0093-7002/87/6408-0627$02.00/0
AMERICAN JOURNAL OF OPTOMETRY & PHYSIOLOGICAL OPTICS

Vol. 64, No. 8, pp. 627–638
Printed in U.S.A.

instruments/techniques

Automatic Infrared Refractors—A Comparative Study

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ABSTRACT

In order to determine the performance of seven automatic infrared (IR) eye refractors, measurements have been conducted on a model eye as well as on normal subjects and patients under standardized conditions. Concerning the model eye, a range of measurement slightly smaller than specified and linearity errors have been detected on several instruments. Using a group of 55 normal ametropic subjects, the results of the automatic refraction were compared to the results of a conventional subjective examination. The spherical equivalent differed by less than 0.51 D in more than 80% of all cases on all instruments. The error of the cylinder power was smaller than 0.51 D in more than 90% of all cases. Larger errors were found on patients with intra ocular lenses, aphakic eyes, or scattering eye media. In each of these groups the automatic refraction was at times either impossible or yielded a wrong result.

Key Words: autorefractors, refraction, objective refractors, automated refraction

During the last decade, hardly any other ophthalmic instruments have undergone as many changes as the automatic IR eye refractors. Since the development of the first instrument in 1971, 32 different automatic refractors by 11 manufacturers have been introduced.

Instruments of the first generation, like Acuity System's 6600 Auto-Refractor[1-3] and the Dioptron[4] already had a high accuracy of measurement, but they took up to 1 min per eye to measure the ametropia.

The second refractor generation was introduced by Humphrey Instruments. Their instruments allow not only an automatic determination of the ametropia but also a subjective measurement of the visual acuity obtained with the proposed corrective lens. Furthermore, they incorporated a subjective refinement capability of the spherical power.

The third generation of automatic refractors, developed about 1980 in Japan,[5] is distinguished by an extremely rapid measurement time. This is attained by omitting the focus control loop system. The whole range of measurement is scanned in less than 1 s. A fast detection system observed the sharpness of the retinal image, stored all data, and calculated the refractive state from the stored data at the end of the measurement.

The first automatic refractor of the fourth and latest generation of automatic refractors was introduced in 1983 by Marco/Nidek. In addition to the automatic refraction capability, a computer-assisted subjective refraction program using conventional refraction techniques such as a fogging test, red/green test, and cross-cylinder test is incorporated in these instruments. Meanwhile, the subjective refraction capability has been incorporated into instruments of several manufacturers.

Besides economy and practicality, the accuracy of measurement is the most important parameter of an automatic refractor. Several investigations dealing with the properties and the accuracy of these instruments have been published,[6-20] but due to the rapid changes in the IR refractor market most of the instruments de-

Received October 2, 1986; revision received December 22, 1986.

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scribed are no longer available. We therefore conducted a comparative study on six new and one older automatic refractor.

All automatic IR refractors have three essential features in common: (1) IR light illuminates the fundus; (2) a computer-controlled opto-electronic detection system analyses the image quality; and (3) a fogging system tries to relax the accommodation.

Canon R-10 and Hoya AR-530

An impressive, conceptually new technique is used in the Canon R-10 refractor. This technique, developed originally by Canon, was also adopted by Hoya. Their instrument, Hoya AR-530, is being built under license with a slightly modified design and software. The automatic refraction is performed without any moving parts according to a modified Scheiner principle. A regular 3-pointed star pattern is imaged through a narrow aperture with a large depth of focus onto the retina. Each arm of the retinal star pattern is imaged through one of three pairs of Scheiner double pinholes on one of three charge-coupled-device linear photodetector arrays (CCD-arrays). The CCD-arrays are located far behind the focal point of the Badal lens, so that a double image of one arm of the star is formed on each CCD-array. The distance between these two images is a measure for the ametropia in each of the three meridians under test. Astigmatism is determined by fitting a $\sin^2$-curve through all three measured data points. These two instruments have no subjective refinement capability.

Humphrey HAR 520 and Humphrey HAR 530

Both the older HAR 520, which is no longer available, and the new HAR 530 have been tested. All autorefractors from Humphrey work according to the optical principle that a light spot imaged sharply onto the retina will be reflected back exactly on the light source itself. A photodetector, located right next to the light source, signals a light minimum when the retinal image is in focus. The spherical ametropia is compensated by a double mirror Badal system that resembles a trombone. Two variable cross-cylinder lens systems (Stokes lenses[30]) correct the astigmatism in two components. An advantage of this measurement technique is that all the meridians are corrected simultaneously, thus eliminating errors due to different accommodative states in different meridians.

