TonoSense: A Novel Device for Intraocular Pressure Measurement

Tarun Jacob

S-ENBM-001

TonoSense: A novel device for intraocular pressure measurement

Tarun Jacob

12th Grade, Niskayuna High School, Niskayuna, NY

Abstract

Glaucoma is the second leading cause of blindness, affecting 1 in 100 people worldwide. Unfortunately, due to its asymptomatic nature, it often goes undetected leading to permanent vision loss. A major risk factor for glaucoma is high intraocular pressure (IOP). Several eye models of varying thickness were built, incorporating corneal thickness and size. An Arduino-based IOP measurement setup integrating the eye model and a force sensitive resistor was constructed. An algorithm was developed to measure pressure with a gentle touch on the eye model. The impact of biomechanical parameters on measured IOP was investigated. Imbert's Fick's Law was proven to be valid, but only under conditions of low corneal thickness. Incorporating these results, a novel finger-tip pressure sensor, *TonoSense* (approximate cost-$18), was developed. It was demonstrated to automatically measure the pressure and display it in real time, potentially enabling a game-changing tonometer in the fight against glaucoma.

Keywords: Glaucoma, intraocular pressure, force sensitive resistor

Introduction

Glaucoma is the second leading cause of blindness, affecting more than 70 million people worldwide and around 3 million in the US. It occurs when an individual's optic nerve becomes damaged, potentially leading to irreversible blindness. Glaucoma is often asymptomatic, and the patient is unaware until vision impact has started, hence why it is often called the *silent thief of sight*, One significant risk factor of glaucoma is high eye pressure, clinically known as intraocular pressure (IOP).

Normally, individuals have an IOP ranging from 10-21 mmHg, while most glaucoma patients have an IOP higher than 21 mmHg. A single IOP value will not indicate whether an individual has glaucoma, since the normal range of eye pressure may vary from individual to individual and different individuals could have different degrees of abnormal eye pressure.

A device used to measure IOP is the tonometer. The Goldmann Applanation Tonometer (GAT) is the gold standard of tonometers. GATs require local anesthetics and must be administered in a hospital setting.

An affordable, easy-to-use, at-home IOP-measuring instrument is still unavailable in the market. Such a device could help save thousands (maybe even millions) of people from vision loss. The proposed pressure sensor, TonoSense, will have the following potential benefits:

- Home monitoring of IOP to detect any substantial changes to provide early detection
- Self-measurement with eyelids closed (no anesthesia required) and correcting for corneal thickness
- Low-cost system

Materials and Methods

The starting assumption of this method is that the eye can be modeled as a spherical cavity filled with fluid. The internal fluid pressure is distributed equally across the surface. If this cavity is compressed with external force, the contact region is flattened. According to the Imbert-Fick Law, the cavity's internal pressure is equal to the force required to flatten part of the sphere divided by the area flattened. This force can be measured by a pressure sensor and the IOP can be estimated. However the accurate measurement of the external force and the extent of flattening of the eye is not easy. The proposed method overcomes these challenges by using a thin film force sensor for pressure measurement. The concept is shown in Fig. 1. The particular force sensor used is a circular force sensitive resistor (FSR) carefully selected such that its area is smaller than the flattening area of the eye.

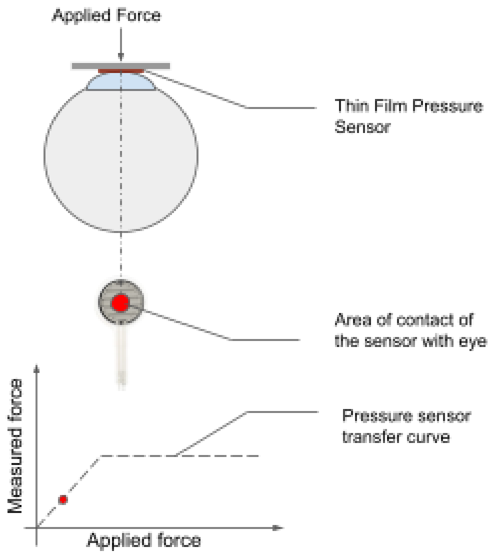

Fig. 1: Proposed IOP measurement concept using a thin film force sensor

With increasing force applied externally to compress the eye, the FSR response increases proportionally (linear) until the FSR area becomes equal to the contact area, at which point the force sensor reading will become constant. The FSR reading will remain constant for any larger force applied. The flattening force is equal to the force value when the measured force vs applied force graph plateaus and the flattened area is equal to the FSR area.

