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Utility of an open field Shack-Hartmann aberrometer for measurement of refractive error in infants and young children

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Abstract

PURPOSE—To assess the utility of an open-field Shack-Hartmann aberrometer for measurement of refractive error without cycloplegia in infants and young children.

METHOD—Data included 2698 subject encounters with Native American infants and children aged 6 months to <8 years. We attempted right eye measurements without cycloplegia using the pediatric wavefront evaluator (PeWE) on all participants while they viewed near (50 cm) and distant (2 m) fixation targets. Cycloplegic autorefraction (Rmax [Nikon Retinomax K-plus2]) measurements were obtained for children aged ≥3 years.

RESULTS—The success rates of noncycloplegic PeWE measurement for near (70%) and distant targets (56%) significantly improved with age. Significant differences in mean spherical equivalent (M) across near versus distant fixation target conditions were consistent with the difference in accommodative demand. Differences in astigmatism measurements for near versus distant target conditions were not clinically significant. Noncycloplegic PeWE and cycloplegic Rmax measurements of M and astigmatism were strongly correlated. Mean noncycloplegic PeWE M was significantly more myopic or less hyperopic and astigmatism measurements tended to be greater in magnitude compared with cycloplegic Rmax.

CONCLUSIONS—The PeWE tended to overestimate myopia and underestimate hyperopia when cycloplegia was not used. The PeWE is useful for measuring accommodation and astigmatism.

Cycloplegic retinoscopy is considered the gold standard for measuring refractive errors in infants and young children. However, an objective instrument that would accurately measure refractive error in infants and toddlers without cycloplegia would be of great value. While traditional tabletop autorefractors are generally not suitable because of their stationary design and their close working distance,[1,2] there has been some success in estimating refractive error in infants and young children using handheld instruments.[2–37] Measurements in children without cycloplegia often show "instrument myopia," that is, an underestimation of hyperopia or overestimation of myopia because of accommodation.[6,9,10,14,16,25,29–32,38,39] Instrument designers have attempted to deal with this issue by using "non-accommodative" fixation targets, by incorporating a fogging mechanism, or by using a correction factor in estimation of spherical refractive error. However, these methods do not consistently relax accommodation in children. Since accommodation is often variable, applying a simple correction factor has a limited effect on

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increasing accuracy. One study reported less minus overcorrection in noncycloplegic autorefraction of primary school children using an autorefractor with an open-field design and distant target.[39]

The pediatric wavefront evaluator (PeWE) is a prototype handheld open-field Shack–Hartmann aberrometer designed to measure refractive error in infants and young children without cycloplegia. The open-field design has been shown to provide measurements with less minus over-correction in children.[39] The PeWE also features continuous video capture, which increases the likelihood of acquiring centered and well-focused wavefront images for analysis. Its handheld design allows flexibility in aligning the instrument with a young child's eyes while the child views a target through the instrument. The purpose of the present study was to assess (1) feasibility of obtaining measurements in infants and young children by evaluating the instrument's success rate across age in children aged 6 months to <8 years, (2) effectiveness of the open-field design for relaxation of accommodation by comparing non-cycloplegic PeWE measurements of spherical equivalent (M) while children viewed near versus distant fixation targets, and (3) accuracy of noncycloplegic PeWE measurements compared with cycloplegic autorefraction.

Methods and Subjects

Subjects were children aged 6 months to <8 years who participated in a longitudinal study of refractive development between January 2007 and May 2010. The present study includes secondary analyses of PeWE measurements that were collected as part of a larger study of refractive development in order to measure higher-order aberrations and accommodation. The majority of subjects were members of the Tohono O'odham Nation, who have a high prevalence of astigmatism that is present in infancy and persists through grade school.[37,40–44] Children were recruited from the Women, Infants and Children clinics, from the Tohono O'odham Early Childhood Head Start Program, from the Tohono O'odham community, and from kindergarten and first grade classrooms on the Tohono O'odham reservation. Follow-up was attempted yearly until either the child completed the first grade or the study ended (May 2010). This study was approved by the Tohono O'odham Nation and the Institutional Review Board of the University of Arizona and conformed to the requirements of the US Health Insurance Portability and Accountability Act of 1996. Parents provided written informed consent prior to testing.

