A Smartphone-based System for Assessing Intraocular Pressure

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***Abstract* — The measurement of intraocular pressure (IOP) is an important vital sign for the eye, particularly for the diagnosis of glaucoma. Procedures for measuring IOP have been used by eye care professionals for over 100 years, but those without access to such professionals often go undiagnosed. We present a smartphone-based system that can be operated by minimally trained users to measure IOP. The system emulates fixed-force tonometry using a low-cost mechanical attachment to the smartphone. Video is captured through the attachment and then processed in real-time to provide an absolute estimate of the patient's intraocular pressure. Our preliminary assessment with two *ex vivo* porcine eyes demonstrates that the system follows a baseline physical model with correlations of 0.89 and 0.88.**

I. Introduction

Intraocular pressure (IOP) is the innate fluid pressure within the eye. IOP is maintained by the trabecular meshwork, which manages the leakage of the aqueous humor in the anterior chamber of the eye. The typical IOP of humans ranges from 7-21 mmHg with a mean of approximately 16 mmHg. Elevated IOP is an important risk factor for glaucoma, a progressive optic neuropathy that can lead to visual field defects or eventual blindness. A study carried out by Quigley and Broman in 2006 [1] predicts that the global population affected by glaucoma will reach 80 million by 2020; it further postulates that half of the people living with glaucoma are unaware that they have the disease, which can largely be attributed to a lack of resources or incentive for IOP assessment. Glaucoma also imposes a significant burden on the US healthcare system, costing roughly $3 billion USD and over 10 million visits to physicians per year [2].

Tonometry is the diagnostic procedure performed by eye care professionals for measuring IOP. The clinical gold standard for measuring IOP is Goldmann Applanation Tonometry (GAT) [3]. Applanation tonometry in general relies on Goldmann's observation that "the pressure in a sphere filled with liquid and surrounded by an infinitely thin membrane is measured by the counterpressure which just flattens the membrane" [4], also known as the Imbert-Fick law. In GAT, a form of fixed-area tonometry, a topical anesthetic with a fluorescein dye is placed on the eye. When the dye mixes with the tears and the eye is fluoresced with a cobalt blue light, the dye appears as a brighter yellowish green. A split optical prism is then pressed against the eye, resulting in two semicircles. The ophthalmologist adjusts the force exerted by the prism until the semicircles align on opposite ends, indicating that the area of the applanation surface has reached a predetermined quantity. That force measurement is mapped to an IOP value using a clinically validated lookup table [5]. The complement to fixed-area tonometry is fixed-force tonometry. Instead of measuring the force required to make an applanation surface of known area, a cylinder of known mass is allowed to rest on the eye without any external forces and the area of the applanation surface is mapped to an IOP value.

Figure 1. The proposed system emulates fixed-force applanation tonometry using the hardware adapter pictured above. The clear acrylic cylinder is allowed to move freely within the black casing so that its mass provides a constant force on the patient's eye.

Tonometry requires either a trained eye care professional or access to dedicated medical devices. These constraints make tonometry difficult in low-resource environments. Smartphones, on the other hand, have seen a rapid uptake all over the world and contain a myriad of sensors that can be used for mobile health applications. In this paper, we propose a smartphone-based system that allows for minimally trained individuals to perform IOP assessments on other individuals. Rather than requiring precision from specialized hardware or a trained professional, the precision of this system is placed within the smartphone. The user attaches a low-cost smartphone adapter that we have developed to emulate fixed-force tonometry. While the patient lies supine, the cylinder inside the instrument is rested on the patient's eye, allowing the smartphone's camera to automatically detect and measure the applanation surface, from which the patient's IOP may be inferred.

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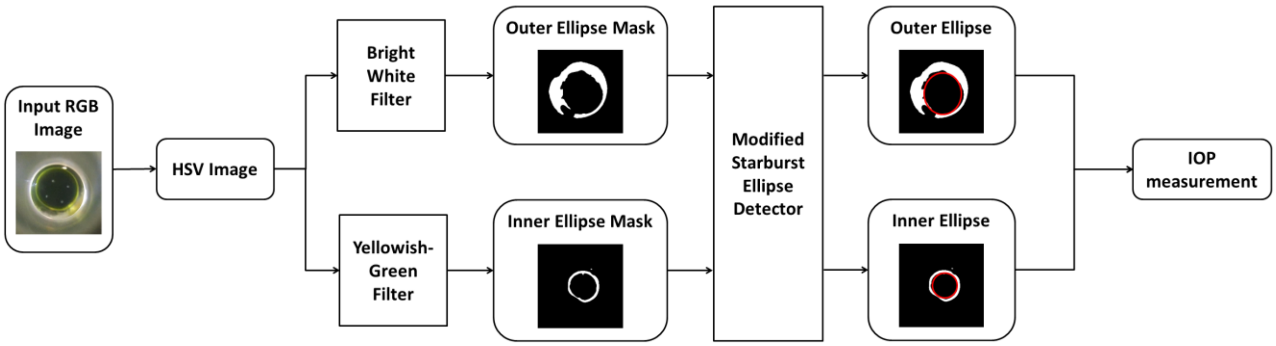

