

Intraocular Pressure Based on Dynamic Bidirectional Applanation and Air-puff Tonometry: A Comparative Study

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ABSTRACT

Aim: The aim of this study is to compare intraocular pressure (IOP) in healthy eyes measured via dynamic bidirectional applanation and air-puff tonometry, and to evaluate the effect of age, gender, the spherical equivalent (SE), mean keratometry (Kmean), corneal hysteresis (CH), and the corneal resistance factor (CRF) on IOP measurements.

Materials and methods: IOP measured in 956 healthy eyes using the ocular response analyzer (ORA) and air-puff tonometer was compared in this cross-sectional retrospective study. Correlations between IOP, and age, gender, SE, Kmean, CH, and CRF were investigated using univariate and multivariate analyses. Bland–Altman plots were used to determine the level of agreement between the IOP values obtained with the two devices: IOP via air-puff tonometer (IOP-air-puff) and corneal-compensated IOP (IOPcc) using ORA (ORA-IOPcc). Linear mixed modeling was used to evaluate the effects of the study parameters on IOP. Intermethod reliability was established by calculating intraclass correlation coefficients (*r*).

Results: The mean age of the patients was 39.56 ± 14.44 years. The mean IOPair-puff and ORA-IOPcc were 16.72 ± 2.37 mm Hg and 13.75 ± 3.12 mm Hg, respectively ($p < 0.001$). The mean CH and CRF were 11.14 ± 1.61 mm Hg and 10.53 ± 1.65 mm Hg, respectively. Multivariate analysis showed that both CH and CRF were significantly correlated with IOP-air-puff and ORA-IOPcc ($p < 0.001$). The 95% limit of agreement for IOP-air-puff and IOPcc was -2.843 to 8.784 . There was a significant correlation between IOP-air-puff and ORA-IOPcc ($r = 0.443$, $p < 0.001$); the R^2 value was 0.196.

Conclusion: A low degree of agreement was noted between IOP-air-puff and ORA-IOPcc. The present findings show that air-puff tonometry overestimates IOP, as compared to ORA.

Clinical significance: IOP based on air-puff tonometry must be interpreted in conjunction with other ophthalmologic findings and the same IOP measuring device should be used for follow-up evaluations.

Keywords: Air-puff tonometry, Corneal hysteresis, Corneal resistance factor, Intraocular pressure, Ocular response analyzer.

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INTRODUCTION

IOP is well known to be the only modifiable risk factor for the development and progression of glaucoma.^{1–3} The IOP level and IOP fluctuation during follow-up are the most important risk factors for the progression of glaucoma.^{1,3–5} An increase in the mean IOP of as little as 1 mm Hg is important;³ therefore, accurate assessment of IOP is crucial for the diagnosis of glaucoma and optimal treatment.

IOP was first measured via Goldmann applanation tonometry in the mid-1950s. In its current incarnation (little has changed since the 1950s), Goldmann applanation tonometry remains a popular and widely used method of tonometry, although it is not accurate enough to measure the true IOP.⁶ As such, the air-puff tonometer, ocular response analyzer (ORA) (Reichert, Corp., Buffalo, NY), dynamic contour tonometer, and other commercially available handheld tonometry devices have been developed.

Air-puff tonometry is a form of applanation tonometry that employs a calibrated column of compressed air to briefly flatten the corneal apex. It is the most common type of tonometry used for routine eye examination and screening purposes. Air-puff tonometry is used to measure IOP without anesthetizing the ocular surface and is associated with a lower risk of contamination than other types that use tonometers that make contact with the cornea during measurement. Similar to applanation devices, air-puff tonometers are affected by such corneal characteristics such as central corneal thickness (CCT) and ocular rigidity.⁷

The ORA is a modern tonometer designed to measure IOP while taking into consideration the variability in each patient's

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corneal biomechanical properties, as well as to measure corneal biomechanical parameters. Unlike conventional noncontact tonometry, the ORA measures both inward and outward movements of the cornea. As such, the ORA provides 2 IOP values (Goldmann-correlated IOP [IOPg] and IOPcc), and novel metrics indicative of corneal biomechanical properties (CH and the CRF). IOPg is the mean of the 2 applanation pressures (inward and outward). IOPcc is an empirically derived value indicative of IOP that is independent of corneal thickness and biomechanical properties.⁸ CH is a measure of the viscous dampening properties of the cornea, whereas CRF is correlated to CCT and is strongly associated with corneal elastic response.

