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Modelling Intraocular Lens Design Based on Image Analysis

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ABSTRACT

Intraocular lenses (IOLs) are commonly used to treat ocular diseases such as cataracts. The International Organization for Standardization (ISO 11979) recommends examining IOLs using real model eyes with the lenses in situ, although this process can also be simulated in silico with an accurate IOL haptic design. One way to create this design is by using software such as Abaqus, which generates a finite element mesh configuration with a linear element set up and directly tests it in the model eye using the same program. While this process is like those reported in other studies and includes most of the software necessary for generating the result automatically, there is an alternative method for generating the IOL haptic design — microscopic image analysis. The purpose of this study was to evaluate the image quality of IOL using microscopic analysis. Several IOL images were captured using a microscope and the converted into vector images and the steps were repeated after two weeks. The structural changes in the images were measured using the Structural Similarity Index Measure (SSIM). All the tested IOLs have SSIM values greater than 0.7. The greatest value was extracted from the simplest IOL shape design. Our result suggests that image analysis for IOL modelling is a reliable method and best for simple IOL shape design.

1. Introduction

In the presence of Intraocular lens (IOL) for cataract treatment, there is a few in silico Finite Element Analysis (FEA) software that has been used for medical device such as ABAQUS®, ANSYS®, COMSOL® and STAR CCM+® [1] where the implantation status for intraocular lenses was simulated using the finite element method (FEM) [2]. Testing and equipment for quality inspection of IOLs must undertake in-situ measurements in a physical model eye, replicating the real human eye condition, to meet the ISO-11979 criteria [3].

The optical performance measures must meet the minimum parameters outlined in ISO 11979-2:2014. For example, in Toric IOLs, rotation along the optical axis is a significant problem, and

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rotational stability may be essential for satisfactory visual results. The main purpose of this process is to ensure appropriate positional stability to prevent IOL tilt and decentration [4]. According to the study, patients who use IOLs have final retinal images that are no better than those of healthy individuals and IOL shape is one of the causes which has a significant impact on spherical-like aberrations. The researcher believed that IOL tilt and dislocation also decrease visual acuity and the quality of the retinal image [5].

Due to these design challenges, FEA is an excellent tool for testing multiple prototypes and materials to quickly get at the best design at the optimal cost [6]. Theoretical modelling is primarily reliant on geometric and material data from experimental research, and as a result, it is vulnerable to any innate experimental errors. If the experimental data used to specify a model is missing or incorrect, the model's findings may be of poor quality [7].

Take an example of the most common software used which is Abaqus where it takes a less computationally intensive method to the three-dimensional-like (3D) problem. In this study [8], after a mesh convergence study, this FE mesh configuration was achieved. Despite the increased number of nodes on the quadratic elements model, comparative simulations performed with linear and quadratic elements converged for the same size of the element. As a result, all the following simulations were run with linear elements to reduce complexity and computational weight.

Since the loading requirements are axially symmetric, the model described here uses a simple cross-section of a human lens. Then, a 2D model was implemented. The cross-section geometry of a one-piece IOL (Alcon SN60WF-Novartis® from Alcon, Fort Worth, TX, USA) was used to create the cross-section for this axisymmetric model [8]. To the best of the authors' knowledge, none of the studies explain how they obtained the 2D mesh configuration to be inserted into the finite element process and some mentioned that the manufacturers contributed the IOL design data [9]. Thus, this study was conducted to explore how to obtain 2D mesh configuration in a low-cost way from microscopic image analysis which is the extraction of information from data in the form of pictures [10] when the original designs of the IOL are not accessible.

2. Materials and Methods

In this experimental study, data collection was done by creating IOLs digital designs from physically available IOLs in the market as the subjects. The instrument used for data collection includes a microscope and image editing software such as Adobe Photoshop and Inkscape. This microscope was equipped with High-Definition Multimedia Interface (HDMI) Universal Serial Bus (USB) 36 megapixels (MP) 60 frames per second (FPS) together with 130X C-Mount Lens and light-emitting diode (LED) Ring Lighting. HDMI is a compact audio or video interface that functions in transmitting uncompressed digital data which stands for a digital alternative to consumer analogue standard such as D-Terminal and radio frequency (RF) [11]. Whereas 36 megapixels, which is a high-resolution specification result in model precision that will benefit the photo-realistic textures [12] and 60 FPS which is considered a high frame rate will increase the quality of video perceived [13]. C-Mount Lens is commonly used in a variety of applications which is a microscope with automated control of lens features [14] combined with 130X magnifications.

