

## High Rate Internal Pressurization of the Human Eye to Determine Dynamic Material Properties

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*This paper has not been screened for accuracy nor refereed by any body of scientific peers  
and should not be referenced in the open literature.*

### ABSTRACT

*Over 1.9 million people suffer from eye injuries in the United States each year, occurring mainly from automobile accidents, sports related impacts, and military combat. A common injury prediction tool used for eye injuries is computational modeling, which requires accurate material properties to produce reliable results. The purpose of this study is to create a high rate pressurization system to analyze the rupture pressure of human eyes and to determine the dynamic material properties of human sclera. A high rate pressurization system was used to create a dynamic pressure event to the point of rupture in 12 human eyes. The internal pressure was dynamically induced into the eye with a drop tower while the rupture pressure was measured with a small pressure sensor inserted through the optic nerve. Measurements were obtained for the diameter of the globe, the thickness, and the changing coordinates of the optical markers. A relationship between true stress and true strain was determined for each test specimen in the equatorial and meridional direction to show any directional effects. It was found that the average rupture stress was  $13886 \pm 4807$  kPa, the average maximum true strain in the equatorial direction was  $0.041 \pm 0.014$ , and the average maximum true strain in the meridional direction was  $0.058 \pm 0.018$ . It was also found that the average rupture pressure for the human eye was  $836 \pm 130$  kPa. In comparing these data with previous studies, it is concluded that the loading rate directly affects the rupture pressure and that the human eye is both anisotropic and viscoelastic.*

### INTRODUCTION

Over 1.9 million people suffer from eye injuries in the United States each year, occurring mainly from automobile accidents, sports related impacts, military combat and other accidents (McGwin et al., 2005; Kennedy et al., 2007). As a result of trauma, approximately 30,000 people become blind in one eye every year in the United States (Parver, 1986). Determining material properties will provide needed information for establishing injury criteria for the human eye. One of the most versatile ways to analyze these injuries is through computer modeling. Several ocular computer models have been created, but most have been designed to study corrective eye surgery and are only accurate for static solutions (Hanna et al., 1989;

Sawusch and McDonnell, 1992; Wray et al., 1994; Bryant and McDonnell, 1996). A few models have been used for dynamic events, with the most up to date and accurate model being the Virginia Tech Eye Model (VTEM), created by Stitzel (Stitzel et al., 2002). Previously, uniaxial tensile strip tests were performed on the sclera and cornea for the first dynamic computer model presented by Kisielewicz and Uchio (Kisielewicz et al, 1998; Uchio et al., 1999). Because the human eye is an anisotropic viscoelastic material, the material properties must be determined at a higher rate to produce more accurate results. Uchio found peak rupture stress using static material properties to be 9.40 MPa, whereas the VTEM, with more realistic dynamic modeling, found peak rupture stress to be 23.00 MPa (Uchio et al., 1999; Stitzel et al., 2002). Unfortunately, all existing models lack accurate material properties of the ocular globe. Therefore the purpose of this study is to determine dynamic material properties for the human sclera.

## METHODS

Material properties were determined by inducing a high rate internal pressure into the eye to measure rupture pressure, stress, and strain. High rate pressurization was accomplished with a hydraulic system that utilized a drop tower to pressurize the human eye in a dynamic event (Figure 1). To initiate the event, a weight was dropped onto a piston which was inserted into the hydraulic cylinder. Preparation of the system included adding water through the cylinder to act as the medium for pressurization and to produce an approximate initial intraocular pressure of 1.99 kPa. Connecting the eye to the system was a 16-gage intravenous needle inserted into the optic nerve. In order to secure the optic nerve to the needle, a medical suture was used while a cylindrical placement guide held the eye in place. To ensure that the optic nerve was sealed, it was covered with a flexible coupling material and then secured with a plastic fastener. Each human eye was stamped with 5 optical markers to provide a method for measuring strain (Figure 2). High speed video was taken at 10,000 frames/sec with a resolution of 512 x 512 to determine the strain and to confirm the location of the rupture. Internal eye pressure measurements for the rupture tests were collected at 30 kHz.

