Variations of Intraocular Pressure Measured by Goldmann Applanation Tonometer, Tono-Pen, iCare Rebound Tonometer, and Pascal Dynamic Contour Tonometer in Patients With Corneal Edema After Phacoemulsification

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**Précis:** Edematous corneas had lower Goldmann applanation tonometer (GAT) intraocular pressure (IOP) compared with other tonometers. A significant, mild negative correlation between central corneal thickness (CCT) and GAT IOP was found in a group of significant edematous corneas with CCT increases of >100 μm.

**Purpose:** To compare the IOP that was randomly obtained with the GAT, Tono-Pen, iCare, and Pascal dynamic contour tonometer in patients with corneal edema after phacoemulsification.

**Materials and Methods:** Corneal edema was quantified by CCT measurement. The agreement between IOP measurements assessed by different instruments was evaluated using Bland-Altman plots. The relationship between CCT and IOP was investigated using the coefficient of correlation. The CCT and IOP were compared between the periods of postsurgical edema and after its resolution.

**Results:** The mean age of 60 patients was 75.9 ± 7.8 years. CCT increased significantly after surgery, by an average of 96.1 ± 39.9 μm (P < 0.001). Relative to the IOPs measured with the GAT in edematous eyes: the mean difference in Tono-Pen IOPs was 4.7 mm Hg; 95% LOA, −2.2 to 6.8 mm Hg. For Pascal dynamic contour tonometer, was 3.0 mm Hg; 95% LOA, −0.4 to 6.5 mm Hg. Edematous corneas had significantly lower GAT IOP than Tono-Pen IOP: 12.3 ± 3.2 versus 16.9 ± 3.1 (P = 0.02). Pearson correlation coefficients (r) showed a high correlation between the 4 tonometers in eyes without edema. There was a significant, mild negative correlation between CCT and GAT IOP (r = −0.25, P = 0.02) in a group of significant edematous corneas with CCT increases of >100 μm: GAT IOP decreased by 3.1 mm Hg for every 10-μm increase in CCT.

**Conclusions:** IOP readings with GAT tended to be lower than those obtained with the other tonometers, especially the Tono-Pen. GAT IOP readings in cases of severe corneal edema should be interpreted with caution.

**Key Words:** intraocular pressure, tonometers, corneal edema, Bland-Altman plots

Intraocular pressure (IOP) is a crucial component in the glaucoma management. This is of clinical concern because erroneous IOP measurements may lead to misdiagnosis, and undertreatment or overtreatment of glaucoma. Although the gold standard for IOP measurements is the Goldmann applanation tonometer (GAT), previous studies have shown that the accuracy of GAT IOPs depends on factors such as corneal hysteresis (CH), corneal resistance factor, corneal curvature, corneal hydration, and central corneal thickness (CCT). The GAT overestimates IOP in eyes with a thicker-than-average cornea and underestimates IOP in eyes with a thinner-than-average. This concept could not be applied in eyes with corneal thickening because of increased corneal hydration.

Several tonometers have been developed to overcome the limitations of the GAT. These include the dynamic contour tonometer (DCT), Tono-Pen, and rebound tonometer (RT). A study in glaucomatous eyes without corneal edema showed a good concordance between the GAT and iCare RT.

Several studies have been published on the variations of IOP values obtained with contact and noncontact tonometers in eyes with corneal edema after surgery, and the reported results are contradictory.

It remains unclear whether the corneal edema after cataract surgery will affect the variations of IOP measured with different tonometers, especially in cases of obvious edema. The present study compared IOP readings obtained with the GAT, Tono-Pen, iCare, and Pascal dynamic contour tonometer (PDCT) in eyes that had corneal edema after phacoemulsification and in the same eyes after the edema had resolved.

**MATERIALS AND METHODS**

**Study Design**

A single-center, prospective, comparative study was performed at Songklanagarind Hospital, Thailand, between May 2014 and January 2018. The study adhered to the tenets of the Declaration of Helsinki and was performed according to...
the principles of Good Clinical Practice. The ethics committee of Prince of Songkla University approved the study. All patients provided written informed consent. The study was registered prospectively with the Clinical Trials Registry (NCT01998568).

