



ORIGINAL ARTICLE

Comparison of refractive assessment by wavefront aberrometry, autorefractometry, and subjective refraction[☆]



Jeffrey R. Bennett^{a,*}, Gina M. Stalboerger^a, David O. Hodge^b, Muriel M. Schornack^a

^a Department of Ophthalmology, Mayo Clinic¹, Rochester, MN, United States

^b Biostatistics Unit, Mayo Clinic, Jacksonville, FL, United States

Received 10 July 2014; accepted 27 October 2014

Available online 11 December 2014

KEYWORDS

Aberrometry;
Autorefractometry;
Refraction;
Refractive errors;
Wavefront

Abstract

Purpose: To compare refractive assessment results obtained with an aberrometer, an autorefractor, and manual subjective refraction (SR) in a healthy population with optimal visual potential.

Methods: Sixty adults aged 18–59 years with visual acuity of 20/25 or better, no media opacity, and no known corneal or retinal abnormalities were recruited during the course of routine eye examination. Refractive error in both eyes of each patient was assessed by 3 methods: manual SR, a Nidek 530-A autorefractor (AR), and a Nidek OPD-II Scan wavefront aberrometer (OPD). The order of testing was randomized. One technician collected all OPD and AR measurements, and 1 optometrist performed manual SR. Refractive measurements were converted from spherocylindrical prescriptions to power vectors and compared between methods by 2-factor repeated measures and Bland–Altman analysis.

Results: Analysis of the power vectors followed by a log transformation showed no significant difference in refractive results between AR, OPD, and SR ($P = .63$). Bland–Altman analysis identified mean differences (95% CI of limits of agreement) of -0.06 (-0.67 to 0.55) for OPD vs SR, 0.001 (-0.522 to 0.524) for AR vs SR, and 0.06 (-0.541 to 0.662) for AR vs OPD.

Conclusion: Agreement between all refractive assessments was comparable to previously reported agreement between repeated measures of SR. Agreement between AR and SR was slightly stronger than between OPD and SR. Although both the OPD and AR results, in general, showed a high level of agreement with SR, results beyond $\pm 0.50D$ (5.8% for AR, 10% for OPD) would discourage prescribing spectacles directly from either instrument.

© 2014 Spanish General Council of Optometry. Published by Elsevier España, S.L.U. All rights reserved.

Abbreviations: AR, Nidek 530-A autorefractor; COAS, Complete Ophthalmic Analysis System; OPD, Nidek OPD-II scan aberrometer; SR, subjective refraction.

[☆] Presented at the annual meeting of the American Academy of Optometry, Orlando, Florida, November 14, 2009.

* Corresponding author at: Department of Ophthalmology, Mayo Clinic, 200 First Street SW, Rochester, MN 55905, United States.

E-mail address: bennett.jeffrey@mayo.edu (J.R. Bennett).

¹ Mayo Clinic does not endorse any of the products mentioned in this article.

<http://dx.doi.org/10.1016/j.optom.2014.11.001>

1888-4296/© 2014 Spanish General Council of Optometry. Published by Elsevier España, S.L.U. All rights reserved.

PALABRAS CLAVE

Aberrometría;
Autorefracción;
Refracción;
Errores Refractivos;
Frente de onda

Comparación de la evaluación refractiva mediante aberrometría por frente de onda, autorefractómetro y refracción subjetiva

Resumen

Objetivo: Comparar los resultados de la evaluación refractiva obtenidos mediante aberrómetro, autorefractómetro y refracción subjetiva manual (RS) en una población sana con un potencial visual óptimo.

Métodos: Se reclutó a sesenta adultos de edades comprendidas entre 18 y 59 años, con agudeza visual de 20/25 o superior, sin opacidad de medios, y sin anomalías retinianas o corneales, en el curso de un examen ocular rutinario. Se evaluó el error refractivo en los dos ojos de cada paciente mediante tres métodos: RS manual, un autorrefractómetro (AR) Nidek 530-A, y un aberrómetro por frente de onda Nidek OPD-II Scan (OPD). El orden de las pruebas fue aleatorio. Un técnico recolectó todas las mediciones de OPD y AR, y un optometrista llevó a cabo la RS manual. Las mediciones refractivas se transformaron de prescripciones esferocilíndricas en vectores de potencia, comparándose entre sí los tres métodos mediante mediciones repetidas de dos factores y análisis de Bland-Altman.