In order to acquire the internal eye pressure, an in situ pressure sensor was utilized. In this test series, the pressure was measured from a small pressure sensor made by Precision Measurement Company (Model 060, Ann Arbor, MI) that was inserted into the eye through the optic nerve. The pressure transducer was rated for a range of 0-3.45 MPa which was more than adequate for our expected pressure results and had a frequency response in excess of 10 kHz. Because the diameter was also changing with time due to the expansion, motion analysis software was used to measure the movement of the diameter during the test (TEMA, Image Systems, Sweden).

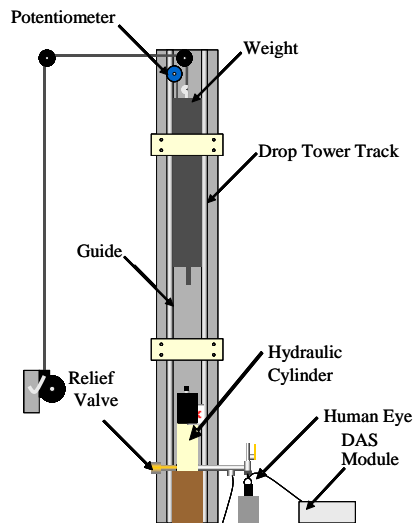


Figure 1: Schematic of the high rate pressurization system used to determine material properties.

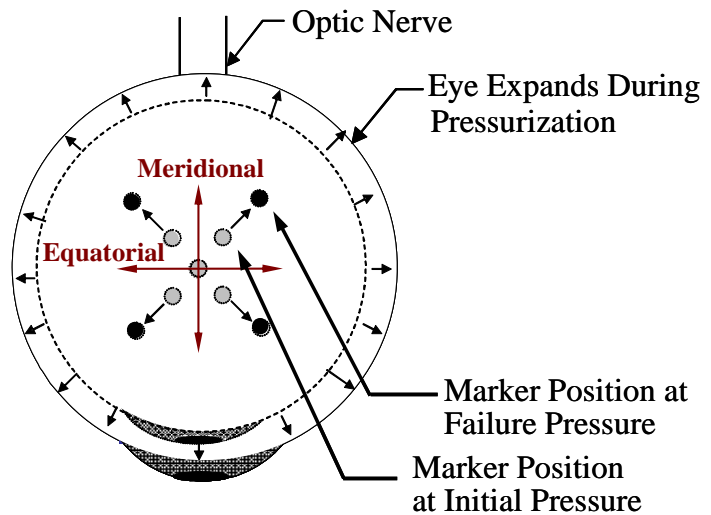


Figure 2: The expansion of a human eye shown with optical markers.

Each specimen was examined with a high accuracy laser to determine the thickness of the sclera after testing. The eyes were sectioned at the optical marker location and kept in saline solution during the test procedure. Measurements were taken with a Microtrak II high speed laser with accuracy of 2.5 micrometers. This method reduced the effect of swelling.

True stress was then calculated using the internal pressure (P), along with the outer radius (R) and the thickness (T) (Equation 1). Assuming that the eye is a spherical pressure vessel, Equation 1 was used to calculate the true stress. A relationship was derived to relate the radius and the thickness, where  $R_2$  was the outer radius,  $R_1$  was the original outer radius, and  $r_1$  was the original inner radius. Assuming that the sclera is incompressible, the thickness for each change in the radius was found and used in Equation 1 to find the true stress (Equation 2).

