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Calibration and validity of an eccentric photorefractor

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Summary

A new graphical calibration method was developed to convert the photorefractive reflex into refractive error. With this graphical method, the refractive error can be obtained for pupil sizes and for photorefractive reflex sizes which have not been precalibrated. In the conventional method, the refractive error associated with non-precalibrated pupil and reflex sizes is obtained by interpolating between neighbouring precalibrated points. This introduces error because the relationship between refractive error and pupil and reflex size is not linear. Three hundred and sixty-one children aged between 36 and 65 months were clinically examined and photorefracted. The refractive error obtained using retinoscopy and the eccentric photorefractor agreed well with each other, although the photorefractor tended to under-estimate refractive error. Using the referral criteria developed by Chan, O. Y. C. and Edwards, L. M. (Refraction referral criteria for Hong Kong Chinese Children. *Ophthal. Physiol. Opt.* **14**, 259–256, 1994), the photorefractor had a sensitivity of 74.6% and a specificity of 96.4%. All the under-referred cases were borderline, having just failed the referral criteria. All the cases with hyperopia of > +2.0 D, astigmatism of > 1.25 D and visual acuity of worse than 6/18 were identified. Copyright © 1996 The College of Optometrists. Published by Elsevier Science Ltd

Introduction

Photorefraction is an objective photographic technique which can be used to screen for strabismus and abnormal refractive error (Kaakinen, 1979; Kaakinen and Tommila, 1979; Hay *et al.*, 1983; Norcia *et al.*, 1986; Millodot, 1993). Kendall *et al.* (1989) found that these conditions constituted 88% of visual problems in children aged less than six years. Since photorefraction involves only the taking of photographs, something which is usually associated with laughter and happy occasions, children are usually not afraid of being photorefracted.

The size of the photorefraction reflex obtained from a photograph of both eyes of a subject can be converted into a value for refractive error. In previous studies (Kaakinen, 1979, 1981; Kaakinen and Tommila, 1979; Day and Norcia, 1988; Wang and Qu, 1988), the calibration was done by taking photographs of a model eye which was pre-set at different refractive errors and pupil diameters. The size of the photographic reflex was measured and compared with that obtained from the real eye.

Edwards (1991a) calibrated her photorefractor by taking photographs of model eyes with four different pupil sizes (4, 5, 6 and 8 mm) and with pre-set refractive error ranging from +5.00 to −5.00 D in steps of 0.25 to 0.50 D for low refractive error, and 1.00 D steps for high refractive errors. All photographs were taken at a distance of 4 m. A table was then produced showing the refractive error associated with given reflex and pupil sizes. Interpolation was done in order to obtain the refractive error when the pupil diameter or reflex size measured from the photograph fell between two precalibrated values. However, the relationship between reflex size, pupil size and refractive error is not linear (Bobier and Braddick, 1985; Howland, 1985; Crewther *et al.*, 1987; Bobier *et al.*, 1992). Errors are inevitably introduced into the interpolated results.

In the present study, a new graphical calibration method to convert photorefractive reflexes into refractive errors was developed. In addition, the accuracy and the validity of the eccentric photorefractor used in the present study was evaluated.

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The photorefractor used

An eccentric photorefractor was constructed using a single lens reflex camera (Minolta X-700), a 500 mm, *f*-8 catadioptric (mirror) lens (Tokina TM500), a twin flash unit (Olympus T28) and an Olympus T power control. The power control allows either flash to be fired as desired. The two flashes were attached so that one was horizontal and tangential to the top, and the other was vertical and tangential to the side of the lens casing. This allows the photorefractor to photograph either the vertical or the horizontal meridian of the eyes without rotating the flash or the camera. *Figure 1* shows a photograph of the photorefractor.

