Tzu Chi Medical Journal 25 (2013) 43–46

Contents lists available at SciVerse ScienceDirect

Tzu Chi Medical Journal

journal homepage: www.tzuchimedjnl.com

Original Article

Comparisons of wavefront refraction, autorefraction, and subjective manifest refraction

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ARTICLE INFO

Article history:
Received 5 November 2012
Received in revised form
10 December 2012
Accepted 27 December 2012

Keywords:
Autorefraction
Subjective manifest refraction
Wavefront refraction

ABSTRACT

Objectives: To compare cycloplegic wavefront refraction, autorefraction, and subjective manifest refraction.
Materials and Methods: Thirty-one myopic eyes in 17 patients were studied. Subjective manifest refraction was measured and deemed as the true refraction status. After inducing cycloplegia by administering 1% tropicamide, cycloplegic autorefraction was measured using a Topcon autorefractor, and wavefront refraction was measured with an Allegretto wave analyzer. Refraction data were presented as the spherical equivalent and astigmatism. Astigmatism was converted to vector power and analyzed by the Alpins method.
Results: Both cycloplegic wavefront refraction and autorefraction showed good correlations with subjective refraction. The adjusted R^2 value was 0.9726 between cycloplegic autorefraction and subjective manifest refraction, and 0.9693 between cycloplegic wavefront refraction and subjective manifest refraction. Compared with subjective manifest refraction, a myopic shift of -0.14 ± 0.06 D was noted in cycloplegic wavefront refraction ($p = 0.0182$). However, cycloplegic autorefraction was not different from subjective manifest refraction ($p = 0.55$). Astigmatism in both wavefront refraction and autorefraction differed from subjective astigmatism ($p < 0.0001$ for both). The difference of astigmatism vector power from subjective refraction was 0.16 D larger in the cycloplegic wavefront refraction group than in the cycloplegic autorefraction group ($p = 0.0039$).
Conclusion: Autorefraction gives a better estimate of subjective manifest refraction than wavefront refraction in both the spherical equivalent and astigmatism.

1. Introduction

The primary goal of refractive surgery is to achieve independence from spectacles and contact lenses. However, along with the dramatic advances introduced by new technologies such as excimer laser platforms with higher repetition rates, faster eye trackers, and customized ablation profiles, the primary goal of refractive surgery has evolved and aims to provide “super vision”.

Monochromatic aberrations include low-order and high-order aberrations. The two most common low-order aberrations are defocus (myopic and hyperopic spherical errors) and regular astigmatism, both of which can be measured by autorefractors and wavefront aberrometers. However, detection of high-order aberrations can only be done by wavefront aberrometers. Concomitant elimination of high-order aberrations, instead of correction of only defocus and regular astigmatism, relies on wavefront aberrometers for the measurement of all aberrations. However, the accuracy and efficacy of this advanced technology and complicated instrument still need to be validated. Therefore, the purpose of this study was to compare the measurements of cycloplegic autorefraction, wavefront refraction, and subjective manifest refraction.

2. Materials and methods

This research followed the tenets of the Declaration of Helsinki, and informed consent was obtained from each patient before the study. The patients were excluded if they had any other ocular

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http://dx.doi.org/10.1016/j.tcmj.2013.01.006

disease or previous ocular surgery that would affect the refractive status. During the visit, a series of evaluations was carried out as follows: (1) a baseline subjective manifest refraction was determined by fogging, duochrome tests, and astigmatism dials with trial lenses, including cross-cylinder refraction. (2) Two drops of tropicamide (Mydriacyl 1% ophthalmic solution, Alcon Laboratories, Fort Worth, TX, USA) were administered to the studied eyes with an interval of 10 minutes for mydriasis and cycloplegia. Twenty minutes after the second drop, when the photopic pupil sizes were no less than 7 mm, cycloplegic autorefraction was measured using an autorefractor (RM-A7000; Topcon, Tokyo, Japan) by automatically averaging three measurements of the central 3 mm of the entrance pupil. (3) Finally, three consecutive wavefront measurements were performed using the Allegretto wave analyzer (WaveLight Laser Technologies AG, Erlangen, Germany). Fogging of the accommodation target was turned off during measurements. An optic zone of 6 mm was chosen for wavefront analysis.

