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Abstract. Postoperative residual astigmatism is one of the unsatisfying visual outcomes of phacoemulsification resulting from surgically induced astigmatism (SIA). Various SIA calculators have been introduced to assist surgeons in calculating SIA for toric intraocular lens (IOL) determination. The aim of this study was to compare SIA values calculated using three different Holladay incorporated method SIA calculators. A data set of 80 eyes from 72 subjects who had undergone uneventful phacoemulsification using less than 3 mm clear corneal incision technique were included in the study. The preoperative and postoperative *K*-readings were computed into the three online Holladay incorporated method SIA calculators which were the SIA Calculator version 1.1 (SIAC1.1); Single Case SIA Calculator (SCSIAC); and Panacea SIA Calculator version 8(6.0) (Panacea). The mean individual SIA values obtained from each calculator were compared. There were no significant differences in mean individual SIA between the calculators ($p > 0.05$). Pearson's correlation coefficients for all compared calculators achieved 0.99. The ranges of 95% limit of agreement between calculators were too small and tight, ranged from -0.012 to 0.012 only. In conclusion, the SIAC1.1, SCSIAC and Panacea produced a comparable SIA value among calculators. Hence, either one can be used interchangeably.

1. Introduction

Surgically induced astigmatism (SIA) is an astigmatism induced by cataract surgery procedure. SIA may originate from the changes of corneal curvature during corneal incision in cataract surgery [1] and remains as a leading cause of postoperative residual astigmatism, affecting postoperative visual outcome [2,3]. This SIA value is important to help surgeon in determining the correct location for corneal incision that could minimize the pre-existing astigmatism [4-6].

SIA is calculated as the difference between postoperative and preoperative corneal astigmatism [7,8]. Astigmatism value is a vector which involves magnitude and meridian [7]. Therefore, any mathematical methods for SIA calculation that calculates the magnitude of the astigmatism but disregards its meridian (simple subtraction; algebraic; Cravy methods) or does not consider the meridian in aggregate data (Naylor; Jaffe; Kaye methods) are unacceptable [9-11]. SIA determination

through vector analysis (Alpins; Holladay methods) and polar analysis (Naeser method) are the accepted methods in computing SIA [10,12-14].

The manual SIA calculations are time-consuming and exposed to computation error when involving large number of cases. Numerous online SIA calculators have been invented based on the accepted methods to minimize the errors and facilitate surgeon in determining individual SIA of patients. Commonly incorporated methods in SIA calculator is Holladay method. However, the comparison of SIA values obtained from these available Holladay incorporated method SIA calculators have yet to be conducted.

Hence, the objective of this study was to compare the mean individual SIA values calculated from three different Holladay incorporated method SIA calculators: *1)* the SIA Calculator version 1.1 (SIAC1.1); *2)* the Single Case SIA Calculator (SCSIAC); and *3)* the Panacea SIA Calculator version 8(6.0) (Panacea).

2. Methods

This comparative cross-sectional study assessed the mean individual SIA of 80 eyes (*n*=72) who had undergone uneventful phacoemulsification at International Islamic University Malaysia Eye Specialist Clinic (IESC), Kuantan, Pahang. The phacoemulsification was done using clear corneal incision of less than 3 mm. The exclusion criteria included postoperative period of less than 6 weeks, subjects who had corneal scars, irregular corneal astigmatism, corneal dystrophies, pellucid marginal degeneration and previous history of ocular surgery [15].

Subjects were explained about the purposes, benefits and risks of the study before they agreed to participate. All subjects provided informed consent to participate in the study in accordance with the Declaration of Helsinki [16]. Ethical approval was obtained from International Islamic University Malaysia (IIUM) Research Ethics Committee (Reference Number: IREC 2018-065).