Resultados: El análisis de los vectores de potencia, seguido de una transformación logarítmica, no reflejó ninguna diferencia significativa de los resultados refractivos entre AR, OPD, y RS ($P=0,63$). El análisis de Bland-Altman identificó diferencias medias (95% de IC de los límites de acuerdo) de $-0,06$ ($-0,67$ - $0,55$) D para OPD frente a RS, $0,001$ ($-0,522$ - $0,524$) D para AR frente a RS, y $0,06$ ($-0,541$ - $0,662$) D para AR frente a OPD.

Conclusión: La concordancia entre todas las evaluaciones refractivas fue comparable a la concordancia previamente reportada entre las mediciones repetidas de RS. La concordancia entre AR y RS fue ligeramente superior que entre OPD y RS. Aunque en general los resultados de OPD y AR reflejaron un elevado nivel de concordancia con RS, los resultados que exceden la diferencia de $\pm 0,50$ D (5.8% para AR, 10% para OPD) no permiten realizar la prescripción de gafas con cualquiera de ambos instrumentos.

© 2014 Spanish General Council of Optometry. Publicado por Elsevier España, S.L.U. Todos los derechos reservados.

Introduction

Manual subjective refraction (SR), which is frequently based on manual retinoscopy or current spectacle prescription, is the standard for comparison of new instruments that assess refractive error in clinical practice.¹⁻⁵ The status of SR as the standard for determination of spectacle prescription has been established by convention and by the definition of "endpoint" as the combination of lenses that provides the best-corrected visual acuity. However, the procedure is, by definition, subjective. Variability in patient responses to small changes in prescription, along with intraexaminer and interexaminer inconsistency, limits the precision and repeatability of the procedure.⁶⁻⁹ In addition, considerable practice is required to master the technique of manual SR, and the process of performing the test can be clinically time-consuming. Therefore, technology that could decrease the time required for refraction, or even allow for delegation of refractive data collection to technicians, could potentially increase efficiency in optometric practice.

Two such technologies are autorefractors and wavefront aberrometers. Autorefraction is widely accepted as a clinically valuable starting point for SR.^{1,2,8,9} Autorefractors offer rapid automated assessment of refractive error and are now commonly used in ophthalmic practice. Along with autolensometers and automated phoropters, they can be incorporated into comprehensive automated SR systems that allow technicians with minimal training to collect and

refine refractive data. Both SR and autorefraction measure low-order aberrations: sphere (defocus) and astigmatism. However, higher-order aberrations (coma, trefoil, spherical aberration) can also degrade the quality of the optical image received by the retina. Wavefront aberrometers can measure both lower- and higher-order aberrations. If superior visual acuity can be achieved by correction of higher-order aberrations compared with a spherocylindrical prescription, aberrometry could eventually replace SR as the standard for refractive assessment.

The purpose of this study was to evaluate agreement in the spherocylindrical prescription generated by an aberrometer, refractive assessment by an autorefractor, and manual SR in an optometric clinic. If the data obtained by the different methods are comparable, use of an automated system may decrease the time needed to collect refractive data without loss of prescription accuracy. Because adult patients without significant eye problems represent the largest patient demographic group seen in our clinic for routine eye examination, use of an automated method may then substantially increase the productivity of our clinic.

Methods**Patients**

This study was approved by our institutional review board, and the research followed the tenets of the Declaration of

Helsinki. Adults aged 18–59 years reporting to our department of ophthalmology for a routine eye examination were recruited for inclusion in the study between January 6 and February 28, 2009. Patients were excluded from study participation if they currently wore contact lenses, had best-corrected visual acuity of less than 20/25, or had a history of any corneal, lenticular, media, or retina abnormality. Patients also were excluded if they had clinically diagnosed cataracts at the time of enrollment or had undergone cataract extraction or refractive surgery. All included patients gave verbal consent and written Health Insurance Portability and Accountability Act authorization.

