Deformation of the globe under high-speed impact: Its relation to contusion injuries

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Enucleated pig eyes in 10 per cent gelatin were submitted to nonperforating injury in order to record and measure the deformations of the eye and explain the mechanism of damage at the vitreous base. High-speed motion pictures and single flash high-speed photographs were used for this purpose. The general theory of the central impact of two bodies was correlated with previous and present experiments. Reconstruction of the motion was based on the constancy of the mass of the globe and on the experimental data obtained. This reconstruction was used to determine local accelerations of the ocular coats, distension of the walls, energetic balance and magnitude of the forces involved. A theory was proposed to explain the damage observed at the vitreous base.

Key words: vitreous base, photography, pigs, enucleation, mathematical analysis, eyeball contusion, lens capsule, ora serrata, pars plana ciliaris.

Damage to the peripheral retina and pars plana ciliaris from nonperforating trauma of the eye often results in retinal breaks along the border of the vitreous base: dialysis along the posterior border and linear breaks in the epithelium of the pars plana ciliaris along the anterior border.1 Weindenthal and Schepens2 duplicated these breaks by traumatizing enucleated pig eyes, mounted in gelatin, with an air rifle projectile. They demonstrated experimentally that equatorial expansion of the globe under impact is partially responsible for the damage. With Weindenthal's model we investigated, by high-speed photography and cinematography, the very rapid deformations of the globe caused by the projectile and the mechanism by which damage was produced to the ocular tissues.

Materials and methods

Eyes and molds. The pig eye was chosen by Weindenthal because of its similarity to the human eye in the area of the ora serrata and pars plana ciliaris. Pig eyes were enucleated and traumatized within 2 to 4 hours after the animal's death.

Each eye was mounted in a separate gelatin mold consisting of a 5 by 5 by 8 cm. container made with flat glass plates. The eye was suspended in the container by threads, and liquid 10 per cent gelatin at a temperature of 30° to 40° C. was poured in the container leaving the anterior part of the eye exposed (Fig. 1). The liquid gelatin was then allowed to gel.

In order to study the stretching of the ocular coats, fine black threads were sutured to the sclera and small knots made in it as reference points. Changes in the length of the globe's axis were measured with reference to the dimensions of the axes before impact.

Mounted in gelatin, the eyes had a pressure varying between 15 and 20 scale readings with a Schiötz tonometer. The normal reading in vivo was about 5 scale readings.* No attempt was made...
Globe deformation under high-speed impact

6. Steel BB
4. Contact Assembly
2. 10% Gelatin
3. Gun
5. Glass Mold
7. Magnesium Missile

Fig. 1. Enucleated pig eye mounted in 10 per cent gelatin in a glass mold. The muzzle of the air rifle with its contact assembly is shown to the right. The insert illustrates the two types of missiles used.

to normalize the intraocular pressure of the enucleated eyes. Fluid injected into the intraocular cavity might have escaped from the globe through the needle track during impact. Any method of increasing the pressure externally would have limited movements of the globe during impact. Since damage to ocular tissues, observed under these conditions, was similar to that observed when the globe was left in situ, it did not seem important to normalize the pressure.

Two human eyes were used which had been enucleated 12 and 24 hours before the experiment. The donor* was a 24-year-old woman whose eyes had been removed 4 hours after death from uremia.

Missiles. The ocular injury was produced by a specially modified air rifle† which fired a standard projectile called a BB (0.345 gr.) at an average speed of 69.3 M. per second (±2.5 per cent). This speed was selected to insure a nonpenetrating trauma of the cornea since it had been established that penetrating injury occurred at speeds higher than 72.0 M. per second. It was necessary to use a magnesium projectile, of greater length but identical speed and weight as the steel BB, to measure the depth of the corneal indentation during impact because this indentation was larger than the diameter of the BB (0.45 cm.). The density of steel is 7.8 and that of magnesium is 1.7 (Fig. 1). With either projectile, the same amount of kinetic energy was delivered to the eye (K.E. = ½ mv.² = 0.68 joule). The mold containing the eye was rigidly mounted at a distance of 2 to 3 cm. from the muzzle of the gun. This was necessary to insure alignment of the center of the cornea with the missile path. The disadvantage of this type of mounting was a small deformation of the cornea before impact due to the air blast.