Study Population, Demographics, and Ocular Characteristics
The study subjects had all undergone uneventful, sutureless clear corneal phacoemulsification, with intracapsular-lens implantation under topical anesthesia. All operations were performed by 1 surgeon (W.K.). The patients were enrolled on the first day postsurgery, and only if 2 investigators (W.K. and A.T.) were in agreement about the diagnosis of corneal edema. The inclusion and exclusion criteria are summarized in Table 1. Patient age, sex, and eye laterality were obtained from clinical records. Recruited patients underwent assessment of best-corrected visual acuity (BCVA) between the periods of postsurgical corneal edema and after its resolution. The automated keratometry including corneal astigmatism and radii of curvatures were obtained (ARK-1a; NIDEK, Tokyo, Japan).

CCT and IOP Measurements
Posturgical corneal edema was quantified by CCT measurement. All CCT measurements were obtained by the same operator (A.T.) using an ultrasound pachymeter (SP-100; TOMEY, Tokyo, Japan). Following the CCT measurement, IOP was measured with the 4 types of tonometers in random order; GAT (Haag-Streit AG, Koeniz, Switzerland), Tono-Pen (Reichert Technologies Inc., Depew, NY), RT (iCare; Tiotat Oy, Espoo, Finland), and PDCT (Ziemer Ophthalmic Systems AG, Port, Switzerland). A quality index of ≥3 on the PDCT was accepted. A reliability index of <5% was accepted on the Tono-Pen. A single drop of tetracaine hydrochloride 0.5% (Alcon Laboratories, Fort Worth, TX) was used before the pachymetry and IOP measurement. Three IOP measurements with each tonometer were performed on each eye, and the averaged values were used for the analyses. All IOP measurements were made by the same operator (W.K.). All measurements were conducted in the morning (8 to 9 AM), with the patient seated. IOP values were obtained within 10 minutes, to prevent circadian effects on IOP. The study patients were observed until the corneal edema had resolved, then the CCT and IOP were measured again in the same order, for comparison.

Statistical Analysis
Descriptive statistics were used to summarize patient demographics and baseline ocular characteristics. The normal distribution of each data set was confirmed using the Kolmogorov-Smirnov test. The IOPs and CCTs were reported as the mean and SD of the mean. BCVA, CCT, and IOP were compared between eyes with edema and after the resolution of edema. Bland-Altman plots were generated to assess the range of agreement between Tono-Pen and GAT, iCare and GAT, and PDCT and GAT. The relationships between differences in IOP measurement between each tonometer, as compared with the GAT were evaluated using Pearson correlation coefficients. The correlations between age, BCVA, and corneal curvature and the IOPs measured by the different tonometers were evaluated using the Pearson and the Spearman rank correlation method when appropriate. Simple linear regression equations were calculated to assess the relationships between the CCT and IOP values obtained from the GAT, Tono-Pen, iCare, and PDCT. CCT and IOP values were entered as independent and dependent variables, respectively. The statistical analysis was performed using R Statistical Software (version 3.3.0; Foundation for Statistical Computing, Vienna, Austria). P-values <0.05 are considered to be significant.

RESULTS
Sixty eyes of 60 cataract patients were included in the cohort composed of 32 males and 28 females. The mean age was 75.9 ± 7.8 years (mean ± SD). Baseline preoperative CCT was 515.2 ± 31.8 µm. The mean CCT of eyes with corneal edema was 619.2 ± 51.6 µm. There was a statistically significant increase in CCT (by 96.1 ± 39.9 µm, P < 0.001) in edematous corneas postsurgery, a mean increase of 20%. The CCT decreased to 522.5 ± 32.2 µm when the edema was resolved, with a mean follow-up of 17.5 ± 9.3 days

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**TABLE 1. Summary of Inclusion and Exclusion Criteria**

| Inclusion Criteria | Exclusion Criteria |
|--------------------|--------------------|
| Age > 18-y old and older | Related to surgical procedures |
| Patients who had corneal edema involving the center of cornea after phacoemulsification | Combined phacoemulsification and trabeculectomy |
| Patients willing to comply with the study protocol and sign the consent form | Clear cornea phacoemulsification that has suture on the cornea |
| | Previous history of intraocular surgery, ocular trauma before phacoemulsification |
| | Vitrectomized eye |
| | Related to underlying and ocular history |
| | History of glaucoma or ocular hypertension or using antiglaucoma medication |
| | History of diabetic retinopathy staged as severe nonproliferative or worse |
| | Pregnant or breast-feeding women |
| | Related to the difficulty of having reliable measurements |
| | History of refractive surgery or any keratoplastic procedure |
| | Corneal opacities |
| | Wears contact lenses |
| | Astigmatism > 2.5 D |
| | Subjects with having poor or eccentric fixation or nystagmus |
| | Excessive eye squeezing |
| | Known allergy to topical anesthesia and fluorescein solution |