The aim of the present study is to compare IOP in healthy eyes measured via dynamic bidirectional applanation and air-puff

tonometry, and to evaluate the effect of age, gender, the SE, Kmean, CH, and CRF on IOP measurements.

MATERIALS AND METHODS

This retrospective study included 956 eyes in 478 patients that presented to the ophthalmology clinic for a routine eye examination. Patients were consecutively included in the study according to the inclusion and exclusion criteria. Inclusion criteria were ORA and air-puff tonometry measurement at the time of examination and a waveform score (WS) ≥ 3.5 .⁹ The presence of any ocular disease, including glaucoma (cup-disc ratio >0.3 , cup-disc asymmetry between eyes, and an IOP >22 mm Hg via both air-puff tonometry and ORA measurement), a history of ocular surgery or trauma, contact lens use, and regular use of eye drops were the exclusion criteria. All the patients underwent a full ophthalmological examination, including best-corrected visual acuity based on the Snellen acuity chart, slit-lamp biomicroscopy, and dilated fundus examination. Patients with a best-corrected visual acuity $<20/25$ and with corneal astigmatism of ≥ 3 diopters⁶ were excluded from the study. The study protocol was approved by the Institutional Review Board and was performed in accordance with the tenets of the Declaration of Helsinki.

The primary outcome measures were age, gender, SE, Kmean, CH, CRF, and two IOP measurements—IOP via an air-puff tonometer (IOP-air-puff) and IOPcc via the ORA (ORA-IOPcc). The IOP-air-puff value was the mean of three air-puff tonometer measurements (CT-80 Non-contact Tonometer, Topcon, Japan). The CT-80 is reported to provide results comparable to those provided by a Goldmann applanation tonometer, in terms of the magnitude and repeatability of the measured IOP.¹⁰ Among the four consecutive ORA measurements performed in each patient, the measurement with the highest WS was accepted as the IOPcc value. All measurements were performed between 0800 and 1800. Diurnal variation in IOP, which is a well-known phenomenon,¹¹⁻¹³ was not taken into consideration because air-puff tonometer and ORA IOP measurements were performed consecutively during the same examination.

Statistical analysis was performed using the NCSS (Number Cruncher Statistical System) 2007 (Kaysville, Utah, USA). Descriptive statistical methods (frequency, percentage, and mean \pm SD), the Shapiro–Wilk test, and graphics were used to evaluate the study data. The Wilcoxon signed rank test was used to compare IOP-air-puff and ORA-IOPcc values. Linear mixed modeling was used to evaluate the effects of the study parameters on IOP-air-puff, ORA-IOPcc, CH, and CRF. Pearson’s correlation analysis was used to assess the strength of correlation between the measurements. Bland–Altman plots were used to evaluate the degree of agreement between IOP-air-puff and ORA-IOPcc. Intermethod reliability was established by calculating intraclass correlation coefficients (*r*). Results were evaluated at the 95% CI and the level of statistical significance was set at $p < 0.05$.