Photographic recordings. Photographic recordings consisted of high-speed single flash photography and cinematography. In single flash high-speed photography‡ (Fig. 2), the object was illuminated during a very short time so that all motion seemed to have "stopped" on the photograph. The experiment took place in complete darkness. The camera, focused on the eye, was opened for one second during which the gun was fired. When the bullet left the gun, it closed momentarily a pair of electrical contacts consisting of 0.0015 inch steel blades. A resulting voltage pulse was sent through an adjustable delay line* to an electronic flash unit,† which produced a short but powerful flash of light. The exposure time was thus equal to the length of the light pulse (3 μsec), and the intensity of the flash was about 7 million beam candlepower. The light flash was intentionally produced between 0.1 and 10 μsec. after the voltage pulse depending on the phase of motion to be photographed. The delay was preset and measured for each exposure with a cathode ray oscilloscope. The use of direct development film with high sensitivity‡ made the procedure very versatile. This technique would have been inefficient if only one picture per eye could have been taken. The deformations of the globe under repetitive impact were so similar that no changes greater than the experimental error could be detected. This permitted the use of the same eye for repeated impacts and photographs. However, no measurements of eyes after the fifth impact were taken into account. Pictures of the undistorted eye were taken before and after a series of impacts. A total of 213 single flash pictures of pig eyes were taken.

With high-speed cinematography (Fig. 3) the object to be photographed was continuously illuminated, and the film was exposed during very short times by a fast shutter. The camera§ was driven by a motor at speeds between 5,000 and 9,000 frames per second. Some time was required before the film reached the desired speed, then the gun was fired by a pair of solenoids actuated by an event synchronizer inside the camera. A 60 cycle per second flashing light was incorporated into the camera, and its flashing was recorded on the film to permit the establishment of a time scale of events.

The high-speed negative films used were 100 feet long. Their relatively low sensitivity required powerful illumination by 3, 025 watt projectors.

*General Electric 1531-p2.
†General Electric 1531-A.
§Hycam. K1001, Red Lake Laboratories.
¶Polaroid Type 57 (5000 ASA black and white).
||Eastman Kodak Tri-X (ASA 400) and 4-X (ASA 443).
Fig. 2. Schematic illustration of the setup for single flash high-speed photography.

Fig. 3. Schematic illustration of the setup for high-speed cinematography.
This method was more informative than the single flash procedure since the complete event was recorded in one film strip. The picture quality, however, was inferior because of the lower sensitivity of the film and the longer exposure time (50 to 70 μsec instead of 3 μsec). Ten high-speed movies were taken of pig eyes and 2 of human eyes.

Other methods. Static indentation of the globe was performed with a known force by cylinder having a hemispherical end of the same diameter of the BB projectile (0.45 cm.). The resulting strain of the anteroposterior diameter was measured for each load.

The impact of a BB projectile was also applied on a rubber sphere filled with water. The sphere had an inside diameter of 25 mm. and a thickness of 1.7 mm. The deformations of the rubber sphere...
were recorded by a single flash technique. The sphere was mounted in air and attached by its posterior pole to a rigid wall. The existence of a shockwave was investigated by placing a small crystal pressure detector* at the posterior pole of the rubber ball and recording its electrical signal with an oscilloscope.

Results

Seventy-five pig eyes were traumatized in the center of the cornea. Most experiments recorded deformations of the sagittal plane. The structure of the ocular coats in the pig gave no indication that relative deformations would lack symmetry around the axis of the eye. Nevertheless, a few experiments were performed to investigate the deformation of the equatorial plane. Figs. 4 and 5 show examples of the recorded single flash pictures and frames of the high-speed movie films. Thirty eyes traumatized by single impact were placed in formalin fixative immediately after trauma. They were examined with the aid of a dissecting microscope a few days after fixation. The damage was qualitatively the same as that observed by Weidenthal and Schepens,* but the percentage of damaged eyes was smaller. Lower ocular pressure before the experiment and lower missile speed (62.3 M. per second instead of 65.4 M. per second) may account for the difference.

