Clinical evaluation of refraction using a handheld wavefront autorefractor in young and adult patients

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Purpose: To determine the accuracy of measurement by the SureSight autorefractor (software version 2.0) and the influence of accommodation.

Setting: Pediatric Section, Department of Ophthalmology, University of Hamburg, Hamburg, Germany.

Methods: In a series of comparative measurements, autorefractor readings were compared with cycloplegic retinoscopy in 195 eyes of 108 patients (1 to 81 years) measured under cycloplegia. Ninety-six eyes were also measured without cycloplegia.

Results: The wavefront autorefractor was able to refract human eyes from a distance of 0.35 m. The accuracy was lower than that with conventional tabletop autorefractors. A difference of less than 0.51 diopter (D) was found in 68% of the spherical equivalents under cycloplegia. Many emmetropic and hyperopic children accommodated during the noncycloplegic measurements and were minus-overcorrected up to −6.13 D. In our group of young patients (2 to 17 years), 47% were minus-overcorrected by more than −2.00 D.

Conclusions: The wavefront autorefractor uses a new method to determine the refractive state of the eye from a distance. It was less accurate than other conventional autorefractors. A benefit is its application in infants and disabled and uncooperative subjects. Cycloplegia is necessary in young hyperopic patients.

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Most automatic eye refractors currently in use are based on well-known optical principles such as streak retinoscopy, the Scheiner method, or the knife-edge principle.[1–3] During the past 30 years, these autorefractors have reached a high state of perfection. By incorporating modern computer and video technology, it has been possible to simplify the optical construction, reduce the measurement time, and improve the accuracy of measurement without changing the underlying optical principles.[4,5]

A completely new way of measuring the refractive state of the human eye is based on wavefront analysis. This technique was originally developed by Liang and coauthors[6] and provides a rapid, noninvasive, and objective measure of the wave aberration of the eye. In 1997, Liang and Williams[7] developed the technique further and were able to present the most complete data on the various optical errors of the human eye to date.

Another promising ophthalmic application of wavefront analysis is in the field of wavefront-guided laser in situ keratomileusis (LASIK). When the wave aberrations of a given human eye are known, it may be possible to calculate a customized ideal ablation profile that corrects not only spherical and cylindrical components but also high-order refractive errors such as spherical aberration.[8,9] Several companies have begun to incorporate wavefront aberrometers into their laser systems to support topography-guided ablation.[9,10]

The first autorefractor based on wavefront analysis is the SureSight® (Welch Allyn). It is small and can be

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handheld without a table and chin rest. These features make it suitable for measuring very young children and disabled or uncooperative patients. In this respect, it is comparable to the Nikon Retinomax® handheld autorefractor.[11]

An interesting feature of the wavefront autorefractor is its fairly large working distance of 0.35 m. Although this distance is smaller than that used by photorefraction devices,[12–14] it is large enough to perform a valid refraction in children who would normally show strong resistance when an examiner comes into close range with a huge conventional autorefractor.

In the present study, we evaluated the accuracy of the wavefront autorefractor in ametropic patients with and without cycloplegia. The influence of accommodation when measuring children and adults without cycloplegia is also discussed.

Patients and Methods

Patients

The accuracy of the wavefront autorefractor was studied in 2 groups of patients recruited from the outpatient department and ward of the University Eye Hospital, Hamburg-Eppendorf. Group 1 consisted of 195 eyes (108 patients, aged 1 to 81 years) measured under cycloplegia. The median spherical equivalent (SE) was +0.75 diopter (D) ± 2.04 (SD) (range −8.13 to +5.75 D; 51 eyes with myopia, 138 with hyperopia, and 6 with emmetropia). The mean cylinder power was −0.70 ± 0.62 D (range 0 to −3.75 D).

Group 2 consisted of 96 eyes (51 patients, aged 2 to 76 years) from Group 1 who were also measured without cycloplegia. The median SE of the 96 eyes was +1.13 ± 2.24 D (range −7.75 to +5.75 D). The mean cylinder power was −0.76 ± 0.76 D (range 0 to −3.75 D). A subgroup of these patients consisted of 27 children (57 eyes, aged 2 to 17 years). The median SE was +1.25 ± 2.07 D (range −6.50 to +5.75 D). The mean cylinder power was −0.71 ± 0.71 D (range 0 to −3.00 D).

All patients were first screened by an ophthalmologist. Patients with heterotropia, eccentric fixation, suppression, opacities of the optical media, or any disease of the retina were excluded. Cycloplegia was carried out by application of 1 drop of cyclopentolate 1% and a second drop 10 minutes later. After a waiting period of 20 minutes, retinoscopy and the measurement with the SureSight was performed. In children younger than 3 years, cyclopentolate 0.5% or tropicamide 5% was used instead of cyclopentolate 1%. Patients with dark irides were given an additional dose if it was judged that cycloplegia was incomplete on the basis of pupil activity and variability in the retinoscopic neutral point.

Working Principle of the Wavefront Autorefractor

Wavefront analysis does not require moving optical components. The data acquisition is based solely on optical imaging and electronic calculations. The patient must look straight at the device. A circle of 8 green blinking diodes is provided to attract the patient's attention. The optical setup is shown in Figures 1A and 1B. An infrared beam from a laser diode is directed into 1 eye. When it emerges from the instrument, the beam can be seen by the patient as a red spot. This serves as an additional fixation target. The beam has a small diameter and is thus imaged on the retina with a large depth of focus. The diameter of the laser focus on the retina is small and almost independent of the degree of ametropia. The beam is reflected at the retina and propagates back to the autorefractor, where it enters the instrument, passes the beam-splitter, and reaches the essential part of the optical construction—the so-called