RESULTS

In total, 266 (55.6%) of the patients were females and 212 (44.4%) were males. The mean age of the patients was 39.56 ± 14.44 years (range: 11–91 years). Kmean, and mean SE, IOP-air-puff, ORA-IOPcc, CH, and CRF are shown in Table 1. Univariate analysis showed that CH and CRF were significantly correlated with IOP-air-puff (Table 2); for every 1 mm Hg increase in CH, IOP-air-puff increased 0.243 mm Hg,

Table 1: Summary of study parameters

Variables	Mean \pm SD (min–max)
SE	-0.80 ± 2.15 (–12.75 to 6.50)
Kmean	43.14 ± 1.49 (36.25–47.75)
IOP-air-puff	16.72 ± 2.37 (10.00–21.00)
ORA-IOPcc	13.75 ± 3.12 (5.30–24.90)
CH	11.14 ± 1.61 (6.30–17.30)
CRF	10.53 ± 1.65 (6.00–15.60)

ORA-IOPcc, corneal-compensated IOP measured via ocular response analyzer

and for every 1 mm Hg increase in CRF, IOP-air-puff increased 0.816 mm Hg ($p < 0.001$; linear mixed modeling). Multivariate analysis showed that age, CH, and CRF were significantly correlated with IOP-air-puff (Table 2); for every 1 year increase in age, IOP-air-puff decreased 0.010 mm Hg, for every 1 mm Hg increase in CH, IOP-air-puff decreased 1.174 mm Hg, and for every 1 mm Hg increase in CRF, IOP-air-puff increased 1.845 mm Hg ($p = 0.011$, $p < 0.001$, and $p < 0.001$ respectively; linear mixed modeling).

Univariate analysis showed that gender, age, Kmean, and CH were significantly correlated with IOPcc (Table 3); females had significantly lower ORA-IOPcc values than males ($p = 0.003$); for every 1 year increase in age, ORA-IOPcc increased 0.043 mm Hg, for every 1-diopter increase in Kmean, ORA-IOPcc decreased 0.381 mm Hg, and for every 1 mm Hg increase in CH, ORA-IOPcc decreased 1.192 mm Hg ($p < 0.001$) (linear mixed modeling). According to multivariate analysis, CH and CRF were significantly correlated with ORA-IOPcc (Table 3); for every 1 mm Hg increase in CH, ORA-IOPcc decreased 3.512 mm Hg and for every 1 mm Hg increase in CRF ORA-IOPcc increased 2.864 mm Hg ($p < 0.001$; linear mixed modeling). Age was significantly correlated with CH; for every 1 year increase in age, CH decreased 0.021 mm Hg ($p < 0.001$; linear mixed modeling). Kmean was significantly correlated with CH; for every 1-diopter increase in Kmean, CH increased 0.150 mm Hg ($p = 0.001$; linear mixed modeling).

There was a significant difference between IOP-air-puff and ORA-IOPcc values ($p < 0.001$; Wilcoxon signed rank test); IOP-air-puff values were a mean 2.970 mm Hg higher than ORA-IOPcc values (Fig. 1). Bland–Altman plots produced a 95% limit of agreement between IOP-air-puff and ORA-IOPcc of -2.84 to 8.78 mm Hg. The difference between IOP-air-puff and IOPcc increased as the mean of IOP-air-puff and ORA-IOPcc increased. A significant correlation was noted between IOP-air-puff and ORA-IOPcc ($r = 0.443$, $p < 0.001$; Pearson’s correlation analysis). IOP-air-puff values explained 19.6% of the variance in ORA-IOPcc values ($R^2 = 0.196$). The intraclass correlation coefficient was 0.427 which indicated fair reliability between the two IOP measurements (95% CI: -0.072 to 0.666). As seen in Figures 2 and 3, the difference between the 2 IOP measurements increased as IOP-air-puff increased and decreased as ORA-IOPcc increased ($r = 0.335$, $p < 0.001$, and $r = -0.696$, $p < 0.001$, respectively).