The experiment started by capturing eight available IOLs images using the microscope has been showed in Figure 1. As the IOLs were transparent, there is a special technique to make sure the shape and edge of the IOLs were successfully traced and differentiate from the background. It makes it easier as the base of the microscope was already black in colour in contrast to the transparent IOLs. The microscope used was not implemented with the light source, so an additional light source was used to illuminate IOLs.

Fig. 1. Microscope used for this study

However, it caused shadow to form beside the edge of the IOLs and might affect the IOLs' edge tracing. To enhance the image of the IOLs for edge tracing, the image had colour inverted where the colour of the IOLs and the background were reversed so, the shadowing effect reduce as illustrate in Figure 2.

Fig. 2. Colour Inverted of IOL Image

Then, images of captured IOLs from a microscope traced their edges using open-source image editing software such as GIMP using automatic edge detection algorithm tools to make sure the geometry of the design accurate. Mesh quality and size need to be given critical attention as it will cause inaccuracies when the element went too large and unnecessarily model size increment when it became too small [6]. Next, black, and white images of IOL been auto traced using Inkscape to create a high-resolution trace is illustrated in Figure 3 to have an efficient FEA process [4].

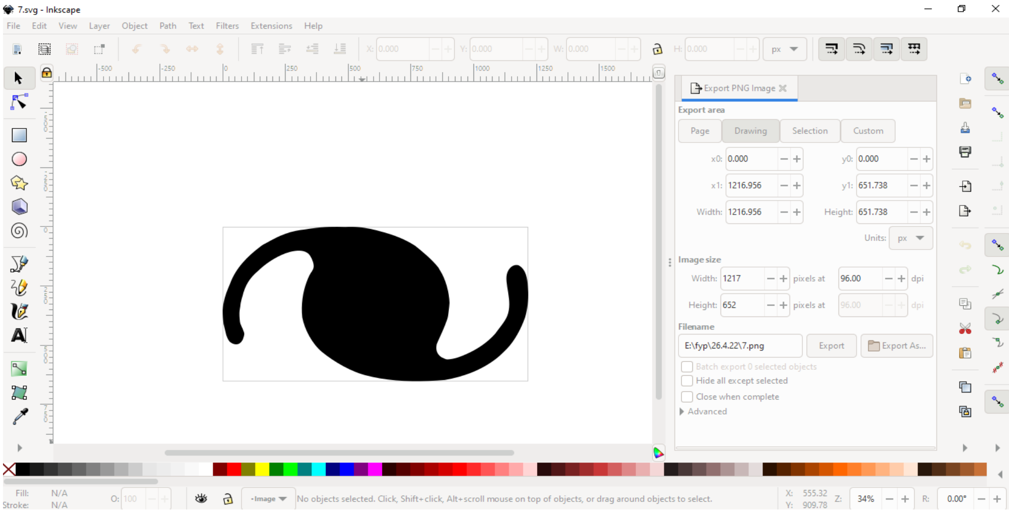

Fig. 3. Autotrace the black and white image using Inkscape

After two weeks, the steps were repeated to observe the quality image of the IOLs design using Structural Index Measure between the first-time image captured and the images after two weeks apart being calculated. Structural Index Measure or Structural Similarity Index Measure (SSIM) is a method to compare similarities between two images that also can be a quality measure [15]. SSIM is theorized to be related to how well the Human Visual System (HVS) perceives quality. The SSIM is developed by representing any image distortion as a combination of three elements, namely loss of correlation, luminance distortion, and contrast distortion, as opposed to utilizing conventional error summation techniques.

The similarity between the two photos, x and y, is determined using this index. In this investigation, the vectorized IOL picture from the first and second weeks will be compared. The SSIM can be computed using the formula as in

$$SSIM(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \tag{1}$$

Where c_1 and c_2 are constants, $\mu_x$and μ_y are the average of x and y, σ_{xy} is the covariance of x and y and σ_x^2 and σ_y^2 are the variance of x and y [16].

The SSIM's maximum value is 1. Numerous studies claim that the range of SSIM values is 0 to 1, however in reality, the lowest SSIM value might be as low as 1. This is due to the rarity and irrelevance of negative values [17]. The cut-off value for the SSIM in this study is 0.7 as following previous research of the Diabetic Screening System only accepts retinal images with SSIM values greater than or equal to 0.7 as input or otherwise, the input image is repeated [18].

