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ORIGINAL RESEARCH

# Evaluation of the Accuracy of Modern Toric Intraocular Lens Formulas Based on Anterior Corneal Measurements

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**Purpose:** We aimed to evaluate the postoperative refractive astigmatism prediction error (RAPE) of three modern toric intraocular lens (IOL) formulas, which estimate posterior corneal astigmatism, using anterior corneal measurements with a swept-source optical coherence tomography biometer, ARGOS® (ARGOS).

**Material and Methods:** This retrospective study included 33 eyes of 33 patients who underwent uneventful cataract surgery implanted with Clareon toric IOLs (model CNW0Tx) using digital guidance. Back-calculation was performed using the KANE toric, Emmetropic Verifying Optical (EVO) toric v2.0, and Barrett toric IOL formulas employing preoperative measurements with the ARGOS biometer, and surgically induced astigmatism was set to 0 diopter (D). RAPE was defined as the difference between the predicted refractive astigmatism and actual subjective refractive astigmatism 1 month after surgery. The Wilcox–Holladay–Wang–Koch statistical method was used to compare the toric IOL formulas.

**Results:** Mean and standard deviation (SD) of RAPE for KANE toric, EVO toric, and Barrett toric formulas were −0.02 ± 0.44 D (95% CI: −0.18 to 0.14), 0.03 ± 0.44 D (95% CI: −0.13 to 0.19), and 0.03 ± 0.43 D (95% CI: −0.12 to 0.18), respectively. The median absolute RAPE were 0.20 D for the KANE toric, 0.23 D for the EVO toric, and 0.27 D for the Barrett toric. The centroid and SD of RAPE for each toric formula were 0.09 ± 0.46 D at 3.25°, 0.04 ± 0.50 D at 172.34°, and 0.02 ± 0.45 D at 103.50°, respectively. No significant difference was noted between the Barrett toric and KANE toric in the x axis ($p = 0.001$).

**Conclusion:** This study provides a further evaluation of the accuracy of modern toric IOL formulas for astigmatism prediction, even though only anterior corneal measurements from ARGOS were used for toric IOL calculations.

**Keywords:** toric intraocular lens, astigmatism, refractive prediction error, biometry

## Introduction

Toric intraocular lenses (IOLs) with cylindrical power can decrease postoperative residual astigmatism and provide uncorrected visual acuity without requiring spectacles.[1] The accurate calculation of IOL power for spherical power before cataract surgery is crucial for postoperative patient satisfaction. Furthermore, accurate calculation of cylindrical power for toric IOLs is essential, as residual astigmatism is associated with patient satisfaction. Visual acuity and reading performance are affected even if a low level of residual astigmatism, such as 0.50–0.75 D, remains following cataract surgery.[2]

Several factors cause errors involving refractive astigmatism prediction, such as IOL misalignment from the target axis, IOL tilt, surgically induced astigmatism (SIA), and inaccurate preoperative corneal measurements, leading to more residual astigmatism than expected.[3–7] Moreover, postoperative residual astigmatism may be overestimated in eyes with with-the-rule astigmatism and underestimated in eyes with against-the-rule astigmatism if only anterior corneal refractive power is utilized for cylindrical power selection for toric IOLs.[8,9]

Some toric IOL calculation formulas that estimate and consider posterior corneal astigmatism (PCA) from anterior corneal measurements have been developed; although most auto kerato-refractometers or biometers that are frequently utilized in preoperative corneal measurements generally measure only the anterior corneal surface.[10–17] The KANE toric

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IOL formula utilizes the predicted effective lens position (ELP) calculated using the KANE formula, and total corneal astigmatism is calculated using a specific algorithm with regression, theoretical optics, and artificial intelligence.[15] The Emmetropic Verifying Optical (EVO) 2.0 toric IOL calculation formula is based on a thick lens and vergence and considers theoretical PCA prediction and different IOL geometries.[13,14,17] The Barrett toric IOL formula derives the predicted ELP calculated using the Barrett Universal II formula and incorporates a theoretical model to estimate PCA when determining the required cylindrical power.[10–12] Regarding the spherical equivalent (SE), the KANE, EVO, and Barrett Universal II formulas have accurate refractive predictions.[18–23]