Through mathematical calculation, the wavefront sphere (SPH) and wavefront cylinder (CYL) can be estimated from the three second-order modes: C_4 for defocus; C_3, and C_5 for astigmatism.

$$\text{SPH} = -\frac{8}{\text{OZ}} C_4 - \frac{1}{2}\,\text{CYL}$$

$$\text{CYL} = -\frac{8}{\text{OZ}} \sqrt{C_3^2 + C_5^2}$$

where OZ = wavefront diameter.

On the basis of subjectively sensing the clearest image, subjective manifest refraction is therefore considered the gold standard in estimating the true refractive status. Wavefront refraction and cycloplegic autorefraction were compared with subjective manifest refraction, which stood for the true refraction status. Both the spherical equivalent and astigmatism were calculated and compared. The Alpins method of astigmatism analysis was used for comparing astigmatism [1,2]. The magnitude and the axis of the cylinder were converted to vector power [1,2]. The discrepancy of vector power between wavefront refraction and subjective manifest refraction and that between autorefraction and subjective manifest refraction were calculated and the assumed residual astigmatism after astigmatism correction in each group was compared.

2.1. Statistical analysis

Data were expressed as means ± standard error of the mean. A paired t test was used to compare the spherical equivalent and astigmatism between autorefraction and subjective manifest refraction, and between wavefront refraction and subjective manifest refraction, as well as the discrepancy of astigmatism vector power from subjective manifest refraction in cycloplegic wavefront refraction and cycloplegic autorefraction. Simple linear regression was used to study the correlation between the spherical equivalent of wavefront refraction and that of subjective manifest refraction, and between autorefraction and subjective manifest refraction. A p value ≤0.05 was considered to be statistically significant. The Stata version 8.0 software (StataCorp LP, College Station, TX, USA) was used for statistical analysis.

3. Results

Thirty-one eyes from 17 myopic patients (16 females) were used in this study. The mean age of the patients was 29.1 ± 1.3 years (range: 16–47 years). Subjective manifest refraction and measured wavefront refraction and autorefraction are shown in Table 1.

Table 1
Sphere, cylinder, and spherical equivalent of three measurements.

	Subjective manifest refraction	Cycloplegic wavefront refraction	Cycloplegic autorefraction
Spherical error (D)	−5.87 ± 0.32 (−2.5 to −8.5)	−5.93 ± 0.30 (−2.73 to −8.71)	−5.77 ± 0.33 (−2.50 to −9.0)
Cylindrical error (D)	−0.47 ± 0.08 (0 to −1.25)	−0.64 ± 0.05 (−0.19 to −1.19)	−0.47 ± 0.08 (0 to −1.25)
SE (D)	−6.10 ± 0.32 (−2.375 to −8.5)	−6.25 ± 0.30 (−2.93 to −9.11)	−6.07 ± 0.33 (−2.63 to −9.00)
p compared with subjective SE	—	0.0182*	0.5529

Data are expressed as means ± SEM.
*Statistically significant.
SE = spherical equivalent.

Compared with subjective manifest refraction in the spherical equivalent, there was a significant myopic shift of cycloplegic wavefront refraction by −0.14 ± 0.06 D ($p = 0.0182$), while cycloplegic autorefraction was not significantly different from subjective manifest refraction ($p = 0.55$).

Both cycloplegic wavefront refraction and autorefraction showed good correlations with subjective refraction (Figs. 1 and 2). The adjusted R^2 value was 0.9726 for the correlation between cycloplegic autorefraction and subjective manifest refraction, and 0.9693 for that between cycloplegic wavefront refraction and subjective manifest refraction. Cycloplegic autorefraction showed a higher correlation with subjective manifest refraction than cycloplegic wavefront refraction.