Whereas the old HAR 520 and the new HAR Alpha, HAR 500, and HAR 505 can only determine the corrected visual acuity, the new HAR 530 offers a subjective refraction capability including the patented three bar astigmatism measurement (PAM-test) well-known from the Vision Analyzer.[21]

Marco/Nidek AR-1600

The Marco/Nidek AR-1600 works according to Scheiner's double pinhole principle. Two light emitting diodes (LED's) illuminate an aperture, which is imaged onto the retina. The point of coincidence of the two reflected images serves as a focus indicator. The different meridians are measured by a coupled rotation of the illumination and the electronic detection system. The total measurement time is 0.5 s. Before the actual measurement the "best" spherical lens is determined and used as a starting point during the fogging procedure of the fixation target. Further background information on the efficiency of the fogging technique has been published.[22]

The instrument is capable of performing a true computer-assisted monocular subjective refraction. A cheaper instrument, the Nidek AR-1100, without subjective refraction capability, is also available from the same manufacturer.

Nikon NR-7000

Similar to the first autorefractor "Safir Ophthalmetron,"[23,24] all instruments manufactured by Nikon use a technique derived from streak retinoscopy. An IR-LED is located in the center of a rotating slit drum. The emerging light bundles sweep across the cornea with a frequency of 720 Hz. The light reflected from the fundus is observed by a photodetector, which is optically conjugate to the pupil plane. The ametropia in the meridian under test is determined from the time delay of the fundus reflex in the pupil. Astigmatism is determined with the help of a rotating prism, which changes the orientation of the illuminating beam. After the instrument is adjusted to the eye, a preliminary correction is measured and a slightly fogged fixation target presented. The Nikon NR-7000 offers full subjective refraction capability, whereas the cheaper version Nikon NR-5000 does not.

Topcon RM-A6000

Two autorefractors are available from Topcon Instruments: the RM-A6000 tested in the present study, and the RM-A6500, which has an additional subjective refraction capability. Both instruments work similarly to the Nidek instrument (Scheiner double pinhole principle). Two LED's with a diameter of 0.9 mm and a separation of 2 mm are imaged in the pupil of the eye and simulate the Scheiner pinhole apertures. A photodetector observes the degree of coincidence between the two images on the fundus. The focus is adjusted by an axial displacement of the illumination and detection systems. First the Badal system is focused in one meridian, then the measurement system rotates by 180° while continuously taking readings. Accommodation is relaxed by a fogged starburst fixation target.

METHODS

In order to obtain information on the performance and the accuracy of these instruments, two types of measurements were conducted. Measurements on a model eye reveal the performance under controlled conditions. Measurements on human subjects reveal errors under normal working conditions.

Measurements on a Model Eye

The measurements on a simplified model eye yield results that are free of subjective influence. The model eye is a black plastic trough, filled with water, with a convex-concave spherical lens in its frontal plane modeling the human cornea. An adjustable aperture is mounted behind the lens at the location of the human iris. An eye lens is omitted. The retina is simulated by a dark gray, concave plastic surface that is adjustable in sagittal direction. The focal length (f′) of the water-filled model eye is 26.8 mm ± 0.1 mm. It was determined by a He-Ne-laser autocollimation technique, and transformed to a wavelength of 550 nm. With this model eye the following data have been determined.

Range of Measurement

The range of measurement was determined by moving the model retina in small steps from an extreme hyperopic to the largest myopic position that the instruments were capable of measuring. The results show if the instruments are applicable on subjects with a very high ametropia, e.g., aphakic eyes.

Linearity

The back vertex power of the model eye can be calculated from theory for a given vertex distance VD according to the elementary formula

$$S = (ff'/x' + f - VD)^{-1} \qquad (1)$$

where x' denotes the displacement of the model retina from the image focal point, $f = -20.09$ mm, $f' = 26.8$ mm, and $VD = -12$ mm.

The linearity of each eye refractor is evaluated from the difference between the back vertex power expected from theory, and the autorefractor result displayed by the instrument. The observed differences indicate if systematic errors are to be expected, especially in cases of very high ametropia. The autorefractor readings were obtained in steps of 1 mm. Repeated trials were carried out with every instrument in order to obtain information on the reproducibility on the model eye. The vertex distance was set to 12 mm. Only the Humphrey HAR 520 and HAR 530 were set at 13.5 mm and afterwards transformed to 12 mm.

Minimal Pupil Diameter

As all automatic refractors analyze the light that is reflected from the fundus, a certain minimal pupil diameter is necessary. This pupil diameter is defined by the spatial dimensions of the illuminating light rays and the amount of light needed by the optoelectronic detection system. Hence, automatic refractors are often not applicable on patients with small pupils, e.g., on glaucoma patients under pilocarpine treatment. The lower limit of the pupil diameter was determined by decreasing the size of the aperture in steps of 0.2 mm until a measurement was no longer possible or errors larger than 0.75 D occurred.

Measurements on Normal Ametropic Subjects

The accuracy of measurement on normal subjects was determined by comparing the results of the automatic refraction with the outcome of a conventional subjective examination. All measurements were carried out on a group of 55 subjects with clear eye media and high visual acuity, who were recruited mainly from the staff of the university eye clinic. The subjects' ages varied between 20 and 68 years with a corresponding mean of 36 years and a SD of 14 years. The spherical ametropia of our subjects varied between −5 and +5 D, and the cylinder power did not exceed −2.5 D. Even though very high ametropias were not present, the group represents the vast majority of patients seen in an optometric practice.

