BRIEF COMMUNICATION

IN VIVO MEASUREMENTS OF THE VISCOELASTICITY OF THE HUMAN VITREOUS HUMOR

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ABSTRACT A point source of light against a dark background is perceived by the human retina as a point image enhanced by off-axis points (rays if the source is polychromatic) of light scattered from objects along the optic axis. As a consequence of movement of the vitreous humor, scattering centers imbedded there impart to this scattering pattern a corresponding movement. A method has been devised to give the vitreous humor reproducible initial conditions and to record the observed relaxation of the scattering pattern to its new rest position. The vitreous humor is found to be overdamped, and the heretofore unreported shear elastic modulus has been determined. A striking gravitational effect is revealed by comparing observations along a horizontal optic axis with ones along a vertical optic axis. For the former, gravitational torque is found to dominate the elastic torque. The reason nature has developed a slow-responding gravitational sensor in the vitreous humor is not clear.

INTRODUCTION

Under certain easily obtainable conditions, it is possible to observe a damped oscillation in one's own vitreous humor. When a point source of light against a dark field is observed with the eyes wide open, relaxed and motionless, the point source is imaged by the retina, of course, but where the dark field should be imaged the retina is decorated with points of light of the same color as the source, or with prismatic rays if the point source is polychromatic. The sun attenuated by natural objects gives an impressive display of polychromatic rays. Stars seem not to be intense enough. A laser, adequately attenuated, may be used.

We all see these rays, normally first during childhood, and soon accustom ourselves either to ignore these decorations, or to block out the bright source of light with our hand if we wish to examine objects which otherwise would be partially or totally obscured.

It is easy to show and to understand that the light that strikes the retina around the image of a bright light source is light scattered from the materials in the eye and from its surface. Recently, the forward scattering has been measured in vitro with laser light (1, 2), and partially treated theoretically (3).

During observation of a scattering pattern, many persons can detect its tendency to move about, depending on previous head and eye movements, and it is this movement of the scattering pattern that allows for the first time the determination of the viscoelastic coefficients of the vitreous humor of the human eye in vivo.

BIOPHYS. J. © Biophysical Society · 0006-3495/80/03/539/06 $1.00
Volume 29 March 1980 539-544

We shall describe a method for reproducibly observing the relaxation of the vitreous humor after an initial rotational impulse and stress. Analysis reveals the viscoelastic coefficients as well as a surprising gravitational response by the vitreous humor.

METHOD

Fig. 1 is a schematic of the arrangement for observing a point source of light along a horizontal optic axis, or, with the addition of a mirror, along a vertical optic axis. We used a 1-mW He-Ne laser whose beam was diverged over a 3-m path to the observer by a 10-mm focal length telescope ocular. Potentiometer shafts are fixed to a yoke which constrains the observer's head to rotate around the optic axis, then stay stationary, and to a rotatable cross-hair which the observer can move with his hands to follow the observed rotation of his scattering pattern. Electrical signals are led from the potentiometers to a two-pen recorder with constant time sweep.