DISCUSSION

In the present study, there was a significant difference in mean IOP measurements obtained via an air-puff tonometer (16.72 mm Hg) and ORA (13.75 mm Hg), even though they were positively correlated with each other. Furthermore, Bland–Altman plots showed that there were fairly wide intervals of agreement

Table 2: Effect of study parameters on IOP-air-puff measurements

		IOP-air-puff				95% CI	
		Estimate	Std. error	t	p	Lower	Upper
Univariate	Intercept	16.771	0.153	109.921	<0.001*	16.471	17.070
	Gender (F)	-0.099	0.205	-0.484	0.629	-0.501	0.303
	Intercept	16.845	0.297	56.805	<0.001*	16.262	17.427
	Age	-0.003	0.007	-0.463	0.643	-0.017	0.011
	Intercept	16.690	0.107	155.654	<0.001*	16.480	16.901
	SE	-0.032	0.043	-0.742	0.458	-0.115	0.052
	Intercept	20.578	2.822	7.293	<0.001*	15.036	26.120
	Kmean	-0.090	0.065	-1.370	0.171	-0.218	0.039
	Intercept	14.003	0.520	26.927	<0.001*	12.983	15.024
	CH	0.243	0.046	5.308	<0.001*	0.153	0.333
Multivariate	Intercept	8.118	0.415	19.543	<0.001*	7.303	8.934
	CRF	0.816	0.039	21.009	<0.001*	0.740	0.892
	Intercept	11.592	1.674	6.923	<0.001*	8.302	14.881
	Gender (F)	0.099	0.110	0.894	0.372	-0.118	0.315
	Age	-0.010	0.004	-2.554	0.011 [†]	-0.018	-0.002
	SE	0.006	0.026	0.245	0.807	-0.045	0.058
	Kmean	-0.030	0.038	-0.803	0.422	-0.105	0.044
	CH	-1.174	0.059	-19.903	<0.001*	-1.290	-1.059
	CRF	1.845	0.057	32.524	<0.001*	1.734	1.957

Linear mixed model, **p* < 0.01, [†]*p* < 0.05

Table 3: Effect of study parameters on ORA-IOPcc measurements

		ORA-IOPcc				95% CI	
		Estimate	Std. error	t	p	Lower	Upper
Univariate	Intercept	14.176	0.195	72.521	<0.001*	13.792	14.561
	Gender (F)	-0.775	0.262	-2.957	0.003*	-1.290	-0.260
	Intercept	12.058	0.374	32.201	<0.001*	11.322	12.794
	Age	0.043	0.009	4.796	<0.001*	0.025	0.060
	Intercept	13.742	0.139	98.970	<0.001*	13.469	14.014
	SE	-0.004	0.056	-0.079	0.937	-0.115	0.106
	Intercept	30.173	3.610	8.358	<0.001*	23.082	37.263
	Kmean	-0.381	0.084	-4.554	<0.001*	-0.545	-0.217
	Intercept	27.031	0.575	47.035	<0.001*	25.903	28.159
	CH	-1.192	0.051	-23.574	<0.001*	-1.292	-1.093
Multivariate	Intercept	14.818	0.692	21.424	<0.001*	13.461	16.175
	CRF	-0.102	0.064	-1.580	0.114	-0.228	0.025
	Intercept	22.828	0.146	155.934	<0.001*	22.540	23.116
	Gender (F)	0.003	0.010	0.292	0.771	-0.016	0.021
	Age	2.164×10^{-4}	3.508×10^{-4}	0.617	0.538	4.729×10^{-4}	0.001
	SE	-1.107×10^{-4}	0.002	-0.048	0.962	-0.005	0.004
	Kmean	-0.002	0.003	-0.717	0.474	-0.009	0.004
	CH	-3.512	0.005	-650.380	<0.001*	-3.522	-3.501
	CRF	2.864	0.005	559.460	<0.001*	2.854	2.874

Linear mixed model, **p* < 0.01

ORA-IOPcc; corneal-compensated IOP measured via ocular response analyzer

for intermethod analysis, and agreement varied depending on the IOP level. The wide limits of agreement between these methods indicate that one IOP value cannot be satisfactorily substituted for another.