For each patient, 3 different refractive measurements were performed: manual SR, autorefraction with the Nidek 530-A autorefractor (Nidek Co, Japan, for Marco, Jacksonville, Florida), and aberrometry with the Nidek OPD-Scan II wavefront aberrometer. Both instruments are used in our clinical practice as part of the Marco EPIC Refraction System.

Autorefraction

The Nidek 530-A autorefractor (AR) uses zonal ring image technology to obtain refractive measurements. A ring of superluminescent diode light is projected through a fixed, 2.6-mm pupillary zone onto the retina and then reflected back onto sensors in the instrument. The sensors interpret the shape of the reflected rings as myopia, hyperopia, and astigmatism. The magnitude of each shape is then referenced as a spherocylindrical refraction. A single refractive result from this instrument consists of at least 3 measurements, which are then analyzed to produce a single spherocylindrical result.

Aberrometry

The Nidek OPD-II Scan aberrometer (OPD) measures wavefront error using dynamic skiascopy.¹⁰ The instrument projects, (1,440) individual beams of light through the pupil onto the retina and measures differences in the time it takes for the beams to reach the instrument's sensors after being reflected off the retina. Beams projected along relatively hyperopic optical paths within the visual system will reach the sensors sooner than those passing along more myopic paths. This time-dependent analysis calculates wavefront errors for a visual system. Lower-order aberrations (sphere and astigmatism) are measured in a 2.6-mm zone in the pupil, just as with a traditional autorefractor. The OPD also measures the low-order wavefront error across a 4- to 6-mm zone in the pupil. From this blended zone of low-order wavefront analysis, a sphere, cylinder, and axis are determined by using Zernike vector analysis. Additionally, a root-mean-square wavefront error is calculated. The OPD compares the 2.6-mm autorefraction with the larger zone wavefront analysis, along with the root-mean-square value, to determine which of the 2 refractive error measurements should be used as a starting point for the SR. Theoretically, this combined process should create a measurement of greater accuracy than autorefraction alone.

Refractive assessment

The order of the 3 refractive assessments (SR, AR, and OPD) was randomized for each patient. Patients' eyes were neither dilated nor treated with cycloplegic drugs before refractive assessment. All measurements were obtained during a single examination. All measurements from the AR and OPD were acquired by 1 technician, and 1 successful measurement was taken on each instrument, in normal room illumination. The OPD was set to the 4-mm zone for all measurements. Each patient's visual acuity with the AR and OPD results was measured using a projected Snellen chart in a 20-foot-equivalent refracting lane. One optometrist performed SR (including binocular balance) on both eyes of all patients in the same refracting lane, using the same illumination (lights slightly dimmed to improve contrast on a projected eye chart) as for AR and OPD refractive assessments. The starting point for the refraction was either manual retinoscopy or the patient's habitual spectacle prescription. The optometrist was masked to the results of AR and OPD and the technician to the SR results. Each spherocylindrical lens result was converted to a power vector. The Pythagorean length of each power vector was measured using a spreadsheet formatted with the transposition formula designed by Thibos et al.¹¹ This length, termed "*B*" by Thibos and Horner,¹² is the overall blur strength of a spherocylindrical refractive error and was the sole refraction measurement data point used for statistical analysis.

Statistical analysis

The *B* measurements of both instruments were statistically compared with the SR. Measurements obtained by AR were also compared with those calculated by OPD. Our sample size (60 patients, 120 eyes) provided 90% confidence to detect a difference of 0.25 D. The estimated parameters were compared among the 3 methods using a 2-factor repeated-measures analysis of variance, with the 2 factors being the eye and the method of measurement. A log transformation was used to run the models given the nature of the distribution. Bland–Altman plots showing mean and 95% CI of limits of agreement were also used to assess agreement between refraction methods. SAS software version 9.3 was used for statistical analysis.