2.1. Surgically induced astigmatism calculators

The SIAC1.1 was developed by Sawhney and Aggarwal in 2010, and it is a free software that must be downloaded as Microsoft Excel format via https://www.insighteyeclinic.in/SIA_calculator.php [8]. The SCSIAC is an online calculator by EyeData.Net, and it can be accessed at https://eyedata.shinyapps.io/sia-calculator/ [17]. The Panacea can be retrieved from http://www.panaceaiolandtoriccalculator.com, which is compatible with Internetwork Operating System (iOS) devices [18].

These three calculators apply Holladay method of astigmatic analysis [19]. This method is conceptually based on vector analysis using the Cartesian coordinate-based system such that Holladay method converts the astigmatic corrections to X and Y vector components according to the equations (1) to (4) [19];

$$X_{preop} = C_{preop} \times \cos(2 \times A_{preop}) \tag{1}$$

$$Y_{preop} = C_{preop} \times \sin(2 \times A_{preop}) \tag{2}$$

$$X_{postop} = C_{postop} \times \cos(2 \times A_{postop}) \tag{3}$$

$$Y_{postop} = C_{postop} \times \sin(2 \times A_{postop}) \tag{4}$$

where $_{preop}$ is the before surgery condition, $_{postop}$ is the after surgery condition, C is the magnitude of astigmatism and A is the angle of the steep meridian. Subsequently, the magnitude of SIA is obtained as in the equation (5);

$$\left| \text{SIA magnitude} \right| = [(X_{postop} - X_{preop})^2 + (Y_{postop} - Y_{preop})^2]^{\frac{1}{2}} \tag{5}$$

Finally, the axis of the SIA (A_{SIA}) is determined using X_{SIA} and Y_{SIA} components as in the equations (6) to (11);

$$\theta = 0.5 \arctan\left(\frac{X_{SIA}}{Y_{SIA}}\right) \tag{6}$$

$$A_{SIA} = \theta; \text{ when } Y \geq 0 \text{ and } X > 0 \tag{7}$$

$$A_{SIA} = \theta + 180°; \text{ when } Y < 0 \text{ and } X > 0 \tag{8}$$

$$A_{SIA} = \theta + 90°; \text{ when } X < 0 \tag{9}$$

$$A_{SIA} = 45°; \text{ when } X = 0 \text{ and } Y > 0 \tag{10}$$

$$A_{SIA} = 135°; \text{ when } X = 0 \text{ and } Y < 0 \tag{11}$$

where $Y_{SIA} = Y_{preop} - Y_{postop}$ and $X_{SIA} = X_{preop} - X_{postop}$

All SIA calculators in this study require the input of keratometric readings (K-reading). K-reading is the measurement of the magnitude of corneal curvature in dioptric power (D) and its direction recorded as meridian in degree. K-reading is measured at two principal meridians of the cornea anterior surface; steepest meridian (steep-K) and flattest meridian (flat-K). The preoperative and postoperative K-readings were measured using the IOLMaster700 (Carl Zeiss Meditec, Jena, Germany). All K-readings were computed into the three SIA calculators following each calculator's instructions. The magnitudes of steep-K ($K1$) and flat-K ($K2$) including $K2$ meridian obtained from the IOLMaster700 were entered into each SIA calculator. Subsequently, the $K1$ meridian, and the magnitude and meridian of the SIA were automatically generated. In this study, we only included the magnitude of the SIA values for the analysis which fitted to the research objective.

2.2. Statistical analysis
Data analyses were done using IBM Statistical Package for the Social Sciences (SPSS) software version 25.0 and MedCalc version 18.2.1. Data normality was assumed when the Z-score was less than 3.29 for a sample size of $50 < n < 300$ [20]. The Z-score calculation is as in equation (12);

$$Z\text{-score} = \frac{\text{Skew value}}{\text{Standard error of the skewness}} \tag{12}$$

The mean individual SIAs obtained from three calculators were analyzed using one-way repeated measures analysis of variance. The strength of linear relationship between calculators was evaluated using Pearson's correlation coefficient (r-value). An excellent correlation is considered when the r-value is more than 0.90. The significance level (p) of less than 0.05 was set to determine differences of the comparison. Inter-calculator agreement was assessed using 95% limit of agreement (LOA). The LOA was determined as the mean difference $\pm$ 1.96 multiplied by the standard deviation of the difference. Higher agreement is indicated by lower LOA [21].