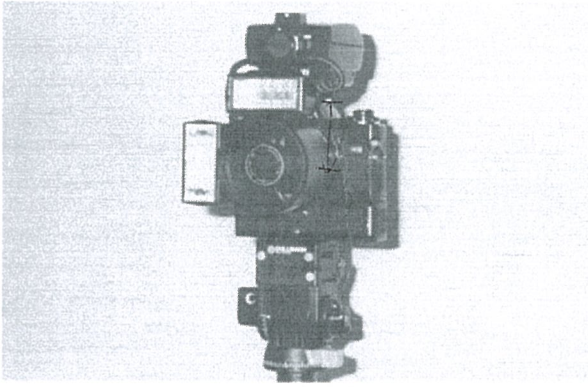


Figure 1. The photorefractor used in the present study.

The new graphical calibration

Theoretical consideration for the new calibration

In the present study, a new graphical calibration method was developed to convert photographic results (photorefractive reflexes) into refractive error. *Figure 2* shows diagrammatically how a photographic crescent is formed in a myopically defocused eye and *Figure 3* shows the same optical analysis in a hyperopically defocused eye.

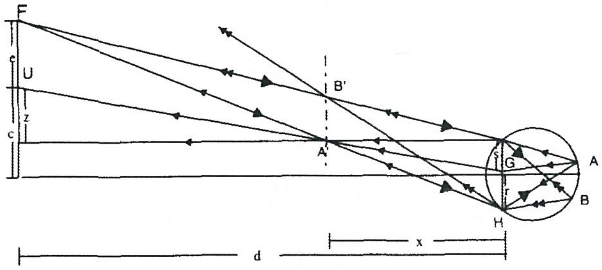


Figure 2. Crescent formation with a myopically defocused eye. A flash source *F* is positioned at a distance *e* above the extreme edge *U* of the entrance pupil of the camera lens. The distance from the entrance pupil to the eye under test is *d*. Light from the flash enters the myopic eye and is focused in front of the retina; a blurred image AB is therefore formed on the retina. This retinal image will in turn form an aerial image B'A' at the far-point plane of the eye. If the eye is sufficiently myopic, light returning from this image will enter the camera lens to produce a reflex on the film. In myopia, the reflex (denoted by *z*) is in the side of the pupil corresponding to the direction of flash offset (sign convention has been ignored).

Considering triangles FA'U and GA'H in *Figure 2*:

$$\frac{2r - s}{x} = \frac{e}{d - x}$$

$$2r - s = \frac{ex}{d - x}$$

$$2r - s = \frac{e}{(d/x) - 1}$$

$$2r - s = \frac{e}{(d/x) - (d/d)}$$

$$2r - s = \frac{e}{d}\left(\frac{1}{(1/x) - (1/d)}\right)$$

$$s = -\frac{e}{d}\left(\frac{1}{X - D}\right) + 2r \qquad \text{where } X = 1/x \text{ and } D = 1/d$$

$$s = -ed^{-1}\,(X - D)^{-1} + 2r \tag{1}$$

Considering triangles FA'U and HA'G in *Figure 3*:

$$\frac{2r - s}{x} = \frac{e}{d + x}$$

$$2r - s = \frac{ex}{d + x}$$

$$2r - s = \frac{e}{(d/x) + 1}$$

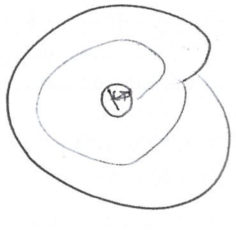
$$2r - s = \frac{e}{(d/x) + (d/d)}$$

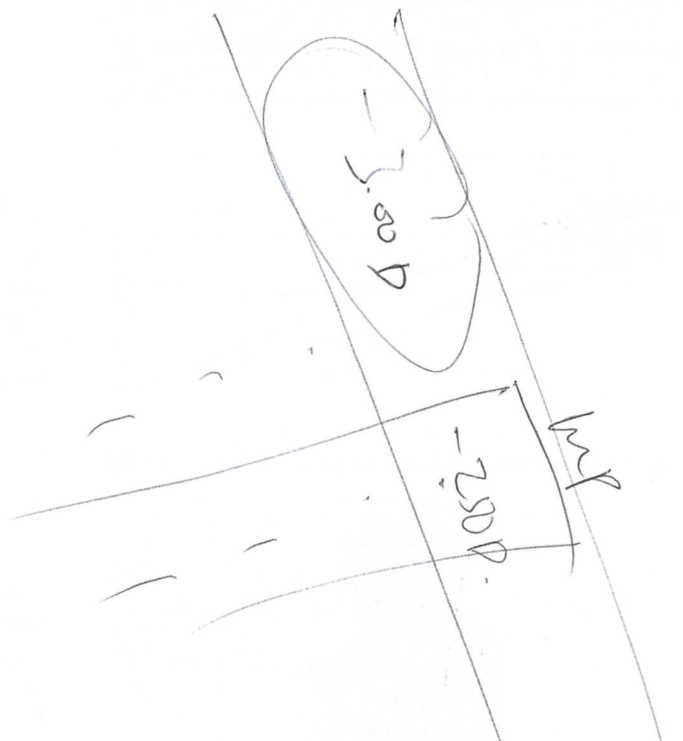
$$2r - s = \frac{e}{d}\left(\frac{1}{(1/x) + (1/d)}\right)$$

$$s = -\frac{e}{d}\left(\frac{1}{X + D}\right) + 2r \qquad \text{where } X = 1/x \text{ and } D = 1/d$$

$$s = -ed^{-1}\,(X + D)^{-1} + 2r \tag{2}$$

Equations (1) and (2) show how the relationship between the size of the reflex (s) and the inverse of relative defocus of the eye with respect to the working distance of the photorefractor (i.e. $(X-D)^{-1}$ in a myopic eye and $(X+D)^{-1}$





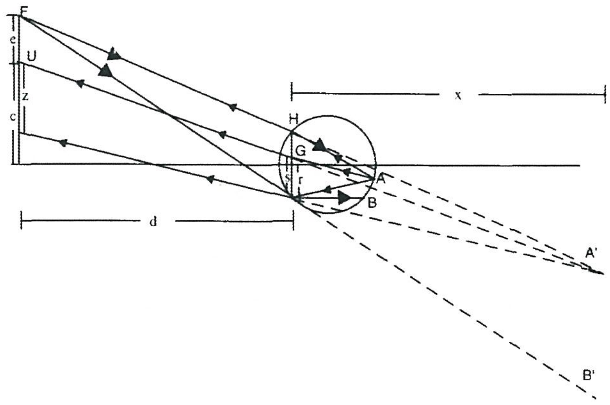


Figure 3. Crescent formation with a hyperopically defocused eye. A virtual image A′B′ of the retinal image is formed behind the eye at the far-point plane. A waist of ray (*Z*) enters the camera aperture. A crescent of width *s* appears in the plane of the pupil in a position opposite to the direction of offset of the flash (sign convention has been ignored).

in a hyperopic eye). Since the eccentricity of the flash (e) and the working distance of the photorefractor (d) are fixed and known, the relationship between (s) and $(X \pm D)^{-1}$ is linear for a particular pupil size ($2r$).

The slope ($-e/d$) in the equations is the negative value of the eccentricity of the flash relative to the outer extremity of the entrance pupil of the camera lens (e) divided by the working distance of the camera (d) with respect to the eye; d was set at 4 m in the present study. The value of e for the photorefractor used was 0.0169 m. As a result, the theoretical value of the slope is −0.00421.

Trial calibration using a model eye

To validate this analysis, a trial calibration was carried out using a Perkins–Weale practice eye set at 8.5, 7.4 and 5.0 mm pupil diameters and refractive errors ranging from +6.0 to −5.0 D in steps of 0.25 to 0.75 D. The refractive errors were confirmed using retinoscopy.

The model eye was positioned 4 m from the photorefractor and the room light was turned off when pictures were taken to avoid the reflection of overhead fluorescent light tubes from the lens surface of the model eye, which might obscure the photorefractive reflex. Kodak colour transparency film (HC100) was used in the study.