Results

The mean age of the 60 patients was 43.25 years (range, 21–58 years). A total of 360 spherocylindrical prescriptions (3 assessments of both eyes of 60 patients) were converted to a single power vector length as described above (Table 1). The 2-factor repeated-measures analysis of variance of the log power vector revealed no statistically significant difference in power ($P = .63$) among the 3 methods of assessment.

We also analyzed our data (*B* values) using Bland–Altman plots. Comparison between OPD and SR revealed a mean (SD) difference of -0.06 (0.31) D and 95% CI of -0.67 to 0.55 D (Fig. 1). AR showed slightly better agreement with SR than did OPD; the mean (SD) difference was 0.001 (0.262) D (95% CI, -0.522 to 0.524 D) (Fig. 2). When comparing AR with SR, 94.2% of measurements were within ± 0.50 D, approximately

Table 1 Log transformation of data for the repeated-measures analysis.

Method	No.	Log (power vector + 1)	
		Mean (SD)	Median (range)
AR	120	0.902 (0.514)	0.757 (0.163–2.466)
OPD	120	0.890 (0.501)	0.770 (0.000–2.330)
SR	120	0.901 (0.519)	0.757 (0.000–2.399)

Abbreviations: AR, Nidek 530-A autorefractor; OPD, Nidek OPD-II Scan aberrometer; SR, subjective refraction.

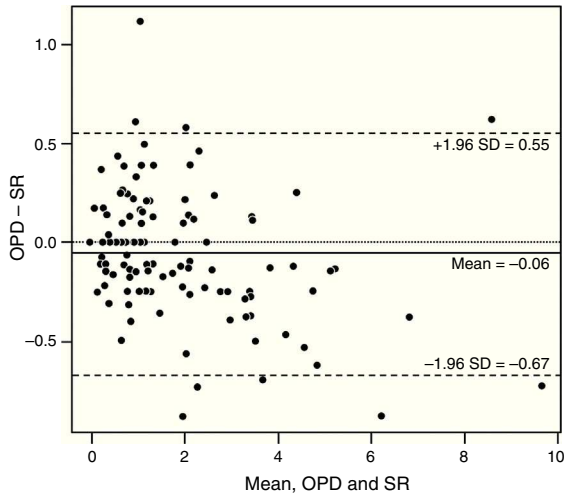


Figure 1 Bland–Altman plot. Comparison of power vector results between the Nidek OPD-II Scan aberrometer (OPD) and subjective refraction (SR). The 95% limits of agreement are indicated by the upper and lower dashed lines, and the mean is indicated by the solid line.

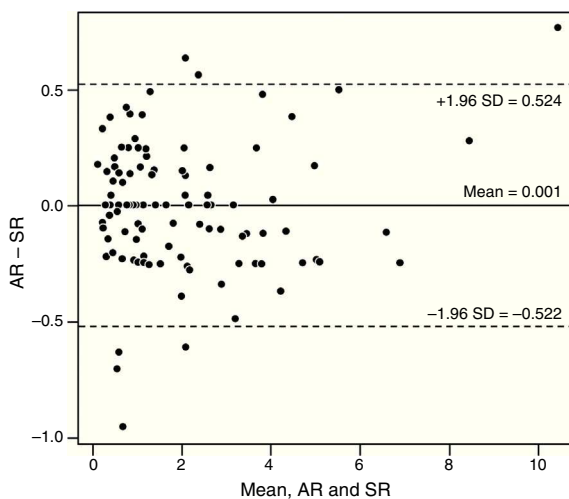


Figure 2 Bland–Altman plot. Comparison of power vector results between the Nidek 530-A autorefractor (AR) and subjective refraction (SR). The 95% limits of agreement are indicated by the upper and lower dashed lines, and the mean is indicated by the solid line.