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TABLE 2. Demographics, Baseline Characteristics, and Parameters of Eyes

| Demographic Characteristics | N = 60 |
|-----------------------------|-------|
| Age/years (mean ± SD, range) | 75.9 ± 7.8, 54-90 |
| Male/female, n (%)          | 32 (53)/28 (47) |
| Parameters of eyes          |       |
| Right/left, n (%)           | 35 (58)/25 (42) |
| Corneal astigmatism, mean ± SD (D) | 0.72 ± 0.63 (0.05-1.93) |
| Corneal curvature, mean ± SD (mm) | 6.72 ± 0.24 |
| Eyes with CCT increase > 100 μm, n (%) | 25 (42) |
| BCVA/log MAR, median (IQR), range |       |
| Eyes having edematous cornea | 0.60 (0.39-0.79), 0.20-1.60 |
| Nondematous cornea          | 0.20 (0.09-0.20), 0.0-0.39 |
| CCT, mean ± SD (μm)         |       |
| Baseline preoperative CCT   | 515.2 ± 31.8 (450-605) |
| Eyes having edematous cornea postoperation | 619.2 ± 51.6 (543-721) |
| Nondematous cornea postoperation | 522.5 ± 32.2 (485-600) |
| Mean increase of CCT        | 96.1 ± 39.9 (30-171), P < 0.001* |
| IOPs obtained on edematous cornea, comparison with GAT as a reference, mean ± SD, range (mm Hg) |       |
| GAT                          | 12.3 ± 3.2 (5-20) |
| Tono-Pen                     | 16.9 ± 5.1 (9-25), P = 0.02† |
| iCare                        | 14.6 ± 3.2 (8-21), P = 0.35† |
| PDCT                         | 15.3 ± 3.1 (10-24), P = 0.21† |
| IOPs obtained on nondematous cornea, comparison with GAT as a reference, mean ± SD, range (mm Hg) |       |
| GAT                          | 13.4 ± 3.6 (7-23) |
| Tono-Pen                     | 15.0 ± 3.2 (9-22), P = 0.29† |
| iCare                        | 13.6 ± 3.6 (6-24), P = 0.76† |
| PDCT                         | 15.3 ± 3.4 (8-21), P = 0.63† |

*Student t test.
†Repeated measured analysis of variance with Bonferroni adjustment for multiple comparisons.

When measured on edematous corneas, the mean IOP was 12.3 ± 3.2 mm Hg with the GAT, 16.9 ± 3.1 mm Hg with the Tono-Pen, 14.6 ± 3.2 mm Hg with the iCare, and 15.3 ± 3.1 mm Hg with the PDCT (SDC Fig., Supplemental Digital Content 1, http://links.lww.com/IJG/A492). A significant difference was only found between the mean IOP values obtained with the GAT and Tono-Pen (P = 0.02). No significant differences were found between the IOPs obtained with the 4 tonometers in eyes without corneal edema.

In eyes with corneal edema, the mean difference between Tono-Pen and GAT IOPs was 4.7 mm Hg with 95% limits of agreement (LOA) of −0.3 to 9.6 mm Hg. Comparing GAT versus iCare, the mean difference was 2.3 mm Hg; 95% LOA, −2.2 to 6.8 mm Hg. Comparing GAT versus PDCT, the mean difference was 3.0 mm Hg; 95% LOA, −0.4 to 6.5 mm Hg. The Tono-Pen showed the largest difference in IOPs compared with the GAT, whereas the iCare showed the smallest differences compared with the GAT (Figs. 1A, C, E). IOPs measured in eyes without corneal edema, the Bland-Altman plots show good overall agreement between the different tonometers (Figs. 1B, D, F).