All automatic refractions were carried out by a skilled technician who has had many years experience in operating automatic refractors and a medical student who collected data in the preparation of her thesis. The ordering of the automatic refractions was changed in a random sequence. Three measurements were taken in rapid succession on all Japanese instruments, which have measurement times well below 1 s. The mean of these independent measurements is calculated automatically by these instruments and was taken for comparison. The Humphrey HAR 530 was tested, including and excluding automatic relaxation of accommodation ("Auto +"). The latter mode was tested because it is factory installed on all new instruments in order to reduce the measurement time.

All subjective refractions were performed by the two authors, who were unaware of the autorefractor outcomes. Subjective refraction was performed according to conventional techniques on a standardized Snellen chart at distance. After the determination of the preliminary spherical correction, astigmatism was corrected using the Jackson cross-cylinder technique.[25] Binocular balancing was carried out with the "von Graefe" prism test (6 Δ base-down before one eye) and the red/green test. In order to ensure that no minus-overcorrection had been produced by the red/green test,[26,27] the spherical endpoint refraction was controlled in a final step by fogging with plus lenses.

In order to obtain additional information on the reproducibility of the autorefractor readings, 10 independent readings were taken with each of the 7 IR refractors on 10 subjects. Before each measurement the instruments were displaced and readjusted. The error distribution of the spherical equivalent (SE) was calculated for each eye separately and permits a direct comparison between all instruments.

Criteria for the Accuracy of Measurement

Information on the accuracy of measurement is obtained by the following four parameters[16,28,29]:

1. Differences in the spherical power are revealed by the "error of the spherical equivalent (Δ SE)"

$$\Delta\, SE = (S_a + \tfrac{1}{2} C_a) - (S_s + \tfrac{1}{2} C_s)$$

S_a, C_a, S_s, and C_s denote the automatically and subjectively obtained spherical and cylindrical values. A negative value of Δ SE indicates that more "minus" was indicated by the autorefractor.

2. The "error of the cylinder power (Δ C)" is calculated by

$$\Delta\, C = C_a - C_s$$

A negative Δ C indicates that a stronger cylinder lens was proposed by the automatic instrument.

3. The "axis error (Δ A)" in diopters is determined by

$$\Delta\, A = 2\, C_s \sin(\Delta\, \varphi)$$

This formula weights the actual axis difference in degrees $\Delta\,\varphi$ with the subjectively determined cylinder power, and has the advantage that all results can be compared regardless of their actual cylinder powers. Given an astigmatism of 1 D, e.g., an axis error Δ A of 0.5 D is equivalent to an axis difference of 14.5°.

4. The "total cylindrical difference (TCD)"

$$TCD = \sqrt{C_a^2 + C_s^2 - 2C_aC_s\cos(2\Delta\,\varphi)}$$

is a measure of the total error of the astigmatic correction. TCD weights the difference of the cylinder powers with the axis difference. TCD is always positive, as it is calculated as absolute value of the vector difference between both cylindrical corrections.

Measurements of Patients

Concerning patients with impaired vision, it is most helpful when accurate refractor results can be obtained, as in these cases determining a precise endpoint refraction is often very cumbersome and time consuming. An autorefractor that is capable of refracting these difficult patients is therefore highly desirable. Unfortunately, it is well-known from previous studies[14,16,17] that the accuracy of automatic refractors can be reduced severely on problematic patients.

In the present study we refracted 40 aphakic eyes, 107 eyes with intraocular lenses and 140 cataract eyes. The comparability of these results is not as good as in our group of normal subjects, because it would have been an unreasonable demand to refract every patient with all seven instruments. Therefore, no detailed results will be described but only general tendencies.

RESULTS AND DISCUSSION

Measurements on the Model Eye. Range of Measurement

The examination of the range of measurement gave the results listed in Table 1. Due to differences between our model eye and the human eye, a systematic error cannot be excluded, although the error should be equal for all instru-

TABLE 1. Range of measurement; all data are valid for a vertex distance of 12 mm.

Instrument	Manufacturers' Specifications (D)	Measured on the Model Eye (D)
Canon R-10	−15 to +15	−13.25 to +13.25
Hoya AR-530	−15 to +15	−13.50 to +13.25
Humphrey HAR 520	−14 to +16	−14.50 to +14.50
Humphrey HAR 530	−14 to +16	−15.25 to +13.50
Nidek AR-1600	−17 to +22	−16.75 to +20.50
Nikon NR-7000	−15 to +15	−13.25 to +12.50
Topcon RM-A6000	−20 to +20	−19.25 to +17.50
Rodenstock PR 50	−20 to +20	−20.0 to +20.0
Aus Jena KoRe 110	−38 to +18.5	−38.0 to +18.5

ments. The range of measurement is smaller than specified in all cases. In rating the performance, the reader should keep in mind that a measurement limit of, e.g., +14 D could be too low for some aphakic eyes. The largest range is covered by the Nidek NR 1600 and the Topcon RM-A6000. These instruments approach the range of the classical manual refractor PR 50 from Rodenstock/Coburn, which is given in the table for reference.

