Optical Properties of a Radially Tensioned Liquid-Filled Flexible Lens.

Andrew H. Rawicz, John D. Jones,
rawicz@sfu.ca, jones@sfu.ca,
School of Engineering Science,
Simon Fraser University,
Burnaby, BC, CANADA V5A 1S6

Abstract

The focal length of the lens of the mammalian eye is adjusted (accommodated) by changing the lens curvature due to radial stretching by means of ciliary muscles. Some types of damage to the eye, resulting from trauma, disease or ageing (e.g. cataract), can render the lens unserviceable while leaving the ciliary muscle intact. This opens the possibility of designing a replacement lens, the focal length of which is controlled by the tension in the ciliary muscles. Two different lens modeling approaches were derived expressing the shape of such a lens as a function of the properties of the lens materials and applied radial tension (displacement). Ray tracing is then used to correlate lens shape variability with the changes of its focal length. Several variable focus-lenses were fabricated and experimentally evaluated to prove model predictions. A good agreement is reached.

Index terms

Variable focus elastic lens, radial tensioning.

1. Introduction

Helmholtz has shown [1] that accommodation occurs in the mammalian eye as a result of radial tensioning applied to the circumference of the lens by the ciliary muscle *via* the zonules. The control of focal length by radial tensioning has been investigated experimentally for porcine crystalline lenses and silicone gel lenses by Ehrman *et al.* [2]. However, proper optical transparency has not been obtained.
An alternative to both the natural lens and the molded silicone gel lens is the variable-focus liquid-filled lens proposed by Wright [3]. Prior researchers such as [4, 5, 6, and 7] and more recently [8, 9, and 10] have concentrated on controlling the focal length of this lens via control of its internal liquid pressure. In the present work , we investigate focal length control via radial tension. The motivation is to develop a lens which may replace damaged natural lens in human eye.

This application imposes several conditions on the lens design. One is optical properties which must be similar to the lens in human eye, among them high light transmission in visible range, focal variability range and moderate amount of aberrations. If ciliary muscles are to control the accommodation, mechanical properties (elasticity range, Young's modulus) must be the same as of the natural lens. Besides, there are requirements for dimensional compatibility, biocompatibility, high resistance to fatiguing and generally high reliability. This work concentrates on optical and some mechanical properties of the liquid-filled variable-focus radially-tensioned lens.

2. Fabrication process

A preferred design of the lens for the described application is as shown in Figure 1.
Elastic flange is created by circular bonding of two membranes separated in the middle by refractive liquid. The role of the flange is twofold; stress in the membrane caused by radial stretching force is uniformly distributed and radial force can be safely attached.

2.1. Material selection for the lens-membrane:
Since ultimately this lens would be used as a replacement for a natural lens, materials used to make the lens' membrane should have several required attributes and mechanical/optical characteristics. They are as follows:

- High light transmittance in the visible spectrum;
- Relatively high elasticity and elasticity range but low Young's modulus – ciliary muscles must be able to control stretching the membrane