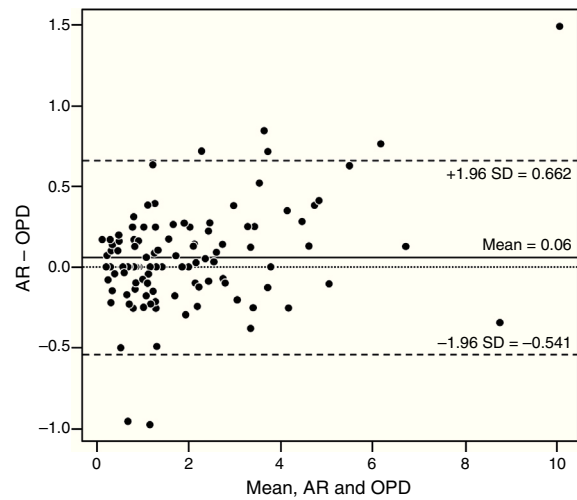


Figure 3 Bland–Altman plot. Comparison of power vector results between the Nidek OPD-II Scan aberrometer (OPD) and the Nidek 530-A autorefractor (AR). The 95% limits of agreement are indicated by the upper and lower dashed lines, and the mean is indicated by the solid line.

80% were within ± 0.25 D, and 7 measurements differed by more than ± 0.50 D. Comparison of OPD and SR found 90% of measurements were within ± 0.50 D, approximately 73% were within ± 0.25 D, and 12 measurements differed by more than ± 0.50 D. Finally, comparison of AR and OPD revealed a mean (SD) difference of 0.06 (0.30) D (95% CI, -0.541 to 0.662 D) (Fig. 3). Visual analysis of the Bland–Altman plots showed most of the points to be in the 2SD range and to scatter consistently around 0. The differences seem systematic and show that the 3 methods of refraction arrive at similar results.

Mean differences of low magnitude, as found between all 3 measures of refractive error, indicated that there was no trend of overminus or underplus refraction for either AR or OPD as compared with SR on the Bland–Altman plots.

Discussion

In this clinical study, the OPD and AR provided reliable information on lower-order aberrations. AR showed slightly closer agreement with SR than did OPD, but the difference was not statistically significant. Based on preliminary estimates, we powered this study to detect a 0.25-D difference in measurements. Approximately 80% of AR results and 72% of OPD results were within ± 0.25 D of SR values. The OPD can provide information that may explain the visual distortion that persists even after correction of spherical and cylindrical refractive error, but aberrometry does not provide a substantial advantage over autorefraction for determination of standard spherocylindrical spectacle prescriptions at this time.

Reliability and repeatability of SR, autorefraction,^{1–4,13–15} and aberrometry have been studied extensively. Both inter-observer and intraobserver variability have been assessed, and data have been obtained both before and after cycloplegia or dilation. A review of several studies concluded that interobserver and intraobserver manual refractive error

assessment generally reaches 80% agreement within ± 0.25 D and 95% agreement within ± 0.50 D.¹⁶ Comparison of AR and OPD versus SR in this study was similar to the interobserver and intraobserver agreement for manual refraction found in prior studies.

Autorefraction was found to be significantly more repeatable than SR by Bullimore et al.¹⁴ Another study showed refractive results obtained with 2 autorefractors to provide close agreement with SR.⁴ Because of excellent repeatability of autorefraction results with various instruments,¹⁻³ and because the AR result for a single measurement is actually the mode of multiple refractive assessments, we believed that a single autorefractor measurement would suffice for the purpose of this clinical study.

Aberrometers create a map of higher-order aberrations of the eye expressed using Zernicke polynomials that are used to calculate a spherocylindrical refractive value. Early wavefront aberrometers, such as the Complete Ophthalmic Analysis System (COAS) were based on Shack-Hartmann methods of assessment, in which a pattern of discrete points of light was projected onto the retina. Deflection of individual points within the array as it was reflected from the retina back to the instrument's sensors allowed for position-based quantification of the higher-order aberration profile of the eye. Unlike early aberrometers, the OPD's assessment of the aberration profile of the human eye is based on time-dependent rather than position-dependent (Shack-Hartmann) optical analysis. Studies evaluating spectacle prescriptions generated by position-based aberrometers (e.g., COAS) have reported similar accuracy and repeatability to autorefraction.^{5,15,17} The COAS also measured higher-order aberrations in model eyes with minimal variation between repeated assessments.¹⁷ Pesudovs et al.¹⁸ compared the COAS aberrometer with autorefraction and SR and found similar levels of agreement between SR, autorefraction, and aberrometry as in the present study. Nissman et al.¹⁹ examined the accuracy and repeatability of a time-based aberrometer and found that the initial measurement did not significantly vary from the mean of 3 measurements. Thus, we concluded that a single measurement with the OPD would provide sufficient data for the purposes of this study.