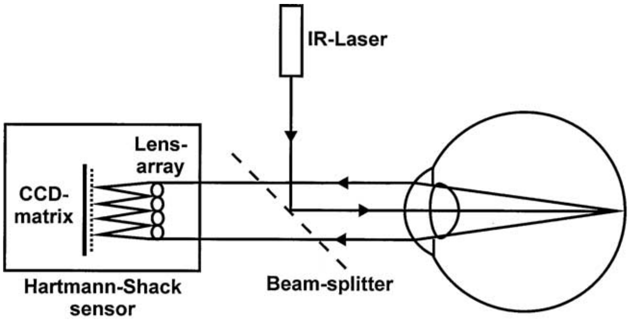

Figure 1A. (Schimitzek) An infrared laser beam is reflected by a beam splitter and sent into the eye. The beam is focused at the macula and diffusely reflected from the fundus. Some of the reflected light rays leave the eye, enter the autorefractor, and fall on a Hartmann-Shack sensor that consists of numerous lenses arranged as a matrix. The multiple images are recorded with a CCD camera.

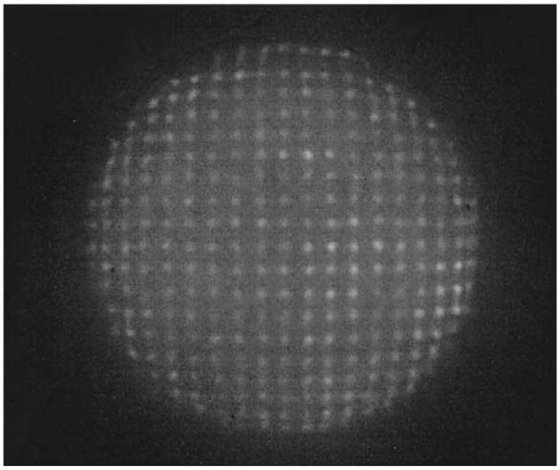

Figure 1B. (Schimitzek) Pattern of light spots projected by the Hartmann-Shack lens matrix on the CCD camera. The refractive state of the eye can be calculated from the distances between all light spots.

Hartmann-Shack sensor. This sensor consists of a matrix of tiny lenses arranged in many rows and columns. These lenses form many small light spots on the active surface of a charged-couple-device (CCD) matrix camera.

The refractive power is calculated from the positions of the light spots according to the following general concept. If the patient has an emmetropic eye, parallel light rays leave the eye. These rays produce light spots on the CCD camera that are uniformly spaced. The distance between the light spots (Figure 1B) is typical in an emmetropic eye. In the case of pure hyperopia or myopia, the light spots are also uniformly spaced. The spot pattern, however, is expanded or contracted compared to that in emmetropia because the light rays that are reflected from the fundus leave the eye divergent or convergent. If the patient has an astigmatic ametropia, a light bundle that is no longer rotationally symmetric leaves the eye. In this case, the distance between the light spots on the CCD matrix varies in a way that depends on cylinder power and axis.

Method of Comparative Measurements

All autorefractor measurements without cycloplegia were taken immediately before the eyedrops were dispensed. After the waiting period, streak retinoscopy was performed under cycloplegia by 1 of us (T.S.) using handheld corrective lenses. The investigator was unaware of the results with the wavefront autorefractor. The cycloplegic measurement with the SureSight followed immediately. The "child mode" explained in the discussion section was not used.

Criteria for the Accuracy of Measurement

To obtain information about the accuracy of the wavefront autorefractor, all readings were compared to the results of cycloplegic retinoscopy. All comparison criteria, with the exception of the J-vector analysis, were used in our earlier studies[1,2,5,11] and allow direct comparison of the wavefront autorefractor described here with autorefractors tested in earlier years.

The difference of the spherical equivalent (DSE) was calculated by

$$DSE = (S_t + 0.5 * C_t) - (S_c + 0.5 * C_c)$$

where S and C denote the spherical and the cylinder powers; the subscripts "t" (test) and "c" (comparison) denote the instrument under test (SureSight) and the comparison technique (cycloplegic retinoscopy). A negative DSE indicates a minus-overcorrection by the instrument under test.

The difference of the cylindrical powers (DC) was calculated by

$$DC = C_t - C_c$$

The weighted axes difference (DA) is a quality criterion based on the power-vector approach. It is evaluated by a mathematical expression in which the difference between the 2 cylinder axes (test and comparison, measured in degrees) is weighted with the cylinder power measured with the comparison method.

$$DA = 2C_c \sin(2\alpha_t - 2\alpha_c)$$

The formula makes it possible to compare axis values, even when the actual cylinder powers are different. C_c is taken as a weighting factor since it is assumed to be more accurate then the cylinder power of the instrument under test. Geometrically, DA is the length of the difference vector between both methods given that the cylinder power found with the SureSight is equal to the cylinder power found with retinoscopy. The resulting number has the dimension "diopter." A value of DA = 0.5 D is equivalent to an axes difference of 14.5 degrees given a cylinder power of 1.0 D.

The J-vector difference ($\Delta\vec{J}$) is a measure of the difference between the cylindrical components. $\Delta\vec{J}$ describes the cylindrical difference in terms of 2 Jackson crossed cylinders with orientations of 0 degrees and 45 degrees, respectively. $\Delta\vec{J}$ is determined using the method of Raasch and coauthors.[15] At first, the J_0 and J_{45} components of the (M, J_0, J_{45}) space described by Thibos and Horner[16] are calculated from the results of the SureSight and cycloplegic retinoscopy.

$$\begin{aligned} J_{0t} &= (-C_t/2)\cos(2\alpha_t) \\ J_{45t} &= (-C_t/2)\sin(2\alpha_t) \end{aligned} \quad \text{and} \quad \begin{aligned} J_{0c} &= (-C_c/2)\cos(2\alpha_c) \\ J_{45c} &= (-C_c/2)\sin(2\alpha_c) \end{aligned}$$