Apparatus and Data Processing

The design of the PeWE (Figure 1) is a variation of the Shack–Hartmann system previously described by Straub et al.[45] The PeWE is built around a large acrylic window that allows the subject to view real world targets binocularly. It was designed to allow the examiner to slip the window in front of the child's eyes for measurement while the child views a fixation target with minimal distraction from the target. The window is coated to transmit visible light and reflect infrared light. An infrared superluminescent diode of wavelength 830 nm is collimated and projected into the eye of the subject to create a spot nominally on the retina. Light scattered from the retina encodes the ocular aberrations and emerges from the eye. This light is captured by the PeWE optics and relayed to a lenslet array (Part 0300-7.6-S, Adaptive Optics Associates, Cambridge, MA; 300 mm diameter, 7.6 mm focal length). The spot pattern created by the lenslet array is captured and analyzed with custom software to recover low- and high-order aberrations of the eye. A report on accuracy and validity of the PeWE with simulated refractive errors is provided in e-Supplement 1 (available at jaapos.org).

Output video from the instrument is captured on a laptop computer for each subject encounter. After testing, the video (audio video interleave) file is converted to individual

bitmap image files, which are manually reviewed for quality. The images deemed centered and in-focus (Figure 2) are then put through an automated processing program that analyzes each image and provides measurements of refractive error in the form of power vectors M (spherical equivalent), J0 (astigmatism in the horizontal or vertical meridian [90°/180°]), and J45 (astigmatism in the oblique meridian [45°/135°]).[46–48] For each encounter, mean and median M, J0, and J45 across images, as well the number of images used for processing, are output to a spreadsheet. Encounters on which at least 7 images were obtained were considered "successful" and acceptable for further analysis (see e-Supplement 2, available at jaapos.org, for a detailed report on determination of the minimum number of images necessary for valid measurement).

Noncycloplegic PeWE measurements were attempted on all children. Children aged 3 years and older also completed cycloplegic PeWE and cycloplegic autorefraction using the Retinomax K-plus2 (Rmax [Nikon Inc, Melville, NY]), which provides accurate and reliable measurements of refractive error in children.[9] Right eye measurements were obtained in a dimly lit room whenever possible.

Noncycloplegic PeWE

Younger children sat on a parent's lap and older children sat on a chair by themselves. Children were asked to view a fixation target at 50 cm (near) or 2 m (distance), with testing order counterbalanced across subjects. The target was an animated cartoon screensaver displayed on a tablet computer (visual angle 17.3° × 22.7° at 50 cm, 4.4° × 6.0° at 2 m).

The examiner initiated video capture by pressing a key on a laptop computer. While standing to the side of the child, the examiner placed the instrument in front of and below the child's line of sight, directed the child's attention to the fixation target, and gradually raised the PeWE until the child was viewing the target through the window. The examiner monitored the image quality in real time through video displayed on the laptop computer and adjusted the position of the PeWE to achieve centered and focused video images. The video capture was terminated when the examiner judged that centered in-focus video had been obtained, or when the child was no longer cooperative. The target was then moved to the second target location, and testing proceeded in the same manner.

Cycloplegic Autorefraction and Cycloplegic PeWE

Cycloplegia was achieved with 1 drop proparacaine 0.5% followed by 2 drops of cyclopentolate 1%. Measurements were obtained using both the Rmax and PeWE at least 30 minutes after administration of eye drops. The examiner attempted to obtain Rmax measurements with a confidence of at least 8, per manufacturer recommendations. PeWE measurements under cycloplegia were only obtained with the target at one distance (2 m).

Results

A total of 2841 subject encounters (data collection points) for 1425 subjects were conducted, with some subjects participating at more than one age and therefore contributing data for more than one encounter. Data from 143 encounters were excluded because PeWE measurement was not obtained because of a technical problem with the instrument (eg, instrument out of alignment or instrument and data files damaged because of vandalism). For the remaining 2698 encounters (1403 subjects with 518, 526, 308, and 51 subjects contributing data for 1, 2, 3, and 4 encounters, respectively), mean age at time of measurement was 4.14 years (SD 2.05).