The measured astigmatism and calculated difference vector are shown in Table 2. While analyzing astigmatism, the difference from subjective manifest refraction was 0.44 ± 0.04 D ($p < 0.0001$) in the cycloplegic wavefront refraction group and 0.28 ± 0.05 D ($p < 0.0001$) in the cycloplegic autorefraction group. The difference of astigmatism vector power from subjective refraction was 0.16 D larger in the cycloplegic wavefront refraction group than in the cycloplegic autorefraction group ($p = 0.0039$). Using subjective manifest refraction as the standard, astigmatism measured by cycloplegic autorefraction was more precise than that measured by cycloplegic wavefront refraction.

4. Discussion

Several techniques for wavefront sensing are available, such as Hartmann–Shack and Tscherning systems, Tracey ray-tracing, and

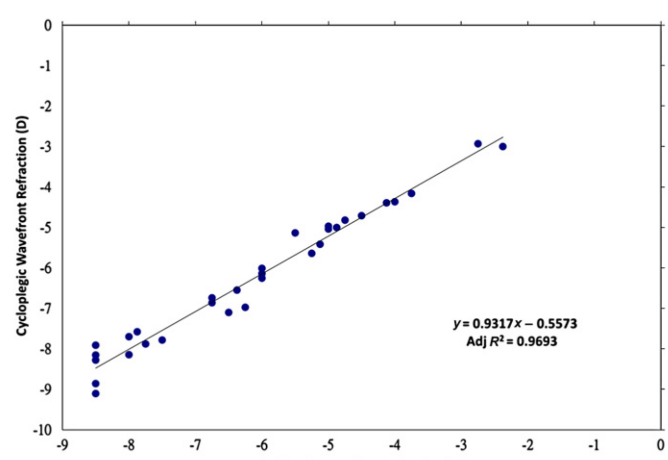

Fig. 1. Correlation between cycloplegic wavefront refraction and subjective manifest refraction.

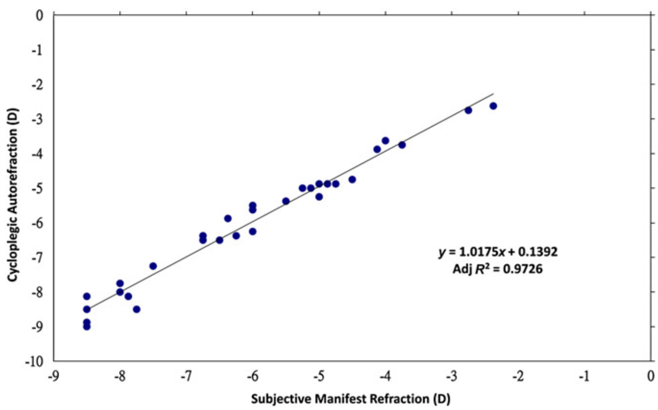

Fig. 2. Correlation between cycloplegic autorefraction and subjective manifest refraction.

optical path difference scans [3,4]. Currently, the Hartmann–Shack and Tscherning systems are the two most predominant techniques for measuring aberrations. In the Hartmann–Shack system, a narrow beam of light is first projected onto the retina and the reflected wavefront is focused by a sensor comprising a lenslet array. A charge-coupled device camera is placed at the plane of all focal spots, and the deviation of each focal spot from the theoretical location is examined [4–6]. A WaveLight Analyzer, the aberrometer used in this study, is a Tscherning-based aberrometer. The Tscherning system sends a light through a dot pattern mask and analyzes the pattern of the light spots projected on the retina. The position of each spot is compared with the ideal grid pattern, and wavefront aberration is reconstructed mathematically from the deviations [3,7].