Interpretation of the photographic recordings. The anteroposterior and equatorial diameters of the eye were measured during deformation and expressed as a percentage of their original value. Results are presented in a graph (Fig. 6) as a function of time after impact. There was an error in measurement of the anteroposterior diameter caused by the different refractive indices, one part of the globe being in the air and the other in gelatin. This error was minimized by the fact that the angle subtended by the eye at the camera objective was small (4 degrees). Measurements of equatorial diameters were

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*Valpey Crystal Corporation.
made in pictures of the posterior pole* and showed no significant differences between the relative deformations of the apparent horizontal and vertical diameters.

The movement of the posterior pole was measured with reference to a fixed point in the mold and was expressed as a percentage of the original anteroposterior diameter. Measurements of the distance between the apparent equator and the posterior pole were also expressed as a percentage of the original anteroposterior diameter. The long oscillations of the eye in gelatin were measured with a frame by frame analysis of two high-speed films. Measurements of the anteroposterior and equatorial diameters of the 2 human eyes showed similar results. The complete phenomenon of the impact on the cornea could be divided into the following periods: compression, decompression, overshooting, and long-time oscillations.

Compression (between 0 and 0.25 msec.). The cornea does not present a marked resistance to the impacting bullet. Even the blast of the gun causes a small deformation before impact. A rapid expansion of the anterior sclera compensates for the volume decrease caused by the corneal indentation. The BB is stopped after about 0.25 msec. by the transient gradient of pressure developed by inertia of the tissues and liquids accelerated by the bullet, and by the tension in the cornea. At this moment, the globe’s anteroposterior diameter is reduced to 59 per cent of its original length, which corresponds to a corneal indentation of 8.5 mm. It is probable that during this period the posterior surface of the cornea comes in contact with the anterior surface of the lens.

Decompression (between 0.25 and 1.00 msec.). The eye acts as a tension spring and pushes the bullet out. The equatorial diameters continue their expansion until 0.40 msec. when they reach their greatest values, 128 per cent of their original length. Simultaneously the vitreous body starts to move posteriorly until the eye assumes a pear shape around 1.0 msec. At the same time the bullet leaves the eye with an average speed of 11.4 M. per second, 5.4 times less than the impacting speed.

Analysis of the recordings for this period of time shows a deformation wave traveling posteriorly on the sclera. This wave originates most probably at the limbus where it is generated by the sudden radial outward movement of the aqueous produced by the indentation. This phenomenon does not appear distinctly on all recordings but seems to be favored by a low ocular pressure which corresponds to a low tension in the ocular coats.

During this period the whole globe starts to move backward. No explanation can be given for the small irregularity in the curve showing the position of the posterior pole versus time (around 0.70 msec. in Fig. 6). This cannot be due to a "shockwave" traveling through the vitreous and applying a force on the posterior pole. In order to travel through the globe in 0.70 msec., its speed should be between 24 and 28 M. per second and a shockwave in water travels at 1,500 M. per second.

Overshooting (between 1.0 and 2.5 msec.). The anteroposterior diameter overshoots up to 112 per cent of its original length, whereas the equatorial diameter decreases, giving the globe an ellipsoid shape. It is clearly visible on the readings that the whole globe moves back as it recovers its normal 100 per cent anteroposterior diameter at about 1.15 msec.

Oscillations (from 2.5 to 100 msec.). Curve No. 3, Fig. 7 represents the oscillation of the posterior pole, which may be considered as the oscillation of the whole globe. Its frequency was estimated at 55 cycles per second. In addition to this oscillation, the fluids inside the eye oscillated, expanding periodically in the anteroposterior and equatorial directions, and this second oscillation is represented in curves No. 1 and No. 4. In these curves, the maximum anteroposterior elongation corresponds approximately to the minimum equatorial di-

*With the use of a 45 degree mirror so that the camera was not located in the axis of the gun.
Fig. 7. Graphic illustration of the change of the dimensions and position of the eye during the first 100 msec. Abscissa: time from impact in milliseconds. Ordinate: percentage of original equatorial or anteroposterior diameter, original diameter being equal to 100. Original position of posterior pole is at 0 and of anterior pole at 100. The changes represented in Fig. 8 are not reproduced here because of the different time scale.

