1^2 e^{-t/\tau_1}}{(\tau_1 - \tau_2)(\tau_1 - \tau_3)} - \frac{\tau_2^2 e^{-t/\tau_2}}{(\tau_2 - \tau_1)(\tau_2 - \tau_3)} - \frac{\tau_3^2 e^{-t/\tau_3}}{(\tau_2 - \tau_3)(\tau_1 - \tau_3)} \right]$$

If one attempts to fit $\theta(t)$ by a power expansion in powers of t of the form:

$$\theta(t) = B_0 + B_1 t + \frac{B_2}{2!} t^2 + \dots + \frac{B_n}{n!} t^n$$

it turns out that

$$B_0 = B_1 = B_2 = 0$$

$$B_3 = 1$$

$$B_4 = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}$$

$$B_5 = \frac{1}{\tau_1 \tau_2} + \frac{1}{\tau_2 \tau_3} + \frac{1}{\tau_1 \tau_3}$$

Because of the presence of the short time constant, the polynomial requires many terms to approximate caloric responses since the polynomial coefficients attempt to fit the initial part of the response. Therefore, it is more suitable to evaluate $\theta(t)$ vs. t numerically.

Ignoring the presence of the short time constant of the canal is a simplification that can readily be justified because of the long delay of the thermal lag.

Then

$$(2) \quad \theta_c(s) \approx \bar{A} T_1 \int \frac{1}{s(s + \frac{1}{\tau_1})(s + \frac{1}{\tau_2})} \quad -1$$

$$\tau_1 = 25 \text{ sec.}$$

$$\tau_2 = 10 \text{ sec.}$$

$$\theta(t) \approx \tau_1 \tau_2 \bar{A} T_1 \left[1 - \frac{\tau_1}{\tau_1 - \tau_2} e^{-t/\tau_1} + \frac{\tau_2}{\tau_1 - \tau_2} e^{-t/\tau_2} \right]$$

$$\approx K T f(t)$$

Figure 1 shows the function $f(t)$ as computed from both (1) and (2) for a unit step input, for the time interval 0 to 75 seconds. There is little difference in the two computed functions; the maximum difference between them is within the thickness of the line on the curve.

It should now be possible to show, analogous to the "Muelder product," that the latency time to the onset of caloric nystagmus follows the relationship, hereafter referred to as the "Caloric Latency Product:"

$$f(\tau_L) T_1 = C = \text{constant}.$$

In figure 2, $f(\tau_L) T_1$ is plotted for several values of C .

To this end, a sequence of experiments is currently being conducted to measure the latency time to the onset of ocular nystagmus for caloric irrigation at various temperatures.

III. FLUID DYNAMIC ANALYSIS OF THE CUPULA-ENDOLYMPH SYSTEM

The primary expenditure of effort on the problem of fluid dynamic analysis of the semicircular canal system has been toward the solution of the Navier-Stokes equations in closed form under the assumptions of laminar flow of a Newtonian Fluid in an inflexible tube when subjected to angular accelerations. From the results of our measurements of the labyrinthine fluids it is clear that the assumptions of a Newtonian Fluid undergoing laminar flow are indeed valid. The validity of the assumption of a "rigid" tube is questioned by some researchers, however. Since the measured densities of endolymph and perilymph are very nearly identical, the canal system must be very nearly neutrally buoyant and thus not appreciably distended by the application of linear or angular accelerations.

Although the Navier-Stokes equations are simple in form, they are difficult to apply in practice. For preliminary analysis it is expedient to use a conformal mapping technique to expand the closed circular tube into an infinitely long straight tube of radius r and to solve the Navier-Stokes equations in cylindrical coordinates, rather than in spherical coordinates. The transformation can later be inverted if necessary. To further justify such a temporary simplification,

the ratio of radii of the torus of the semicircular canal is 20 to 1 and thus the "thin ring" approximations are very applicable (see figure 3).