A positive and statistically significant moderate correlation was found between the GAT IOP measurements and Tono-Pen IOPs (r = 0.70, P < 0.001; Fig. 2A) when IOP was measured in eyes with corneal edema. Comparisons of GAT IOPs versus iCare IOPs (Fig. 2B) and GAT IOPs versus PDCT IOPs (Fig. 2C) showed positive and statistically significant good correlations (r = 0.76, P < 0.001 and r = 0.85, P < 0.001, respectively). Figure 3 shows the correlations between the IOP readings with different tonometers in eyes without corneal edema. A significant-excellent correlation was found between the IOPs measured with the GAT and PDCT (r = 0.92; P < 0.001) in eyes without corneal edema (Fig. 3C).

Figure 4 shows results describing the relationship between the IOPs that were measured with different tonometers and the CCTs, in eyes with edematous corneas. A negative, but statistically insignificant, a correlation was found between GAT IOP measurements and CCT (r = −0.11, P = 0.416; Fig. 4A). IOP measurements with the Tono-Pen, iCare, and PDCT showed slightly positive, but insignificant correlations with the CCTs (Figs. 4B-D). Of 60 eyes, 25 (42%) eyes had CCT that increased > 100 μm from the baseline value. There was a statistically significant increase of 134.4 ± 18.3 μm in CCT in the subgroup of 25 patients with marked corneal edema postsurgery (a mean increase of 26%, P < 0.001). There was a statistically significant negative correlation between CCT and the GAT IOP (r = −0.25, P = 0.02) in eyes with marked corneal edema. GAT IOP decreased by 3.1 mm Hg for every 10-μm increase in CCT in eyes in which CCT increased > 100 μm from the baseline reading. This study did not find correlations between age, visual acuity, or corneal curvature, and the IOPs measured by the 4 tonometers on edematous corneas. When the analyses were performed on measurements from eyes in which the corneal edema had resolved, significant, poor-to-moderate positive correlations between CCT and GAT IOP (r = 0.65, P < 0.001), CCT and Tono-Pen IOP (r = 0.44, P = 0.001), and Tono-Pen and iCare IOP (r = 0.43, P = 0.001), and CCT and PDCT IOP (r = 0.58, P < 0.001) were found.

DISCUSSION

Aging patients with advanced cataracts commonly have corneal edema after phacoemulsification. Erroneous IOP measurements might lead to misdiagnosis, and under- or overtreatment of glaucoma, which are common in this population. Several studies have compared IOP measurements obtained with different tonometers in subjects with corneal edema, but most investigators measured IOP in enucleated cadaveric eyes with an artificial anterior chamber or in eyes with corneal edema artificially induced by contact lens wear. Few studies have reported on IOP measured in patients after cataract surgery. We specifically measured the postsurgical IOP and CCT values after phacoemulsification when the corneas were edematous and compared them with the IOP and CCT values after resolution of the edema. We have found that the eyes with extensive corneal edema after phacoemulsification showed a significant mild negative correlation between CCT and IOP measured with the GAT. IOP readings with GAT tended to be lower than those obtained with the other tonometers, especially the Tono-Pen.
PDCT showed the smallest variability in IOP values in eyes with and without corneal edema. The IOP measurements from the 4 tonometers did not differ significantly in eyes in which the corneal edema had resolved.

Our findings agreed with previously published work by Simon et al\(^3\) who measured GAT IOP on edematous cadaver corneas undergoing osmotically controlled hydration. They found that GAT readings were inversely correlated with change in corneal thickness.\(^3\) The same conclusion was reached by Huang et al\(^17\) who reported that the higher postoperative corneal edema (7% increase in CCT) was associated with the lower GAT IOPs (8 mm Hg underestimation) in cataract patients with a mean age of 62.5 years and a mean increase in CCT of 10% postoperatively. The authors suggested that higher amounts of postoperative corneal edema were associated with lower GAT IOP.\(^17\)

Contrary to this study, Oh et al\(^16\) reported that change in CCT was not significantly correlated with the change in IOP measurements with the GAT and the DCT. Our findings are also contrary to studies\(^6,15\) that previously reported that GAT IOP is overestimated from a contact lens-induced edematous cornea. We speculate that the biomechanical changes might differ between eyes with thickened CCT because of surgery versus contact lens-induced edema. Previous studies\(^4,17,19,20\) shown that the differences in GAT IOP measurements on the edematous cornea, resulting from short-term contact lens wear versus phacoemulsification, may result from differences in the mechanisms of fluid drawn into the cornea. Lu et al\(^4\) reported the short-term