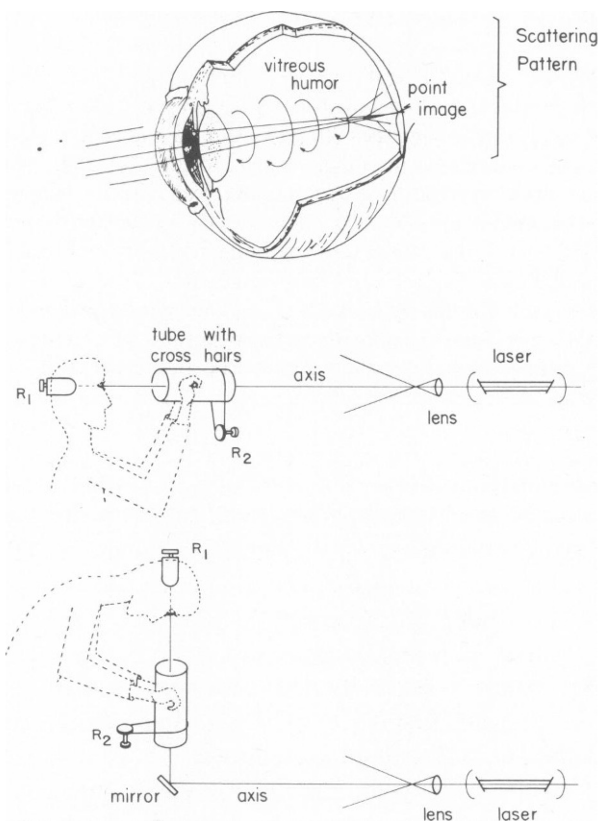

FIGURE 1 Arrangement for observing and recording the rotation of the scattering pattern after an initial impulse and stress given to the vitreous humor by a rotation of the head around an optic axis, either horizontal (above) or vertical (below). R_1 and R_2 are variable resistors that record the initial head rotation and the subsequent cross-hair rotation controlled by the observer in accordance with the rotation of his scattering pattern. The intensity of the laser is attenuated by a divergent lens and by distance. The inset indicates the damped rotation of the vitreous humor to its rest position. The interference of scattered light on the retina is schematized as scattered rays whose retinal image follows the rotation of the vitreous humor. The laboratory was partially illuminated such that no observer imagined a translation of the bright source.

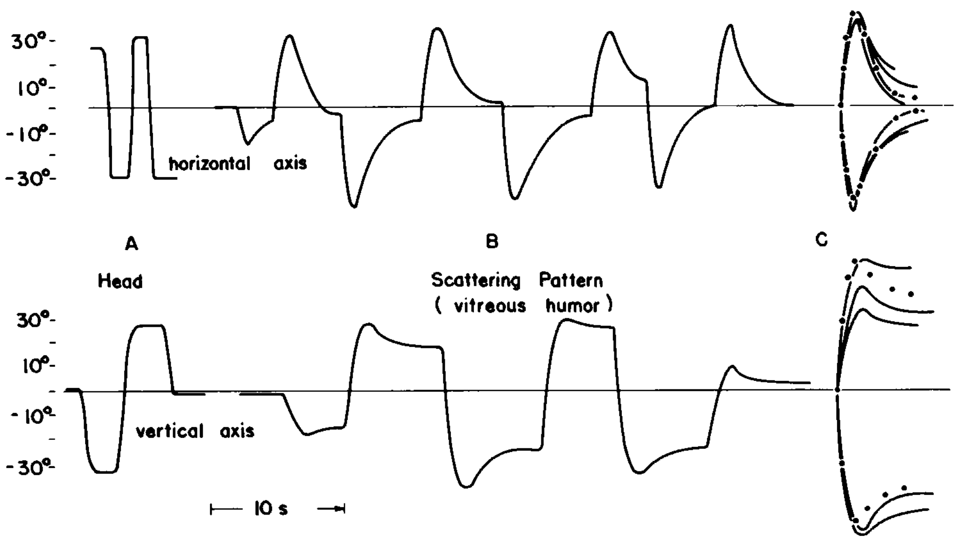

FIGURE 2 Typical data transferred from the recorder paper. Head motion was recorded simultaneously, but is shown schematically here at the left (*A*). The rotation of the vitreous humor (*B*) is shown for a horizontal optical axis (above) and for a vertical optic axis (below). For the latter, the vitreous humor rotation is not influenced by gravity and returns to rest positions determined only by the head position. At right (*C*) data are superposed to compare numerically (dots) with a damped oscillator (Eq. 2).

Since the scattering pattern recorded by the retina is a coherent sum of light scattered by objects in the illuminated cone whose base is near the cornea and whose apex is at the retina, part of the scattering pattern will follow the rotation of the vitreous humor in which the scattering centers are imbedded. Scattering from the cornea and lens will simply remain motionless as long as the head and eye remain motionless. Individuals for whom scattering from the vitreous humor is weak relative to that from the lens and cornea cannot collaborate in the present experiments. Young eyes more often scatter less light, but no obvious age trends in viscoelasticity were revealed by the present experiments.