The ARGOS® (ARGOS, Alcon Vision LLC, Fort Worth, TX, USA), a swept-source optical coherence tomography (SS-OCT) biometer, utilizes segmented refractive indices to measure axial length in contrast to other SS-OCT biometers that use the equivalent refractive index. The ARGOS measures only anterior corneal surface using OCT, combined with a 2.2-mm diameter ring composed of 16 light-emitting diodes.[24,25] Unlike SS-OCT biometers such as the IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) that are capable of measuring total corneal power including the posterior corneal astigmatism, the ARGOS measures only anterior corneal astigmatism. Therefore, toric IOL calculations using the ARGOS rely on predicted posterior corneal astigmatism rather than directly measured values.

Comparing and evaluating the refractive astigmatism prediction error (RAPE) of each toric IOL calculation formula is instrumental for predicting postoperative residual astigmatism accurately. Shammas et al have previously evaluated the RAPE of the Barrett toric IOL formula using measurements obtained using the ARGOS system.[26] However, to the best of our knowledge, no study has evaluated and compared the accuracy in RAPE of the KANE, EVO, and Barrett toric IOL formulas using the ARGOS system.

# Materials and Methods

## Study Design

An institutional review board of a non-profit and independent organization (MINS, Tokyo, Japan; Approval number: 210235) reviewed and approved this retrospective chart review study. Chart data were searched for patients with a history of cataract surgery from June 2022 to January 2023. Written informed consent was obtained from all patients before the study. This study was conducted in accordance with the tenets of the Declaration of Helsinki and Ethical Guidelines for Medical and Biological Research Involving Human Subjects in Japan.

The inclusion criteria included patients aged ≥20 years with cataract and postoperative corrected distance visual acuity ≥0.10 logarithmic minimum angle of resolution (logMAR). Additionally, only eyes implanted with Clareon toric IOL models CNW0T3 to CNW0T9 (Alcon Vision LLC) were included to decrease variability related to the IOL type. Eyes subjected to ocular surgery between cataract surgery and the first month post-surgery, implantation of a capsule tension ring, any ocular disease affecting postoperative visual acuity, or intraoperative complications were excluded. One eye from each patient was included for analysis in this study. If both eyes were eligible for inclusion, the eye that underwent the first operation was included.

## Data Collection and Outcome Measurements

Preoperative biometric data from the ARGOS and patient demographics from medical records were retrospectively collected. Visual acuity and subjective spherical and cylindrical data were collected using a Landolt ring chart 1 month after surgery. After creating a constant 2.4-mm temporal incision, all cataract surgeries including phacoemulsification and IOL implantation were performed by an experienced surgeon (YM) using the Centurion® Vision System (Alcon Vision LLC) at the Eye Care Clinic. The CNW0T toric IOLs were implanted into the capsular bag, and the IOL axes were aligned according to digital guidance provided by the ARGOS system.

Back-calculation was conducted using the KANE toric (https://www.iolformula.com), EVO toric v2.0 (https://www.evoiolcalculator.com), and Barrett toric (https://calc.apacrs.org/toric_calculator20/ToricCalculator.aspx) online toric IOL calculators using preoperative biometry data from ARGOS, with the SIA set to 0 D. All optional parameters such as lens thickness and central corneal thickness were entered in this back-calculation. The EVO toric formula selected ARGOS for biometric measurement. Spherical equivalent predictions for implanted IOL powers and astigmatism predictions for the implanted toric model were collected using the KANE toric, EVO toric, and Barrett toric IOL formulas.