Then the J-vector difference ($\Delta\vec{J}$) between the cylindrical results of the test and the comparison instrument can be written as

$$\Delta\vec{J} = (\Delta J_0, \Delta J_{45})$$

where ΔJ_0 and ΔJ_{45} are defined by

$$\Delta J_0 = (J_{0t} - J_{0c})$$

$$\Delta J_{45t} = (J_{45t} - J_{45c})$$

Our last quality criterion is the total cylindrical difference (TCD). It is the length of the vector $\Delta\vec{J}$. The TCD is a summarizing measure for the cylindrical accuracy of the measurement. When the normal cylinder notation is used instead of the Jackson crossed-cylinder notation, TCD is obtained by

$$TCD = +\sqrt{C_t^2 + C_c^2 - 2C_tC_c\cos[2(\alpha_t - \alpha_c)]}$$

The terminology for this criterion differs in the literature. The term *total cylindrical difference* was introduced by 1 of us in 1987.[5] In our earlier papers,[2] the term *combined cylindrical error* was used. Wesemann and Dick[11] called the above expression the *difference of the cylindrical corrections*. In 2000, Raasch and coauthors[15] proposed the name *astigmatic difference* (see Appendix).

Results

Accuracy of Measurement in Ametropic Patients Under Cycloplegia

Difference of the spherical equivalents. The difference in the SE between wavefront refractor and cycloplegic retinoscopy in 195 eyes is shown in Figure 2a. The frequency distribution is almost normally distributed about the central column. This central column indicates that 45% of the SEs differed by less than ±0.26 D. The other columns show how often larger errors occurred. The maximal differences were −2.38 D and +3.00 D. On average, the SureSight delivered an SE that was in exact agreement with retinoscopy under cycloplegia (DSE_{mean} = −0.01 ± 0.65 D).

Difference of the cylindrical powers. The cylinder powers determined by the SureSight and retinoscopy were very similar. The mean difference was +0.01 ± 0.49 D. The distribution in Figure 2b is almost symmetric and shows few cylinder power differences larger than ±0.50 D. In all eyes that showed no significant astigmatism with cycloplegic retinoscopy, the SureSight displayed cylinder powers ≤1.0 D.

Weighted axes difference. The accuracy of the axis was evaluated in the cases in which a cylinder power of 0.25 D or greater had been determined with the autorefractor and with retinoscopy. This occurred in 167 of 195 eyes. The mean DA was +0.55 ± 0.48 D (Figure 2c). In a few cases, large differences were found; the largest was +2.88 D (cylinder power −1.50 D, axis deviation 74 degrees).

Accuracy of Measurement in Ametropic Patients Without Cycloplegia

Difference of the spherical equivalents. The DSE distribution in Figure 3a is not symmetric. It exhibits a shift toward negative values. The SE measured with the wavefront autorefractor was accurate to ±0.50 D in only 33% of cases. In 47%, the DSE was not larger than ±1.00 D. The mean DSE was −1.59 ± 1.95 D (range +2.75 to −6.13 D).

Difference of the cylindrical powers. The accuracy in measuring cylinder power was similar to the measurement under cycloplegia (Figure 3b). The mean difference was −0.06 ± 0.47 D.

Weighted axes difference. Eighty-one percent of eyes showed a cylinder power of 0.25 D or greater and were included in the analysis. The mean DA was +0.45 ± 0.49 D (Figure 3c). The largest difference was +3.15 D (cylinder power −2.50 D, axis deviation 39 degrees).

Accuracy Indices

Table 1 summarizes the data presented in the histograms (Figures 2 and 3). It indicates how often the differences were smaller than a selected criterion value. This is a measure of the percentage of correct or almost correct results. Data found with 7 table-top refractors of an earlier generation[5] and with the Nikon Retinomax[11] are presented for comparison.

Accuracy of Cycloplegic Measurements. The percentage of correct or almost correct results with the SureSight in cycloplegic eyes (rows 1 and 2) lie below the range found with 7 different table-top autorefractors[5]

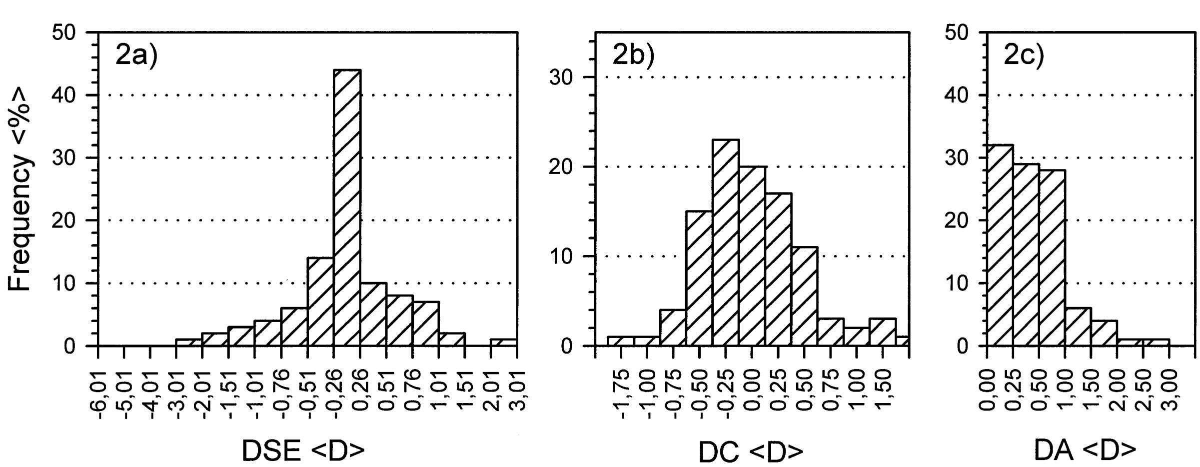

Figure 2. (Schimitzek) Frequency distribution of the differences between SureSight and retinoscopy (Group 1); both measurements under cycloplegia. *2a:* difference of the spherical equivalents; *2b:* difference of the cylinder powers; *2c:* weighted axes difference.