Figure 2. The steps taken to estimate intraocular pressure from an RGB image of the applanation procedure. After converting the image into the HSV space, masks are defined for the clear acrylic cylinder's base (outer ellipse) and the applanation surface (inner ellipse) using color and intensity features as filters. Ellipses are detected on the insides of those masks and then mapped to absolute measurements given the 8 mm diameter of the acrylic cylinder. The diameter of the applanation surface is then mapped to the patient's estimated IOP.

II. Approach

A. Hardware

The hardware adapter is shown in Figure 1 attached to an iPhone case. The most important part of the hardware is the clear acrylic cylinder inside the black casing. The acrylic cylinder is allowed to move freely within the casing, but has notches to ensure that it does not fall out of the adapter. The acrylic cylinder has a diameter of 8 mm and a height of 63 mm. The 8 mm diameter was chosen such that it would capture a fairly large circle from a low eye pressure without being too difficult to use on patients with small palpebral fissures. The height of 63 mm was chosen for two reasons. (1) If the applanation surface is placed too closely to the smartphone's camera, the resulting video becomes difficult to focus and the edges become blurry. (2) This combination of diameter, height, and material leads to a mass of 5.0 g, a mass for which the conversion from applanation surface diameter to IOP has already been clinically validated for human eyes [5], [6]. Although conversion tables for larger masses have been produced, studies have shown that the weight of the tonometer induces an increased pressure due to the displacement of aqueous humor during applanation [6].

The black casing itself is designed such that the acrylic cylinder is optimally positioned in front of the smartphone's back-facing camera. Not only does this positioning include the alignment of the acrylic cylinder with the camera, but also the distance between the base of the acrylic cylinder and the camera. The black casing also blocks out ambient lighting to prevent any extraneous reflections from appearing in the acrylic cylinder.

To enhance the visibility of the acrylic cylinder in the camera, the edge of the cylinder's bottom surface is frosted. To emphasize the applanation surface in the camera, an external LED is mounted on the casing; in the future, the smartphone's flash could be redirected to the outside of the acrylic cylinder via a short fiber optic cable. When this lighting is reflected off of fluorescein dye, it shines as a bright yellowish green.

B. Performing the Assessment

Before receiving the assessment, the patient assumes a supine position. The user conducting the test administers a topical anesthetic with fluorescein dye (Fluorescein sodium 0.25%/Proparacaine 0.5%) to the patient's eye. The user then holds the smartphone over the patient's eye such that only the weight of the acrylic cylinder is applied to it. This means that the smartphone should be as flat as possible (*i.e.*, parallel to the ground) and the user should not apply any extra force on the smartphone (*i.e.*, pressing down). The flatness of the smartphone is measured with the smartphone's accelerometer, operating as a sort of bubble level.

The weight of the acrylic cylinder creates an elliptical applanation surface with a yellowish green outline when the LED is shone on the patient's eye. The smartphone's camera records the applanation of the eye. The frames from the resulting video are then processed using computer vision to give a real-time estimate of the patient's IOP.

C. Video Analysis

Figure 2 outlines the algorithm used to extract an IOP measurement from an RGB image. The overall goal of the algorithm is to detect two ellipses: the base of the clear acrylic cylinder (outer ellipse) and the applanation surface (inner ellipse). Since the diameter of the acrylic cylinder is known, the applanation surface can be assigned an absolute measurement by using the cylinder as a reference. Both of the ellipses should be relatively circular; however, the acrylic cylinder may appear slightly elliptical if the hardware adapter is improperly mounted, and the applanation surface may be elliptical if the patient has significant astigmatism or corneal surface irregularities.

As shown on the far left of Figure 2, the edge of the acrylic cylinder appears bright and white, and the edge of the applanation surface appears as a dimmer yellowish green. By filtering the image according to intensity and color information, binary masks can be produced to select the outlines of the circles. This information is most intuitively recovered from the image after it is converted into the HSV space. The mask for the inner ellipse bounds the hue between 15-45%, the saturation between 35-100%, and the value 15-100%. Together, these thresholds encode the greenish yellow that appears due to the fluorescein. The mask for the outer ellipse is simpler, thresholding the saturation between 0-20% and the value between 25-100%. Both masks are smoothed using morphological filtering operations to create contiguous contours.

