Comparison of the influence of pupil dilation on predicted postoperative refraction and recommended intraocular lens power among Barrett Universal II, Haigis, and SRK/T calculation formulas: a retrospective study

CURRENT STATUS: UNDER REVIEW

BMC Ophthalmology  BMC Series

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DOI: 10.21203/rs.2.17071/v1

SUBJECT AREAS
Ophthalmology

KEYWORDS
Intraocular lens, Pupil dilation, Anterior chamber depth, Lens thickness, White-to-white, Predicted postoperative refraction, Barrett, Haigis, SRK/T
Abstract
Background We investigated the effect of pupil dilation on predicted postoperative refraction (PPR) and recommended intraocular lens (IOL) power calculated using three different generations of IOL power calculation formulas: Barrett Universal II (Barrett) (new generation), Haigis (4th generation), and SRK/T (3rd generation). Methods This retrospective study included 150 eyes. The following variables were measured and calculated using an optical biometer before and after dilation: anterior chamber depth (ACD), lens thickness (LT), white-to-white (WTW), mean absolute change (MAC) in PPR, and recommended IOL power. PPR and recommended IOL power were calculated by Barrett, Haigis, and SRK/T IOL calculation formulas. Correlations between all changes were analyzed. The influence of pupil dilation on recommended IOL power calculated by each formula was also analyzed. Results MAC in PPR before and after dilation was highest in Barrett, followed by Haigis and SRK/T. Significant differences were found among each MAC. Significant changes were observed before and after dilation in ACD and LT but not in WTW. In Barrett and Haigis, there was a significant positive correlation between change in PPR and change in ACD and a negative correlation between change in PPR and change in LT. Correlations were strongest in Barrett followed by Haigis, especially in LT. Change in PPR in Barrett also demonstrated a significant positive correlation with change in WTW. The recommended IOL power using Barrett and Haigis changed before and after dilation in 23.3% and 19.3% cases; SRK/T showed no change. Conclusions In PPR and recommended IOL power, pupil dilation influenced Barrett most strongly, followed by Haigis and SRK/T. Given the stronger correlation between the change in PPR in Barrett and the change in ACD, LT, and WTW, the change of ACD, LT, and WTW is more important to the influence of dilation on Barrett. The influence of dilation on each formula and variables, including ACD, LT, and WTW is key to improving IOL calculation.

Background
As patient expectations about the outcome of a cataract surgery increases, ophthalmologists need to pay special attention to the accuracy of predicted postoperative refraction (PPR). Various intraocular lens (IOL) calculation formulas are available, such as the third generation formula, SRK/T,1) the fourth generation formula, Haigis,2) and the new generation formula, Barrett Universal II.3) Many research
papers studying the accuracy of the predictability of different IOL calculation formulas have been published.\cite{4,5} Most researchers say that Barrett Universal II may be one of the most reliable IOL calculation formulas. Some studies analyzed the influence of preoperative anterior chamber depth (ACD) on PPR in different IOL calculation formulas.\cite{6,7} They concluded that the influence of preoperative of ACD on PPR varies from formula to formula. There is also some research which examined the influence of pupil dilation on biometric parameters such as ACD, lens thickness (LT), white-to-white (WTW), and recommended IOL power using different IOL calculation formulas.\cite{8,9,10} Thus, there are a small number of research papers which conducted the comparison of the influence of pupil dilation on PPR and recommended IOL power calculated using the different generation IOL calculation formulas, and different biometric parameters, such as ACD, LT and WTW. However, to the best of our knowledge, this is the first study which researched the correlation between PPR and recommended IOL power in three different generation IOL calculation formulas, and change in the different biometric parameters, ACD, LT and WTW. Given that the different generation IOL calculation formulas include different biometric parameters, and they can be influenced by pupil dilation, further research in this area could be interesting.

The purpose of this study was to analyze the influence of pupil dilation on biometric variables and recommended IOL power calculated using Barrett Universal II, Haigis, and SRK/T. Additionally, the correlation among all variables was investigated.

**Methods**

150 eyes in 81 patients were analyzed in this retrospective study. The average age was 72.9 ± 7.7 years (range: 51-87 years), and 39.6% of patients were men (Table 1). Cataract operations without any unexpected events were performed at two eye clinics (Yokosuka Chuoh Eye Clinic and Tsurumi Chuoh Eye Clinic). For all patients, monofocal acrylic single piece IOLs (SN60WF, Alcon Laboratories, Inc., Fort Worth, TX, USA) were inserted.
Table 1. Sex and age distribution

| Parameters       | Mean* [range] |
|------------------|---------------|
| Male, %          | 39.60%        |
| Age, years       | 72.9±7.7 years [51 to 87] |

* Data are presented as means ± standard deviations.