![Bland-Altman plots for the comparison between the intraocular pressure (IOP) obtained from Goldmann applanation tonometer (GAT) and other methods. The linear regression lines were plotted. A, Tono-Pen (TON) versus GAT; edematous cornea ($r=0.056$, $P=0.67$). B, TON versus GAT; nonedematous cornea ($r=-0.211$, $P=0.10$). C, iCare versus GAT; edematous cornea ($r=-0.004$, $P=0.97$). D, iCare versus GAT; nonedematous cornea ($r=-0.066$, $P=0.51$). E, Pascal dynamic contour tonometer (PDCT) versus GAT; edematous cornea ($r=-0.086$, $P=0.51$). F, PDCT versus GAT; nonedematous cornea ($r=-0.188$, $P=0.15$). CCT indicates central corneal thickness. *Pearson correlation coefficient. Figure 1 can be viewed in color online at www.glaucomajournal.com.](image-url)
wear of contact lenses causes corneal hypoxia. Hypoxia stimulates the formation of lactate. The lactate acts as an osmolyte that draws water into the corneal stroma across both epithelial and endothelial surfaces. After phacoemulsification, corneal edema may be a consequence of irrigating solutions and phacoemulsification energy on the sodium potassium ATPase pump function at corneal endothelial cells. Previous investigation has shown that lower levels of edema (eg, because of contact lens wear) may increase corneal rigidity. In contrast, higher levels of edema (eg, because of surgical intervention) may be associated with reduced corneal rigidity. The direct comparison of corneal biomechanics during contact lens wear and very soon after cataract surgery is limited by the presence of wound in the early postoperative period.

The DCT is thought to be relatively unaffected by corneal biomechanics. It uses contour-matching instead of the applanation principle. We have found a significant correlation between the IOPs measured with the GAT and PDCT in eyes with and without corneal edema. Bland-Altman plots showed the range of good agreement between the 2 methods. PDCT showed the smallest variability among tonometers in measuring IOP in eyes with corneal edema. In eyes with edematous corneas, IOP measurements with PDCT showed slightly positive, but insignificant correlations with the CCTs. Our results are consistent with those reported by Herr et al, who carried out IOP measurements by GAT and DCT in eyes before and after phacoemulsification. They included only 30 patients with advanced cataracts. CCT increased significantly (by 89.7 ± 107.4 μm, P < 0.001) after cataract surgery. IOP values using the GAT were significantly correlated with DCT measurements in eyes with corneal edema in their study. No significant difference was found between GAT IOP and DCT IOP in the eyes with and without corneal edema. They concluded that GAT and DCT seem to be equally valuable in IOP determination in cases of postoperative corneal edema.

The Tono-Pen is based on the applanation principle, but the application area is smaller than that of the GAT so, theoretically, the Tono-Pen is less affected by CCT than is the GAT. There is no published study on IOP values obtained with the Tono-Pen on living adult eyes with postsurgical corneal edema, rather than cadaveric models. We found, in 60 eyes with postsurgical corneal edema, that the mean IOP values from the Tono-Pen were the highest among the 4 tonometers. IOP readings with GAT were lower than those obtained with the Tono-Pen. The Tono-Pen showed the largest difference in IOPs compared with the GAT. GAT IOP and Tono-Pen IOP showed a positive, statistically significant, moderate correlation in our study. Our results support the previous report of Neuburger et al. They investigated the influence of corneal edema on IOP in 8 artificial anterior chambers using cadaveric corneas. The performance of the Tono-Pen, GAT, RT, and the Ocular Response Analyzer (ORA) was compared; the study suggested that the Tono-Pen outperformed the GAT in eyes with corneal edema. It may be that the relatively small contact area of the Tono-Pen with the cornea cause greater independence from corneal biomechanical properties.
The iCare is a portable RT, on the basis of the induction-based impact principle. The present study shows that the RT IOP was 2.31 mm Hg higher than the GAT IOP ($P = 0.35$) in edematous corneas. We found a slightly positive, but insignificant correlation between IOP measurements with RT and the CCT ($r = 0.19, P = 0.14$). When we performed the analysis in eyes in which the postsurgical corneal edema had resolved, a significant, poor-to-moderate positive correlation of CCT and RT ($r = 0.43, P = 0.001$) was found. Our results are similar with those reported by Fuest et al. who carried out IOP measurements with the GAT and RT in eyes before and after cataract surgery. The mean RT IOP values were 1.1 ± 2.2 mm Hg higher than the GAT values ($P = 0.01$). IOP values from both methods were significantly correlated in nonedematous corneas ($r = 0.94, P < 0.001$) and edematous corneas ($r = 0.94, P < 0.001$). However, unlike our results, Fuest et al. did not find a correlation of GAT IOP and RT IOP to CCT in eyes with and without corneal edema. The CCT in their study increased after surgery by 52.2 ± 35.1 µm, which is less than in our report.