A scaled 35 mm transparency was produced by taking a photograph of graph paper, with 2 mm divisions, at a distance of 4 m. This scaled transparency was projected and the magnification of the projector adjusted until each check of the projected image measured 10 mm (i.e. a linear magnification of 5 times). The setting of the projector was then fixed and remained the same throughout the measuring process. This procedure was repeated regularly in order to ensure that the setting of the projector remained unchanged.

The slides were arranged in random order and the reflex and pupil diameter were measured. The procedure was repeated twice more so that each slide was measured 3 times. All the measurements were done by the same person, OYCC. Since the margin of the reflex inside the pupil could sometimes be difficult to judge (there was not always a sharp demarcating line between the bright reflex and the rest of the pupil), a black line drawn on a white card was used to help to locate the blurred margin of the reflex. The card was placed on the screen and moved until the black line was judged to be overlapping the margin of the reflex. The distance from the margin of the reflex to the edge of the pupil over the bright area was measured and recorded as the size of the bright reflex.

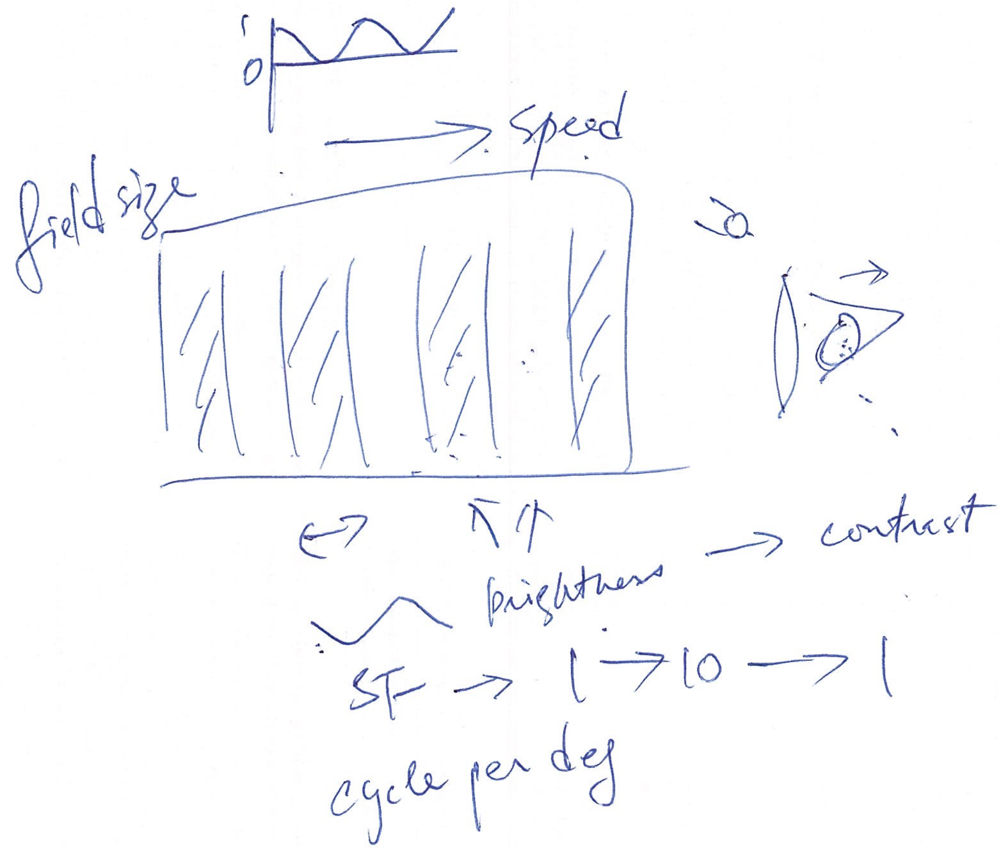
The maximum difference in the reflex size found between the three measurements was 0.8 mm. The three measured values were averaged and the mean was recorded. A summary of the pre-set refractive error, the reciprocal of relative defocus of the eye, and the resultant reflex size obtained is shown in *Table 1*. As there was no reflex, or only a just observable (non-measurable) reflex, on the photographs with refractive error set at 0.00 and ±0.75 D, these points were excluded from the graph and the analysis.