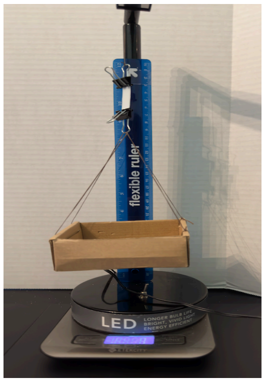

Fig. 2: Apparatus used to measure Young's Modulus of different thicknesses of silicone

To determine the optimal material for the eye model, a stress-strain analysis was performed on thick and thin silicone materials with thicknesses of 750 µm and 375 µm respectively. The material was cut into a rectangular shape and the strip was suspended between two binder clips as shown in Fig. 2. The entire apparatus was placed on top of a weighing scale and force was applied to the strip by placing coins into the compartment shown in Fig. 2.

The Young's Modulus value for each material was calculated by dividing its stress (force by cross-sectional area) by its strain (change in length over the original length). The graphs for the thick and thin silicone are shown in Fig. 3 and Fig. 4, respectively. The thick silicone was shown to have a Young's Modulus value of about 0.75 MPa and the thin silicone had a Young's Modulus of 0.54 MPa.

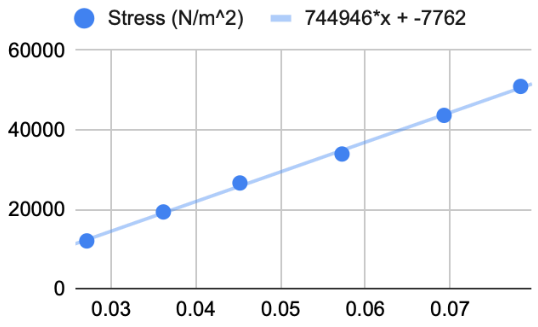

Fig. 3: Stress vs Strain for thick silicone

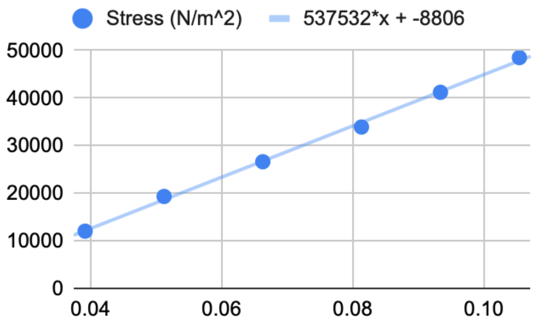

Fig. 4: Stress vs Strain for thin silicone

I. Pressure Measurement System

Fig. 5 shows the functional block diagram of the proposed pressure measurement system. It consists of four parts:

1. *Flexible fluid filled cavity*: model for eye
2. *Pressure sensor*
3. *Arduino Nano*: data acquisition system
4. *Laptop* running the Arduino program