Each of the masks will have some non-uniform thickness due to the application of the dye and extraneous reflections in the cylinder. The diameters of interest correspond to the innermost edges of these masks. Standard circle detection methods would either discover many overlapping circles or none at all, depending on the evenness of the masks. Even worse, only part of the applanation surface may be visible if it overlaps with the sclera, which makes it more difficult to see the fluorescein dye. For these reasons, we apply an adaptation of the pupil contour detection algorithm (Figure 3) used by Li *et al.* in their Starburst work [7].

The ellipse detection starts by assuming the center of the ellipses given that the position of the clear acrylic in the camera's view is known. The algorithm then steps radially at 20 evenly spaced angles until an edge is reached in the mask (illustrated with fewer angles for clarity). This assumes that there are no contours that appear within the mask, which can happen for the applanation surface if the fluorescein pools in the patient's eye. Since extra blobs appear in the middle of the mask due to the distribution of the fluorescein, the radial steps start from a fixed distance just below the minimum expected radius to prevent them from stopping short.

Most of the detected edge points should belong to the desired ellipse, but some may still belong to artifacts along the edge of the contour. The original Starburst algorithm accounts for noisy ellipse points by fitting random subsets of points to ellipses and selecting the ellipse that minimizes the number of outliers. In the case of applanation, there is almost always a clean arc that appears in the image. Instead of randomized subsets of points, as used by Li *et al.*, the proposed system fits contiguous subsets of points (three-quarters of the entire circumference) to ellipses. Although we noted earlier that the base of the acrylic cylinder and the applanation surface may appear elliptical, the ellipses should be relatively rounded. If the percent difference between an ellipse's major and minor axes is greater than 10%, it is automatically rejected. Amongst the rest of the ellipses produced by the different subsets of edge points, the ellipse that best fits the data according to Euclidean distance is selected.

The ellipses recovered from the two masks are then translated into circles with a radius equal to the average of the ellipses' axes. Given that the diameter of the clear acrylic cylinder is 8 mm, the absolute measurement of the applanation surface can be recovered by using the cylinder as a reference. Every time the user performs an applanation, a time series of diameter measurements is produced. The measurements of interest occur when the data is most stable since that is when the weight of the acrylic cylinder should be resting on the eye; therefore, the system combines diameter measurements by taking a mean over the measurements within a standard deviation of 0.25 mm over the course of 0.5 s. The final diameter measurement is mapped to an IOP value using a clinically validated lookup table, such as the one published by Adolph Posner [5].

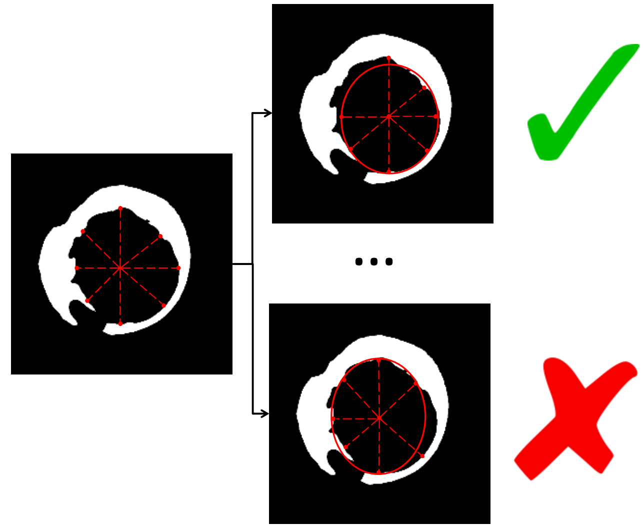

Figure 3. A variation of the Starburst technique by Li *et al.* [7] is used to estimate the innermost ellipse from a binary mask. After candidate points are selected from the inside, contiguous subsets of points are tested with least-squares ellipse fitting until the most circular is found.

III. RESULTS

A. Data Collection

Given the invasive nature of contact applanation tonometry, a feasibility evaluation has been performed on two freshly enucleated *ex vivo* porcine eyes before deploying the system to living human patients. Although there is not a clinically validated table that maps applanation surface diameter to IOP for animal eyes, the Imbert-Fick law still applies. The porcine eyes were inserted into a clay mold such that the iris was horizontal to the ground, as if a patient were supine. The anterior chambers of the eyes were cannulated and the IOP was artificially varied by the height of a saline-filled reservoir. A topical anesthetic with a fluorescein dye (Fluorescein sodium 0.25%/Proparacaine 0.5%) was applied to the eyes to assist in imaging the applanation surface. Tonometry measurements were obtained three times at every 5 mmHg between 15 and 40 mmHg, leading to a total of 32 measurements. Below 15 mmHg, the applanation surface's edge begins to overlap with the edge of the acrylic cylinder, making it difficult to separate the two. The upper bound exceeds the limits of diagnostic significance for elevated IOP.