Considerable variety exists in the methods by which refractive components have been statistically compared, and this variability confounds attempts to compare results between studies. Some studies^{1,8} reported the agreement between each component (sphere, cylinder power, cylinder axis) of a spectacle prescription. Others compared the spherical equivalent powers of multiple refractions, along with degrees of variability in cylinder orientation.^{1,2,6,8} Attempts to compare individual components of a spherocylindrical prescription are complicated by 2 factors: sphere and cylinder are not independent variables, and cylinder axis represents orientation rather than power. Conversion of spherocylindrical prescriptions into power vectors allows for all components of a spherocylindrical prescription to be accounted for and has become the standard by which refractive data are compared.^{4,5,11,14,20,21} The components of a power vector are spherical lens M and Jackson cross cylinders J0 and J45. M, J0, and J45 represent the coordinates of a power vector that can be plotted in a 3D rectangular space. The Pythagorean length of this vector, termed B, can

be calculated using the Thibos spreadsheet¹¹ and was the measure used in our study.

In our clinic, all AR and OPD measurements are obtained in normal room illumination, and SR is performed in slightly dimmer illumination to enhance the contrast of the projected visual acuity chart. Despite differences in illumination, we found no difference in mean refractive error between the 3 methods of assessment. This is probably due to the consistent pupillary zone measured for the AR and OPD, 2.6 mm and 4.0 mm, respectively. It is possible that differences may have been detected if a larger pupillary zone had been set for the OPD, but our primary concern was to assess agreement between methods of refractive error determination as obtained with our standard procedures.

Some reports have suggested that noncycloplegic autorefraction yields consistent bias toward overminused or underplussed refraction compared with SR.²² Because we wished to determine whether the instruments used in our clinical practice were subject to such bias, and to assess whether accommodation was controlled more accurately in SR than in automated assessments of refractive error, we chose to obtain noncycloplegic measurements. Similar to another study comparing SR with an aberrometer,²³ our subjects' pupils were not pharmacologically dilated for refractive measurements. Our study's design was to evaluate patients in our normal clinical setting, unlike a consistent, pharmacologically dilated pupil that would be measured in a scientific setting. Thus, our autorefractor and aberrometer results revealed no statistically or clinically significant bias toward overminused or underplussed correction compared with manual SR. A visual analysis of the Bland-Altman plots shows a relatively even distribution of results between $+0.50$ D and -0.50 D.

We did not include children in our study, since our clinical population consists primarily of adults. Therefore, we also cannot comment on the agreement between SR, AR, and OPD measurements in children.²⁴ Furthermore, we excluded subjects older than 60 years, so we cannot state whether AR and OPD are similar to SR in that population.

Numerous authors have alluded to the subtle, but critical, differences between measuring refractive error and determining a spectacle prescription.^{18,20} Measuring refractive error is simply data collection; determining a spectacle prescription requires evaluation of multiple data points, including, but not limited to, assessment of refractive error. Several studies examining patient acceptance of spectacles based solely on autorefraction, compared with those incorporating SR, found better initial acceptance of SR,^{25,26} particularly during the first 2 weeks of wear.²⁶ That study, however, reported considerably wider limits of agreement between autorefraction and SR²⁶ than those noted in the present study. It is possible that spectacle prescriptions generated by current autorefractors or aberrometers may be more similar to SR than prescriptions generated by older instruments and therefore may be more acceptable to patients. Although differences between the mean values obtained with all 3 assessments are clinically insignificant, relatively wide limits of agreement (approximately ± 0.50 D) would, in our assessment, preclude prescribing spectacles directly from either the AR or OPD measurement. However, the limits of agreement between SR and either AR or OPD were at least as close as those reported for measures of

repeated SR (either performed by the same person on multiple occasions or by 2 different observers). This suggests that it may be acceptable to prescribe autorefractor results directly if a review of objective refractive data is consistent with other data used in the determination of a spectacle prescription (patient's subjective assessment of vision, habitual spectacle prescription, and visual acuity through the habitual prescription).