$$\sigma_T = \frac{P(t) \cdot R(t)}{2 \cdot T(r)} \quad (\text{eq.1})$$

$$T = R_2 - \sqrt[3]{R_2^3 + r_1^3 - R_1^3} \quad (\text{eq.2})$$

Strain of the eye was determined from the high speed video of the events. Motion analysis software was used to track the location of each of the 5 optical markers at each point in time. These data were then analyzed using an original MATLAB code to calculate the true strain in both the equatorial and meridional direction. Groups of two optical markers and the origin were created to start the calculation. The deformation gradient tensor (F) for each group was then determined by analyzing the position vectors (Equation 3), where x and y were the original positions of the markers and X and Y were the deformed positions of the markers. The Logarithmic (true) strain tensor (E) was found using Equation 4. Using true strain reflects the non-linearity of the human eye and is consistent with the stress and strain formulation used in computational models. A relationship between true stress and true strain was found for each direction using a characteristic average and the corresponding standard deviations. A statistical analysis was performed using a student T-test to determine the significance between the strain results for the equatorial and meridional directions.

$$F = \left( \begin{bmatrix} X_1 & X_2 \\ Y_1 & Y_2 \end{bmatrix}_{t=1} \right) \left( \begin{bmatrix} x_1 & x_2 \\ y_1 & y_2 \end{bmatrix}_{t=0} \right)^{-1} \quad (\text{eq.3})$$

$$E = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} = \ln \sqrt{F \cdot F^T} \quad (\text{eq.4})$$

In this study, 12 human eyes were procured and kept in a saline solution in glass jars and refrigerated for no longer than 15 days before they were tested, similar to previous studies. As stated in previous literature, the time after death prior to testing does not correlate to the degradation of the corneo-scleral shell with an  $R^2$  value of 0.14 (Kennedy et al., 2004). A statistical analysis was done using a student T-test to determine the significance of the differences between the current study and previous rupture pressure studies.

## RESULTS

The high rate pressurization of 12 human eyes resulted in a mean rupture pressure of  $836 \pm 130$  kPa (Table 1). The time to rupture was measured and resulted in a mean of  $30.78 \pm 6.87$  ms. The dynamic loading rate ranged from 216.47 kPa/s to 694.66 kPa/s with an average loading rate of  $470.55 \pm 175.61$  kPa/s. The strain for the equatorial direction ranged from 0.0193 to 0.0673 and for the meridional direction ranged from 0.0262 to 0.0908. In comparison, the meridional direction showed a significant difference in strain when compared to the equatorial direction ( $p=0.02$ ) (Figure 3). The true stress for the twelve tested eyes

resulted in a range from 6839 kPa to 20374 kPa (Table 1). The stress-strain relationships determined using the above methods show that the general trends for both directions are similar but demonstrate significant directional effects relative to strain ( $p=0.02$ ). The characteristic averages for both directions show the directional effects (Figure 3).