Figure 4 shows reflex size plotted against the inverse of relative defocus obtained from a model eye set at three different pupil diameters (8.5, 7.4 and 5.0 mm). The slopes of the three straight lines were −0.005, −0.00467 and 0.00449 (mean = −0.00472). The mean slope was close to the theoretical value of −0.00421. The y-intercepts agree with their corresponding pupil sizes except that all were about 0.5 mm (0.30 to 0.77 mm) smaller than the measured

Table 1. Reflex sizes obtained with different pupil sizes using a model eye

Refractive error in the model eye (D)	$(X+D)^{-1}$	*Pupil sizes (mm)*		
		5	*7.4*	*8.5*
+6.00	0.16	4.30	NA	NA
+5.25	0.182	4.13	6.00	7.00
+4.50	0.211	4.00	5.87	6.76
+3.75	0.25	3.83	5.80	6.73
+3.12	0.297	3.63	5.10	6.43
+2.25	0.4	3.13	4.37	5.80
+1.50	0.571	2.43	3.63	4.67
+1.00	0.8	1.53	NA	NA
+0.75	1.0	NA	2.13	NA
0.00	4.0	–	–	–
−0.75	2.0	–	–	–
−1.50	0.8	0.77	3.10	3.30
−2.25	0.5	1.93	4.13	5.03
−3.00	0.364	2.87	4.77	6.17
−3.75	0.286	3.03	5.23	6.67
−4.50	0.235	3.2	5.53	6.57
−5.00	0.211	3.3	5.63	NA

NA: photograph was not taken.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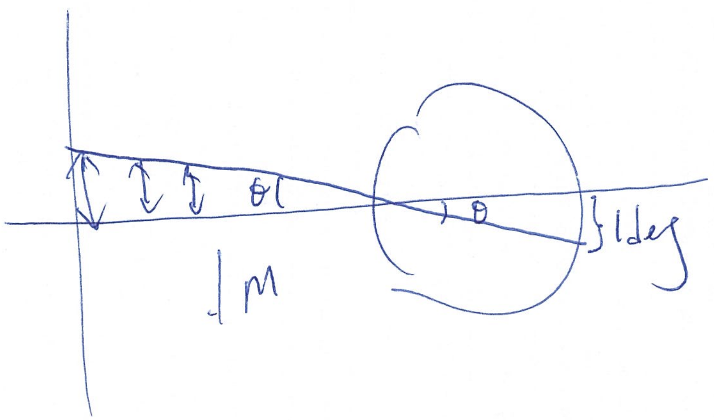
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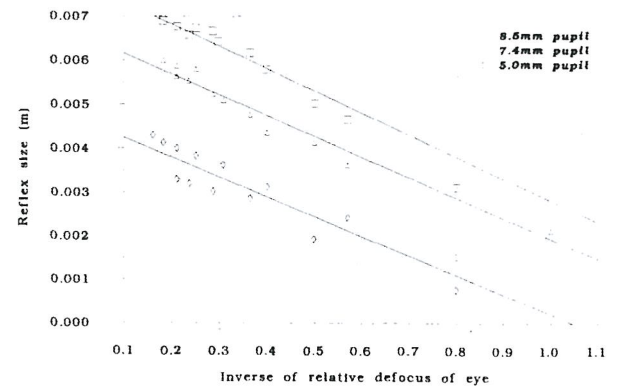


Figure 4. Reflex sizes obtained using three pupil sizes. The equation representing the 8.5 mm pupil line:
$y = 0.0078 - 0.005x \quad r = 0.975.$
The equation representing the 7.4 mm pupil line:
$y = 0.0066 - 0.0047x \quad r = 0.982.$
The equation representing the 5.0 mm pupil line:
$y = 0.0047 - 0.0045x \quad r = 0.937.$

values. The results shown in *Figure 4* confirm that the relationship between (s) and $(X \pm D)^{-1}$ is linear, that the slope of the equations is close to $-e/d$ and that the y-intercept is close to the size of the pupil, although about 0.5 mm smaller than the actual pupil size.