Aberrometry may eventually change the way we measure and correct optical aberrations in the human eye; Thibos et al.²⁷ suggested that it may eventually become the new standard for optimal correction of refractive error. Aberrometry can provide a tremendous amount of data on total aberration in the eye but appears to be no more accurate than autorefractor in its calculation of a spherocylindrical spectacle prescription. Currently, we can map refractive error on the basis of evaluation of higher-order aberration,²⁸ but translation of this measurement into refractive correction has proved challenging. Although higher-order aberrations can be at least partially corrected in refractive surgery, methods to incorporate the personalized correction of higher-order aberrations into spectacle or contact lenses are still in early stages of development. Spectacle lenses currently marketed as having "digital" or "high-definition" optics do not use patients' higher-order aberration maps to create truly customized lenses. Studies have examined some of the requirements for contact lens correction of higher-order aberrations,²⁹ but such custom contact lenses currently are not commercially available. Scleral lenses may eventually provide an ideal platform for incorporation of aberrometry results into a refractive device; the lenses tend to be rotationally very stable and are made of rigid gas-permeable materials that can be lathed with great precision.³⁰ As lens manufacturing technology evolves, it may be possible to use all of the data from wavefront analyzers to create lenses that truly provide outstanding visual clarity.

Both aberrometry and autorefractor can provide, at the very least, a reasonable starting point for SR. Although our AR and OPD results, in general, showed a high level of agreement with SR, the limits of agreement observed with both methods of automated data collection do not allow us to recommend prescribing spectacles directly from either the aberrometry or the autorefractor measurement without considering other refractive data. However, for cases in which data provided by these instruments are consistent with other information regarding a patient's refractive error, prescribing directly from a single AR or OPD measurement could eliminate the need for manual refraction in a healthy population with optimal vision.

Conflict of interest

The authors have no conflicts of interest to declare.

Acknowledgments

The study design was approved by our institutional review board, and all patients provided informed consent. This work was supported in part by Research to Prevent Blindness,

New York, NY, through an unrestricted grant to the Department of Ophthalmology, Mayo Clinic.