This study was approved by the ethical committees of both eye clinics. Consent to use their medical data for this research was given by all patients whose postoperative best-correction vision was higher than 20/40 without any history of eye problems and intraocular or corneal operations. This research followed the tenets of the Declaration of Helsinki in the entire data collection process.

All biometric variables, including ACD, LT, WTW, PPR, and recommended IOL power, were measured and calculated before and after pupil dilation by IOL Master 700 (Carl Zeiss Meditec AG, Jena, Germany). PPR and recommended IOL power were calculated using three different generation IOL power calculation formulas, Barrett Universal II, Haigis, and SRK/T for SN60WF (Alcon Laboratories, Inc.), using a constant of 119.0 provided by User Group for Laser Interference Biometry.

After the pre-dilation examination, topical tropicamide and phenylephrine (Midrin-P®, Santen, Osaka, Japan) were applied every 15 minutes. After full dilation, the post-dilation examination was performed.

The mean change in ACD, LT, and WTW and mean absolute change (MAC) in PPR in each formula were analyzed. The correlation of the variables above was also investigated. Additionally, the difference in coincidence rate of recommended IOL power in each formula between before and after pupil dilation was checked. Finally, based on the collected data above, the influence of pupil dilation on all variables was analyzed.

To compare change in ACD, LT, and WTW and change in PPR in each formula before and after dilation, the Wilcoxon signed-rank test was used. To investigate the correlation of the variables, the Spearman’s rank-order correlation test was used. The difference in recommended IOL power within ±0.5D was regarded as coinciding. To compare recommended IOL power, the Fisher’s exact test was applied. $P < 0.05$ was regarded as statistically significant in this research. The Bell Curve for Excel,
version 1.03 (Social Survey Research Information Co, Ltd., Tokyo, Japan) was used to analyze statistical data.

Results

The mean pre-dilation ACD, LT, and WTW were 3.08 ± 0.40 mm (range: 2.08–4.28 mm), 4.57 ± 0.46 mm (range: 3.44–5.87 mm), and 11.87 ± 0.37 mm (range: 10.8–12.8 mm), respectively (Table 2).

Table 2. Effect of pupil dilation on anterior chamber depth, lens thickness, and white-to-white

| Parameters | Mean*, mm | Mean difference post-
| D** | D = 0 | D > 0 | P |
|---|---|---|---|---|---|---|
| Pre-dilation | Post-
| ACD | 3.08 ± 0.40 | 3.14 ± 0.41 | 0.06 ± 0.03 | 0 (0.0%) | 0 (0.0%) | 150 (100.0%) | < 0.0001 |
| LT | 4.57 ± 0.46 | 4.55 ± 0.41 | -0.02 ± 0.01 | 124 (82.7%) | 24 (16.0%) | 2 (1.3%) | < 0.0001 |
| WTW | 11.87 ± 0.37 | 11.88 ± 0.38 | 0.02 ± 0.11 | 49 (32.7%) | 39 (26.0%) | 62 (41.3%) | 0.16 |

* Data are presented as means ± standard deviations.

** D is the difference post- minus pre-dilation.
ACD, anterior chamber depth; LT, lens thickness; WTW, white-to-white

Table 2 indicates the influence of pupil dilation on ACD, LT, and WTW. ACD and LT significantly changed after dilation (P < 0.0001), but WTW did not. There was a significant positive correlation between pre-dilation ACD and change in ACD (Spearman's rho = 0.25, P = 0.0017); however, a significant correlation was not seen between LT and WTW (Spearman's rho = 0.092, P = 0.26, and Spearman's rho = -0.016, P = 0.85, respectively) (Figure 1). MAC in PPR using each formula is shown in Table 3. MAC in PPR in Barrett Universal II was highest (0.047 ± 0.029), followed by Haigis (0.035 ± 0.019), and then SRK/T (0.0052 ± 0.0053). Significant differences were found among each MAC in PPR (P < 0.0001).
Table 3. Mean absolute change in predicted postoperative refraction between pre- and post-pupil dilation in the three formulae

| Formulae | Mean absolute change*, diopter |
|----------|-------------------------------|
| SRK/T    | 0.0052 ± 0.0053               |
| Haigis   | 0.035 ± 0.019                 |
| Barrett  | 0.047 ± 0.029                 |

* Data are presented as means ± standard deviations.

P < 0.0001 for SRK/T vs. Haigis, SRK/T vs. Barrett, and Haigis vs. Barrett.