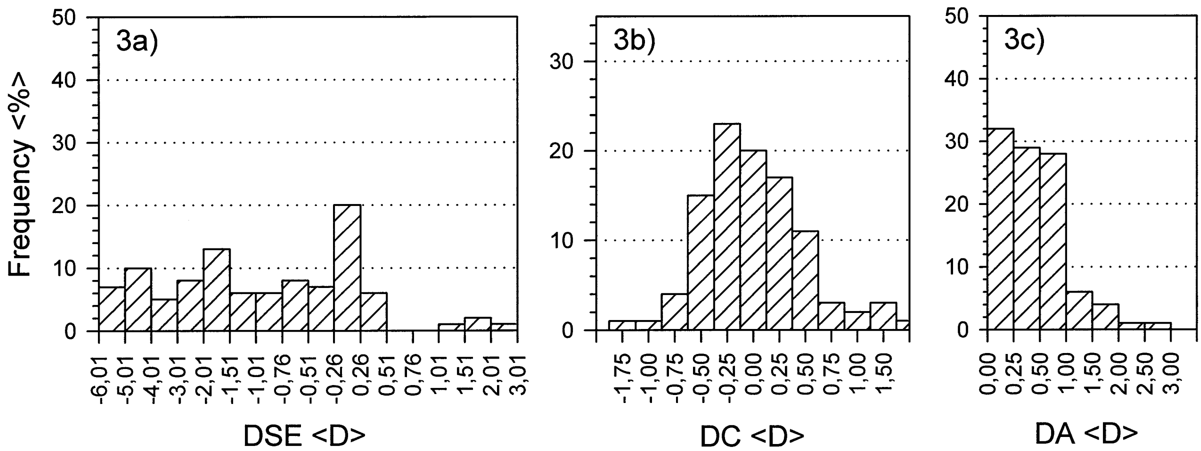

Figure 3. (Schimitzek) Frequency distribution of the differences between SureSight and retinoscopy (Group 2, SureSight without cycloplegia). *3a:* difference of the spherical equivalents; *3b:* difference of the cylinder powers; *3c*: weighted axes difference. The percentage of minus-overcorrected cases (DSE $<$ 0 in *3a*) is much larger than in Figure *2a*. The distributions in *3b* and *3c* are similar to those in Figures *2b* and *2c*.

Table 1. Frequency of "correct or almost correct" results obtained in eyes under and without cycloplegia with the SureSight. The percentages indicate how often the result of the SureSight differed by less than ±0.51 D or 0.63 D from cycloplegic retinoscopy. Data from 2 other studies that used the same criteria on 7 table-top autorefractors and the handheld Retinomax refractor are presented for comparison.

	Comparison Criterion (%)			
Measurement	**|DSE| ≤0.5 D**	**|DC| ≤0.5 D**	**|DA|* ≤0.5 D**	**TCD* ≤0.63**
SureSight under cycloplegia vs. cycloplegic retinoscopy (Group 1, n = 195)	68	86	62	58
SureSight under cycloplegia vs. cycloplegic retinoscopy (Group 2, n = 96)	65	79	70	59
SureSight without cycloplegia vs. cycloplegic retinoscopy (Group 2, n = 96)	33	84	75	65
Retinomax K-Plus vs. subjective refraction (adult patients without cycloplegia)[11]	88	95	87	91
Cycloplegic Retinomax K-Plus vs. cycloplegic retinoscopy (children)[11]	72–82	86	85–87	74–76
Range of 7 table-top autorefractors (adult patients without cycloplegia)[5]	84–95	90–97	84–93	83–92

DSE = difference of the spherical equivalent; DC = difference of the cylindrical powers; DA = weighted axes difference; TCD = total cylindrical difference

*Only patients with a cylinder power greater than zero with both methods (test and comparison method) were included.

(row 6) and the handheld Retinomax[11] (rows 4 and 5) The 4 quality criteria for the SureSight varied from 58% to 86%. This indicates that the present version of the wavefront autorefractor is less accurate than the other established conventional autorefractors.

Accuracy of Noncycloplegic Measurements. The accuracy of the SE was substantially lower without cycloplegia (row 3). The number of correct or almost correct spherical results dropped from 65% to 33%. The accuracy of the cylinder power was about the same as the results under cycloplegia (84% versus 79% and 86%). The results of DA were even slightly better than under cycloplegia. This indicates a slightly higher accuracy in measuring the axis of the astigmatism. A potential explanation may be found in the effects of disturbing peripheral aberrations that occur in wide pupils of cycloplegic eyes or the higher risk of measuring outside the optical axis.