The diagnosis and follow-up of glaucoma is primarily dependent on IOP measurement. Nonetheless, there is no clear line between a safe and an unsafe IOP, but for screening purposes, an IOP >22 mm Hg is considered an important risk factor for the



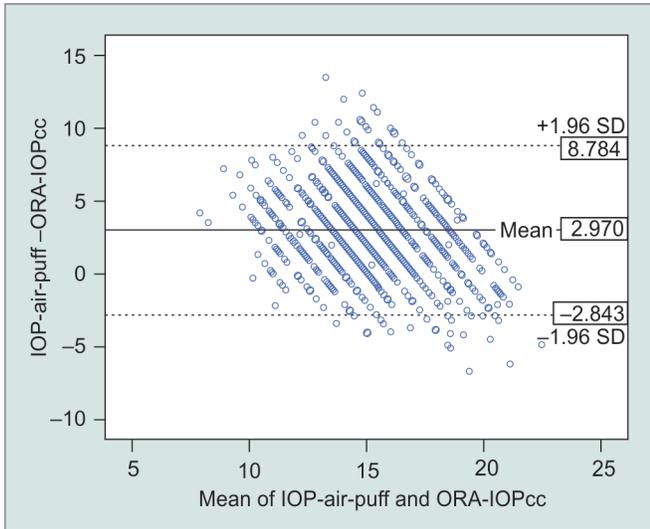


Fig. 1: Bland–Altman plots of the difference in IOP-air-puff and ORA (ORA-IOPcc), vs the mean of the 2 measurements

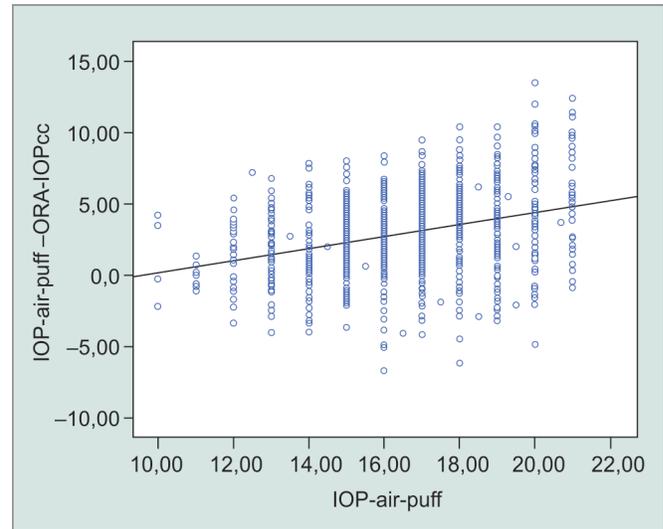


Fig. 2: Correlation between IOP-air-puff, and the difference between IOP-air-puff and ORA-IOPcc ($r = 0.335, p < 0.001$)

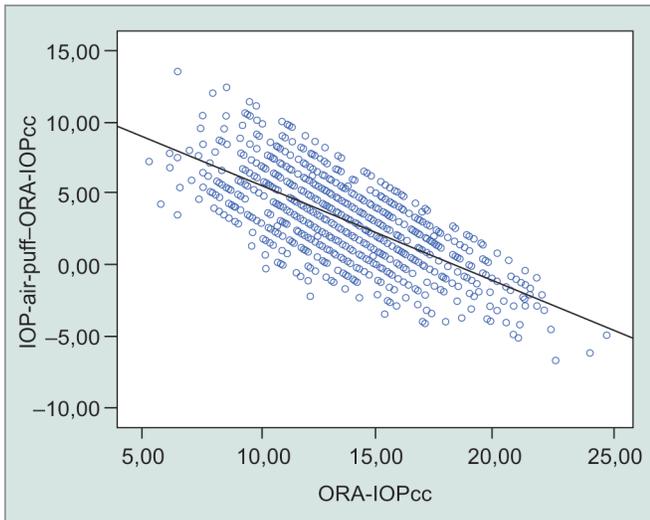


Fig. 3: Correlation between ORA-IOPcc, and the difference between IOP-air-puff and ORA-IOPcc ($r = -0.696, p < 0.001$)

development of glaucomatous damage. Goldmann applanation tonometry was once considered the gold standard for IOP measurement, but the procedure is affected by corneal physical properties, of which CCT and corneal viscoelasticity most strongly affect IOP measurements.^{6,14–16}