The equation to be solved in cylindrical coordinates can be reduced to the form

$$(3) \frac{\partial^2 v(r,t)}{\partial r^2} + \frac{1}{r} \frac{\partial v(r,t)}{\partial r} = \frac{1}{\mu} \frac{\partial P(t,\ell)}{\partial z} + \frac{1}{\nu} \frac{\partial v(r,t)}{\partial t} - a_z(t)$$

where

$$\begin{aligned} \mu &= \text{viscosity} & a_z(t) &= \alpha(t)R \\ \nu &= \text{kinematic viscosity} & \alpha(t) &= \text{angular acceleration} \\ R &= \text{long radius of torus} & v(r,t) &= \text{velocity of fluid} \\ r &= \text{radius of torus duct} & P(t,\ell) &= \text{pressure in fluid} \\ t &= \text{time} & \ell &= \text{length along duct} \end{aligned}$$

subject to the boundary condition

$$v(a,t) = 0$$

If the cupular damping term is ignored, then the solution of

$$(3) \text{ for } a_z(t) = -4c \text{ is} \quad (c \text{ is a constant})$$

$$v(r,t) = ca^2 \left[1 - \frac{r^2}{a^2} - 8 \sum_{i=1}^{\infty} \frac{J_0(\lambda_i r)}{(\lambda_i a)^3 J_1(\lambda_i a)} e^{-\lambda_i^2 \nu t} \right]$$

Since cupular displacement is proportional to the integral of the flow through the tube it is convenient to evaluate the average of $v(r,t)$ over the cross-section of the tube. Then:

$$\bar{v}(t) = \frac{ca^2}{2} \left[1 - 32 \sum_{i=1}^{\infty} \frac{e^{-\lambda_i^2 \omega t}}{(a\lambda_i)^4} \right]$$

where λ_i 's are the solutions of the 'zero' order Bessel function, $J_0(\lambda_i a) = 0$.

Further consideration of (3) by inclusion of the cupular damping term leads to the results that the dynamic behavior of the semicircular canals can in fact be described by a transfer function in the form:

$$\frac{\theta_c}{\alpha}(s) = \sum_{i=1}^{\infty} \frac{A_i}{s^2 + 2\zeta_i \omega_i s + \omega_i^2}$$

Note that this analytical model is of the form measured experimentally. The evaluation of the constants A_i , ζ_i , and ω_i is being worked on at the present time. This is difficult because of problems in calculating the cupular deflection "spring constant."

Analysis of "Flexible Canals"

Nystagmus in the presence of counter-rotating motion poses the question of whether or not the semicircular canals, because of their flexibility, are subject to excitation by

counter-rotating motion. It is shown by the simple counter-rotation of a glass filled with liquid that a circulation (∇) in the fluid can be induced by counter-rotation. This can be shown qualitatively to be the result of the free surface of the fluid, and that it is a result of the initial transient of the motion (the start of the counter-rotation motion).

The semicircular canals are being analyzed to determine whether their flexibility can allow a circulation in the presence of counter-rotating motion. It is anticipated that this work will be completed in the first half of 1967.

IV. ROTATING CHAIR SIMULATOR

A rotating chair simulator has been designed and is currently being constructed to be used in various experiments investigating the human vestibular system. The chair portion will be an entirely enclosed module in which the subject will sit upright seeing no outside reference, his head supported by a head rest, and his mouth fixed to a bite board. He will be wearing photoreceptor goggles to monitor eye nystagmus or he will manipulate a joystick or both. His head will be positioned above the axis of rotation.

The chair will be powered by two 7-1/2 ft-lb. torque motors connected directly to the shaft of the chair. They will be driven by an amplifier in such a manner as to develop a maximum of 15 ft-lbs. of torque. This amount of available torque will allow the chair to be driven with a sinusoidal acceleration whose peak ranges from 10 degrees/sec² to 100 degrees/sec² at any frequency in the range .01 cps to 1 cps.

During closed loop operation, a simple position feedback will be used employing a 15 turn, 20 K potentiometer. The potentiometer has been geared so that a maximum of 42 revolutions of the chair is possible in a closed loop operation. In open loop, the number is unlimited, and the chair can be operated at constant velocity or acceleration. The rotating chair simulator is expected to be completed during the first part of 1967.