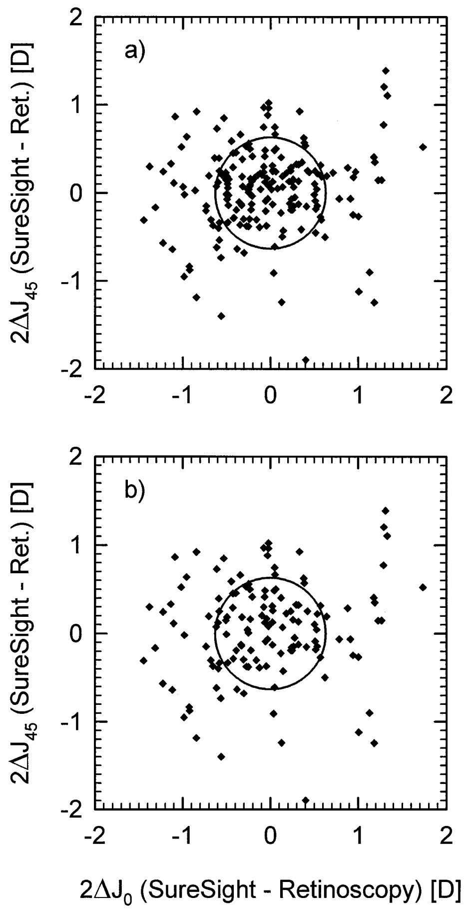

Figure 4. (Schimitzek) Two-dimensional polar plot of the vector difference $2\Delta\vec{J}$ between the cylindrical corrections obtained with cycloplegic retinoscopy and cycloplegic SureSight in Group 1. *a:* All patients (N = 195). *b:* Patients with astigmatism ≥0.5 D (n = 136). $\Delta\vec{J}$ was calculated for each eye. All vectors start at the origin. For clarity, only the endpoint of each vector is shown. The distance of each diamond from the origin indicates the discrepancy between the 2 methods. All data points inside the circle denote measurements in which the TCD was smaller than our criterion difference of 0.63 D.

Further Analysis of the Cylindrical Differences

Results of the J-vector analysis of all patients in Group 1 are shown in Figure 4. The 2-dimensional scatterplots visualize the distribution of the $\Delta\vec{J}$ vectors calculated for all eyes. All difference-vectors start at the origin. For clarity, only the endpoint of each vector (the tip of the vector) is denoted by a black diamond; the entire vector is not shown. (As cylindrical differences were measured in the conventional way and not in Jackson crossed-cylinder units, both axes in Figure 4 are scaled in units of $2\Delta J$ [see Appendix].)

The distance of each diamond from the origin characterizes the discrepancy between SureSight and retinoscopy. Diamonds lying exactly at the origin indicate measurements in which cylinder power and cylinder axis obtained with both measurement techniques were identical. All vectors whose endpoints lie within the circle have a length of TCD < 0.63 D and were listed in Table 1 as "correct or almost correct" cylindrical results.

The scatterplot depicted in the upper panel of Figure 4 indicates an almost random distribution of the cylindrical differences. This indicates that the cylindrical results found with the SureSight were, on average, equal to the results found with retinoscopy. A thorough statistical analysis with the Kolmogorov-Smirnov normality test reveals, however, that the data are normally distributed ($P = .05$) along the horizontal ΔJ_0 axis only. The distribution along the vertical ΔJ_{45} axis has a marked kurtosis (k = 1.77), indicating an excess of data points inside the circle, and so it fails the normality test.

The lower panel (Figure 4b) shows the same data as in Figure 4a, but all patients with a cylinder power less than 0.5 D were omitted; 136 eyes were plotted. The excess in the center disappeared. Now the data pass the normality test in both directions. The number of large differences (points outside the circle) is almost unchanged.

Our quality criterion (TCD ≤ 0.63 D) is met by 61% of all measurements in Figure 4a and 51% in Figure 4b. The decreasing percentage indicates that the discrepancy between SureSight and retinoscopy increases with increasing cylinder power.

Influence of Accommodation in Patients Under and Without Cycloplegia

The individual SEs measured by the SureSight in Group 2 are plotted against results obtained by cycloplegic retinoscopy in Figure 5. The upper panel shows the data points obtained under cycloplegia and the lower panel, the results without cycloplegia. To learn more about the changes with age, all patients in Group 2 were divided into 3 subgroups. The first subgroup (triangles) comprised "children" (aged 2 to 6 years [n = 32] and 8 to 17 years [n = 25]). Squares denote "young adults" (aged 20 to 40 years [n = 18]). Diamonds denote "old adults" (older than 40 years [n = 21]). The data points of 2 patients with a myopia < -4 D lie outside the plotted area.

All data points in the upper panel of Figure 5 lie close to the diagonal line that represents ideal agree-

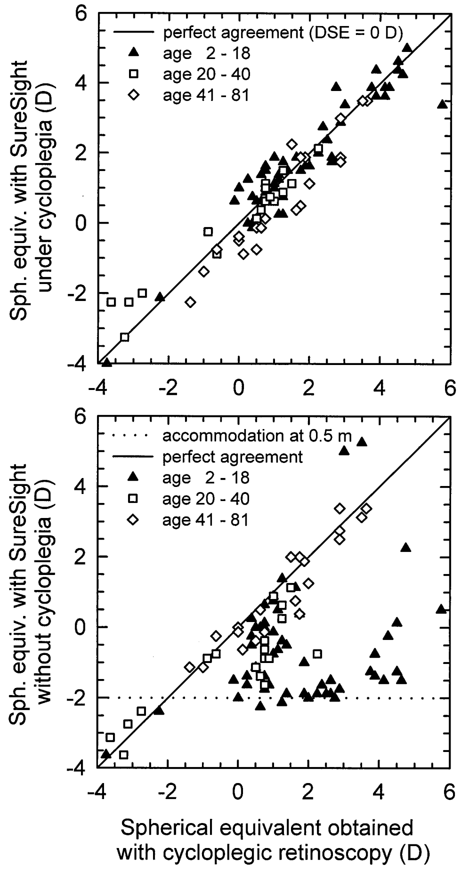

Figure 5. (Schimitzek) Individual SEs measured by the SureSight versus cycloplegic retinoscopy (Group 2). *Upper panel:* Both measurements under cycloplegia. *Lower panel:* SureSight without cycloplegia. The cycloplegic results agree well with retinoscopy. All data points lie close to the diagonal line that indicates perfect agreement. Without cycloplegia, many data points lie below the diagonal DSE = 0 D line, indicating a minus-overcorrection. The accommodating patients are mainly children (triangles) and young adults (squares). The additional dotted line at −2 D shows the autorefractor reading that would be expected when patients accommodate at a distance of 0.5 m.

ment. This illustrates the fact that the SEs found with the wavefront autorefractor under cycloplegia were similar to the values obtained with cycloplegic retinoscopy.