Fig. 8. Graphic reconstruction of the changes in shape of the eye based upon a constant volume assumption. The shaded area represents the impacting BB. Phase 1: millisecond from the time of impact to 0.25 msec. Phase 2: millisecond from 0.25 msec. to 1.00 msec.
ameter. The frequency of this oscillation is about 90 cycles per second. The oscillation in gelatin (curve No. 3) stops after 50 msec., whereas the corneal oscillation is fully attenuated by 100 msec. (curves No. 2 and No. 4). Similar movements of the eye fluids were found by Tillett, Rose, and Herget in their study of perforating injury with a BB.

**Graphic reconstruction.** These experimental data and further analysis of the shape of the eye after impact made it possible to reconstruct graphically the phenomena resulting from the impact. Average dimensions, derived from measurement of 10 nontraumatized pig eyes after fixation, were used as original values (100 per cent) in this reconstruction. The volume of the globe was assumed to remain constant during its deformation. This assumption rests on the fact that during the whole event (about 100 msec.) no fluid could leave the eye by forced diffusion through its walls. The constant volume assumption was used to determine shapes that were not visible on the recordings. Fig. 8 shows the results obtained, all volumes being computed within 2 per cent of the original volume of 6.88 c.c. by graphical integration. A schematic representation of the changes in shape is illustrated in Fig. 9. With the help of this reconstruction it was possible to compute the relative length of the 12 o'clock meridian and the relative surface of the globe (Fig. 10). Elongations as high as 5 per cent were observed in the cornea and 3 per cent in the sclera at the equator.

**Static indentation.** The stress-strain relation of the anteroposterior diameter of the eye when indented by a 0.45 cm. diameter hemispheric surface is shown on Fig. 11 which represents the average of 4 measurements. Rupture of the cornea at the site of loading occurred with a load of approximately 11 kg.

**Discussion**

**Kinematics and dynamics of a central impact on the eye.** When a body having a mass M and a velocity V collides with a body at rest and having a mass M' it can be demonstrated that the energy T lost by the incident body during the impact is equal to:

\[
T = \frac{1}{2} \left( \frac{MM'}{M+M'} \right) (1 - g^2) V^2
\]

or

\[
T = \frac{1}{2} MV'^2 - \frac{1}{2} M'V_0^2 - \frac{1}{2} MV^2
\]

where

- \( V_0 \) = speed of \( M' \) after impact,
- \( V' \) = speed of \( M \) after impact,
- \( g \) = coefficient depending on the elastic properties of both bodies, \( g \) is often called coefficient of restitution since it is a measure of the energy loss. It is defined by:

\[
g = \frac{V_0 - V'}{V}
\]

When \( g = 0 \), the impact is said to be plastic and the 2 colliding bodies remain in contact after impact. When \( g = 1 \), the

*The velocities of the centers of both bodies are colinear.
impact is said to be perfectly elastic and there is no loss of energy.

If \( E \) is the kinetic energy of the impacting body, equation 1 becomes:

\[
\frac{T}{E} = (1 - g^2) \left( \frac{1}{1 + \frac{M}{M'}} \right)
\]

A graphic representation of this equation for various values of \( g \) is given in Fig. 12. It shows clearly that for the same kinetic energy of the impacting body the absorbed energy decreases with the speed. It is postulated that a certain damage is produced to the tissue by a certain amount of absorbed energy. This means that for a given kinetic energy, speed is the factor producing the damage. In other words, to produce equivalent damage, less energy is required with high speed and small mass missiles than with low speed and large mass missiles.

Available experimental evidence fits the curves of Fig. 12. Weidenthal and Schepps² made experiments with a relative mass, \( \frac{M}{M'} \) of 0.079 with high speed and with a relative mass of 51.33 with low speed. They observed no damage to the eye in the latter case.

The bullet, after impacting the eye with a speed of 62.3 M. per second (0.669 Kg.-M.), was pushed out at a speed of 11.4 M. per second (0.0224 Kg.-M.). Thus 96.7 per cent of the impacting energy was used by the system and dissipated in free oscillations, heat absorption due to friction, and damage to the structures of the eye.