Fig. 2 shows results for an individual observer transferred from the strip chart. Fig. 3 shows a composite of results from several observers. The movement of the scattering pattern invariably shows but

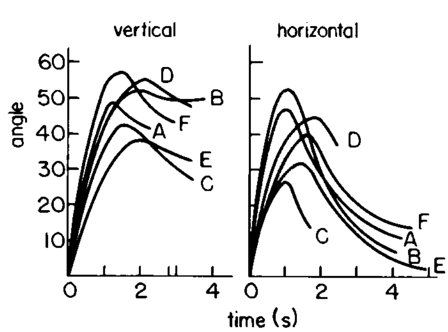

FIGURE 3 Variations of the observed rotations of scattering from the vitreous humor among different observers normalized to equal head rotations of 60°. From *A* to *F*, the ages of the observers are 18, 26, 28, 38, 47, and 50, respectively. Other observers, although unable to operate the apparatus, could verify the time from beginning to maximum rotations, and the overdamped nature of the relaxation. The essential features of the response of the vitreous humor to eye movements are independent of age and the viscoelastic parameters vary among individuals by less than a factor of two.

a single maximum in the rotation, and no variations among observers as great as a factor of two in the position of the maximum or in the subsequent decay constant. The movement resembles that of an overdamped oscillator starting with an initial velocity and an initial displacement. However, the data for a horizontal optic axis show that the vitreous humor returns after several seconds to a rest position only a few degrees different for head positions 30° each way from vertical. Evidently, the vitreous humor returns nearly to the same position relative to the vertical, not to the same position relative to the head.

To test this gravity effect, a second series of observations were made along a vertical optical axis, and the results are also shown in Fig. 2. The results show that the final rest positions of the vitreous humor more nearly follow the positions of the head. The remarkable difference between the rest positions of the scattering pattern for horizontal and vertical gaze can be explained by recognizing that the vitreous humor is resting in a position influenced by gravity.

One is led to model the vitreous humor as a torsional pendulum attached to the eye walls and supported in a viscoelastic medium. When the optic axis is horizontal, the angular displacement, θ, of a point in the vitreous humor relative to the head should follow the equation

$$I\ddot{\theta} + \Gamma\dot{\theta} + K\theta + mgl \sin(\theta + \phi) = 0, \qquad (1)$$

where m, I, Γ, and K are the mass, moment of inertia, damping constant, and elastic restoring constant of the vitreous humor, and ϕ is the angle of the head with the vertical. l is the distance between the axis of rotation and the center of mass of the vitreous humor. When the optic axis is vertical, gravity supplies no restoring torque around the optic axis, and the term with the gravitational constant g does not appear in the equation of motion.

If the damping term $\Gamma/2I$ is larger than the frequency $\sqrt{K/I}$, θ for vertical gaze may be written

$$\theta = Ae^{-(\Gamma/2I)t} \sinh(\beta t - \delta), \qquad (2)$$

where

$$\beta = \sqrt{\frac{\Gamma^2}{4I^2} - \frac{K}{I}},$$

which shows a single maximum rotation followed by a relaxation to a rest position, in agreement with the observation. For a vertical optic axis, the rest position is related simply to θ_0, the initial rotation of the head. For a horizontal optic axis, the final position of the scattered pattern is determined by the equilibrium between the gravitational torque and the elastic torque; that is

$$K\theta_0 = mgl \sin(\theta_0 + \phi). \qquad (3)$$

The observations shown in Fig. 2 show that the gravitational restoring torque mgl dominates the elastic restoring torque K when the optic axis is horizontal. The rotation θ around a horizontal optic axis follows from Eq. 1 and shows the same features as expression 2, which was used as an approximation for comparison of parameters.

Numerical analysis was simplified by establishing well-defined initial conditions. If the head is rotated through an initial angle θ_0 in a time Δt, short compared with the response time of the vitreous humor, the vitreous humor begins its movement with an initial displacement $-\theta_0$ relative to the head, now fixed, and with an initial velocity calculable from the impulse given the vitreous humor during the prior displacement of the head

$$\dot{\theta}_0 = \frac{1}{I}\int_{\Delta_0}^{0} (K\theta + \Gamma\dot{\theta})\mathrm{d}t \simeq -\frac{\Gamma}{I}\theta_0; \qquad (4)$$

that is, the impulse is supplied mainly by viscous coupling to the eye walls during Δt.

DISCUSSION

A numerical analysis yields the parameters in Table I. Points calculated from Eq. 2 with these parameters are shown together with the experimental data in Fig. 2.