The primary endpoint was RAPE, defined as the difference in each toric formula between the predicted refractive astigmatism and actual subjective refractive astigmatism 1 month after surgery. Other endpoints included refractive prediction error (RPE) and the percentage of eyes with absolute RPE and residual astigmatism (categorized as ≤0.25, ≤0.5, ≤0.75, and ≤1.0 D). RPE was defined as the difference in each toric formula between the predicted SE and the actual subjective SE 1 month after surgery. The mean RPE was optimized and adjusted to zero for each formula to eliminate systematic errors due to the IOL constant variations based on the previously reported method.[27] Additionally, the distribution of preoperative corneal astigmatism and recommended toric models for each toric formula were evaluated. The angle of error between the IOL axis planned by the ARGOS system and the actual IOL axis taken by a slit-lamp microscope 1 month after surgery was measured as IOL misalignment. In this study, high-resolution slit-lamp photographs were obtained, and the IOL axis was determined using image-based rotational analysis. Typical subconjunctival blood vessels or iris patterns were utilized to ascertain proper eye alignment. Several previous studies assessing toric IOL prediction accuracy have adopted the 1-month postoperative refraction as their primary evaluation point, as refractive outcomes are generally considered to be sufficiently stable at this time.[28] Therefore, the use of 1-month refraction in the present study aligns with established methodology in the literature and provides a clinically relevant basis for comparing the performance of modern toric formulas.

## Statistical Analysis

The sample size required for RAPE (with a confidence level of 95% and a confidence width of 0.25 D, which is less than the minimum measurement for subjective refraction) was calculated to be 33 eyes, when the standard deviation (SD) of the RAPE was 0.70 D.[15]

JMP® Pro (version 18; SAS Institute Inc., Cary, NC, USA) and R software (v. 4.1.2, R Software Service, Inc.) were used for all statistical analyses. Preoperative and postoperative corrected and uncorrected visual acuity were converted to logMAR visual acuity. Furthermore, the mean and SD of patient demographics, RAPE, RPE, IOL misalignment, and visual acuity were calculated. The Wilcox–Holladay–Wang–Koch (WHWK) statistical method was used to compare the toric IOL formulas.[29] The RAPE was evaluated for both centroid values via vector analysis and arithmetic mean absolute values. The RAPE vectors for each toric formula were plotted as double-angle plots.[30] The threshold for statistical significance was set at $p < 0.05$.

# Results

This study included 33 eyes from 33 patients. Table 1 summarizes the patient demographics for these eyes. The mean ± SD for age of the patients in this study was 70.3±13.9 years. The mean preoperative corneal astigmatism was 1.60 ± 0.67

**Table 1** Patient Demographic Data

| | Mean (SD) |
|---|---|
| Age, year | 70.3 (13.88) |
| Male/female (patients), number | 16/17 |
| Averaged keratometry, D | 44.67 (1.59) |
| Keratometric astigmatism, D | 1.60 (0.67) |
| Axial length, mm | 24.31 (1.68) |
| Preoperative corrected visual acuity, logMAR | 0.41 (0.36) |
| Postoperative corrected visual acuity, logMAR | −0.04 (0.07) |
| Postoperative uncorrected visual acuity, logMAR | 0.00 (0.11) |
| Residual astigmatism, D | 0.19 (0.41) |
| IOL misalignment, ° | 3.37 (3.85) |

**Abbreviations**: D, diopter; IOL, intraocular lens; logMAR, logarithm of the minimum angle of resolution; SD, standard deviation.

**Table 2** Refractive Astigmatism Prediction Error for KANE, EVO, and Barrett Toric

| | Mean ± SD (D) | Median Absolute | Centroid ± SD (D) | X Axis ± SD (D) | Y Axis ± SD (D) | Eyes with ≤0.5 D (%) |
|---|---|---|---|---|---|---|
| KANE | −0.02 ± 0.44 | 0.20 | 0.09 ± 0.46 at 3° | 0.09 ± 0.40 | 0.01 ± 0.23 | 81.1 |
| EVO | 0.03 ± 0.44 | 0.23 | 0.04 ± 0.50 at 172° | 0.03 ± 0.45 | −0.01 ± 0.23 | 84.8 |
| Barrett | 0.03 ± 0.43 | 0.27 | 0.02 ± 0.45 at 103° | −0.01 ± 0.40 | −0.02 ± 0.21 | 84.8 |

**Abbreviations**: D, diopter; SD, standard deviation.

D and mean residual astigmatism was 0.19 ± 0.41 D. The mean and SD of IOL misalignment 1 month after surgery was −0.05 ± 5.15° and the mean absolute value was 3.38 ± 3.85°.