Linearity

The ametropia of the model eye was measured in steps of 1 mm across the whole range of displacement. All instruments showed a very high reproducibility on the model eye. Repeated measurements at a given displacement of the model retina did not differ by more than 0.25 D with respect to each instrument. Thus, the results of our linearity measurements indicate the degree of systematic deviations of the autorefractor results from the actual ametropia of the model eye. The x axis in Fig. 1 shows the ametropia of the model eye and the respective displacement of the model retina. The ordinate plots the difference between the SE of the autorefractor reading on one hand, and the theoretically expected ametropia calculated according to formula 1 on the other. The results of each instrument are represented by a continuous curve joining the data points by spline interpolation. In order to simplify the figure, the extremely small SD of the data is omitted. The error bars at the top of the figure indicate the possible measurement error deriving from the focal length of the model eye, which was determined with an accuracy of ±0.1 mm.

The Topcon RM-A6000 and the Nidek NR-1600 show an almost ideal performance. The deviation from the actual ametropia of the model eye is approximately zero across the whole measuring range. The deviations of the Canon R-10 and the Hoya AR-530, for which absolutely identical results were obtained, are also small. Larger deviations from the theoretically expected ametropia were found in the extreme myopic range with both instruments from Humphrey and the Nikon NR-7000. At a displacement of 6 mm, for example, the spherical results of the HAR 520 and the HAR 530 differed by more than −1.5 D from the actual ametropia of the model eye, a value which is more than 6 times larger than the error bar shown at the top of the graph. The similar curves of these two instruments in Fig. 1 indicate that the results were not caused by a possible wrong adjustment of the vertex distance.

Minimal Pupil Diameter

The measured minimal pupil diameter is listed in Table 2. Inasmuch as the pupil of the model eye is located at exactly the same position as in the human eye, systematic measurement errors should be small. The HAR 520 and HAR 530 displayed results down to a diameter of 2.0 mm, but these results differed up to 1 D from the normal reading with wide pupil and therefore were rejected.

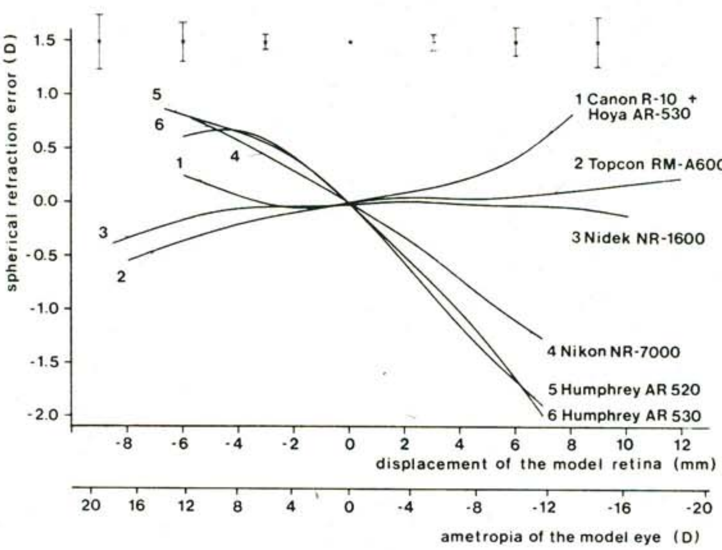

FIG. 1. Linearity of the spherical autorefractor results on the model eye. The curves indicate systematic deviations from the actual ametropia in the extreme myopic and hypermetropic ranges.

Results on Normal Ametropic Subjects

The frequency distribution of the differences between the automatically determined ametropia and the result of the subjective refraction is plotted in the histograms in Figs. 2 to 4.

From the histograms the following information can be obtained. The percentage distribution around zero shows how often the automatic refractors displayed the correct or nearly correct result. These data are also summarized in short form in Table 3. In addition the histograms show how many larger errors occurred. Thirdly, the frequency distributions reveal systematic deviations from the result of the subjective refraction.

Fig. 2 shows the distribution of the error of the SE. The results of the HAR 520 and the HAR 530 are equally distributed around zero, whereas the results of most Japanese instruments are slightly shifted toward positive values. In this connection it is apparent that the spherical results of the Nidek NR-1600 are systematically displaced toward positive values. At first we suspected an adjustment error of this specific instrument, but the observed plus-overcorrection is intended by the manufacturer. They advocate that a moderate plus-overcorrection in a refractometer result is better than a minus-overcorrection, thereby guaranteeing that the final subjective refinement starts from a fogged refractive state and accommodation is counteracted.[a]

TABLE 2. Minimal pupil diameter.