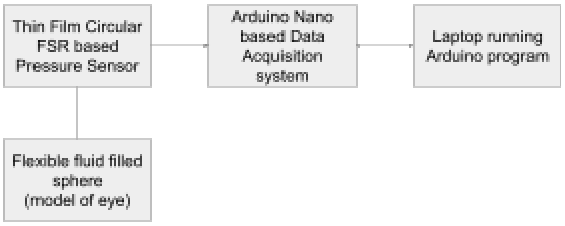

Fig. 5: Functional block diagram of pressure measurement system

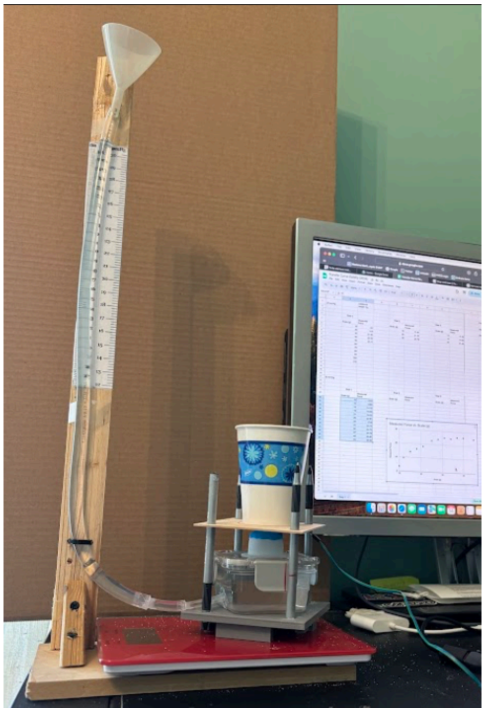

Fig. 6: Imbert Fick's Law

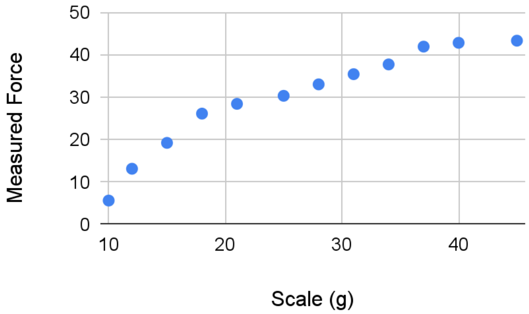

Fig. 7: Transfer Curve at 22 mmHg

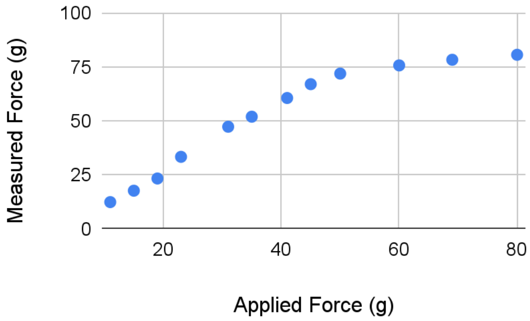

Fig. 8: Transfer Curve at 30 mmHg

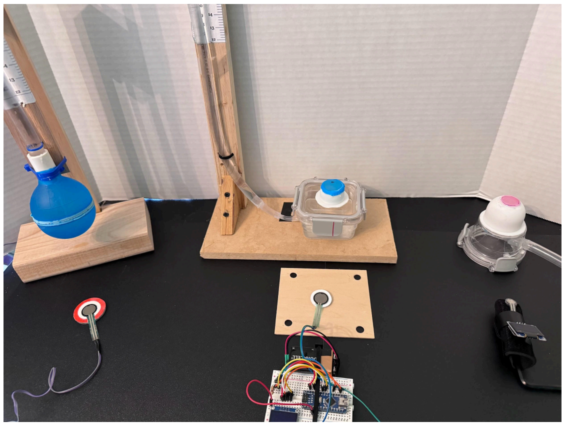

Fig. 9: Three models and corresponding sensors

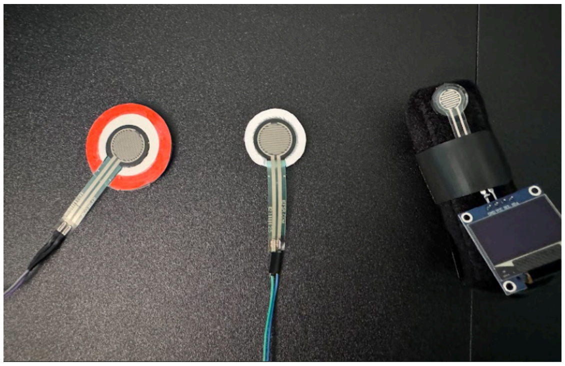

Fig. 10: Second model of eye built using water filled balloon

Fig. 11: Three eye models and corresponding experimental apparatus

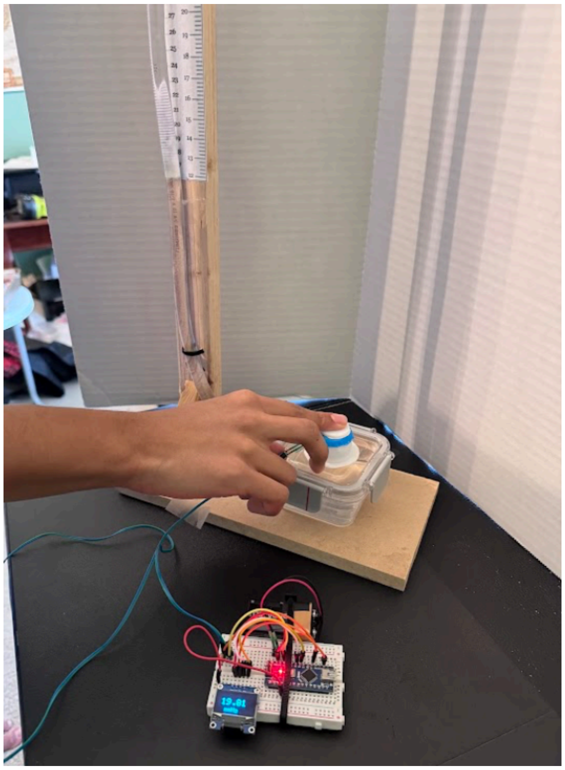

Fig. 12: Measuring the IOP of the Hybrid Silicone Model

From the saturated (flat) region of the FSR transfer curve (measured vs. applied force) IOP can be computed as shown in Fig. 7 and 8. The measured FSR transfer curves at two fluid pressures resemble the theoretical curves. The ratio of measured force and fluid pressure is approximately the same (area of the FSR), proving Imbert Fick's Law.

II. System Design and Calibration

A force sensor was constructed by gluing an FSR to the center of a square wooden plate and then soldering two wires to the FSR. Then, these wires were inserted into a breadboard to create a simple voltage divider circuit using the FSR and a 10 kΩ resistor. This circuit was connected to an Arduino Nano. Next, this construction was placed on top of a weighing scale.

The FSR was calibrated by placing objects with known weights onto the FSR and measuring the resistance of the FSR at each of these weight values. Then, the resulting Resistance vs. Weight scatter plot was fitted with a power series curve. This regression equation was pasted into an Arduino program, which allowed it to accurately output the amount of force being applied at a given instant.

III. FEM Model

A finite element (FE) model was developed using OnScale Solve to simulate a more realistic biomechanical model. First, a 3D eye model was developed using OnShape CAD software, incorporating the cornea and sclera and their corresponding thicknesses.

This model was then brought into OnScale Solve and additional ocular parameters (e.g. density, Young's Modulus and Poisson's Ratio) were inputted to improve the validity of the model compared to the eye.

A model simulation was created and a strain analysis was done by applying a force of 0.33 N, simulating the 20 mmHg pressure in the human eye. The results from the analysis are shown in Fig. 13. They indicate that the most strain is on the central region drawn in red, which is prone to buckling.