The mean ± SD of RAPE for the KANE toric, EVO toric 2.0, and Barrett toric IOL formulas were −0.02 ± 0.44 D (95% CI: −0.18 to 0.14), 0.03 ± 0.44 D (95% CI: −0.13 to 0.19), and 0.03 ± 0.43 D (95% CI: −0.12 to 0.18), respectively (Table 2). The median absolute RAPE was 0.20 D for the KANE toric, 0.23 D for the EVO toric 2.0, and 0.27 D for the Barrett toric formula (Table 2). No significant difference in absolute RAPE was observed between the toric IOL formulas ($p > 0.05$, WHWK method). Table 2 lists the centroid values of RAPE for each toric IOL formula. The centroid value ± SD of the RAPE for the KANE toric, EVO toric 2.0, and Barrett toric formulas were 0.09 ± 0.46 D at 3°, 0.04 ± 0.50 D at 172°, and 0.02 ± 0.45D at 103°, respectively. No significant difference was noted between the Barrett toric and KANE toric formulas in x axis ($p = 0.001$). Figure 1 displays a double-angle plot of the RAPE vectors for each toric IOL formula. Figure 2 shows the distribution of preoperative corneal astigmatism and recommended toric model for each formula. Nineteen of the 33 eyes (57.6%) were recommended the same toric power model using the three toric formulas.

The median absolute RPE was 0.28 D with the KANE formula, 0.30 D with the EVO 2.0 formula, and 0.30 D with the Barrett formula (Table 3). The proportions of eyes within an absolute RPE of 0.5 D were 75.8% for the KANE formula, 75.8% for the EVO 2.0 formula, and 72.7% for the Barrett formula.

## Discussion

The KANE, EVO 2.0, and Barrett Universal II formulas have been shown to offer accuracy in the prediction of postoperative SE.[18–23] However, comparison studies of the RAPE for the KANE toric, EVO toric, and Barrett toric remain limited. Herein, these modern toric formulas demonstrated accurate astigmatism prediction despite the utilization of only ARGOS-measured anterior corneal data, as PCA was estimated rather than directly measured.

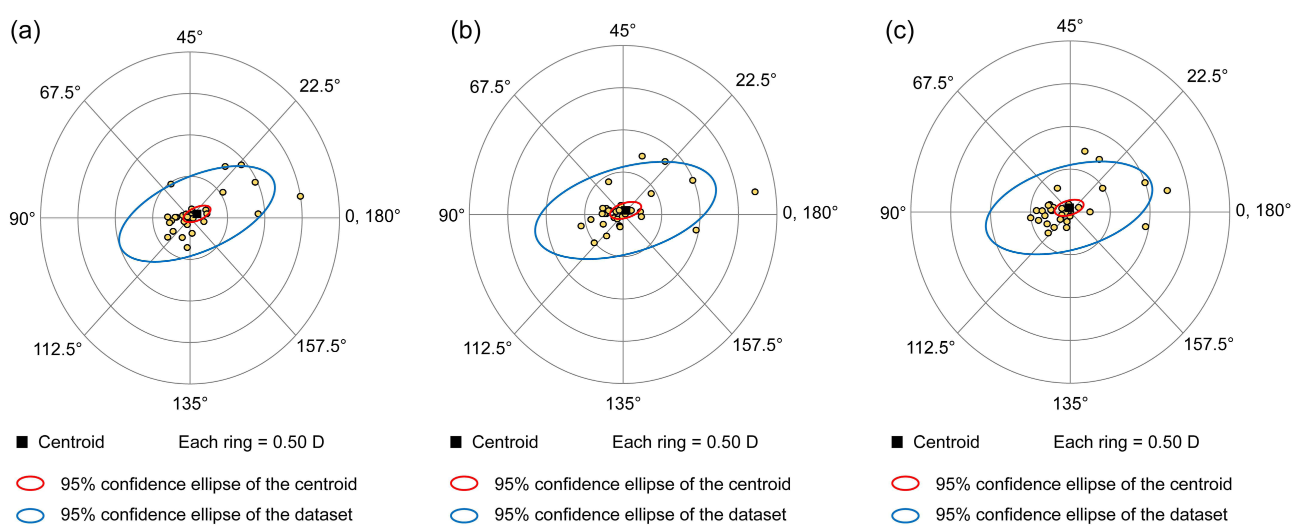


**Figure 1** Double-angle plots of the refractive astigmatism prediction error. (**a**) KANE toric; (**b**) EVO toric; (**c**) Barrett toric.