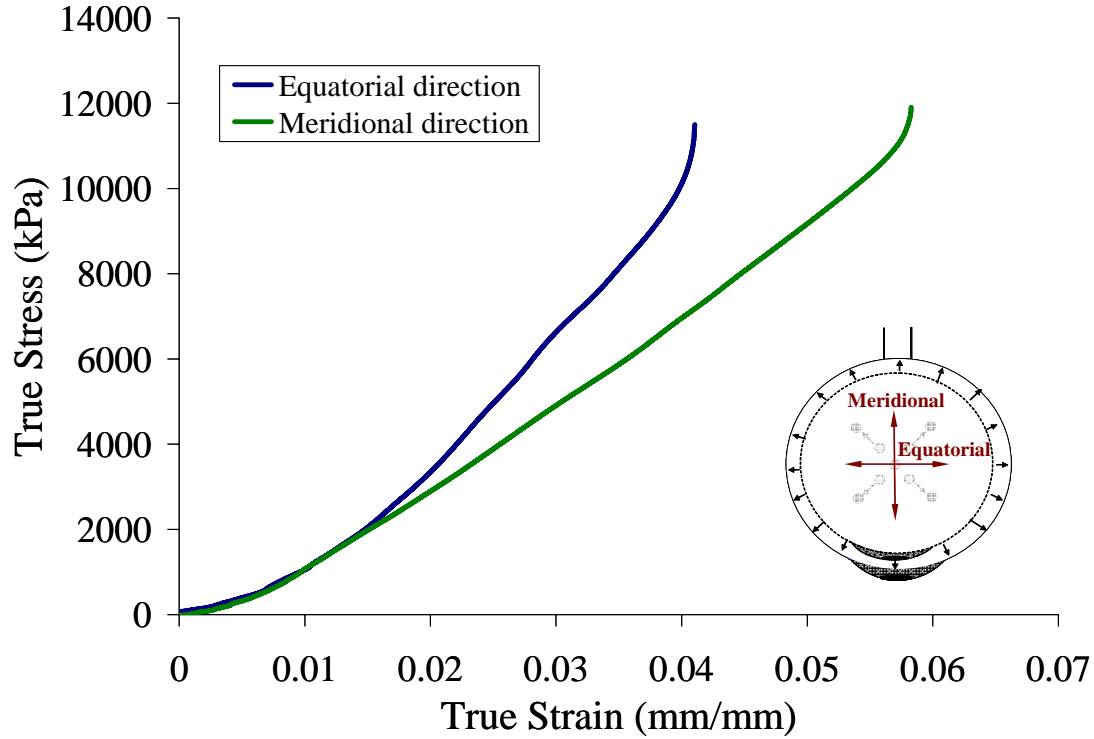


Figure 3: Stress-strain response for the equatorial and meridional directions represented by a characteristic average.

Table 1. Rupture pressure and true stress and true strain results for 12 human eye tests.

Test	Rupture Pressure (kPa)	Time to Rupture (ms)	Thickness (mm)	Maximum Equatorial Strain	Maximum Meridional Strain	Maximum Stress (kPa)	Rupture Direction	Rupture Location
1	695.97	21.23	0.46	0.027	0.059	12150.27	equatorial	equator
2	801.04	23.80	0.56	0.030	0.042	12625.56	equatorial	equator
3	708.91	26.13	0.81	0.027	0.067	6839.00	equatorial	equator
4	778.13	28.07	0.59	0.038	0.091	10307.18	equatorial	equator
5	909.52	28.67	0.47	0.034	0.072	17025.48	equatorial	equator
6	963.02	28.77	0.51	0.051	0.051	15157.01	meridional	equator
7	1009.31	29.33	0.62	0.067	0.070	20374.41	equatorial	equator
8	979.84	29.77	0.44	0.058	0.038	20202.72	equatorial	equator
9	944.46	31.47	0.54	0.040	0.071	18157.50	equatorial	equator
10	884.40	37.33	0.85	0.019	0.049	8080.93	equatorial	equator
11	760.19	38.97	0.49	0.052	0.064	17299.91	equatorial	equator
12	603.38	45.87	0.57	0.048	0.026	8410.23	equatorial	equator
Average	836.51	30.78	0.58	0.041	0.058	13885.85		
Standard Deviation	130.23	6.87	0.13	0.014	0.018	4806.48		

Previous material property studies have been performed on the eye but none with the entire globe present (Battaglioli and Kamm, 1984; Ahearne et al., 2007). Ahearne used an indentation technique to characterize the material properties for human and porcine corneas (Ahearne et al., 2007). Battaglioli tested the compressive properties of sclera after bisecting the equator and removing the lens, iris, and choroid (Battaglioli and Kamm, 1984). These material properties represent not only a section of the eye rather than the entire globe, but also a static analysis rather than high rate.