V. PUBLICATIONS

The following two papers were presented at the Third Symposium on the Role of the Vestibular Organs in Space Exploration held in Pensacola, Florida, January 23-27, 1967:

Physical Properties of the Labyrinthine Fluids
and Quantification of the Phenomenon
of Caloric Stimulation

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Yao T. Li

Jacob L. Meiry

Abstract

The physical properties of endolymph and perilymph (viscosity, density, thermal coefficient of viscosity, and coefficient of thermal expansion) which are pertinent to the quantification of the dynamic behavior of the human vestibular sensors have been evaluated. Descriptions and error analyses of the instruments used for the measurements are presented.

The phenomenon of caloric stimulation of the semicircular canals is described quantitatively, and a dynamic model is presented. To verify the proposed model, the human's response to caloric stimulation is compared to his response to angular acceleration stimulation.

A REVISED DYNAMIC OTOLITH MODEL

Laurence R. Young and Jacob L. Meiry

Abstract

The basic dynamic otolith model of Meiry was based on observed relations between perceived direction of linear motion and input acceleration. Although this model correctly predicted phase of perceived velocity for lateral oscillation and time to detect motion under constant acceleration, it failed to account for at least two observations:

i) Behavioral and electrophysiological data indicate a sustained steady otolith output to sustained tilt angle. The model's perceived acceleration or tilt output decayed to zero with a time constant of 10 seconds.

ii) Dynamic counterrolling data agree with the model at higher frequencies. The experimental counterrolling at zero frequency, however, indicates a static component of otolith output with no phase lag referred to acceleration; whereas the model had no static output and approached 90 degrees of lead at zero frequency.

At the suggestion of Dr. H. Von Gierke, a static component was included in the otolith model. The revised linear model, which allows steady state response to acceleration, is shown in Fig. 1.

This revised linear model will act approximately as a velocity transducer over the mid-frequency range ($0.19 < \omega < 1.5$ rad/sec.). The transfer function from specific force to perceived tilt or lateral acceleration has a static sensitivity of 0.4.

Physical Properties of Labyrinthine Fluids at 35°C

	Human Endolymph	Human Perilymph	Cat Perilymph	Measurement Accuracies	H ₂ O
Specific Gravity	1.00	1.00	1.00	±2%	1.00
Coefficient of Expansion	$-4.4 \times 10^{-4} / ^\circ\text{C}$	$-4.4 \times 10^{-4} / ^\circ\text{C}$	$-4.4 \times 10^{-4} / ^\circ\text{C}$	±5%	$4.0 \times 10^{-4} / ^\circ\text{C}$
Viscosity (centipoise)	.852	.802	.780	±2%	.7225
Specific Viscosity	1.18	1.11	1.08		
Temperature Coefficient of Viscosity	-2.4%/°C	-2.3%/°C	-2.5%/°C	±10%	-2.0%/°C