Since the movement of the anterior pole of the eye was the same as that of the bullet (mass: 0.345 gr.) during impact, it was possible to estimate the force applied to the eye by the bullet. A graphic integration of this movement in Fig. 13 shows a maximum acceleration of the center of the cornea (80 x 10 M. per second per second) around 0.15 msec.
WEIDENTHAL & SCHEPENS
AND PRESENT STUDY

Fig. 12. Graphic representation of the relation between absorbed energy $T$ and relative mass of impacting bodies $\frac{M}{M'}$. The body in motion has a mass $M$ and kinetic energy $E$; the body at rest has a mass $M'$. Abscissa: relative mass $\frac{M}{M'}$. Ordinate: loss of energy expressed in percentage of total kinetic energy (percentage of $\frac{T}{E}$). Curves were made for various values of the coefficient of restitution $g$. The point representing experimental conditions studied by Weidenthal and Schepens, and by the present study are noted on the chart.

Fig. 13. Graphic representation of the displacement ($x$), speed ($v$), and acceleration ($y$). Displacement ($x$, thin line), speed ($v$, thick line), and acceleration ($y$, dashed line) of the anterior pole of the eye. Abscissa: time after impact, in milliseconds. Each number on the ordinate must be multiplied by $10^{-1}$ vms for $x$; by $10^3$ cm/sec for $v$; and by $10^7$ cm/sec$^2$ for $y$. 
The corresponding force $F$ is (action = reaction)

$$F = M \cdot Y = 276 \text{ newtons (28 Kg. force)} \tag{5}$$

where $M$ is the mass of the bullet (0.345 gr.) and $Y$ the acceleration. The graph in Fig. 13 assumes a central impact, with an acceleration which is always normal to the cornea and no tangential acceleration.

Similar computations were performed to investigate the acceleration of different points of the eye. Both tangential and normal accelerations of the sclera were found to be greatest in the area corresponding to the zone of damage to intraocular structures. The meridional distension of the sclera was also maximal in this area. This would cause sheering forces between the ocular coats if their moduli of elasticity were different.

**Theory explaining the damage observed.**

It was initially thought that damage at the vitreous base occurred when the lens was pushed anteriorly, because of the forced mass movement caused by wall deformation. The same theory, called the return-shock theory, was mentioned by Frenkel to explain rupture of the zonules as a result of blunt trauma. Our experiments, however, do not support this view. When the lens was pushed anteriorly (between 0.70 and 2.5 msec.) the anterior part of the eye was relatively contracted because the fluid had accumulated in the posterior segment. At that moment the vitreous base was not tugging on the choroid and retina. In fact, distance measurements computed from the recorded shape of the eye, at that stage, even show that the vitreous base was probably in a relaxed state during this period.

Because of the viscosity and inertia of the fluids in the ocular cavity it is possible that negative pressures could be responsible for some of the damage. Along this line a theory of formation and sudden collapse of cavities has been propounded to explain brain damage by an impact on
Table I. Deformation of the globe under high-speed impact

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<th>Variations of the distance:</th>
<th>Posterior pole of the lens—vitreous base</th>
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<tr>
<td>Time (msec.)</td>
<td>Percentage of distance before impact</td>
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The greatest traction on the vitreous base occurred around 0.40 msec. The damage at the vitreous base reported by Weidenthal and Schepens and observed in this study strongly indicates severe traction on the vitreous base following impact. The vitreous body is firmly attached to the retina and epithelium of the pars plana ciliaris in the region of the ora serrata and to the posterior lens capsule. Between 0 and 0.40 msec, after impact the lens is pushed posteriorly at the same time as the envelope of the globe overlying the vitreous base is pushed in a centrifugal direction. It is at 0.40 msec, after impact that the perimeter of this part of the globe is largest (Fig. 8). At that time, therefore, the distance between vitreous base and posterior pole of the lens is increased. The variation of this distance during the total event was computed graphically (Fig. 14). It turns out that at 0.40 msec, the above mentioned distance is greatest with 128 per cent of its initial value (Table I). At that time, the intraocular pressure, in the area of the vitreous base, is markedly increased and exerts a force in a direction which is opposite to that of traction on the base. As the zonule and lens capsule are distensible, traction on the suspensory ligament and the lens itself causes less damage than traction acting directly on the vitreous base which is less distensible.

The greatest shearing forces in the retina are located along the posterior border of the vitreous base, which explains why damage occurred frequently in this region. The retina is pushed against the choroid by increased intraocular pressure, but this force is overcome by the strong pull exerted on the vitreous base. These conditions are aggravated by the fact that the ocular coats, including the retina, are distended during that particular phase of the impact.

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REFERENCES