3. Results

All the data obtained were analysed using Image multi-scale structural similarity (MS-SSIM) which is available online (http://darosh.github.io/image-ms-ssim-js/test/browser_test.html). Table 1 presents the outcomes of the Structural Similarity Index Measure (SSIM) for various Intraocular Lens (IOL) images, each characterized by specific specifications. The study explores the image quality assessment of these IOLs using microscopic analysis. The SSIM values, which quantify the similarity between pairs of images, were employed to gauge structural changes in the IOL images over a two-week interval.

Table 1
Result of SSIM Value for IOL Images

IOL	Specification	SSIM Value
1	No data	0.815
2	MICAY26P1231 +2.0 T:10.75MM, B: 6.15MM	0.805
3	S. 6.00x13.00 AC 9.5D	0.745
4	MICAGF 1231 +28.0 T: 10.75MM, B: 5.75MM	0.748
5	MO18-AC01 6D OPTIC FLEX 12.5, B:6.0	0.779
6	MICA26P1231 +18.58 t: 10.75MM B: 6.15MM	0.777
7	14548MF +19.08 OPTIC 6.0MM, OVERALL, 12.50MM	0.854
8	MICRO + AY123 +2.0	0.766

Figure 4 illustrates the differences in the IOL designs that has been implemented in this study and this study classified complexity of IOL shape design based on their loops where single loop IOL categorized in simple design and the others as complex design according to previous study [19]. The results showed that all the IOLs achieved a SSIM greater than 0.7. The value of the SSIM followed the complexity of the IOL shape where the simplest one such as IOL number 7 resulted in greater SSIM value than other designs meanwhile the complex shape designs such as IOL number 4, 6 and 8 yielded lower SSIM values.

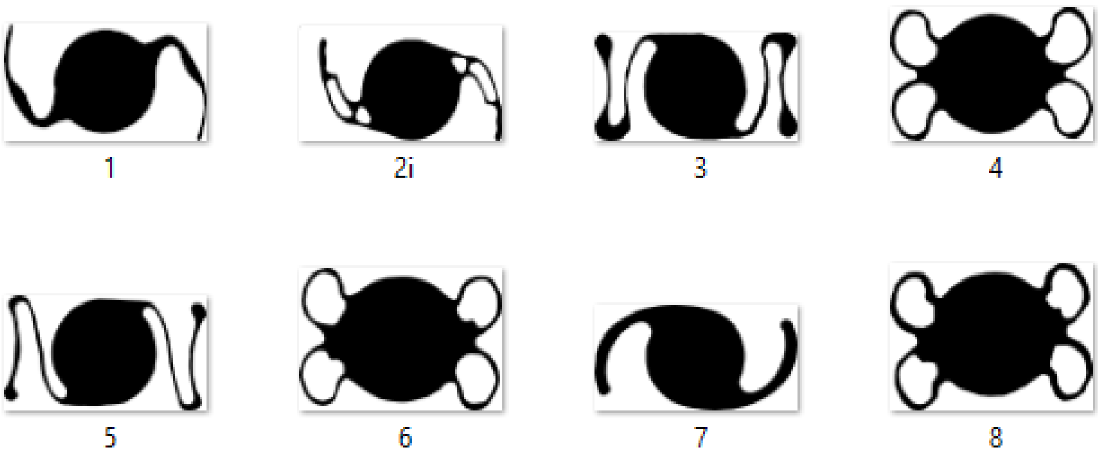

Fig. 4. IOL Designs Implemented in this Study

4. Discussions

The SSIM values in Table 1 suggest that all tested IOLs exhibit SSIM values greater than 0.7, indicating a significant level of similarity between their images before and after the two-week period. Notably, the IOL with the simplest design (row 7) demonstrated the highest SSIM value of 0.854, suggesting minimal structural changes over the two weeks. Table 1 provides a concise overview of the SSIM values for various IOLs, illustrating the reliability of microscopic image analysis as a method for evaluating IOL image quality and demonstrating its effectiveness, particularly for IOLs with simpler shapes.

In this study, we did the reverse process of IOL design acquisition to gain image data for the compression test and the random IOLs used were categorized based on their complexity and the simplest IOL shape designs have greater image quality due to lesser image noise. Noise in digital pictures is a particular kind of visual distortion. It resembles the film photographic grain, although it can also resemble spots of discoloration. There are several factors that can cause image noise in photography including photographs in low lighting and shadowy images [20].