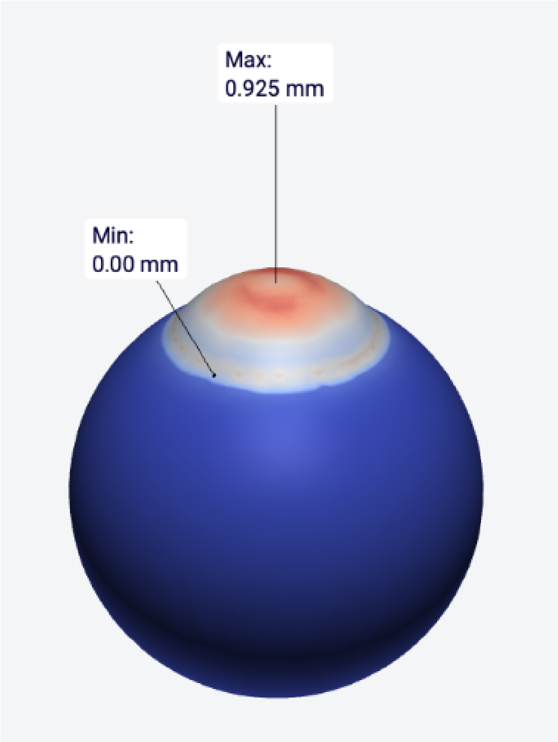

Fig. 13: FEM Model of the eye

Results and Analysis

To determine the accuracy of TonoSense in determining the internal fluid pressure of fluid-filled spheres, a graph of Sensor Pressure against Water Column Pressure was plotted for the Thin Silicone Model. Two trial runs were conducted, with 7 data points taken per trial. The average of the Sensor Pressure values for these two trials was plotted against the water column pressure. (results shown in figure 14)

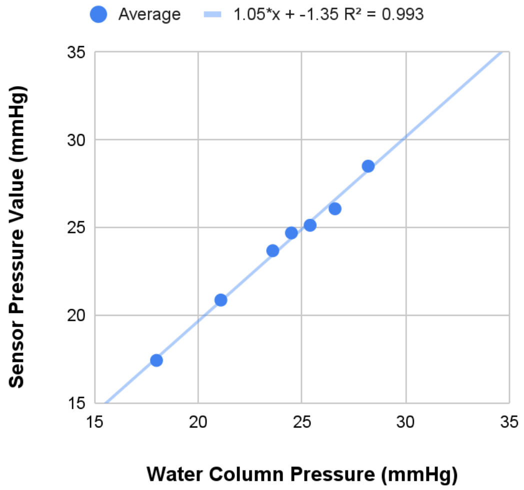

Fig. 14: Measured pressure vs. Actual pressure graph for Thin Silicone Model

A good linear proportional relationship between the measured and actual pressure was obtained in the measurement (R2 value of 0.993).

The impact of the type of eye model on the measured pressure was determined by setting all three models to the same internal fluid pressure and using *TonoSense* to measure the IOP in each model.

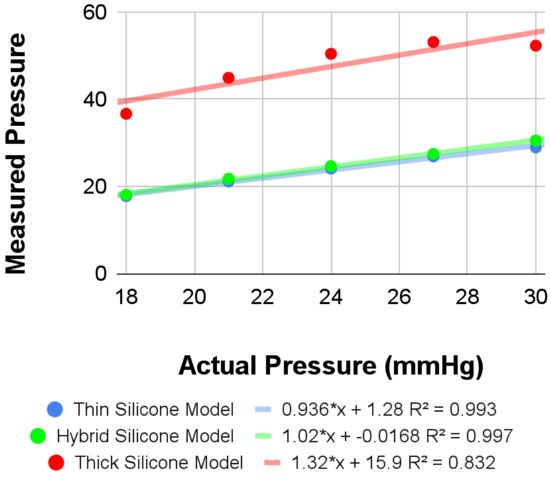

Fig. 15: Measured pressure vs Actual pressure plots for three eye models

As shown in Fig. 15, there was much more variability for the Thick Silicone Model (R^2 value of 0.832), compared to the Thin Silicone Model and Hybrid Silicone Model, which had R^2 values of 0.993 and 0.997, respectively. The Hybrid Silicone Model had the slope closest to all three models, indicating that it is the best model for IOP measurement.

Fingertip-based IOP Device

A fingertip-based IOP device was developed, embedding the FSR (shown in Fig. 17) into a finger cap which users would wear. The eye model that was tested was a water-filled silicone sphere, which had a thin outer layer that modeled the cornea and eyelid of a human eye.

To construct this device, the FSR was isolated from the wooden platform to which it was attached in previous experiments. The FSR was glued onto a circular acrylic disc.

Two wires were soldered to the ends of the FSR and were embedded inside a glove. The FSR was connected in series with a 10 kOhm resistor to create a voltage divider circuit and this was connected to an Arduino Nano as before. An i2C OLED display module was wired to the Nano and this display was used to read out the real-time pressure in mmHg.