Table 1

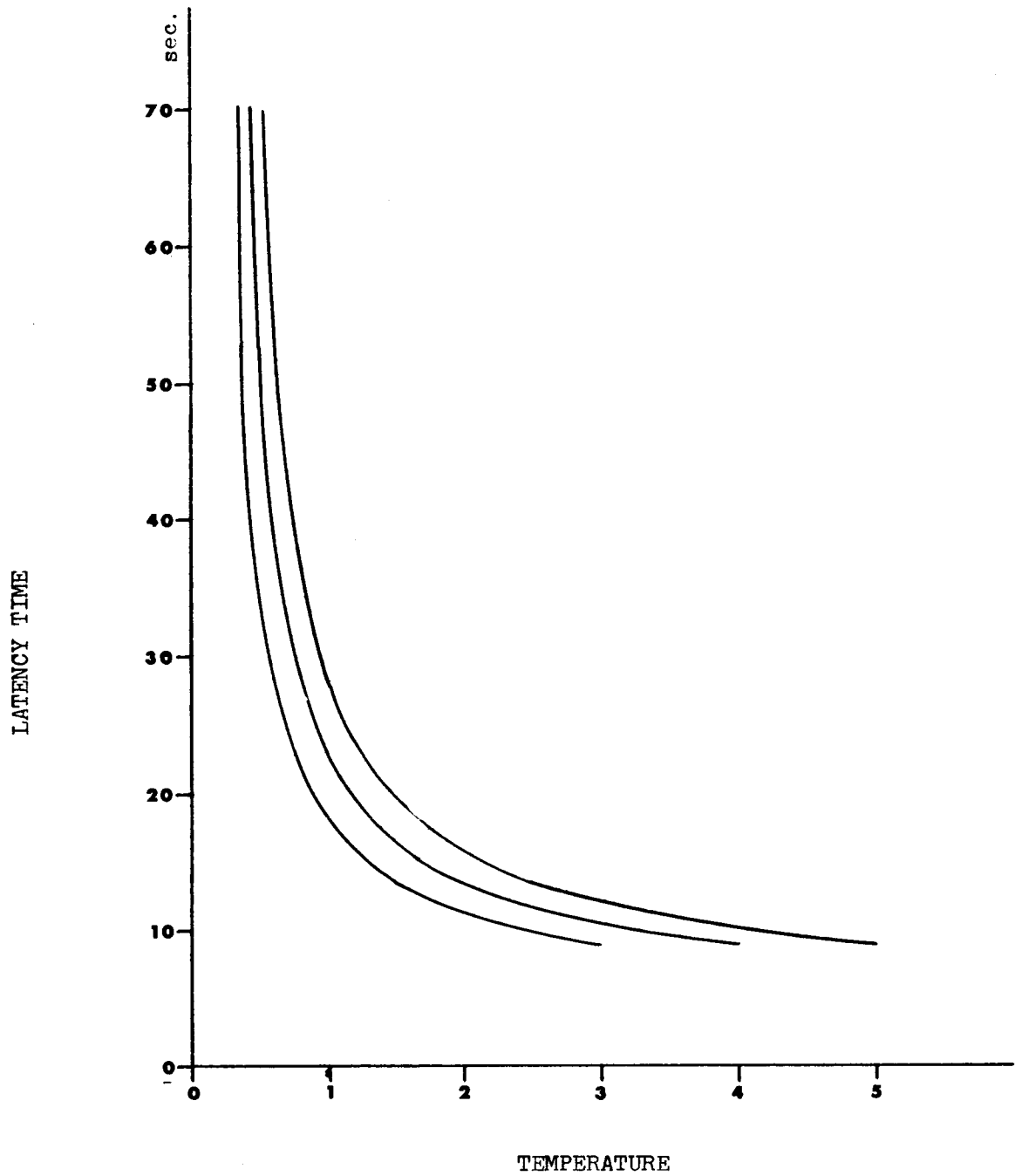
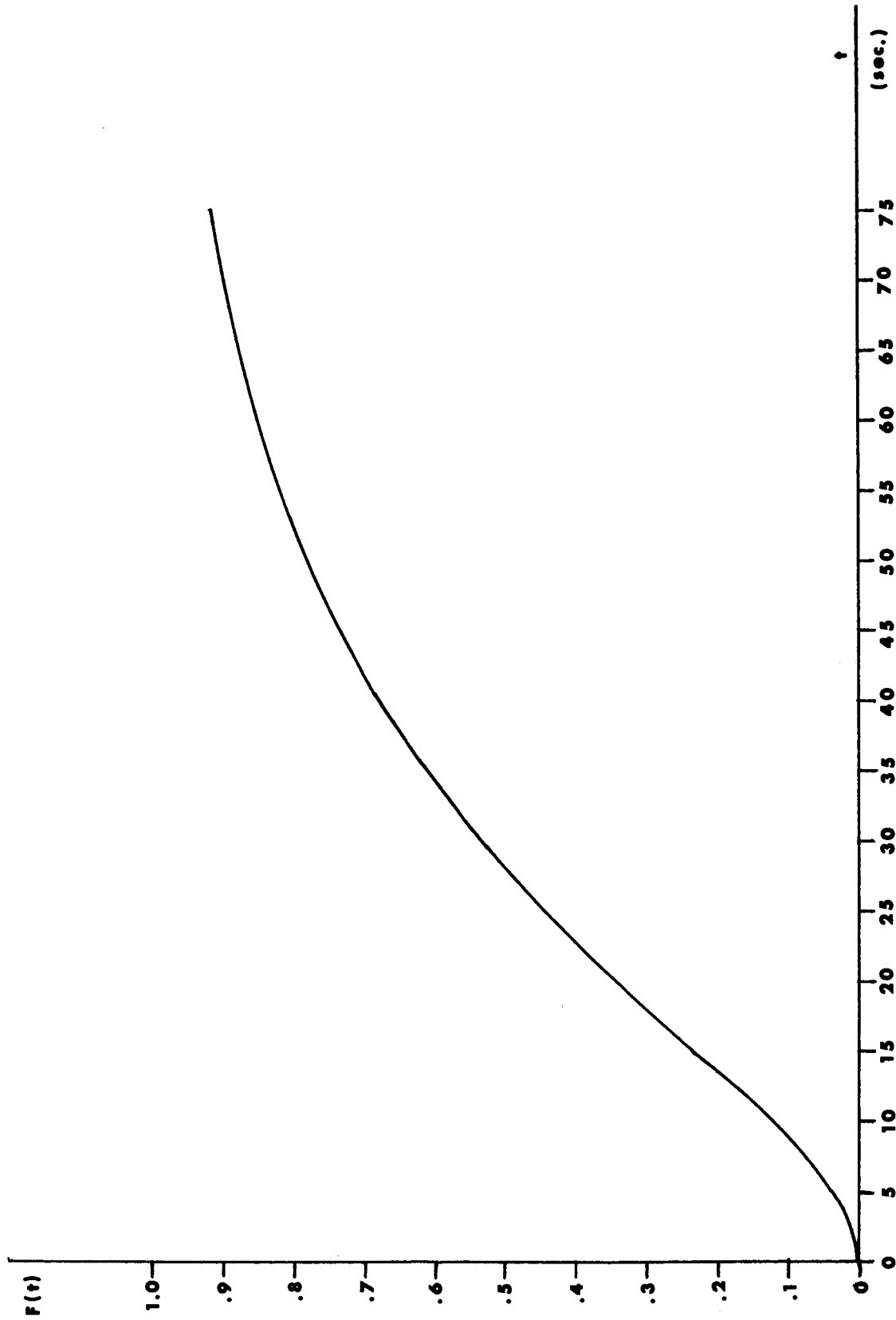