In Barrett Universal II and Haigis, there was significant positive correlation between change in PPR and change in ACD (Spearman's rho = 0.95, P < 0.0001, and Spearman's rho = 0.93, P < 0.0001 respectively); however, this correlation was not observed in SRK/T (Spearman's rho = 0.029, P = 0.63) (Figure 2). On the other hand, in Barrett Universal II and Haigis, there was a significant negative correlation between change in PPR and change in LT (Spearman's rho = -0.89, P < 0.0001, and Spearman's rho = -0.78, P < 0.0001, respectively); nonetheless, this tendency was not found in SRK/T (Spearman's rho = -0.063, P = 0.45) (Figure 3). Only in Barrett Universal II, there was a significant positive correlation between change in PPR and change in WTW (Spearman's rho = 0.19, P = 0.022). This correlation was not found in Haigis and SRK/T (Spearman's rho = 0.14, P = 0.082, and Spearman's rho = 0.15, P = 0.067, respectively) (Figure 4).

The coincidence rates of recommended IOL power before and after pupil dilation in each formula are displayed in Table 4. In 23.3% of cases in Barrett Universal II and 19.3% of cases in Haigis, recommended IOL power changed after dilation. In all cases, recommended IOL power coincided before and after dilation in SRK/T. The inconsistency rate in Barrett Universal II and Haigis was significantly higher than SRK/T (P < 0.0001). In Barrett Universal II, recommended IOL power changed more frequently than in Haigis; however, the difference in coincidence rate was not significant.
Table 4. Coincidence of recommended IOL power between pre- and post-pupil dilation in the three formulas

| Number of eyes | SRK/T       | Haigis  | Barrett  |
|---------------|-------------|---------|----------|
| Coincidence   | 150 (100.0%)| 121 (80.7%)| 115 (76.7%)|
|               | 0 (0.0%)    | 29 (19.3%) | 35 (23.3%) |

P < 0.0001 for SRK/T vs. Haigis or Barrett, and P = 0.48 for Haigis vs. Barrett.

IOL, intraocular lens; SRK/T

Discussion

In this study, PPR and recommended IOL power calculated by three different generation formulas, Barrett Universal II, Haigis and SRK/T were influenced by pupil dilation in different ways. Barrett Universal II was the most sensitive to pupil dilation, followed by Haigis. SRK/T was not influenced by pupil dilation. The change in ACD and LT before and after pupil dilation were more closely involved in influencing Barrett Universal II and Haigis. The change in WTW before and after pupil dilation also influenced only Barrett Universal II.

The improvement of the accuracy of the biomechanical measurement and PPR has gained attention as they are important in choosing the most suitable IOL. Therefore, we have to consider all factors that influence the biomechanical variables and PPR.

Regarding the biomechanical parameters, different generation IOL calculation formulas include different parameters to estimate the effective lens position (ELP), an important factor for PPR. Although the detailed components of the formulae are complex, the vital part for its comprehension is as follows. SRK/T uses corneal curvature radius and axial length (AL), which was published by Retzlaff et al. in 1990. ELP is estimated based on the ACD and AL in Haigis. and Barrett Universal II (new generation formula) uses AL, corneal curvature radius, ACD, LT, and WTW. Many studies have investigated the influence of pupil dilation on these biometric measurements. In a clinical setting, pupil dilation is a vital process of preoperative examination. Therefore, it is important to analyze the possible influence of pupil dilation on PPR and recommended IOL power in third, fourth, and new
generation IOL power calculation formulas, and to investigate the correlation between variables. In many studies, AL and corneal curvature radius are not affected by pupil dilation.\(^{10-12}\) However, ACD was reported to be influenced by pupil dilation.\(^{10-14}\) Compared to ACD, few researches have dealt with the influence of pupil dilation on LT and WTW. Wang X et al.\(^{8}\) demonstrated that LT was significantly affected by pupil dilation. The results on ACD and LT are logical because the ciliary muscles relax and dilator muscles contract through pupil dilation, and as a result, the lens becomes thinner and ACD becomes deeper. It is controversial whether pupil dilation influences WTW. While Huang et al.\(^{10}\) and Arriola-Villalobos et al.\(^{15}\) insisted that WTW was affected by pupil dilation, the opposite result was reported by Wang et al.\(^{8}\) Although the researchers attributed the discrepancy in the influence of pupil dilation on WTW to the error of examinations and imaging artifact, the real mechanism remains unknown.

In our research, while ACD significantly increased after dilation, LT significantly decreased, which are consistent with other studies.\(^{16}\) WTW did not significantly change. When it comes to the influence of pupil dilation on PPR and recommended IOL power, the outcomes of past research vary from formula to formula and from research to research. Rodriguez-Raton et al. showed that PPR in SRK/T was not affected by pupil dilation, but PPR in Haigis was.\(^{12}\) Adler et al. also indicated similar results. The results were reasonable since SRK/T does not include ACD as a biometric parameter, which is significantly affected by pupil dilation, whereas, Haigis does. Our research also showed while PPR in SRK/T did not change after pupil dilation, while PPR in Haigis significantly changed. Concerning Barrett Universal II, although many studies demonstrated the superiority of the accuracy of PPR in Barrett Universal II compared to other formulas\(^{4,5}\), the research which dealt with pupil dilation influence on PPR and recommended IOL power in Barrett Universal II has not been published. Our research indicated that MAC in PPR calculated by Barrett Universal II was the largest, followed by Haigis and SRK/T. This suggests that Barrett Universal II was the most sensitive to pupil dilation, followed by Haigis, and then SRK/T. The difference in the sensitivity to pupil dilation among the
formulas was significant. This tendency was also seen in the coincidence of recommended IOL power in each formula before and after dilation. The recommended IOL power calculated by Barrett Universal II changed most frequently among the formulas, although it was not statistically significant between Barrett Universal II and Haigis. Although some studies demonstrated that the recommended IOL power in Haigis was significantly affected by pupil dilation but not in SRK/T\textsuperscript{10,12,16}, our research was the first to show that Barrett Universal II may be even more sensitive to pupil dilation than Haigis, considering PPR and recommended IOL power.