Without cycloplegia (lower panel), many data points obtained by the SureSight fell below the diagonal line. These data points indicate a minus-overcorrection by the wavefront autorefractor. It is obvious from Figure 5 that minus-overcorrected results were more frequent in emmetropic and hyperopic patients. More than 50% of all children with hyperopia ≥1.0 D were minus-overcorrected by more than −2.0 D. Ten of 57 children eyes showed a minus-overcorrection of −2.0 D to −4.0 D. An even larger minus-overcorrection of −4.13 D to −6.13 D was seen in 15 eyes. The median of the difference between the SEs under and without cycloplegia in the subgroup of children was −2.22 D.

The data of the emmetropic and hyperopic young adults (squares) also lie consistently below the diagonal line. The old adults, however, show no significant differences under and without cycloplegia.

Discussion

Analysis of Autorefractor Problems Caused by Accommodation

In the present study, a large number of children and young adults accommodated during the noncycloplegic autorefraction. What was the reason for this undesired accommodation?

Conventional autorefractors suffer from "instrument myopia." Conventional autorefractors measure at close range and use special fogging techniques to relax accommodation. These fogging techniques work well on adults and reduce the so-called instrument myopia substantially. In children, however, these fogging techniques are less effective.[11] A physiological explanation for the undesired instrument myopia is that the children "feel" the fixation target very close to their eyes.

Distant autorefractors suffer from "fixation myopia." Several companies have tried to develop computerized eye refraction devices that operate from a longer distance. The first fully operational instrument of this kind was the Topcon pediatric refractor PR1100.[17] Modern alternatives are the PowerRefractor[14] and the SureSight. In addition, a new open-field autorefractor has been recently introduced by Shin-Nippon.[18,19] This autorefractor is a successor to the well-known Canon R1 and allows a binocular field of view through a large beam splitter. However, all these refractors have a common disadvantage: They do not have a fogging system.

Distant autorefractors use real fixation targets that are mounted close to the front end of the instrument or to the wall of the examination room. When a hyperopic patient is asked to look at the fixation target, he or she may start to accommodate. As a result, the autorefractor will measure the eye not in its relaxed position but in a state of pseudo-myopia.

When a patient accommodates exactly at the front end of the SureSight (0.35 m), the instrument should detect an SE of −2.86 D regardless of the actual ametropia of the patient. When the patient accommodates to an object at a greater distance, the spherical autorefractor result will lie between −2.86 and 0 D. We denote this special type of pseudomyopia caused by accommodation at a real object by the physiological term *fixation myopia*.

A closer inspection of Figure 5, lower panel, reveals that the behavior of our young hyperopic patients can be explained by fixation myopia. Most of our hyperopic children did not appear as hyperopes but as myopes. A large percentage appeared as −1.50 to −2.25 D myopes, indicating that these young patients accommodated at distances close to 0.5 m. Almost all other hyperopic children showed up as myopes with SEs from −1.5 to 0 D.

Figure 6 illustrates the general properties of fixation myopia from a different perspective. The graph plots the degree of undesired accommodation against the SEs of the distance refraction determined with retinoscopy. When the patient fixates and accommodates at a real point somewhere in the space between the distance of the autorefractor and infinity, his or her amount of accommodation will fall somewhere within the triangular hatched area shown. The horizontal boundary (accommodation = 0 D) denotes that the patient does not accommodate at all. The diagonal line [accommodation = 1/(distance of eye refractor)] reflects the situation in which the patient accommodates exactly at the autorefractor. The vertical extent of the hatched area in Figure 6 depends on the spherical distance refraction of the eye and increases with the degree of hyperopia. All values within the hatched area are possible.

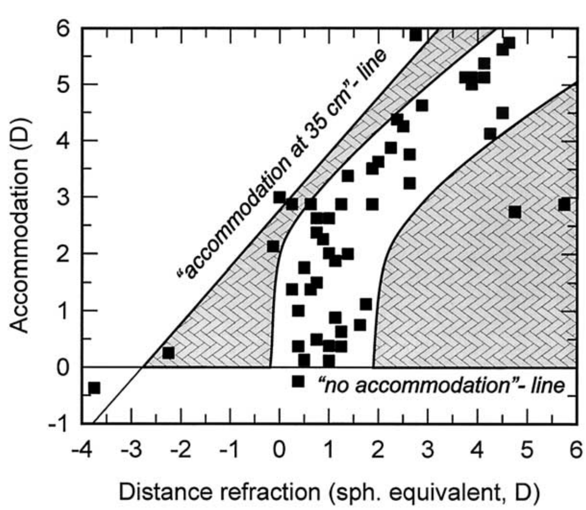

Figure 6. (Schimitzek) Accommodation in children without cycloplegia during the automatic measurement as a function of the spherical distance refraction. The 2 boundary lines define the possible range of accommodation caused by fixation myopia. The accommodation increases with the degree of hyperopia. Most data points lie within a narrow band.

The accommodation found with the wavefront autorefractor in our group of children without cycloplegia is included in Figure 6 as black squares. The data points form a narrow channel inside the hatched region.

All children with spherical distance refractions larger than +2.0 D accommodated between +3.0 and +6.0 D. The mean accommodation in children with an SE between +2.0 and +3.0 D was +3.5 D and between +4.0 and +5.0 D, +5.0 D. The mean accommodation in children with spherical distance refractions of less than +2.0 D was unpredictable. Some children accommodated exactly at the instrument, others accommodated at a greater distance. Cases with +3.0 D accommodation as well as cases with no accommodation were found.

The scatter of the data in Figure 6 indicates that the amount of accommodation that occurs with the SureSight in hyperopic patients cannot be predicted before the measurement. This is a serious handicap in young patients because they are mostly hyperopic (at least in our white population) and have a large range of accommodation.