Noncycloplegic PeWE

Results of noncycloplegic measurements with the PeWE are shown in Table 1. Measurement success for near targets was 70%; for distance targets, 56%. Success rates increased significantly with age for both near and distance (χ^2 test; $P < 0.001$). Analyses conducted within each age group, indicated that the success rate was significantly higher at near than at distance ($P < 0.001$).

Results from the 1362 encounters at which successful near and distant target condition noncycloplegic PeWE measurements were obtained are summarized in Table 2. Near versus distance measurements of M, J0, and J45 were strongly correlated ($P < 0.001$). However, *t* tests indicated significant differences across near versus distance in mean measurements of M, J0, and J45 ($P < 0.001$ for M and J0, $P < 0.02$ for J45).

Agreement between near and distance noncycloplegic PeWE measurements by age is summarized in Table 3. There were significant effects of age on agreement for M ($P < 0.002$) and J0 ($P < 0.03$) (effect neared significance for J45, $P < 0.07$). Post hoc comparisons with Bonferroni correction indicated that 1 to <2-year-olds showed significantly less change in M from near to distance fixation than 3 to <4, 4 to <5, and 5 to <6-year-olds (*P*s < 0.04). There was also a trend toward greater variability (SD) in 1 to <2-year-olds. Post hoc comparisons yielded no significant differences across age groups for agreement (near verses distance) in J0 and J45 measurements.

Noncycloplegic PeWE versus Cycloplegic Rmax

Results are shown in Table 4 for the 966 encounters where successful results were obtained for near and distance noncycloplegic PeWE and cycloplegic Rmax. PeWE measurements (for both near and distance) were significantly correlated with Rmax measurements ($P < 0.001$ for M, J0, and J45). However, *t* tests comparing mean values for PeWE near and distance fixation to those for the Rmax yielded significant differences in M, J0 and J45 ($P < 0.001$). The PeWE tended to overestimate myopia or underestimate hyperopia by about 1.00 D at distance and 2.00 D at near, and it tended to over-estimate both J0 and J45.

Separate repeated measures analyses of variance for M, J0, and J45 data were conducted to assess accuracy of PeWE at near and distance by age group (Table 5). There were significant main effects of age at both near ($P < 0.04$) and distance ($P < 0.05$). However, post hoc comparisons with Bonferroni correction yielded a significant difference in accuracy only for distance results between the 5 to <6 years and the 6 to <7 years age groups.

Discussion

The present study provides data regarding the feasibility of examining infants and toddlers without cycloplegia using an autorefractor or vision screener with the general design of the PeWE. Our success rates for near (70%) and distance (56%) fixation are less than ideal; furthermore, success rates may have been elevated because of the fact that many children participated on more than one occasion and may have been more cooperative as they became more familiar with the PeWE. And whereas the success rates for the present study are comparable to those reported for two previous large population-based studies with respect to infants tested by the Retinomax, they were poorer than the success rates for toddlers and young children.[2,20]

Several strategies could be implemented to increase measurement success. Testers had to judge, based on real-time monitoring of the video, whether or not they were obtaining sufficient data during testing. Providing testers with more precise feedback regarding data quality during the measurement process might improve success rates. Other strategies entail

modifying the target design and testing environment. Success rates were lower for measurement at distance. Many children may have had difficulty seeing the target at distance because of astigmatism-related blur and the smaller visual angle of the stimulus. Children may have also been more vulnerable to distraction when the target was at distance. A more salient and attractive target is likely to improve subject cooperation with regard to fixation.