For this study, the primary limitation in the stress calculation was the measurement of the thickness. Thickness measurements were taken using a laser, but even with this precise instrument, variability is still present. With the use of true stress the thickness is more accurately represented. However, because the thickness varies across the eye it still can only be approximated. When determining the Green-Lagrangian strain of the human eye, the driving limitation was the accuracy with which the software tracked the optical markers. The change in the coordinates during a static event was divided by the total change in location throughout the dynamic event to find the percent error in the software. The average tracking error for the strain calculations was found to be 0.54%. Another consideration lies within the difference between a two dimensional strain calculation and a three dimensional calculation. The optical markers were created from a stamp to ensure that they were no more than 3.81 mm apart which produced an average error of 1.23% when using the two dimensional calculation. Although the previous ocular material property studies were conducted on sections of eyes rather than the entire globe, the strain results from the current study are consistent with previous results (Yamada and Evans, 1970; Battaglioli and Kamm, 1984; Uchio et al., 1999).

## **CONCLUSIONS**

This study used a high rate pressurization system and motion analysis software to determine the dynamic material properties of the human sclera and the rupture pressure for the human eye. Measurements of internal eye pressure, thickness, diameter, and optical marker location were found and used to calculate true stress and true strain for each specimen. A relationship between stress and strain was found along with the rupture pressure for each of the 12 human eyes tested. Results show a significant difference in the maximum strain between the equatorial and meridional directions ( $p=0.02$ ), while still maintaining a similar trend. Stress, strain, and rupture pressure values from the current study are consistent with previous trends, which conclude that the human eye is both anisotropic and viscoelastic. This study presents dynamic material properties of the human sclera and a mean globe rupture pressure that can be used for establishing injury criteria to help prevent eye injuries in the future.

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## DISCUSSION

PAPER: **High Rate Internal Pressurization of the Human Eye to Determine Dynamic Material Properties**

PRESENTER: ***Jill Bisplinghoff, Virginia Tech - Wake Forest University Center for Injury Biomechanics***

QUESTION: *Erik Takhoumts, NHTSA*

Why didn't you calculate true stresses and strains using the Finite Element model? You could use a Finite Element model of the eye to backup true stresses and true strains.

ANSWER: For the model, there were different material properties used, so we wanted to find dynamic material properties to then put into the computational model to improve it.

Q: But you still have to calculate true stresses and true strains based on certain assumptions that you give analytically in closed-form solutions.

A: Right, and our results are true stress and true strain.

Q: You could have done the same thing from using Finite Element analysis. You could back them up automatically.

A: Okay.

Q: *Guy Nusholtz, Daimler Chrysler*

Two questions that are connected: Why did you think there would be a difference in the pressures in two locations in the eye? You tested for it, but why did you think you would need to test for it?

A: Because it was a high-rate test, we wanted to make sure that because of the way the needle was inserted into the optic nerve, that there wasn't any sort of pressure difference between where the needle was and the jet of the stream. We just wanted to make sure that there is no difference within the eye.

Q: The difference should be related to the speed of sound through the eye. So unless there's a void—So you didn't suspect that there was a void there? That's why you were testing pressure? The other thing is: Do you have a mechanism for why it's strain-rate-dependent? Is it an inertial effect or is it a material property type of effect? Or, is it something else that I haven't mentioned? You look confused.

A: I'm not sure.

Q: You're not sure? Okay. So you know there's a strain in the effect, but you don't understand why. Okay. Thank you.

Q: *Costin Untaroiu, University of Virginia*

Nice study, very nice data. Two questions: I don't know. I am not specialized in the eye, but you assume that the thickness is constant, right? You have a sphere, right?

A: Yes.

Q: And you consider that the thickness of that shell around is constant, right?

A: Correct.

Q: There is some data from literature where it's that constant or not?

A: For this study, we feel like assuming that it's a spherical pressure vessel is a good assumption and something that's needed to find the stress in this case.

Q: Okay. Another question: You measure strain from 2-D.

A: Yes.

Q: But actually, you have 3-D.

**A:** Correct.

**Q:** Did you try computational—a simple—You take a sphere and take some points and measure from 2-D and 3-D how much is the difference because it's not 2-D, your sphere.

**A:** Right. We did look at a calculation. We made sure that the five optical markers were close enough together to reduce that error to 1%. So we did look at that.

**Q:** And you have 1%?

**A:** Yes.

**Q:** Okay. Thank you.