Figure 1
Calculated normalized cupular response ($f(t)$) as a function of time

PREDICTED LATENCY TIME



TEMPERATURE

Figure 2

Plot of $T_1 f(t) = C$ for several values of C

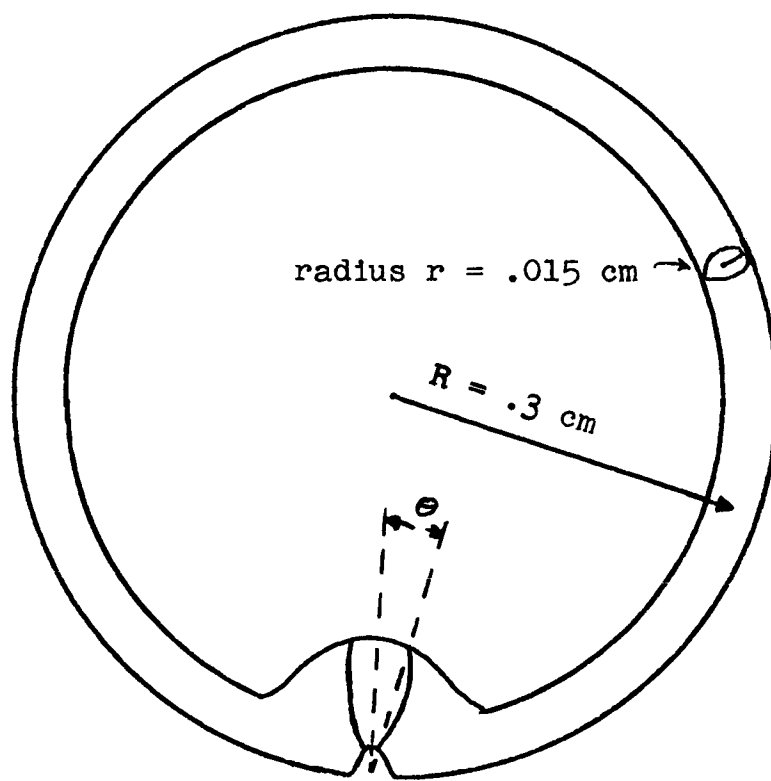


Figure 3
Simplified Rigid Model of
Semicircular Canal