Instrument	Manufacturers' Specifications (mm)	Experimentally Determined (mm)
Canon R-10	2.9	3.2
Hoya AR-530	2.9	3.0
Humphrey HAR 520	2.0	3.2
Humphrey HAR 530	2.0	3.2
Nidek AR-1600	2.9	2.3
Nikon NR-7000	2.9	3.1
Topcon RM-A6000	2.9	2.3

[a] Marco Medical Products, the American distributor of Nidek autorefractors, is aware of the plus-overcorrection intended by the manufacturer. They readjust all instruments that are sold in the U.S.A. in a minus direction by 0.5 D.

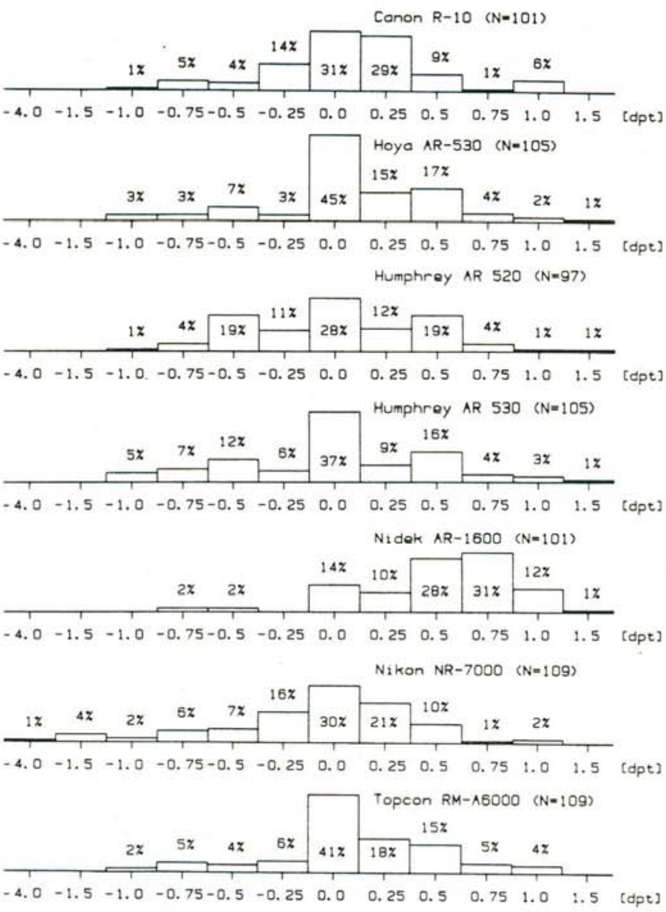

FIG. 2. Frequency distribution of the error of the spherical equivalent (Δ SE) on normal ametropic subjects (see footnote [a]).

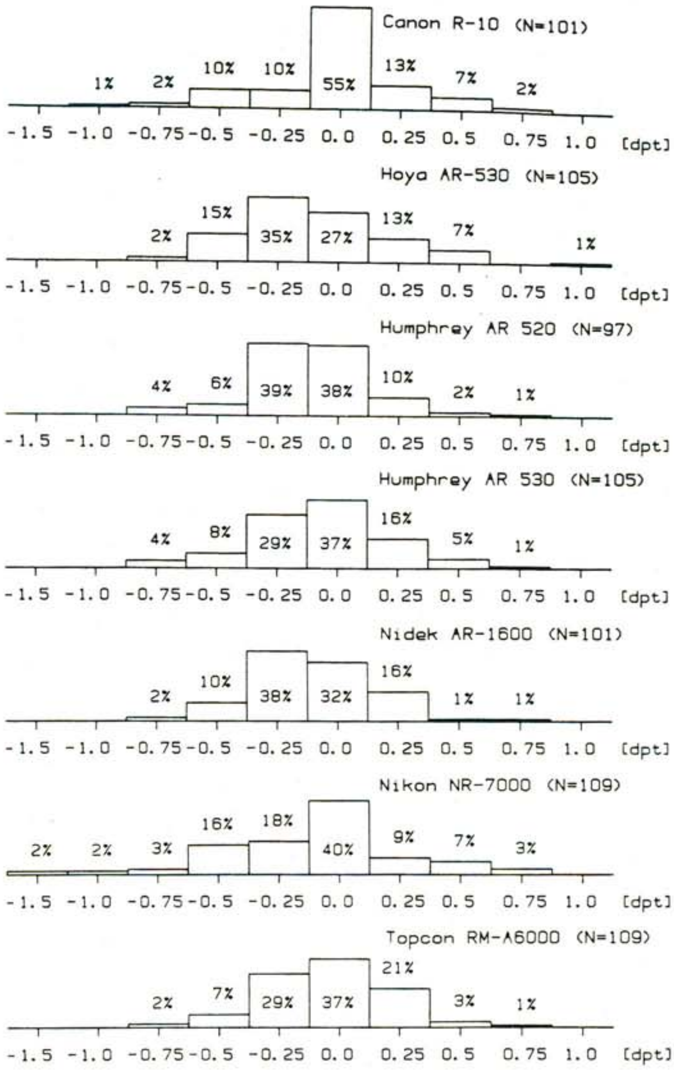

FIG. 3. Frequency distribution of the error of the cylinder power (Δ C) on normal ametropic subjects.