Methods of wavefront reconstructions include Zernike polynomials, Fourier transform, and Taylor monomials [8]. Zernike polynomials are presented in the following equation.

$$W(Rr,\theta) = \sum_{i=1}^{n} c_i Z_i(r,\theta)$$

A Fourier transform is presented in the following equation:

$$W(Rr,\theta) = \sum_{i=1}^{M^2} a_i(k,\varphi)\exp\left[j\frac{2\pi}{M}kr\cos(\theta-\varphi)\right]$$

There is some debate about which method—Zernike or Fourier—is superior in wavefront reconstruction. In the study conducted by Yoon et al [9], Zernike polynomials outperformed the Fourier method in representing aberrations. In contrast, however, Wang et al [10] and Dai [11] suggested Fourier transform reconstructed ocular aberrations more accurately than Zernike polynomials. The WaveLight Analyzer reconstructs wavefronts based on Zernike polynomials, presenting monochromatic aberrations as 27 different modes and the power of each mode is quantitatively described as Zernike coefficients, from C1 to C27.

Ametropic eyes present refractive error, including spherical and cylindrical errors. Although spectacles and conventional refractive surgeries correct these low-order aberrations, high-order aberrations can only be reduced by wavefront-guided refractive surgery.

Table 2
Astigmatism of three measurements and their differences.

No. of eye	Subjective manifest refraction		Cycloplegic wavefront refraction				Cycloplegic autorefraction			
	Power	Axis	Power	Axis	Difference vector		Power	Axis	Difference vector	
					Power	Axis			Power	Axis
1	0	0	−0.33	4	0.33	94	0	0	0	0
2	−1	180	−0.7	3	0.31	173	−1	179	0.035	45
3	0	0	−0.79	8	0.79	98	0	0	0	0
4	−1	180	−1.18	153	1	36.1	−1.25	161	0.77	45
5	0	0	−0.38	93	0.38	3	0	0	0	0
6	0	0	−0.28	89	0.28	179	0	0	0	0
7	0	0	−0.7	4	0.7	94	0	0	0	0
8	0	0	−0.49	38	0.49	128	−0.75	47	0.75	137
9	0	0	−0.85	76	0.85	166	−0.75	75	0.75	165
10	0	0	−0.66	155	0.66	65	−0.75	121	0.75	31
11	−0.5	155	−0.54	161	0.12	103	−0.5	154	0.02	20
12	−0.5	180	−0.49	157	0.39	33	−0.75	4	0.26	102
13	0	0	−0.64	129	0.64	39	−0.5	144	0.5	54
14	0	0	−0.19	147	0.19	57	−0.25	139	0.25	49
15	−1	67	−0.79	43	0.75	93	−1	60	0.24	109
16	−0.5	110	−0.62	156	0.81	85	−0.25	128	0.33	97
17	0.25	175	−0.24	70	0.13	120	−0.25	175	0.5	85
18	−0.5	131	−0.4	131	0.1	131	−0.5	131	0	0
19	−1.25	175	−1.19	166	0.39	31	−1	178	0.28	164
20	−1	175	−0.72	164	0.43	14	−1	1	0.21	133
21	−0.75	5	−0.46	169	0.43	22	−0.75	8	0.08	142
22	0	0	−0.48	9	0.48	99	−0.5	82	0.5	172
23	−1	180	−0.94	7	0.24	146	−0.75	177	0.27	8.57
24	−0.5	5	−0.26	170	0.3	18	−1	9	0.51	103
25	−0.75	175	−0.36	171	0.4	179	−0.75	178	0.08	132
26	−0.5	180	−0.92	173	0.45	75	−0.5	16	0.28	143
27	−1	170	−1.09	167	0.14	53	−1	4	0.48	132
28	−1.25	8	−0.72	16	0.59	178	−1.25	11	0.13	146
29	0	0	−0.3	131	0.3	41	−0.5	160	0.5	70
30	−0.75	170	−0.98	168	0.24	72	−0.75	169	0.03	35
31	−1	10	−1	1	0.31	51	−0.75	9	0.25	13

Power is in diopter, and axis is in degree. The difference vector is the difference between estimated astigmatism and subjective manifest astigmatism, which is analyzed by the Alpins method.