3. Results
The mean age of the subjects was 67 ± 10 years (40 to 81 years). There were 31 males (39%) and 49 females (61%) with majority of the subjects were Malays (85%) and the remaining were Chinese (15%). The Z-scores of mean individual SIA for the SIAC1.1, SCSIAC and Panacea were 1.61, 1.64 and 1.61, respectively. The normality results showed that the mean individual SIAs were normally distributed with the Z-scores of less than 3.29 [20].

3.1. Agreement between the calculators

There were no significant differences observed in determining SIA values between the calculators (p = 0.141). The Pearson's correlation coefficient showed excellent correlation between the calculators. All the pairwise comparisons revealed that the calculators are in agreement to each other in determining SIA values. The results of Bland and Altman analysis demonstrated that the range of 95% LOA of the compared calculators were smaller than ±0.013 D as shown in Table 1.

Table 1 Summary values of mean differences, Pearson's correlation coefficient and Bland-Altman analysis of SIAs.

Compared Calculators	[a]Mean difference (D)	[b]r-value	Lower 95% LOA (D)	Upper 95% LOA (D)	Range 95% LOA (D)
SIAC1.1 vs SCSIAC	0.001	0.999	-0.010	0.012	0.022
SIAC1.1 vs Panacea	0.000	1.000	0.000	0.000	0.000
SCSIAC vs Panacea	-0.001	0.999	-0.012	0.010	0.022

[a]All calculators were not significantly different to each other (p > 0.05).

[b]All calculators were significantly correlated to each other (p < 0.001).

4. Discussions

The advancement of surgical technique for cataract surgery has enhanced the expectation of visual outcome from patient and surgeon. It can be achieved if the amount of SIA is predictable and accurately measured prior to cataract surgery [7,22,23]. In this study, we compared mean individual SIA values obtained using three different SIA calculators. All the three calculators provided single individual case analysis which include the magnitude and meridian of the SIA for each individual subject. To analyze the results, we compared the magnitude of mean individual SIA from all calculators. All three SIA calculators in this study employed Holladay method. Our study exhibited that there were no statistically significant differences of SIA values between the three compared calculators in determining individual SIA values for each patient. These nominal differences were also within clinical acceptance range. It is expected that the results were not significant as all calculators utilized similar analysis concept of Cartesian coordinates of Holladay method in calculating their SIA values.

Ofir et al. [24] reported that SIA values calculated by Holladay method using *K*-preoperative and *K*-postoperative data from three keratometry devices (the Lenstar LS900, IOLMaster500 and Atlas Topographer) provided a good agreement result. Nevertheless, no research on agreement of SIA calculators incorporating Holladay method has been explored. In this present study, our results found good agreement in the SIA values between the three Holladay method calculators (the SIAC1.1; SCSIAC; Panacea) by using *K*-reading data obtained using one keratometry device of the IOLMaster700. Based on the inter-calculator agreement of the SIAC1.1, SCSIAC and Panacea result, it indicates that Holladay method produces identical results regardless of model of the SIA calculators.

Each calculator utilizes different platforms in operating the SIA calculator. Thus, it will benefit surgeons by providing more flexibility and accessibility in calculating accurate SIA using any available platforms, operating systems or devices; the results obtained remain significantly equivalent.

All calculators used in this present work do not provide multiple aggregate data analysis and coherence which are clinically applicable. Further research study is warranted to verify the agreement of these SIA calculators when compared to advanced SIA calculators of Holladay method such as the SIA Calculator version 2.1, SIA Calculator version 3.1 [8] and Hill's SIA Calculator [25].

5. Conclusions

Our study concluded that all calculators evaluated in this study provided comparable SIA results. This interchangeability finding suggests that surgeon can employ any of these calculators to calculate the individual SIA.

Declaration

The authors have no financial interest in any calculators and devices used in this research.

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