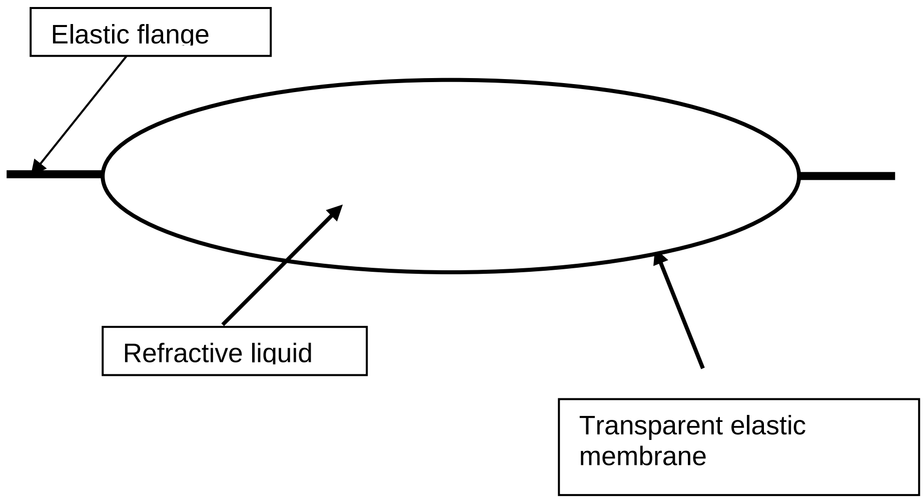

Figure 1. Cross-sectional view of the proposed lens

- Biocompatibility and non-permeability;
- Bond ability either through welding or gluing with the bonded zone retaining elasticity;
- High resistance to fatigue related failures.

From our earlier experiments [5] and from CRC Material tables we were able to eliminate most of considered materials finally retaining Latex. . Samples of thin Latex were cut from non-lubricated condoms Trojan™

For optical characterization of the fabricated lenses we have chosen sugar solution in water mainly for its easy controlled RI.

Test procedures and set-ups were designed to test the characteristics and functionality of fabricated lenses. The testing system involved a lens stretching mechanism, some basic optic apparatus to form an image through the lens, and an imaging system to capture the picture for processing

Mathematical model.

To describe the shape of variable-focus lens and its changes in radial tension we first adapted mathematical model proposed in [5]. The original model described curvature changes in an elastic circular membrane with fixed rim. The pressure was exerted on one side of the membrane by pumping refractive liquid between a flat glass window and the membrane. The curvature of the membrane was controlled by the liquid pressure.

The equation describing cross-sectional shape of created this way lens is described by:

$$\mathbf{Y(x) = (p/4T)(a^2 - x^2),} \quad \mathbf{1}$$

Where, **p** is liquid pressure, **T** is the membrane tension, **a** is lens radius, and **x** is a distance from optical axes (rotational symmetry axes) of the variable lens. In [5] **a** was fixed, which caused that numerical solution had to be sought to the model equations. In the case of radially tensioned lenses we noticed that the lens volume remains constant due to incompressibility of liquid

$$\mathbf{V = 2\Pi \int_o^a xY(x)dx = \Pi\, p/8Ta^4 = const = V_o,} \quad \mathbf{2.}$$

The multiplier “2” is used to reflect the fact that the lens is bi-convex.

This condition simplified notation in a manner allowing for analytic solution.