Based on the findings shown in *Figure 4*, a nomogram consisting of many parallel lines was produced as shown in *Figure 5*. Each of these lines represents the relationship between s and $(X \pm D)^{-1}$ for a specific pupil size. The slope of these lines was obtained by averaging the slopes of the three straight lines obtained in *Figure 4*. The average empirical slope of −0.00472 was used in the nomogram instead of the theoretical slope of −0.00421 because, practically, it was difficult to locate the effective margin of the flash and thus the eccentricity of the flash (e) could not be measured accurately. As a result, the theoretical value of the slope may not be as useful as the average slope obtained empirically.

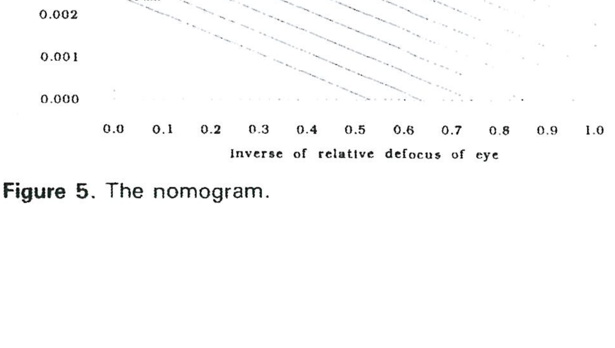


Figure 5. The nomogram.

The y-intercept of the line represents the size of the pupil. However, as shown above, the y-intercept was always about 0.5 mm less than the actual pupil size. Consequently, as shown in *Figure 5*, the line representing the 8 mm pupil was drawn to intercept the y-axis at 7.5 mm (0.0075 m) and the line representing the 7.5 mm pupil was made to intercept the y-axis at 7 mm, and so on.

Using the nomogram developed in *Figure 5*, any photorefractive reflex and pupil size can be converted into refractive error.

Accuracy and validity of the photorefractor

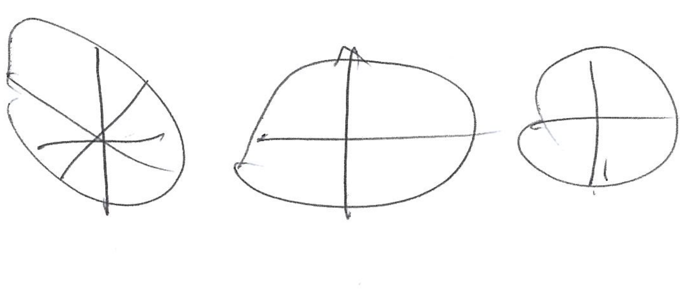
In order to evaluate the accuracy and the validity of the photorefractor, 361 children, aged between 36 and 65 months, were recruited from two kindergartens for clinical and photorefractive examinations. In the clinical examination, binocular vision was assessed using the cover test, refractive error was measured using non-cycloplegic retinoscopy (with the child wearing a pair of +1.5 D binocular fogging lenses) and visual acuity was measured using a STYCAR letter-matching chart with confusion bars. Children were considered to have visual problems when they had any one of the following conditions: the presence of a heterotropia, hyperopia of +2.0 D or more, myopia of −1.0 D or more, astigmatism of 1.0 D or more, anisometropia of 1.25 D or more, visual acuity worse than 6/12 in either eye and/or a difference in visual acuity of more than one line between two eyes (Chan and Edwards, 1994).

Photorefraction was performed after the clinical examination. During photorefraction, the child was asked to look (without the use of fogging lenses) at a flashing device (a cluster of four flashing LEDs) which was attached to the lens casing of the photorefractor. Photographs were taken, at a working distance of 4 m, first with the vertically positioned flash and then with the horizontally positioned flash. Since the vast majority of Hong Kong Chinese children have with-the-rule astigmatism and most of the remaining children have against-the-rule astigmatism (Edwards, 1991b; Lam, 1991a,b; Chan and Edwards, 1993) it is neither necessary nor economical to photorefract oblique meridians of the eye. Consequently, only the vertical and horizontal meridians of the eye were refracted.