Clear corneal phacoemulsification may change ocular biomechanical properties. Increases in CCT, and reductions in CH and corneal resistance factor have been reported after phacoemulsification. Postoperative corneal edema leads to a change of corneal viscoelastic properties, resulting in a lower damping capacity of the cornea. Reduction in CH may be associated with the underestimation of IOP during measurement with the GAT.

Gür Güngör et al. examined the impact of postoperative corneal edema on the IOP measured by the GAT and the ORA. The mean age of their patients was 65.7 years (range, 60 to 69 y). One day after surgery, CCT had increased significantly (mean increase of 27%) compared with preoperative CCT. Their mean increase in CCT is comparable with that in our study, which is 20% for all eyes and 25% for eyes with extensive corneal edema. GAT IOP was significantly underestimated compared with the ORA.

To our knowledge, this is the first study to compare IOP values obtained with the GAT, Tono-Pen, iCare, and PDCT in eyes with surgically induced corneal edema. We believe that these results may be applicable in the typical clinical setting, in which aging patients undergo phacoemulsification and experience corneal edema. This study differs from previous reports in which the IOP and CCT were compared in eyes before and after surgery. Our study has been done in postsurgical cataract patients. We have specifically measured the post-surgical IOP and CCT values when the corneas were edematous and compared them with the IOP and CCT values after resolution of the edema. We hypothesize that clear corneal phacoemulsification might affect the energy-damping and elasticity properties of the cornea, so the comparison of IOP readings should be made postoperatively to control for the effect of postsurgical corneal biomechanical changes.

We acknowledge several limitations in this study. First, the sample size was relatively small, which may explain the weak and nonsignificant correlations. Second, the results cannot extrapolate to corneal edema resulting from other pathologies, such as bullous keratoplasty, Fuchs endothelial dystrophy or corneal refractive surgery. Third, we could not compare the IOP values obtained with the 4 tonometers to the true IOP measured by manometry. Finally, we did not study corneal biomechanical effects on IOP variations, by using the noncontact ORA, because of limited resources.

**FIGURE 3.** Correlations between the intraocular pressure (IOP) readings with different tonometers in eyes with nonedematous cornea. A, Goldmann applanation tonometer (GAT) and Tono-Pen ($r = 0.845$, $P < 0.001$). B, GAT and iCare ($r = 0.811$, $P < 0.001$). C, GAT and PDCT, Pascal dynamic contour tonometer (PDCT) ($r = 0.921$, $P < 0.001$). Figure 3 can be viewed in color online at www.glaucomajournal.com.
CONCLUSIONS

IOP measurement with 4 different techniques showed good-to-excellent correlations and good agreement when obtained from nonedematous corneas. The IOP readings with the Tono-Pen, iCare, and PDCT showed moderate-to-good correlations with those obtained with the GAT in eyes with corneal edema. PDCT showed the smallest variability in IOP measurements in eyes with and without corneal edema. The GAT tended to underestimate IOP in cases of postsurgical corneal edema, especially when CCT increased by >100 μm. This study provides meaningful information to aid in the choice of tonometers for clinical practice in the setting of corneal edema after phacoemulsification. Further studies are needed to better understand the effect of postsurgical corneal edema on IOP measurements with common tonometers, including the study of the corneal biomechanical properties by the ORA.

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