From formula 2. we find that

$$\mathbf{p/T = (8V_o/\Pi)\, a^{-4}} \quad \mathbf{3}$$

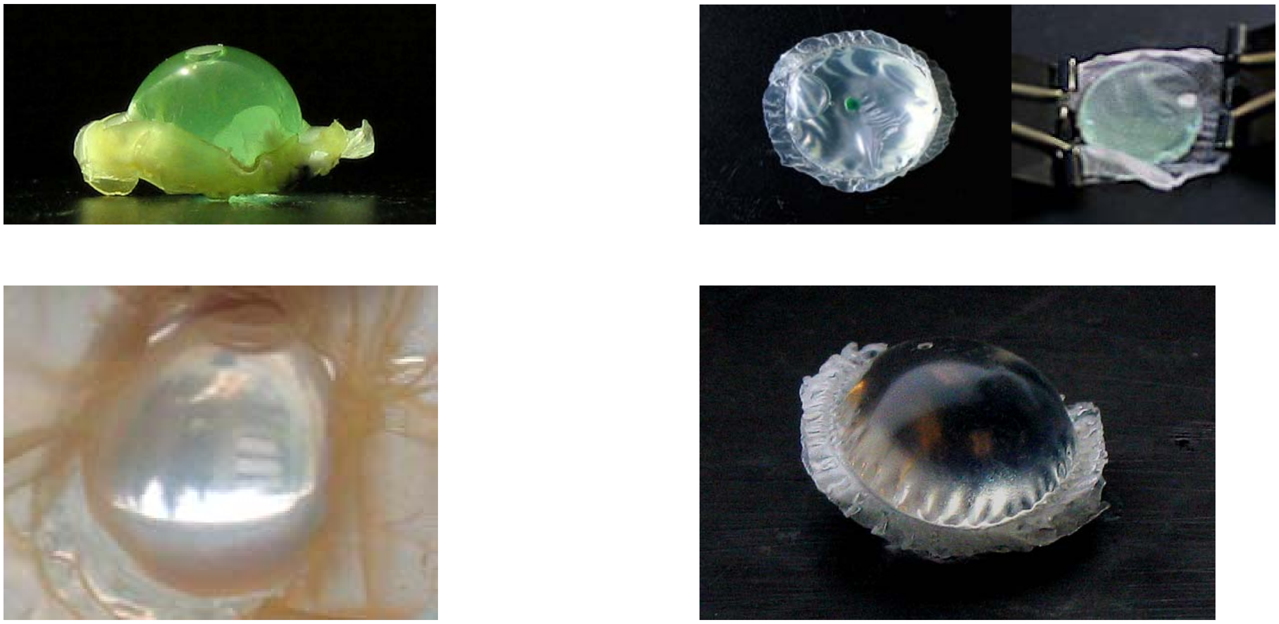

Figure 2. Some of the fabricated lenses.

After substituting 3. to 1. we obtain shape formula with lower number of unknown parameters:

$$Y(x) = 2V_0(a^2 - x^2)/\Pi a^4, \qquad 4.$$

Now we calculate the radius of the lens curvature using the formula:

$$R(x) = [1 + (dy/dx)^2]^{3/2}/(d^2y/dx^2),$$

and using Ray Tracing we determine focal lengths of the lens for different **a** values.

V_o was determined to be 0.215 cm^3 , thickness of un-tensioned lens d= 0.43 cm, and the values of **a** are given in Table 1. together with calculated from the model and measured values of focal lengths.

2a Lens diameter [cm]	Calculated focal length [cm]	Measured focal length [cm]
1.6 (no tension)	2.4	2.55
1.7	2.6	2.6
1.9	3.01	3.2
2.0	3.72	3.6
2.2	4.5	4.6
2.4	5.36	5.4

Table 1. Comparison of experimental and calculated values of focal length of the radially tensioned lens

Although the agreement between focal length values measured and calculated from the model is good, the model has a tendency to undervalue.

References:

[1] H. von Helmholtz, Handbuch der Physiologischen Optik. Pp, 143-172, Dover, New York, 1909,

[2] K. Ehrmann, A. Ho, and J-M Perel, "Evaluation of Porcine Crystalline Lenses in comparison with Molded Polymer Gel Lenses with Improved *ex vivo* Accommodation Simulator", Proc, SPIE, Vol. 5688, pp. 240-251, Bellimgham, WA, 2005,

[3] B. M. Wright, "Improvement in or relating to variable-focus lenses," UK Patent 1,209,234 (11 March 1968)

[4] N. Sugiura, S. Morita, "Variable-focus liquid –filled optical lens", Appl. Opt. Vol. 32, 4181-4186 (1993),

[5] A. Rawicz, I. Mikhailenko, "Modelling a variable-focus liquid-filled optical lens", Appl. Opt. Vol. 35, No. 10, 1587-1589, (1996),

[6] C.H. Wu, "Variable lens assembly", US Patent 5,233,470 (1993),

[7] S. Kurtin, "Variable focal length lens", US Patent 5,138,494 (1992),

[8] D. Shaw, T.E. Sun, "Optical properties of variable-focus liquid-filled optical lens with different membrane shapes", Applied Optics

[9] D-Y Zhang, N. Justis, V. Len, Y. Berdichevsky, and Y-H. Lo, "High-performance fluidic adaptive lenses", Appl. Opt. Vol. 43, No. 4, 783-787, (2004),

[10] R. Kuwano, T. Tokunaga, Y. Otani, and N. Umeda, "Liquid pressure varifocus lens", Optical Review, Vol. 12, No.5, 405-408, (2005),