Second, we evaluated the usefulness of the PeWE open-field design in relaxing accommodation in order to obtain valid measurements of refractive error in the absence of cycloplegia. If hyperopic subjects were accurately accommodating, we would expect mean M to be −2.00 for the 50 cm target and −0.50 for the 2 m target, that is, a 1.50 D difference in accommodative demand between the two conditions. Mean values of M were generally consistent with the difference in accommodative demand to the near versus the distant targets (−1.25 D for near [0.75 D accommodative lag] and −0.15 for distance [0.35 D accommodative lag]). Thus subjects tended to underaccommodate to the targets, but the PeWE was able to measure changes of accommodation in response to near versus distance targets (1.10 D change measured with 1.50 D change in accommodative demand). Some of the underaccommodation observed may have been because of the inclusion of myopic children who were unable to focus near targets by accommodating. However, this would likely have had a minimal effect on the results because only 18 (1.8%) of 966 subjects with Rmax data in addition to near and distance PeWE measurements (ie, children aged ≥3 years) had a myopic spherical equivalent ≥1.50 D per Rmax. Analyses examining effects of age indicated that 1 to <2-year-olds showed significantly less change in M, that is, less change in accommodation, from near to distance fixation than did 3- to <6-year-olds. There was also a trend toward greater variability (SD) in this age group. These findings are consistent with our observations that children in this age range are often distracted and less cooperative. We were initially concerned that subjects might look at the beamsplitter of the PeWE, rather than through the PeWE window, thus overaccommodating. The results suggest that this was not the case, as subjects tended to underaccommodate. Finally, results indicated that differences in measurements of astigmatism at near versus at distance were not clinically significant and did not vary by age. This was expected, as accommodation typically has only a small influence on measurements of astigmatism,[49–53] although changes in astigmatism with accommodation have been reported.[54]

Overall, results comparing measurements obtained for near versus distant target conditions suggest that the PeWE without cycloplegia might be useful for assessment of accommodation and astigmatism in infants and young children.

Our final assessment examined accuracy of the noncycloplegic PeWE for near and distant fixation target conditions compared with cycloplegic Rmax measurements in children age 3 to <8 years of age. Analysis of M data indicated that PeWE tended to overestimate myopia or underestimate hyperopia by about 1.00 D at distance and 2.00 D at near. The high correlation between noncycloplegic PeWE and cycloplegic Rmax measurements of M indicate that the PeWE provides valid measurements, and with the properly selected cutoff values, may be useful for screening for significant spherical refractive errors.[55] However, in its present form and using the procedures outlined here, it is limited in its ability to accurately measure magnitude of spherical refractive error without cycloplegia. Reducing peripheral distraction and revising the nature of the fixation target may result in more reliable relaxation of accommodation and more accurate measurements. For example, research suggests that binocular targets receding into the distance result in maximum relaxation of accommodation.[56]

Compared to Rmax with cycloplegia, PeWE without cycloplegia tended to overestimate both J0 (about 0.25 D) and J45 (about 0.17 D), but these effects were small and of minimal clinical significance. This is consistent with the results of a previous study in which we found little difference between cycloplegic and non-cycloplegic measures of astigmatism in this population.[9]

The present study has several limitations. First, the study population had a high prevalence of with-the-rule astigmatism. Second, the instrument under study is not commercially available and in its current form requires significant data processing in order to provide estimates of refractive error (eg, analysis of the data required manual review of thousands of images). Third, an optimal study design would have compared PeWE to the gold standard for infants and toddlers, that is, cycloplegic retinoscopy. However, these data were collected as part of a longitudinal study in which we used Rmax to measure refractive error to ensure consistency in measurements across children and over time and because a previous study of this population established the validity of Rmax measurements.[9]

In conclusion, the PeWE is prone to “instrument myopia” when measuring non-cyclopleged children. However, it does seem to accurately reflect changes in accommodation from distance to near targets without cycloplegia, which may prove to be useful in the objective assessment of accommodation in infants and young children. In order to improve the utility of the PeWE, further work is needed to develop software that will automatically score data and testing procedures that will increase measurement success rates and maximize relaxation of accommodation during measurement.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIG 1.
The PeWE is used to measure refractive error in a preschool child as she views a cartoon on a laptop computer.