In this case, IOL has been captured in low lighting conditions where the additional light source was used to brighten the image of the IOL. When the image was shot in low light, electronic or digital noise tended to get worse. According to this study [21], two significant issues result from poor lighting. One is that low-light photographs have a limited dynamic range, losing details and having dark patches that are underexposed. While there is also low signal intensity from insufficient exposure makes high-frequency details difficult to see and causes poor contrast.

In addition, grain appears more prominently against darker objects or backgrounds in shadow areas, one of the sources of visual noise [20]. Shadows are typically caused by the direction of the light. It results when there is no direct lighting and when objects block some areas from direct light [22]. A shadow is a localized reduction in the amount of light that hits a certain surface, and they are also a local change in the amount of light that a surface rejects in the direction of the observer [23]. A major aspect affecting accuracy and contributing to these abnormalities is the amount of shadowing [22].

As this study uses automatic edge detection algorithm tools in the image editor, the image noise gives such an effect on the quality of the edge traced. As mentioned by previous study [24], edge detection focuses on the image's high-frequency elements. The task of edge detection is difficult when dealing with noisy photos. Since the edge itself is made up of high-frequency data, it is frequently the case that these images contain high-frequency noise or irrelevant data that prevents the recognition of continuous edge points. False detections are produced by the noise since the algorithms are frequently misled for an edge.

Statement mentioned in study supports that complicated IOL shape design tended to have more shadow effects than the simpler design hence causing image noise. The fuzzy tools in the image editor which is the automatic edge detection misled the shadow as the edge of the IOLs hence affecting the scale and size of the IOL. Hence, the value of the SSIM was lower in complicated IOL shape design.

During the process of this study, there are several challenges encountered mainly due to IOL being a transparent object itself which needs a special technique in capturing the image of IOL. An image of the clear object is ruined by the shine, which either causes high intensity areas of light or to make it even worse, it will reflect the studio background inside the object itself. Moreover, because the object is transparent, it might be challenging to make a piece of clear object stand out from its surroundings in terms of defining its shape [25]. According to this study [26], in defining the shape and edges of the IOL, there are primarily two methods to do this on a light backdrop with dark edges or on a dark background with light edges.

The IOLs used in this study mostly have ragged edges, not only due to worn-out IOL but also because of the dust of the surrounding that attached to the IOL as the experiment was done in a normal room surrounding. Edge detection is a common first step in many computers vision and pattern recognition applications since it is such a fundamental and significant topic. The performance of the remainder of the computer vision and pattern recognition program is greatly enhanced by a high-quality edge map, which is defined as consisting of absolutely contiguous, well-localized, non-jittered, and one-pixel wide edge segments; in contrast, a low-quality edge map, which has poor connectivity, edge width that changes, incorrect branching and notches, etc., significantly degrades the performance of the rest of the application.

Applying a series of filters to the image is a general method for traditional edge detection algorithms to find edges. To minimize noise and smooth the image, the first step is typically to pass the image through a low pass filter. Edges are high frequency components of an image, so to remove those portions of the image that would have edges, a high pass filter such as a derivative or gradient operator is used. The gradient map, which is the result of the gradient operator, is typically thresholder to remove low-frequency, non-edged portions of the image. The edge areas, which are composed of many pixel-wide, thick strips of the image, are made up of pixels that survive the gradient thresholding.

The last step is to walk through the last few pixels in the edge regions to get thin, continuous, jitter-free, and precisely localized edges [27]. Edge detection techniques like skeletonization, nonmaximal suppression, edge thinning, or the use of morphological operators can be used to complete this crucial but challenging stage. However, numerous post-processing methods have been proposed to enhance the quality of the edge maps generated by conventional edge detectors [28]. So, it was a time-consuming process to capture the detail of the IOL shape and edges as there are many distracters to be edited out in the post-processing part.

5. Conclusion

Result of this study showed that the technique of image analysis used for modelling IOL is reliable and has a good quality image to be used for in silico compression test following requirement from the International Organization for Standardization (ISO 11979) in IOL production where the IOLs should be examined using real model eyes with the lenses' in-situ placement to ensure the optical performance of the IOL in positional stability to avoid tilting or decentration that results in aberration. This microscopic image analysis as a method of modelling IOL can contribute to the designing of a new IOL profile and low-cost simulation compression test as the image data of IOL with the manufacturer did not disclose to the public. However, it needs improvement from the technique of IOL image capturing and the post-processing part with suggestions for further research to seek guidance from professional image editors.

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