In almost all cases the error of the SE did not exceed 1.5 D. A minus-overcorrection of −4 D was found only once with the Nikon NR-7000. This finding is strikingly different from our earlier results[16,17] on the predecessors of the instruments tested here, where spherical errors of between 2 and 4 D appeared with a frequency of up to 6%.

The cylinder power (Fig. 3) also shows a substantially smaller number of large errors. The error exceeded 0.75 D in only a very few cases, whereas in our earlier investigations[16,17] cylinder errors of up to 2 D were found. The frequency distribution of all instruments is concentrated around zero and slightly shifted toward higher cylinder powers.

Concerning the axis error (Fig. 4), the Japanese manufacturers have improved their new autorefractors in comparison to their predecessors. The axis error of these instruments, which amounted up to 2.2 D in our earlier investigation,[16] is now always smaller than 1.2 D, and approaches the high axis accuracy of the Humphrey HAR.

The detailed information of the histograms is summarized in Table 3. The table indicates the number of cases in which the difference between the results of the autorefractor and our subjective refraction was not larger than 0.5 or 0.63 D. From the data summarized in Table 3, it is apparent that the differences between the autorefractors of different manufacturers have become very small. In our earlier investigations on 6 older autorefractors[16,17] the percentage of spherical errors smaller than 0.51 D varied between 66 and 86%. However, in the present

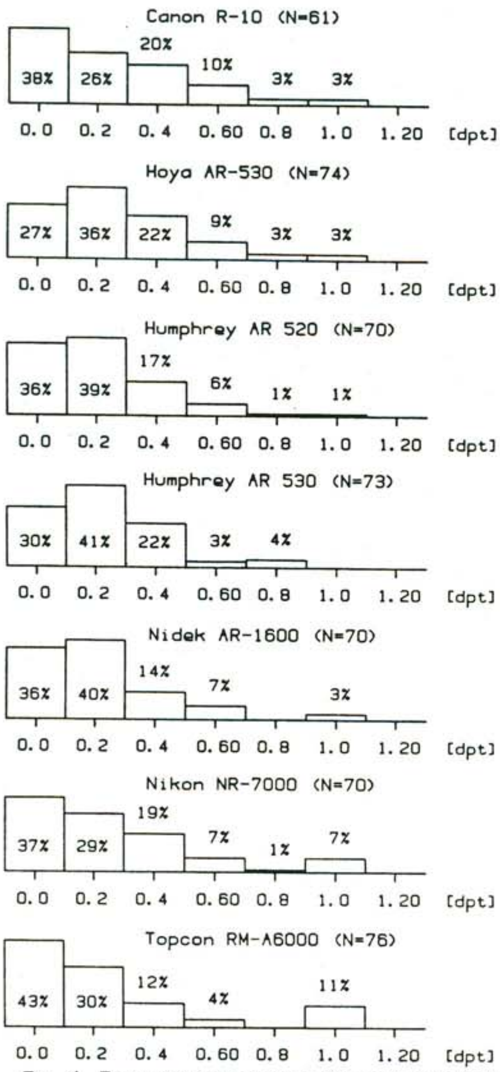

FIG. 4. Frequency distribution of the axis error (Δ A) on normal ametropic subjects.

study the respective percentage is always larger than 80%.

Errors of cylinder power smaller than 0.51 D were found in more than 90% of all cases throughout all instruments. In our earlier investigations[16,17] the instruments tested showed much larger differences in the accuracy of the cylinder power, and a percentage of errors smaller than 0.51 D, which varied between 77 and 93%.

Slightly larger errors were found on the cylinder axis where an error smaller than 0.51 D was found in more than 84% of all cases. The combined cylindrical error was less than 0.63 D in more than 83% of all cases.

The mean differences between the results of the autorefractors and the subjective findings are given in Table 4. On average the SE of almost all instruments is very similar to the results of the subjective refraction. Only the Nidek NR-1600 "overplussed" the sphere by about 0.5 D (see footnote [a]). A comparison between the results of the HAR 530 recorded with and without automatic relaxation of accommodation (Auto +) is interesting. In order to shorten the measurement time, the control loop that fogs the Snellen chart is deactivated without the Auto +, but our data indicate a shift toward minus-overcorrected values from 0 to −0.16 D, a difference that is statistically significant at the 5% confidence level (t-test and Weir test). In this connection, it should be kept in mind that our group of normal subjects was comprised of subjects from 20 to 68 years of age, so that only a smaller subgroup had a large range of accommodation. In this subgroup the shift toward negative values is even larger. The user should therefore activate the fogging control loop on Humphrey refractors to avoid an unwanted minus-overcorrection, especially on young subjects without cycloplegia. The Nikon NR-7000 also has a negative spherical mean,

TABLE 3. Summarizing table on the autorefractor accuracy.