The need for accurate IOP measurement has led to the development of a number of noncontact tonometry methods. The nature of the relationship between the cornea and IOP, and the level of agreement between different types of tonometers are not fully known. The air-puff tonometer is the most commonly used tonometry device, especially in clinics with high patient volume. The advantages of air-puff tonometry are that it does not require the use of anesthetic drops and is not associated with the risk of corneal abrasion during applanation. Additionally, there is no risk of transmitting infectious agents via the tonometer tip, as there is when using a Goldmann applanation tonometer. Despite these advantages, the reliability of IOP measurements obtained via air-puff tonometry remains controversial.

It is recommended that if an air-puff tonometry reading is high, then IOP should be measured using another type of tonometry device.¹⁷ According to Lagerlöf et al.,¹⁸ air-puff tonometer IOP measurements of 20–30 mm Hg are unreliable. In the present study, the difference between IOP-air-puff and ORA-IOPcc values increased as IOP-air-puff measurements increased ($r = 0.335, p < 0.001$). A recently introduced noncontact tonometer, ORA, measures IOP taking into consideration corneal biomechanical properties and, thus, yields a more precise IOP measurement (IOPcc) in vivo. The intra- and interexaminer reproducibility of IOP via ORA is high, and together with corneal biomechanical metrics reliably measures IOP.¹⁹

Although it has been reported that modern versions of the air-puff tonometer correlate well with the Goldmann applanation tonometer,⁷ more recent studies report that it does not. IOP measured via air-puff tonometry was reported to be significantly higher than that measured via Goldmann applanation tonometry.^{17,20–22} Jorge et al.²¹ noted that air-puff tonometry (Reichert R7) overestimated IOP by about 1.7 mm Hg on average, as compared to Goldmann applanation tonometry. The effect of corneal biomechanical properties on differences in IOP measured via air-puff tonometry and Goldmann applanation tonometry has been investigated.²³ CRF, followed by CCT and CH, were the best predictors of differences in IOP between the two techniques. Similarly, Jorge et al.²¹ reported that IOP based on air-puff tonometry was significantly correlated with CRF, but not other dimensional parameters of the eye (corneal curvature, anterior chamber depth, corneal diameter, axial length). They also investigated the level of agreement between air-puff tonometer IOP and IOPcc in 92 eyes, and reported that there was poor agreement between the measurements.

Kouchaki et al.²⁴ investigated the agreement of four tonometry techniques (Goldmann applanation tonometer, dynamic contour tonometer, non-contact tonometer, and ocular response analyzer), and found that the agreement limit was relatively large even though the mean difference of measured IOP by dynamic contour tonometer, noncontact tonometer, and ocular response analyzer with Goldmann applanation tonometer was less than 2 mm Hg. They also stated that CCT and CRF were important influencing factors on

the performance of tonometers. Similarly, Oncel et al.²⁵ compared the IOP measurements of ocular response analyzer, dynamic contour, Goldmann applanation, and noncontact tonometry. They found that ORA IOPcc and dynamic contour tonometry readings were not clinically interchangeable with Goldmann applanation and noncontact tonometry readings.

The level of agreement between IOP measured via Goldmann applanation tonometer and ORA was also investigated and it is reported that ORA overestimates IOP, as compared to the Goldmann applanation tonometer.^{26–28} The mean difference between Goldmann applanation tonometer IOP and IOPcc was 8.3 mm Hg.²⁶ On the other hand, Medeiros et al.²⁹ investigated the level of agreement between IOP based on Goldmann applanation tonometer and IOPcc, and reported that the mean difference in IOP between the 2 devices was essentially zero, but Martinez-de-la-Casa et al.²⁶ study population consisted of glaucoma patients, whereas Medeiros et al.'s²⁹ study included patients without glaucoma. Kotecha et al.³⁰ investigated the agreement of IOP measurements obtained with the Goldmann applanation tonometer, the Pascal dynamic contour tonometer, and the Reichert ocular response analyzer and found that Goldmann applanation tonometry IOP measurements were approximately 2 mm Hg lower than IOP measured with either the dynamic contour tonometer or the ORA. They stated that CRF was associated with the IOP measurement differences between these devices.