The analysis of correlation between the change in PPR and the biometric variables indicated that the newer generation formula is more sensitive to pupil dilation. The change in PPR in Barrett Universal II and Haigis showed a significant positive correlation with the change in ACD and a significant negative correlation with the change in LT, but not in SRK/T. This tendency was more remarkable in Barrett Universal II. This result indicated that the change in ACD and LT significantly influenced the change in PPR in the formulas, which included ACD as a biometric parameter, and it was even more influential on the formula that included both ACD and LT as biometric variables. Additionally, the change in PPR in Barrett Universal II indicated a significant positive correlation with the change in WTW, but not in Haigis and SRK/T. This outcome was persuasive since Barrett Universal II was the only formula that included WTW as a biometric factor. Given the fact that all biometric factors, ACD, LT, and WTW, could be significantly influenced by pupil dilation, it is convincing that the more biometric parameters IOL calculation formula includes, the more influential pupil dilation is on the formula. As a result, recommended IOL power calculated by Barrett Universal II changed in many more cases after pupil dilation compared to Haigis and SRK/T.

Thus, there are biometric factors in the IOL calculation formula that are influenced by pupil dilation. In general, the more modern generation formula is, the more biometric parameters are included. Barrett Universal II is said to be one of the most reliable IOL calculation formulas. However, this study demonstrated that, since it includes many more such biometric variables compared to previous generation formulas; eye specialists have to be familiar with these phenomena to improve the accuracy of IOL calculation.
One of the limitations of this study is that the influence of pupil dilation on prediction error in refraction was not analyzed. This additional research can enable optimization of the constant for measurement with or without pupil dilation. This idea may be more useful to improve the accuracy of IOL power calculation. We plan to analyze this investigation in our future research.

Conclusions
In our study, pupil dilation influenced Barrett most strongly, followed by Haigis and SRK/T, in PPR and recommended IOL power. Given the stronger correlation between the change in PPR in Barrett and the change in ACD, LT, and WTW, the change of ACD, LT, and WTW is essential for the influence of dilation on Barrett. The influence of dilation on each formula and variables including ACD, LT, and WTW is key to improving the accuracy of IOL calculation.

List Of Abbreviations
ACD: anterior chamber depth; AL: axial length; ELP: effective lens position; IOL: intraocular lens; LT: lens thickness; MAC: mean absolute change; PPR: predicted postoperative refraction; WTW: white-to-white.

Declarations
ETHICS APPROVAL AND CONSENT TO PARTICIPATE
This study was approved by the ethical committee at Yokosuka Chuoh Eye Clinic and Tsurumi Chuoh Eye clinic.

CONSENT FOR PUBLICATION
Written informed consent for publication of their clinical details and/or clinical images was obtained from the patients. A copy of the consent form is available for review by the editor of this journal.

AVAILABILITY OF DATA AND MATERIALS
The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

COMPETING INTERESTS
The authors declare that they have no competing interests

FUNDING
This research was unfunded.
AUTHORS' CONTRIBUTIONS
TT conceived the concept, designed, analyzed and interpreted the data, and was a major contributor in writing this manuscript. AM analyzed the data and interpreted the analyzed data. NM supervised the entire process in this study. All authors approved the final manuscript.

ACKNOWLEDGEMENTS
This study was presented in September 2019 at the Meeting of European Society of Cataract and Refractive Surgeons, Paris Expo Porte de Versailles, Paris, France.

We would like to thank Editage (www.editage.com) for English language editing services.

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Figures

Figure 1
Correlation between change in ACD (A), LT (B), and WTW (C) and pre-dilation ACD (A), LT (B), and WTW (C).

Figure 2
Correlation between change in ACD and change in PPD in SRK/T (A), Haigis (B), and Barrett (C).

Figure 3
Correlation between change in LT and change in PPD in SRK/T (A), Haigis (B), and Barrett (C).
Correlation between change in WTW and change in PPD in SRK/T (A), Haigis (B), and Barrett (C).

Figure 4