References

1. McBrien NA, Millodot M. Clinical evaluation of the Canon Autorefractor R-1. *Am J Optom Physiol Opt.* 1985;62:786-792.
2. Kinge B, Midelfart A, Jacobsen G. Clinical evaluation of the Allergan Humphrey 500 autorefractor and the Nidek AR-1000 autorefractor. *Br J Ophthalmol.* 1996;80:35-39.
3. Allen PM, Radhakrishnan H, O'Leary DJ. Repeatability and validity of the Power Refractor and the Nidek AR600-A in an adult population with healthy eyes. *Optom Vis Sci.* 2003;80:245-251.
4. Pesudovs K, Weisinger HS. A comparison of autorefractor performance. *Optom Vis Sci.* 2004;81:554-558.
5. Salmon TO, van de Pol C. Evaluation of a clinical aberrometer for lower-order accuracy and repeatability, higher-order repeatability, and instrument myopia. *Optometry.* 2005;76:461-472.
6. Kratz LD, Flom MC. The Humphrey Vision Analyzer tm: reliability and validity of refractive-error measures. *Am J Optom Physiol Opt.* 1977;54:653-659.
7. Sloane AE, Dunphy EB, Emmons WV, Gallagher JR. A comparison of refraction results on the same individuals. *Am J Ophthalmol.* 1954;37:697-699.
8. Perrigin J, Perrigin D, Grosvenor T. A comparison of clinical refractive data obtained by three examiners. *Am J Optom Physiol Opt.* 1982;59:515-519.
9. Zadnik K, Mutti DO, Adams AJ. The repeatability of measurement of the ocular components. *Invest Ophthalmol Vis Sci.* 1992;33:2325-2333.
10. Buscemi P. Clinical applications of the OPD-Scan wavefront aberrometer/corneal topographer. *J Refract Surg.* 2002;18:S385-S358.
11. Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the description and statistical analysis of refractive error. *Optom Vis Sci.* 1997;74:367-375.
12. Thibos LN, Horner D. Power vector analysis of the optical outcome of refractive surgery. *J Cataract Refract Surg.* 2001;27:80-85.
13. Wood IC, Papas E, Burghardt D, Hardwick G. A clinical evaluation of the Nidek autorefractor. *Ophthalmic Physiol Opt.* 1984;4:169-178.
14. Bullimore MA, Fusaro RE, Adams CW. The repeatability of automated and clinician refraction. *Optom Vis Sci.* 1998;75:617-622.
15. Martinez AA, Pandian A, Sankaridurg P, Rose K, Huynh SC, Mitchell P. Comparison of aberrometer and autorefractor measures of refractive error in children. *Optom Vis Sci.* 2006;83:811-817.
16. Goss DA, Grosvenor T. Reliability of refraction: a literature review. *J Am Optom Assoc.* 1996;67:619-630.
17. Cheng X, Himebaugh NL, Kollbaum PS, Thibos LN, Bradley A. Validation of a clinical Shack-Hartmann aberrometer. *Optom Vis Sci.* 2003;80:587-595.
18. Pesudovs K, Parker KE, Cheng H, Applegate RA. The precision of wavefront refraction compared to subjective refraction and autorefractor. *Optom Vis Sci.* 2007;84:387-392.
19. Nissman SA, Tractenberg RE, Saba CM, Douglas JC, Lustbader JM. Accuracy, repeatability, and clinical application of spherocylindrical automated refraction using time-based wavefront aberrometry measurements. *Ophthalmology.* 2006;113:e1-e2.
20. Elliott M, Simpson T, Richter D, Fonn D. Repeatability and accuracy of automated refraction: a comparison of the Nikon NRK-8000, the Nidek AR-1000, and subjective refraction. *Optom Vis Sci.* 1997;74:434-438.

21. Miller JM. Clinical applications of power vectors. *Optom Vis Sci.* 2009;86:599–602.
22. Choong YF, Chen AH, Goh PP. A comparison of autorefraction and subjective refraction with and without cycloplegia in primary school children. *Am J Ophthalmol.* 2006;142:68–74.
23. Robert Iskander D, Davis BA, Collins MJ, Franklin R. Objective refraction from monochromatic wavefront aberrations via Zernike power polynomials. *Ophthalmic Physiol Opt.* 2007;27:245–255.
24. Joubert L, Harris WF. Excess of autorefraction over subjective refraction: dependence on age. *Optom Vis Sci.* 1997;74:439–444.
25. Bullimore MA, Adams CW, Fusaro RE, Bauman M, Cotteral RM, Sarver JN, et al. Patient acceptance of auto-refractor and clinician prescriptions: a randomized clinical trial. *Vis Sci Applications. Tech Digest Series.* 1996;1:194–197.
26. Strang NC, Gray LS, Winn B, Pugh JR. Clinical evaluation of patient tolerance to autorefractor prescriptions. *Clin Exp Optom.* 1998;81:112–118.
27. Thibos LN, Hong X, Bradley A, Applegate RA. Accuracy and precision of objective refraction from wavefront aberrations. *J Vis.* 2004;4:329–351.
28. Nam J, Thibos LN, Iskander DR. Describing ocular aberrations with wavefront vergence maps. *Clin Exp Optom.* 2009;92:194–205.
29. Marsack JD, Parker KE, Niu Y, Pesudovs K, Applegate RA. On-eye performance of custom wavefront-guided soft contact lenses in a habitual soft lens-wearing keratoconic patient. *J Refract Surg.* 2007;23:960–964.
30. Sabesan R, Johns L, Tomashevskaya O, Jacobs DS, Rosenthal P, Yoon G. Wavefront-guided scleral lens prosthetic device for keratoconus. *Optom Vis Sci.* 2013;90:314–323.