Instrument	No. of Eyes	Sphere |Δ SE|≤0.5 D (%)	Cylinder |Δ C|≤0.5 D (%)	Axis Δ A ≤0.5 D (%)	Astigmatism TCD ≤0.63 D (%)
Canon R-10	101	87	95	84	87
Hoya AR-530	97	87	97	85	88
Humphrey HAR 520	105	89	95	92	90
Humphrey HAR 530 (Auto + on)	105	80	95	93	92
Nidek AR-1600	101	95[a]	97	90	92
Nikon NR-7000	109	84	90	85	83
Topcon RM-A6000	109	84	97	85	86

[a] 0.5 D has been subtracted from the spherical autorefractor result (see footnote [a] in text).

although most results in Fig. 2 lie very symmetrically around zero, because a few subjects were overcorrected in minus.

Slightly higher cylinder powers were found with almost all instruments compared to the subjective refraction (Table 4). On the other hand, this general tendency toward higher cylinder powers should not be interpreted as a disadvantage of automatic refractors, as the refractionist normally prefers a lower cylinder power in doubtful cases, whereas an automatic instrument can only determine the objective state of refraction and is not able to judge whether the objective cylinder power will be tolerated subjectively or not.

The SD's of the error of the SE and the error of the cylinder power are listed in Table 5 and give additional information on the uncertainty of the autorefractor results on normal ametropic subjects. The largest uncertainty of the SE was found on the Nikon NR-7000. The SD of 0.61 D is significantly worse at the 1% confidence level compared to all other instruments. Compared to the averaged SD of the five best instruments (0.384), the SD of the HAR 530 is significantly larger at the 5% confidence level (F-test).

The largest uncertainty in the determination of the cylinder power is found on the Nikon NR-7000 (significant at the 1% confidence level). All other instruments performed equally well.

The results of the reproducibility measurements are illustrated in Fig. 5. The error of the SE is plotted as an ordinate on each panel. Each eye of the 10 subjects is denoted by a vertical bar indicating the error interval in which all 10 independent measurements were found. The small horizontal indicators denote the mean and the SD of the 10 autorefractor results obtained on each eye. The 10 subjects are arranged in the same sequence on all panels so that the error bars plotted one upon another are directly comparable. The Nikon NR-7000 had the lowest reproducibility and the largest spherical error, because a large minus-overcorrection up to −4 D was found on three eyes. Both instruments from Humphrey had difficulty in relaxing the accommodation of subject 5.

TABLE 4. Mean difference between the autorefractor results and the subjective refraction; all data are given in diopters.

Instrument	No. of Eyes	Mean Difference (SE)	Confidence Interval	Mean Difference (C)	Confidence Interval
Canon R-10	101	+0.11	±0.08	−0.02	±0.06
Hoya AR-530	97	+0.10	±0.08	−0.10	±0.06
Humphrey HAR 520	105	+0.02	±0.08	−0.12	±0.05
Humphrey HAR 530 (Auto + on)	105	+0.00	±0.09	−0.07	±0.06
Humphrey HAR 530 (Auto + off)	105	−0.16	±0.09	−0.12	±0.05
Nidek AR-1600	101	+0.47	±0.07	−0.11	±0.05
Nikon NR-7000	109	−0.11	±0.12	−0.09	±0.07
Topcon RM-A6000	109	+0.12	±0.07	−0.05	±0.05

TABLE 5. SD of the difference between the autorefractor results and the subjective refraction; all data are given in diopters.

Instrument	No. of Eyes	SD of Δ SE	Confidence Interval	SD of Δ C	Confidence Interval
Canon R-10	101	0.40	(0.35, 0.46)	0.28	(0.25, 0.33)
Hoya AR-530	97	0.39	(0.34, 0.46)	0.31	(0.27, 0.36)
Humphrey HAR 520	105	0.40	(0.35, 0.47)	0.26	(0.23, 0.30)
Humphrey HAR 530 (Auto + on)	105	0.46	(0.41, 0.53)	0.29	(0.26, 0.34)
Humphrey HAR 530 (Auto + off)	105	0.47	(0.42, 0.55)	0.26	(0.23, 0.30)
Nidek AR-1600	101	0.37	(0.32, 0.43)	0.26	(0.23, 0.30)
Nikon NR-7000	109	0.61	(0.54, 0.71)	0.39	(0.35, 0.45)
Topcon RM-A6000	109	0.36	(0.32, 0.42)	0.27	(0.24, 0.31)