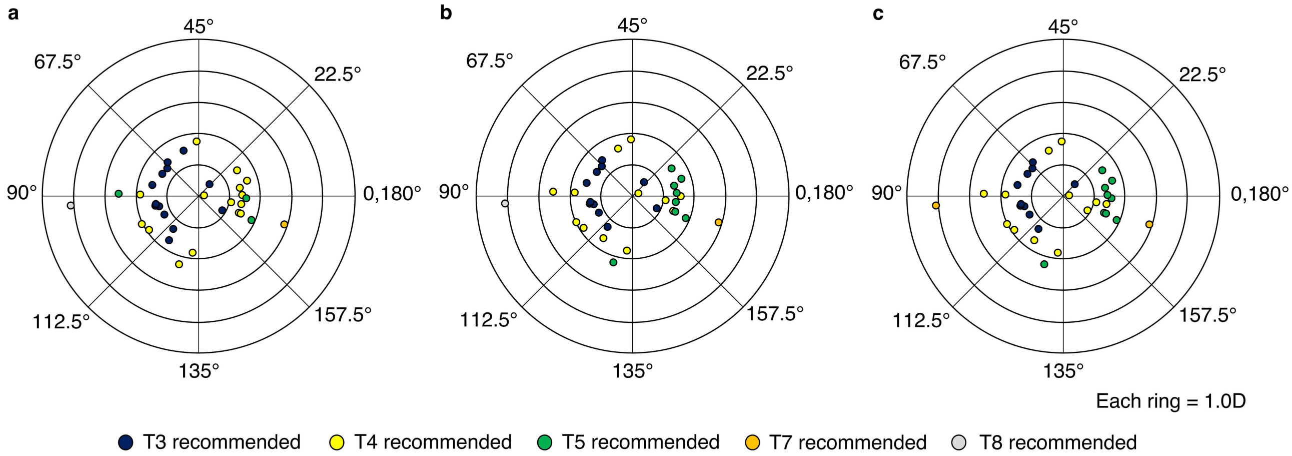


**Figure 2** Double-angle plots of the preoperative corneal astigmatism and recommended toric intraocular lens (IOL) model. (**a**) KANE toric; (**b**) EVO toric; (**c**) Barrett toric.

The findings of this study are comparable to those of previous studies. Shammas et al reported a mean RAPE of 0.41 D with the Barrett toric IOL formula using ARGOS data in eyes with AcrySof IQ toric IOLs.[26] Another study by Yang et al found that the mean RAPE for the KANE toric and Barret toric IOL formulas, measured using IOLMaster 700, was 0.26 D in both eyes with AcrySof IQ toric IOLs.[31] Conversely, the results for RAPE from the current study were better than those from the studies by Kane et al and Yang et al, which reported that the mean RAPE for the KANE toric and Barrett toric in the AcrySof IQ toric IOL were 0.47 D and 0.51 D including 0.60 and 0.59 D, respectively.[15,32] Additionally, the current study's findings of a mean RAPE of 0.32 D and an 84.8% proportion of eyes with a RAPE ≤0.50 D using the EVO toric 2.0 formula was better than those found by Kane et al (0.51 D and 58.9%) and Pantanelli et al (0.57 D and 48.6%).[14,15] In the present study, the corneal incision was performed by an experienced surgeon using a small 2.4-mm incision, decreasing the variability in SIA. Additionally, digital guidance from the ARGOS system was used during surgery to align the toric IOL with the planned axis, leading to a small amount of IOL misalignment from the planned axis following surgery. Furthermore, we utilized the optimized IOL constant for IOL calculations in our clinic, which may explain the differences between our results and those of previous reports.