Theoretically, wavefront-guided ablations correct more high-order aberrations than conventional ablation surgery and hence result in better vision [12]. However, a review of the literature revealed that, surprisingly, wavefront-guided ablations did not have superior visual outcomes when compared with wavefront-optimized ablations [12–14]. Therefore, the method of estimating ocular aberrations and ablation might need to be validated for accuracy and efficacy.

In our study, the spherical equivalent of cycloplegic wavefront refraction demonstrated a more myopic shift from subjective manifest refraction, while there was no significant difference between cycloplegic autorefraction and manifest refraction. The astigmatism measured by the autorefractor was more precise than that from the wavefront aberrometer. Although both cycloplegic wavefront refraction and cycloplegic autorefraction had good correlation with subjective manifest refraction, autorefraction was superior in predicting manifest refraction. The adjusted R^2 value was higher, the intercept was smaller, and the regression coefficient was closer to 1. Pesudovs et al also reported that wavefront refractions were not as precise as standard autorefractions, although not significantly worse clinically [6].

For comparison of wavefront refractions, two influencing facts have to be considered. First, manifest refractions are determined in medium to small pupils with a limited variety of test lenses: only spherical and cylindrical lenses of a scale of at least 0.25 D are available. Wavefront measurement is made in large pupils. Second, spherical and cylindrical lenses chosen by the patient may compensate for not only spherocylindrical aberrations, but also part of their higher order aberrations. It is known that coma can be compensated for, in part, by a cylindrical lens and spherical aberration by a spherical lens at a certain pupil size. High-order aberrations may influence manifest refraction, and can be compensated for by using different spherical and cylindrical lenses when measuring subjective manifest refraction [15,16], while wavefront measurements split clearly between true spherical/cylindrical components and other higher order aberrations. Because of stronger higher order aberrations, sphere components and cylinder components may differ more or less from the manifest refraction.

The myopic shift of wavefront refraction was not likely due to instrument myopia. Other studies also found more myopic refraction when using different kinds of wavefront aberrometers, and the authors of those studies proposed instrument myopia as one of the possible explanations [17–19]. Excessive accommodation might occur when viewing the internal fixation target of the instrument, which can induce instrument myopia of approximately 0.3–0.4 D in wavefront aberrometers [20,21], as well as in autorefractors [19,22]. In our study, causes other than instrument myopia were likely because of the administration of cycloplegic tropicamide. In addition, both instruments shared similar factors of instrument myopia, but wavefront refraction rather than autorefraction showed a significant myopic shift. Therefore, a device or technology-related myopic bias was considered.

Another possible explanation was the different pupil sizes during measurements. A 3-mm smaller region of the pupil was centered when using the autorefractor, and a 6-mm optical zone was chosen when using the wavefront aberrometer. The myopic shift might be due to the more myopic refraction at the peripheral area than in the center of the pupil [23].

Vision quality depends on the perfection of the whole optical system to create a stigmatic image. According to our study results, cycloplegic wavefront refraction, in both parts of the spherical equivalent and astigmatism, was not as precise as cycloplegic autorefraction. When performing wavefront-guided ablations, surgery would be based on less accurate low-order aberrations data than wavefront-optimized ablations. A combination of elimination of high-order aberrations and a less precise correction of low-order aberrations would not lead to a better result. Our results partly explained why wavefront-guided ablations did not show a better result than wavefront-optimized ablations.

In conclusion, autorefraction gives a better estimate of subjective manifest refraction than wavefront refraction in both the spherical equivalent and astigmatism. The benefit of eliminating high-order aberrations in wavefront-guided refractive surgery may be reduced by the less precise estimation of subjective manifest refraction. Although the examined results of the current wavefront aberrometry are not as precise as expected, we hope better results can be obtained with newer or better aberrometers.

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