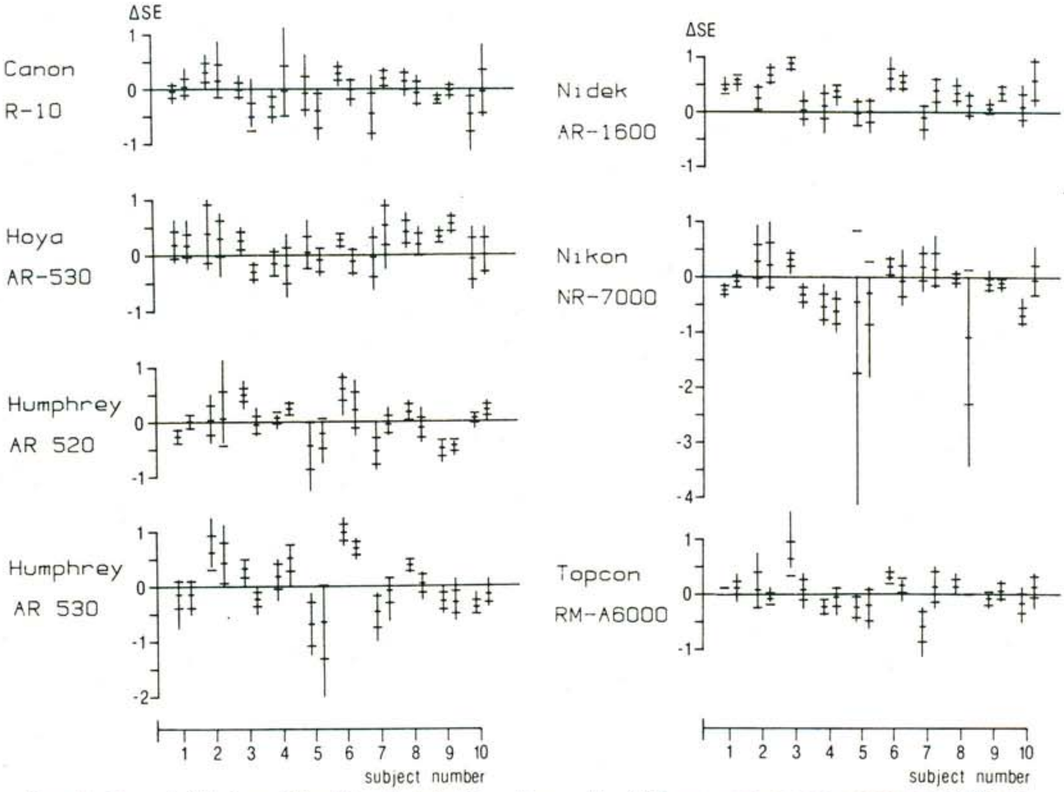

FIG. 5. Error distribution of the SE, calculated from the results of 10 successive measurements on 20 eyes.

Results on Patients

All autorefractors had severe difficulties in measuring the refractive state of some patients.

In 33% of all measurements on aphakic eyes it was impossible to obtain a reading. Among the residual 66%, differences up to 2.5 D from the actual corrective lens occurred.

In 22% of all measurements on eyes with intraocular lenses a reading could not be obtained. The Nikon NR-7000 had the most difficulties; it was unable to obtain a reading in nearly 50% of all cases.

In a total of 140 cataract eyes, with visual acuities ranging from 6/60 to 6/6 (20/200 to 20/20), a reading was not possible in 21% of cases. In 79% we succeeded in obtaining an autorefractor reading, but several results had large errors. Spherical differences up to 6 D and cylindrical errors up to 3 D were not rare. Although the total number of measurements is too small and the comparability is limited, because not every patient could be measured with every instrument, we found that the Humphrey instruments performed slightly better compared to the average and the Canon and Hoya instruments slightly worse on this difficult group of patients.

CONCLUSION

The results of the present study indicate that the differences in accuracy between autorefractors of different manufacturers have become very small. In our previous studies[16, 17] several instruments performed significantly worse than others, but today it has become almost impossible to rate instruments according to their accuracy on normal ametropic subjects. In more than 80% of cases the SE differed by less than 0.51 D from the result of a conventional subjective refraction. The error of the cylinder power was smaller than 0.51 D in more than 90% of all cases, and the axis error was smaller than 0.51 D in more than 84% of all cases.

On the other hand, it is not possible to prescribe spectacles directly from the autorefractor outcome, as all instruments yield larger errors in some cases, and no instrument is capable of performing binocular balancing, which to us is important.

For an accurate preliminary refraction almost all the instruments tested can be recommended without hesitation, as they produce a good starting value for the subjective refinement in more than 90% of normal eyes. Time is saved because an abbreviated Jackson cross-cylinder test can be carried out during the subjective examination. The abbreviated subjective test should consist of the following steps: (1) refinement of sphere; (2) refinement of axis; (3) refinement of cylinder power; and (3) binocular balancing.

However, our positive judgment is only valid for normal subjects. Concerning patients with highly reflecting optical surfaces, scattering eye media, or very high ametropia, the number of instances in which a measurement is impossible or renders a wrong result is much larger. Nevertheless, it seems useful to us to refract problematic patients with an automatic refractor, e.g., with low vision patients the objectively obtained result may be better than the result of the subjective examination.

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CLINICAL COMMENT

This report is the most recent in a series by the authors documenting the performance of commercial automated refractors. They have found that overall performance has improved significantly and consistently among all manufacturers whose instruments were evaluated. Today's refractors handle routine refractive meas-