In the present study, multivariate analysis showed that gender, SE, and Kmean were not correlated with IOP-air-puff or IOPcc values. IOP was reported to decrease with age.³¹ In the present study, age was significantly correlated with IOP-air-puff values, whereas age and ORA-IOPcc were not correlated. In addition, CH and CRF were significantly correlated with IOP-air-puff and ORA-IOPcc values, as expected.

It was reported that repeated tonometry causes a reduction in IOP.^{32–35} Recep et al.³⁴ suggested a time interval of 2 minutes or 10 minutes between successive IOP measurements with a Goldmann applanation tonometer for accurate measurement. Gunvant et al.³⁵ suggested a longer time interval (≥ 15 minutes) between successive IOP measurements using a pulsatile ocular blood flow tonograph. In contrast, it was reported that repeating IOP measurements using an air-puff tonometer does not alter IOP.³⁶ Due to the retrospective nature of the present study, the time interval between IOP-air-puff and ORA-IOPcc measurements, and the order in which they were performed are not known. Nonetheless, the ocular massage effect associated with Goldmann applanation tonometry did not occur during the present study's IOP-air-puff or ORA-IOPcc measurements.

Accurate direct measurement of IOP is only possible using a manometer and puncturing the eye, but currently, all IOP measuring devices used in outpatient clinics indirectly assess IOP. Air-puff tonometers are the easiest type of device to use, and air-puff tonometry is noninvasive and more comfortable for patients than conventional Goldmann applanation tonometry. As such, air-puff tonometry is a suitable method for screening of IOP despite the potential for erroneous IOP measurement. The ORA is a more reliable tonometer that it takes into account corneal physical properties, but it is not used as frequently as the air-puff tonometer. The present study aimed to determine the level of agreement between IOP measured via an air-puff tonometer and ORA. To the best of our knowledge, the present study is the largest

population-based study on the level of agreement between IOP-air-puff and ORA-IOPcc.

The study has some limitations. We do not have data about the Goldmann applanation tonometry measurements of the study population. As such, we could not compare the IOP-air-puff and ORA-IOPcc measurements with Goldmann applanation tonometry measurements, which is the study's major limitation. Another limitation of the present study is the lack of CCT measurements of the study population. As earlier studies reported, IOP measurements are strongly affected by corneal thickness.⁷¹⁶ Also, although we considered that consecutive measurements first with air-puff tonometer or ORA might not have affected the readings of the second measurement, it could have had an impact on the results and that this is may be considered as a limitation of the study. In the present study, IOP was measured only in healthy eyes; greater variability may be encountered when measuring eyes with corneal pathology, a history of corneal surgery, and glaucoma. As such, the present findings should not be generalized to all patient populations.

CONCLUSION

There was a low degree of agreement between IOP-air-puff and ORA-IOPcc values. The air-puff tonometer overestimated IOP, as compared to IOP measured via ORA. The difference in IOP-air-puff and ORA-IOPcc values was significant, which is most probably due to the primary difference between these two devices—during IOP measurement ORA takes into account individual corneal characteristics (corneal thickness and viscoelasticity), whereas the air-puff tonometer does not.

CLINICAL SIGNIFICANCE

Although air-puff tonometer is the most common type of tonometry used for routine eye examination and screening purposes, it may erroneously give higher IOP values than other indirect IOP measurement techniques. It is better to take this into consideration while evaluating IOP air-puff values. Furthermore, the low degree of agreement between IOP-air-puff and ORA-IOPcc values revealed that the same IOP measuring device should be used for follow-up evaluations of the same patient.

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