The fact that most data points lie below the upper boundary of the hatched area indicates further that our young patients did not accommodate exactly at the SureSight but at greater distances. Children with spherical distance refractions larger than +2.0 D accommodated predominantly at distances of about 0.5 to 1.2 m. The accommodation at a greater distance than the distance of the SureSight may be explained by the dim room illumination or by the well-known lag of accommodation in hyperopic children.[20]

The observed increase in accommodation with the degree of hyperopia appears to be typical for a distance eye refractor without a fogging system. In a conventional autorefractor, the amount of accommodation does not normally increase with ametropia. With the Retinomax,[11] for example, about 60% of all hyperopic children with SEs between +2.0 and +8.0 D did not accommodate more than 1.0 D. In these cases, the fogging system worked well.

In conclusion, we can state that minus-overcorrected results occur in table-top autorefractors as well as in autorefractors that operate from a distance. The reasons for the minus-overcorrection are different. In table-top autorefractors, it is mainly the subjective feeling of the close distance to the eye. Both hyperopes and myopes are affected. In autorefractors that operate from a greater distance, the accommodation at or close to a real fixation target is the main cause for the spherical measurement error. Hyperopes and emmetropes are primarily affected.

Child Mode

The manufacturer of the SureSight recommends a special "child mode" when children younger than 7 years are to be measured without cycloplegia. In this mode, a constant value of +2.5 D is added to the spherical result. This constant correction factor is supposed to compensate for a child focusing at the instrument that is only 0.35 m away.

One main goal of vision screening is to detect all hyperopic and anisometropic children at risk for amblyopia and strabismus. Our findings indicate that this goal cannot be reached with the SureSight without cycloplegia. The SE differed by more than −2.0 D from cycloplegic retinoscopy in 47% of the patients under 18 years of age. Adding a constant factor does not solve the problem because the individual degree of accommodation apparent in Figure 5 is unpredictable.

Results in Other Studies of Handheld Autorefractors

A comparison of the present study with others is difficult because of different aims and different ways of analyzing and presenting the results. Harvey et al.[21] evaluated the accuracy of cycloplegic autorefraction by comparing autorefractor results measured with the Nikon Retinomax with cycloplegic retinoscopy. The mean difference and standard deviation of the SE was 0.02 ± 0.37 D and −0.02 ± 0.38 D for the cylinder power. The mean axis deviation was 6.97 ± 13.87 degrees. Analysis of the axis deviations using the vector dioptric distance (VDD) method showed a mean deviation of 0.57 ± 0.28 VD.

El-Defrawy and coauthors[22] compared the Nikon Retinomax and retinoscopy in a group of children younger than 6 years. The mean difference in the SE was 0.09 ± 0.71 D and 0.23 ± 0.13 D for the cylinder power. The mean VDD was 0.97 ± 0.76 VD. These results showed larger variations than those in the study by Harvey et al.,[21] probably because of the prevalence of high ametropia in the group and the age of the children.

Shoemaker[23] tested the agreement between 2 repeated refractive measurements with the SureSight in 21 cooperative, healthy adults. The correlation coefficients between the repeated measures were 0.99 for sphere and 0.94 for cylinder.

Harvey and coauthors[24] compared noncycloplegic results obtained with the SureSight and the Retinomax with those of cycloplegic refraction in preschool children with a high prevalence of astigmatism. The mean differences between cycloplegic refraction and autorefraction for sphere and cylinder, respectively, were 2.27 ± 1.45 D and 0.13 ± 0.44 D for the SureSight and 1.29 ± 0.87 D and 0.15 ± 0.32 D for the Retinomax.

A comparative study of Retinomax, SureSight, PowerRefractor, and retinoscopy without cycloplegia was carried out by Bobier and coauthors.[25] The mean differences in the SEs between autorefraction and cycloplegic retinoscopy in a sample of 43 preschool children were 1.15 ± 1.47 D (Retinomax), −0.49 ± 1.06 D (SureSight), 0.85 ± 0.77 D (PowerRefractor), and 0.64 ± 0.49 D (retinoscopy). In both studies,[24,25] a minus-overcorrection is indicated by a positive sign.

The average minus-overcorrection of 2.27 D found by Harvey and coauthors[24] appears to agree with our findings, whereas Bobier and coauthors[25] found a small plus-overcorrection of 0.49 D with the SureSight. This discrepancy can be explained. Bobier and coauthors used the child mode—an instrument setting that adds a constant values of +2.5 D to all spherical results. This constant correction factor disguises the actual minus-overcorrection in emmetropic or nearly emmetropic patients. It is not effective, however, when patients with ametropias larger than ±2.0 D are to be measured, as we have shown in Figures 5 (lower panel) and 6.

Influence of Patient Selection

Chat and Edwards[18] applied the Shin-Nippon SRW-5000 in children. This autorefractor uses a fixation star at 20 feet. Following our arguments, the star should also stimulate accommodation. If the subjects would focus at the star, all hyperopes should appear as emmetropes [1/(distance SRW-5000) = −0.2 D]. However, they found a high accuracy in children without cycloplegia. Closer inspection of their data, however, revealed their children (primarily Asian) had myopia or moderate hyperopia up to +1.75 D. In such a group, the influence of fixation myopia is weak; it occurs chiefly in patients with greater hyperopia. It would be interesting to evaluate the performance of the Shin-Nippon in young patients with ametropias ranging from +1.0 to +6.0 D.

Applicability of Cyclopentolate and Tropicamide

Cyclopentolate and tropicamide have been shown to be effective cycloplegic agents for the measurement of refractive errors in most healthy infants.[26] Cycloplegic agents, however, are normally not used in routine vision screening tests of young children. Nevertheless, a current survey of pediatric eye centers reports a rising acceptability of cycloplegic drops. In particular, Barry and Loewen[27] discuss the advantages of topical cyclopentolate. It has a sufficient but short effect, a low risk of severe and light complications, and extensive follow-up since its introduction in 1972.