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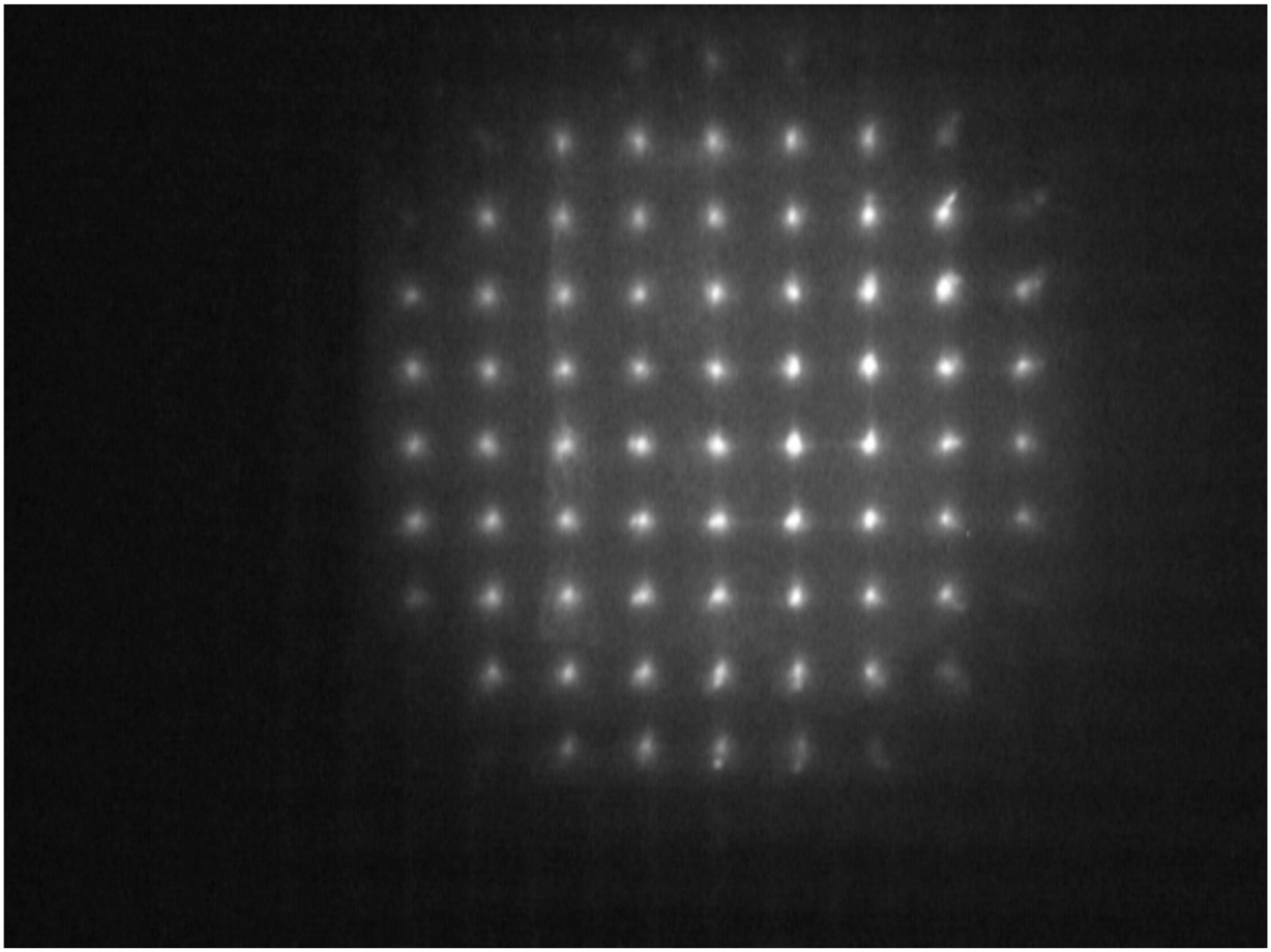

FIG 2.
The videos from each encounter/condition are processed to extract individual images. Images are manually reviewed, and in-focus centered images, as shown in the figure, are selected for analysis. An automated program is used to analyze the images to determine refractive error.