An algorithm was developed for enabling automatic pressure measurement. These were the main steps of the algorithm:

1. Detect "flat region" of response and discard the transient part. The graph in Fig. 16 illustrates the discarding of the transient region.
2. Compute median force value
3. Compute pressure using FSR area
4. Convert to mmHg units

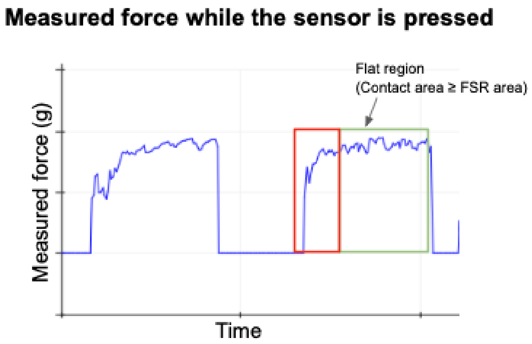

Fig. 16: Graphical example for working of algorithm

Conclusions and Future Work

A novel IOP-measurement device, *TonoSense*, has been developed. Several eye models of varying thickness were built, incorporating corneal thickness and size. An Arduino-based IOP measurement setup integrating the eye model and a force sensitive resistor was constructed. An algorithm was developed to measure pressure with a gentle touch on the eye model.

The impact of biomechanical parameters on measured IOP was investigated. Imbert's Fick's Law was proven to be valid, but only under conditions of low corneal thickness. Incorporating these results, a novel finger-tip pressure sensor, *TonoSense* (approximate cost-$18), was developed. It was demonstrated to automatically measure the pressure and display it in real time, potentially enabling a game-changing tonometer in the fight against glaucoma.

Eye models used in this work did not take into account the real mechanical properties of the cornea. Further research into building more realistic eye models will be conducted in future. Commercially available sensors (FSR) are not optimized for the IOP range. Custom design of the sensors will improve sensitivity.

Finger-tip sensor based pressure measurement has variability in the readings due the changes in positioning of the sensor. Improvement in the measurement procedure and multiple samples will help to reduce variation.

Fig. 17: Proposed fingertip based IOP monitoring device

References

- Ljubimova, Darja. "Biomechanics of the Human Eye and Intraocular Pressure Measurements." *DIVA Portal*, e-book ed., pp. 1-47.
- Brusini, Paolo, et al. "How to Measure Intraocular Pressure: An Updated Review of Various Tonometers." Edited by Bryan Winn. *National Library of Medicine*, National Institutes of Health, 27 Aug. 2021, www.ncbi.nlm.nih.gov/pmc/articles/PMC8456330/. Accessed 22 Jan. 2023.
- Boyd, Kierstan. "What Is Glaucoma? Symptoms, Causes, Diagnosis, Treatment." Edited by David Turbert. *American Academy of Ophthalmology*, 6 Dec. 2022, www.aao.org/eye-health/diseases/what-is-glaucoma. Accessed 22 Jan. 2023.
- "Ocular Tonometry." *Wikipedia*, Wikimedia Foundation, 24 Nov. 2022, en.wikipedia.org/wiki/Ocular_tonometry. Accessed 22 Jan. 2023.
- Clement, C. I., Parker, D. G. A., & Goldberg, I. (2016). Intra-Ocular Pressure Measurement in a Patient with a Thin, Thick or Abnormal Cornea. *The Open Ophthalmology Journal*, *10*(PMC4780515), 35–43.

https://doi.org/10.2174/1874364101610010035

- Gabriela Gonzalez Castro, Fitt, A. D., & Sweeney, J. A. (2016). On the Validity of the Imbert-Fick Law: Mathematical Modelling of Eye Pressure Measurement. *World Journal of Mechanics*, *06*(03), 35–51. https://doi.org/10.4236/wjm.2016.63005
- Han Saem Cho, Sae Chae Jeoung, & Yun Sik Yang. (2022). Development of eye phantom for mimicking the deformation of the human cornea accompanied by intraocular pressure alterations. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-24948-2
- Pandolfi, A. (2020). Cornea modelling. *Eye and Vision*, *7*(1). https://doi.org/10.1186/s40662-019-0166-x
- CJ;, Yuhas PT;Roberts. “Clinical Ocular Biomechanics: Where Are We after 20 Years of Progress?” *Current Eye Research*, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/36239188/. Accessed 14 Mar. 2024.