Weighted Axes Difference

The DA used in this study is not an easy concept to understand because it is expressed in diopters and not in degrees. The multiplication with the cylinder power, however, makes it possible to compare the results in different patients even when the actual cylinder powers are different. Other authors[28–31] calculate the DA regardless of the actual cylinder power. We believe that such a simple DA is not a valid comparison criterion since the results of such an analysis depend strongly on the cylinder power distribution in the selected group of patients. It is well known that the tolerable axes error in eyes with a large cylinder power is small, whereas larger axes error can be tolerated in eyes with a small cylinder power. Our analysis method avoids these problems as it normalizes the axis difference according to the actual cylinder power.

Limitations of Our Patient Selection

Since our group of patients was recruited from an eye clinic, it is not representative of the general public; eg, there was a preponderance of higher ametropias. The percentage of larger measurement errors usually increases with the degree of ametropia. Better agreement can be expected in subjects with small refractive errors.

Limitations of Our Comparison Method

The ideal comparison method (the gold standard) against which the results of a refraction technique can be checked does not exist. This problem has been addressed.[11] In the present study, the accuracy of the SureSight was assessed by comparing its results to cycloplegic retinoscopy. Cycloplegic retinoscopy has also been applied in other comparative studies.[22,25,32,33] In addition, it has been proven by Littmann[34] that retinoscopy is one of the most accurate refraction techniques. Nevertheless, its results are prone to a bias and small errors. Thus, the results of our comparison method may differ from the result of an "ideal" refraction technique. It should by mentioned, however, that according to results by Zadnick et al.[35] both retinoscopy and subjective refraction are suitable for a comparative study because the standard deviation of the results obtained with an accurate retinoscopy and subjective refraction under cycloplegia are almost equal.

Concluding Remarks

The present study has shown that the SureSight wavefront autorefractor can be applied to measure the refractive state of young and adult patients**.** The accuracy of the spherical refraction is very low under noncycloplegic conditions because many patients start to accommodate. This occurs mainly in young children and young hyperopic adults. The accuracy of cylinder power is not affected by accommodation.

Under cycloplegia, the SureSight is an interesting new tool to assess the refractive state, although the accuracy is still lower than that of conventional autorefractors and the range of measurement is limited. The wavefront autorefractor could be used by ophthalmologists who already have a conventional autorefractor and seek an additional device for patients who cannot be measured with the conventional autorefractor; ie, infants and disabled patients.

Appendix

The terms *total cylindrical difference* (TCD) used in the present paper and *astigmatic difference* (AD) used by Raasch and coauthors[15] are mathematically equivalent.

In many of our studies on refraction devices since 1984,[1,2,4,5,11,36] we evaluated the length of the difference vector between the cylindrical corrections measured with the test and the comparison method. This difference served as a measure of the deviations between the 2 measurement techniques. In our earlier papers, this vector difference was called total cylindrical difference.[5,36] In 2000, we used the term *difference of the cylindrical corrections* (DCC)[11] and calculated it according to the formula

$$\mathrm{TCD} = \mathrm{DCC} = + \sqrt{C_t^2 + C_c^2 - 2C_tC_c\cos[2(\alpha_t - \alpha_c)]} \qquad (1)$$

The subscripts "t" and "c" denote the results of the instrument under test and the comparison method, respectively.

In a recent paper, Raasch and coauthors[15] proposed calculating the AD. Their approach was based on the (M, J_0, J_{45}) space of Thibos and Horner.[16] M refers to the spherical equivalent and J_0 and J_{45} refer to Jackson crossed cylinders with orientations of 0° and 45°, respectively.

$$\begin{aligned} J_0 &= (-C/2)\cos(2\alpha) \\ J_{45} &= (-C/2)\sin(2\alpha) \end{aligned} \qquad (2)$$

Raasch and coauthors evaluated the AD from the differences between the J_0 and J_{45} components of 2 refractions in the astigmatic plane.

$$\begin{aligned} \Delta J_0 &= (J_{0t} - J_{0c}) \\ \Delta J_{45} &= (J_{45t} - J_{45c}) \end{aligned} \qquad (3)$$

$$\mathrm{AD} = + \sqrt{(\Delta J_0)^2 + (\Delta J_{45})^2} \qquad (4)$$

When equations 2 and 3 are inserted, equation 4 can be simplified by well-known trigonometric relationships.

$$\begin{aligned} \mathrm{AD} &= \frac{1}{2}\sqrt{[C_t^2\sin^2(2\alpha_t) - 2C_tC_c\cos(2\alpha_t)\cos(2\alpha_c) + C_c^2\cos^2(2\alpha_c) + C_t^2\sin^2(2\alpha_t) - 2C_tC_c\sin(2\alpha_t)\sin(2\alpha_c) + C_c^2\sin^2(2\alpha_c)]} \\ &= \frac{1}{2}\sqrt{\{C_t^2 + C_c^2 - 2C_tC_c[\cos(2\alpha_t)\cos(2\alpha_c) + \sin(2\alpha_t)\sin(2\alpha_c)]\}} \end{aligned}$$

$$\mathrm{AD} = \frac{1}{2}\sqrt{C_t^2 + C_c^2 - 2C_tC_c\cos(2\alpha_t - 2\alpha_c)} \qquad (5)$$

$$\mathrm{AD} = \frac{1}{2}\,\mathrm{TCD} \qquad (6)$$

By comparing equations 1 and 5, it can be seen that the AD used by Raasch and coauthors is mathematically identical to one half of our TCD.

The factor 1/2 in equation 6 derives from the use of different units. Raasch and coauthors characterized the vector difference AD in terms of the power of the equivalent Jackson crossed cylinder, whereas we describe the vector difference TCD in terms of the cylinder power used in prescriptions. Thus, the approach by Raasch and coauthors gives exactly the same result as ours.

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