Table 1

Measurement success rates by age for near and distant target conditions

Age group	Sample size for age group	Percent of age group successful with near target (n)	Percent of age group successful with distant target (n)
<1 y	206	60.2% (124)	46.1% (95)
1 to <2 y	306	60.5% (185)	53.3% (163)
2 to <3 y	363	61.7% (224)	51.8% (188)
3 to <4 y	391	70.6% (276)	52.4% (205)
4 to <5 y	397	71.3% (283)	53.4% (212)
5 to <6 y	426	77.9% (332)	59.6% (254)
6 to <7 y	403	76.4% (308)	59.1% (238)
7 to <8 y	206	81.6% (168)	72.8% (150)
Total	2698	70.4% (1900)	55.8% (1505)

Table 2

Comparison of noncycloplegic PeWE near and distant target condition measurements for encounters on which both measurements were obtained

Measure	Target condition	Mean, D	SD	Std error mean	Mean difference	SD of difference	Correlation (r^2)
M	Near	−1.26	0.98	0.03	−1.05[a]	0.73	0.52[a]
	Distant	−0.21	0.91	0.02			
J0	Near	0.78	0.64	0.02	0.06[a]	0.28	0.81[a]
	Distant	0.72	0.61	0.02			
J45	Near	−0.18	0.33	0.01	−0.01[a]	0.21	0.61[a]
	Distant	−0.16	0.29	0.01			

[a]Statistically significant.

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Table 3

Comparison of noncycloplegic PeWE near and distant target condition measurements by age group

		Difference in M		Difference in J0		Difference in J45	
Age	**N**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
<1 y	80	−0.93	0.77	0.06	0.32	0.00	0.24
1 to <2 y	141	−0.85	0.97	0.09	0.32	−0.02	0.22
2 to <3 y	163	−0.97	0.79	0.06	0.34	−0.04	0.22
3 to <4 y	189	−1.12	0.68	0.09	0.27	0.01	0.18
4 to <5 y	195	−1.18	0.64	0.09	0.31	0.01	0.20
5 to <6 y	238	−1.09	0.62	0.05	0.23	0.00	0.22
6 to <7 y	218	−1.09	0.66	0.01	0.25	−0.04	0.21
7 to <8 y	138	−1.04	0.73	0.04	0.24	−0.04	0.17
Total	1362	−1.05	0.73	0.06	0.28	−0.01	0.21

Table 4

Comparison of noncycloplegic PeWE measurements (near and distant target conditions) to cycloplegic Rmax measurements for encounters on which all 3 measurements were obtained

Measure	Instrument/condition	Mean	SD	Mean difference from cRmax	SD of difference	Correlation with cRmax (*r*)
M	Rmax	0.80	1.05			
	PeWE, near fixation	−1.25	0.95	2.05	1.01	0.50
	PeWE, distance fixation	−0.15	0.82	0.94	0.85	0.61[a]
J0	Rmax	0.50	0.57			
	PeWE, near fixation	0.78	0.67	−0.28[a]	0.31	0.88[a]
	PeWE, distance fixation	0.72	0.64	−0.23[a]	0.31	0.87[a]
J45	Rmax	0.00	0.22			
	PeWE, near fixation	−0.17	0.33	0.17[a]	0.48	−0.45[a]
	PeWE, distance fixation	−0.16	0.29	0.16[a]	0.44	−0.46[a]

Rmax, cycloplegic autorefraction using the Retinomax K-plus2; *PeWE*, noncycloplegic pediatric wavefront evaluator.

[a]Statistically significant, $P < 0.001$.

Table 5

Summary of agreement between noncycloplegic PeWE (near and distant target conditions) and cycloplegic Rmax by age group

Comparison	Age	N	Mean difference	SD
Rmax vs PeWE with *near* target	3 to <4 y	185	2.03	0.99
	4 to <5 y	193	2.16	1.02
	5 to <6 y	234	2.15	0.91
	6 to <7 y	216	1.88	1.07
	7 to <8 y	138	2.02	1.03
	Total	966	2.05	1.01
Rmax vs PeWE with *distant* target	3 to <4 y	185	0.91	0.86
	4 to <5 y	193	0.97	0.86
	5 to <6 y	234	1.05	0.81
	6 to <7 y	216	0.81	0.87
	7 to <8 y	138	0.98	0.89
	Total	966	0.94	0.85

Rmax, cycloplegic autorefraction using the Retinomax K-plus2; *PeWE*, noncycloplegic pediatric wavefront evaluator.