The value of β, small compared with $\Gamma/2I$, shows that the eye is close to critical damping; that is $\sqrt{K/I} \simeq \Gamma/2I$. The numerical value of $\sqrt{K/I} = 1.1\ s^{-1}$ corresponds to a system with natural period (if it were undamped) of ~ 7 s, a remarkably long time for an approximately spherical object weighing but a few grams.

The value of 5° for $A\delta$ for a horizontal optic axis is a consequence of the dominance of the gravitational torque. The value of 40° for $A\delta$ for a vertical axis, rather than the 60° imposed by the initial rotation of the head, results because a scattering center in general is not at the center of the eye, where the fundamental torsion mode excited has its maximum amplitude, but along the optic axis where the rotation is less. The initial velocity of the scattering pattern is also about one half that expected from Eq. 4 for the same reason.

During and after rotation of the head around the optic axis, the eyeball itself makes a small rotation, immediately counter to the head rotation, later following the head rotation. This motion is consistent with a viscous drag by the vitreous humor on the passive eyeball within its socket. Later, as the vitreous humor moves in the direction of the head (Eq. 2), the eye also rotates to "catch up" with the head. This effect is independent of the axis being horizontal or vertical. Even if this effect is an involuntary action of the oblique extraocular muscles, as some authors state (4), the energy input to the vitreous humor is insufficient to modify the interpretation of the present experimental results.

It is possible to verify the relaxation time and overdamped nature of the vitreous humor by following the shadows of "floaters" (*muscae volitantes*) imbedded in the vitreous humor using a virtual point source of light close to the surface of the cornea to sharpen the shadows on the retina. However, it has proved to be difficult for observers to maintain their eyeballs fixed while moving an apparatus to document the rotations and translations of the shadows. (The present experiment is independent of translation of the scattering centers.) Nevertheless, White and Levatin (5) report interesting observations in a postoperative eye (following retina reattachment) and in some normal eyes of the size and motion of floaters. They even report a kind of gravitational effect having to do with the interaction of a detached part of the vitreous humor with a pocket of Newtonian liquid close to the fovea. No viscoelastic coefficients are reported.

TABLE I
NUMERICAL PARAMETERS OF EQ. 2 FOR THE ROTATION OF THE VITREOUS HUMOR AFTER THE INITIAL ROTATIONAL IMPULSE AND STRESS SHOWN IN FIG. 2

	Optic Axis (horizontal)	Optic axis (vertical)
δA	5°	40°
β	$0.03\ s^{-1}$	$0.002\ s^{-1}$
δ	0.001	0.001
$\Gamma/2I$	$1.1\ s^{-1}$	$1.1\ s^{-1}$

No measurements of the shear viscoelastic constants of the vitreous humor are reported in the literature. Bettelheim and Wang (6) have made measurements of the elastic compression modulus down to 3.5 Hz for bovine vitreous humor and report values of $\sim$45 dyn/cm^2 with a loss tangent <1, although it tends to increase with decreasing frequencies. Our result of $\sqrt{K/I} = 1.1\ s^{-1}$ corresponds to a torque constant of only $\sim$3 dyn-cm, and an elastic shear modulus of 0.5 dyn/cm^2. Both numbers are estimated by approximating the vitreous humor as a uniform sphere of specific density one and radius 1 cm in the fundamental torsional mode.

The parameters in Table I correspond to the relaxation of the fundamental torsional mode of the vitreous humor. The present experiments show the vitreous humor to have a significant density gradient; it is known to have large gradients in concentration of its nonaqueous constituents; thus it is very likely to have gradients in its viscoelastic constants as well. When these gradients all are known, a normal mode analysis of the vitreous humor will be possible. Our experiment is concerned only with the fundamental mode of oscillation. However, during observations, one is aware of higher frequency modes of oscillation (all overdamped) as well as much slower relaxations in the vitreous humor. Both will require other experimental techniques for investigation in vivo.

As far as we know, the fact that the vitreous humor rotates against elastic restoring torques in response to gravity (or to acceleration) has not been reported. The human vitreous humor is a slow-responding accelerometer and it is not clear what nature intended.

This research was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo, Conselho Nacional de Pesquisas (Brazil) (CNPq), Financiadora de Estudos e Projetos, and by the National Science Foundation-CNPq joint contract between Harvard University and Instituto de Física e Química de São Carlos.

Received for publication 18 July 1979 and in revised form 26 November 1979.

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