B. Comparison to the Imbert-Fick Law

Although other methods of tonometry are available as a point of comparison for validation, they all have two drawbacks for our validation: (1) they require manual inspection (*e.g.*, Schiøtz or Maklakov tonometers) and/or (2) they are calibrated specifically for *in vivo* human eyes (*e.g.*, GATs). Instead of a comparison to a possibly inaccurate ground truth, we validate our findings against what is expected from the Imbert-Fick law:

$$P = \frac{F}{A} = \frac{mg}{\frac{1}{4}\pi d^2}$$

where P is the intraocular pressure, m is the mass applied to the eye, g is the acceleration due to gravity, and d is the diameter of the applanation surface. Although corrections

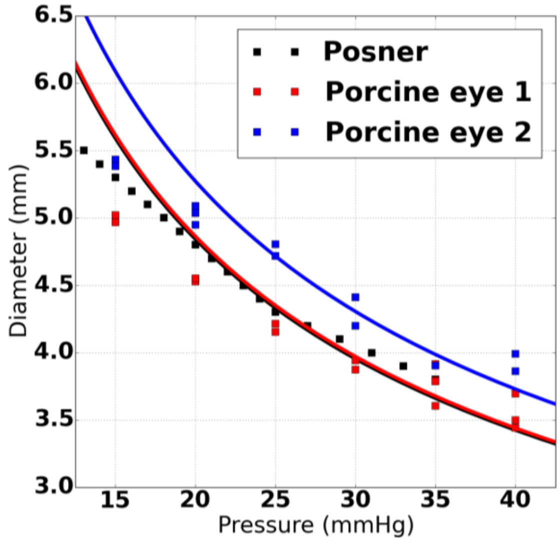

Figure 4. The data recorded from the smartphone system and fit to the physical model expected from the Imbert-Fick law. The two curves lead to coefficients of determination of 0.89 and 0.88.

have been proposed by ophthalmologists to account for properties like the coefficient of ocular rigidity and corneal curvature (*e.g.*, [6]), these models break down for *ex vivo* eyes. The measurements from each of the eyes were independently fit to the Imbert-Fick law using non-linear fitting. The mass parameter was used as the unknown parameter; if the data were to follow the Imbert-Fick law without deviation, the parameter resulting in the best fit would be 5g, the mass of the acrylic cylinder.

Figure 4 shows the models that were fit to the two datasets. The clinical measurements validated by Adolph Posner [5] are also included as a point of reference. Even though Posner only dealt with human eyes, the shape of the data should be similar to that of the *ex vivo* porcine eyes. When compared to the Imbert-Fick law, Posner's data shares a coefficient of determination (R^2) 0.95 and the estimated mass according to the optimal fit is 5.01g, showing that it follows the model very closely. The fit for the first porcine eye leads to a coefficient of determination of 0.89 and an estimated mass of 5.04g. The fit for the second eye does not obey the Imbert-Fick law as well; it results in a lower coefficient of determination of 0.88 and an estimated mass of 5.94g. The regressions overestimate low pressures and underestimates high pressures in all cases, a fact that has been observed by clinicians for other forms of tonometry as well [8]. The most promising observation is that there is a statistically significant separation between the diameters for 20 mmHg and 30 mmHg, the boundary that clinicians consider for the diagnosis of elevated IOP.

IV. Discussion

The Imbert-Fick law assumes that the eye's membrane is perfectly elastic, flexible, and infinitely thin; prior work has shown that these assumptions do not hold for the cornea of the eye. For example, DF Woodhouse [6] notes that the volumetric displacement of aqueous humor induces an increase in the IOP, so he derives a correction term that takes into account the corneal curvature and rigidity. We plan to apply Woodhouse's model once evaluations are performed on cadaveric and *in vivo* human eyes.

It is very important that the entire weight of the acrylic cylinder is the only force applied to the eye during applanation. The smartphone's accelerometer is used to ensure that the cylinder's weight is applied perpendicular to the eye, assuming that the user is supine. However, it is possible that the user can add an additional force by pushing down on the cylinder. When this happens, the cylinder slides into the black casing past a specific depth. This could be solved using a contact sensor, but would require an active sensing mechanism Instead, the next iteration of the hardware design has holes along the edge of the casing at the threshold depth. When the acrylic cylinder is pushed past the holes, additional light is shone into it. This can be detected through the smartphone's camera without additional sensing hardware, making it a more desirable design.

Another planned refinement in the next hardware iteration is the use of a macro lens, which is used in photography when a camera must focus on a small subject at close range. The primary reason that the acrylic cylinder used for applanation is 63mm tall is to ensure that the applanation surface remains in focus during the assessment. With a macro lens, the applanation surface can be much closer to the smartphone camera. Assuming a constant diameter, reducing the height of the acrylic cylinder would decrease its mass, but the cylinder could be made with a denser acrylic or metal rings could be attached to the base to add weight.

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