Previous studies have reported mean PCA of 0.24 and 0.31 D.[33,34] Moreover, 96.6% of eyes with with-the-rule astigmatism and 73.9% of eyes with against-the-rule astigmatism were noted with against-the-rule astigmatism as PCA.[35] Furthermore, when PCA was not accounted for in the cylindrical toric model selection, eyes with with-the-rule astigmatism tended to be overcorrected, whereas eyes with against-the-rule astigmatism were undercorrected.[9] In this study, a stronger cylindrical toric model was recommended preoperatively for eyes with against-the-rule astigmatism than for eyes with with-the-rule astigmatism for all three toric formulas, which allows the estimation of the against-the-rule astigmatism as PCA using the KANE, EVO 2.0, and Barrett toric IOL formulas.

The distributions of the recommended toric models were similar among the three formulas; however, the proportion of eyes for which the same toric model was recommended by the three toric formulas was 57.6%, with the KANE toric formula revealing a slightly lower toric model in eyes with against-the-rule astigmatism preoperatively than that of the other two toric formulas. Kane et al reported that the KANE toric formula with the IOLMaster 500 or 700 revealed

**Table 3** Refractive Prediction Error for KANE, EVO, and Barrett Formulas

| | Mean RPE ± SD (D) | Med Absolute RPE (D) | Percentage of Absolute RPE with (%) | | | |
|---|---|---|---|---|---|---|
| | | | ≤0.25 D | ≤0.50 D | ≤0.75 D | ≤1.00 D |
| KANE | 0.28 ± 0.34 | 0.28 | 36.4 | 75.8 | 90.9 | 97.0 |
| EVO | 0.27 ± 0.35 | 0.30 | 36.4 | 75.8 | 90.9 | 100.0 |
| Barrett | 0.37 ± 0.32 | 0.30 | 36.4 | 72.7 | 81.8 | 93.9 |

**Abbreviations**: D, diopter; Med absolute RPE, median absolute refractive prediction error; RPE, refractive prediction error; SD, standard deviation.

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a significantly lower RAPE than the EVO 2.0 and Barrett toric formulas.[15] Conversely, Liu et al reported that the EVO 2.0 and Barrett toric IOL formulas provided higher and largely comparable predictive accuracies, whereas the KANE toric formula consistently demonstrated lower accuracy than both,[36] consistent with the results of the present study showing a significant difference between the Barrett toric and KANE formulas. This difference may be due to the type of biometer used to measure corneal astigmatism and the sample size.

A primary limitation of this study is its small sample size, which restricts the generalizability of the findings, which warrant cautious interpretation. Nonetheless, the inclusion of only one eye per patient is regarded as a methodological strength. Second, we did not evaluate the effects of IOL misalignment on refractive astigmatism error. However, the mean absolute IOL misalignment in this study was 3.37°, indicating that its impact on astigmatism correction was minimal. Some corneal topographical methods or SS-OCT can be utilized to measure PCA, and some studies have compared the predictive accuracy of the measured and predicted PCA.[26,28,37,38,] Stewart et al reported that toric IOL calculations yield higher predictive accuracy when PCA exhibits a vertical steep axis, in which case formulas using predicted PCA perform well; conversely, in eyes with a non-vertical PCA axis, the use of measured PCA significantly improves refractive prediction accuracy compared with predicted values.[28] Furthermore, although the Clareon toric IOL used in this study generally achieves refractive stability by 1 month postoperatively, corneal stability may take 3–4 months to be fully established in some cases.[30] Therefore, the use of 1-month refraction as the primary endpoint may not capture potential longer-term refractive changes, IOL rotation, or capsular effect. Future studies should underscore comparing the prediction accuracy of the measured and predicted posterior corneal astigmatism using modern toric formulas with larger sample sizes and longer follow-up periods exceeding 4 months.

## Conclusions

The modern toric IOL formulas evaluated in this study demonstrated favorable accuracy in predicting postoperative refractive astigmatism using only anterior corneal measurements obtained with ARGOS. These findings support the clinical utility of anterior-surface–based calculations.

## Data Sharing Statement

The datasets generated and analyzed in this study are available from the corresponding author upon reasonable request.

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## Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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## Disclosure

The author has no conflicts of interest to declare for this work.

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