With the use of the new graphical calibration method, photorefractive results obtained from the photographs were converted into refractive error (to the nearest 0.25 D). Using the above refraction referral criteria, the photorefractive results were compared with the clinical results to determine the validity of the photorefractor (i.e. the percentage of children with and without a visual problem that can be correctly identified by the photorefractor).

Accuracy of the photorefractor

In order to evaluate the accuracy of the photorefractor in



the estimation of refractive error, the meridionial powers of the subjects measured with photorefraction and with retinoscopy, both carried out without cycloplegia, were compared. Results from only the left eye were analysed and since the power from the two principal meridians are unlikely to be independent of each other, vertical and horizontal power meridians of the eye were analysed separately.

Figure 6 shows the accuracy of the photorefractor in measuring refractive errors as compared to the retinoscopy findings in the vertical meridian of the left eye of all the 361 subjects. The amount of over- and under-estimation of refractive errors as obtained using the photorefractor was plotted against the retinoscopy findings. Positive values indicate over-estimation of refractive error and negative values indicate under-estimation of refractive errors. For a subject with hyperopia of +0.75 D and showing no photorefractive reflex in the photograph, the photorefractor would be considered to have under-estimated a hyperopia of 0.75 D. The mean error of the photorefractor in measuring refractive error in the vertical meridian was −0.45 D (SD 0.38). *Figure 7* shows a similar plot but in the horizontal meridian. The mean error in the horizontal meridian was −0.55 D (SD 0.33). If the distribution of the data in *Figures 6* and *7* was assumed normal, 95% of the error would fall between +0.31 and −1.21 D in the vertical meridian and between +0.11 and −1.21 D in the horizontal meridian. The number of points in both *Figures 6* and *7* appears to be less than 361 (the total number of subjects) because of overlapping points. *Figures 8* and *9* show the distribution of error obtained by the photorefractor when compared with the retinoscopy findings.

In the vertical power meridians (*Figure 8*), refractive error was under-estimated in 309 cases, over-estimated in 22 cases and correctly estimated in 30 cases. Although the refractive error in only 8.3% of the cases was correctly estimated, under-estimation of refractive error of over 1.0 D was found in only 8 of the 361 cases, all having hyperopia of 1.25 D or more. In the remaining 353 cases, the error in the estimation of refractive error was within 1.0 D. The maximum under-estimation of refractive error was found in a case with hyperopia of +2.75 D and the under-estimation was 1.75 D.

In the horizontal power meridians (*Figure 9*), refractive

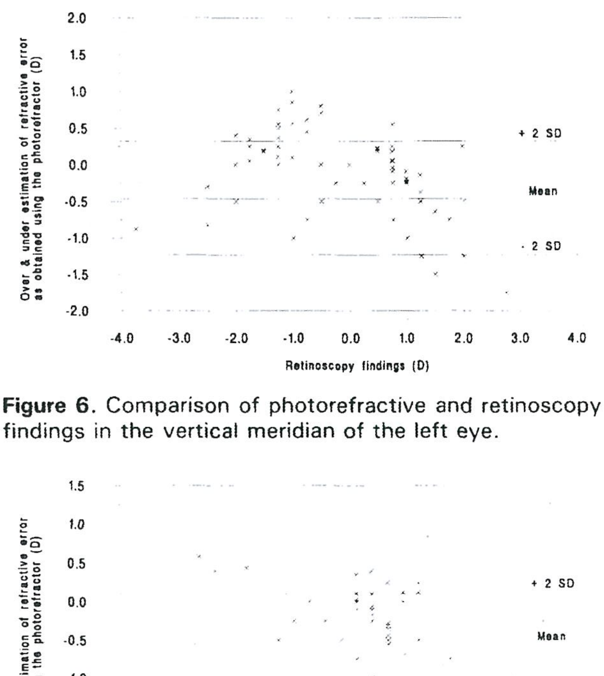


Figure 6. Comparison of photorefractive and retinoscopy findings in the vertical meridian of the left eye.

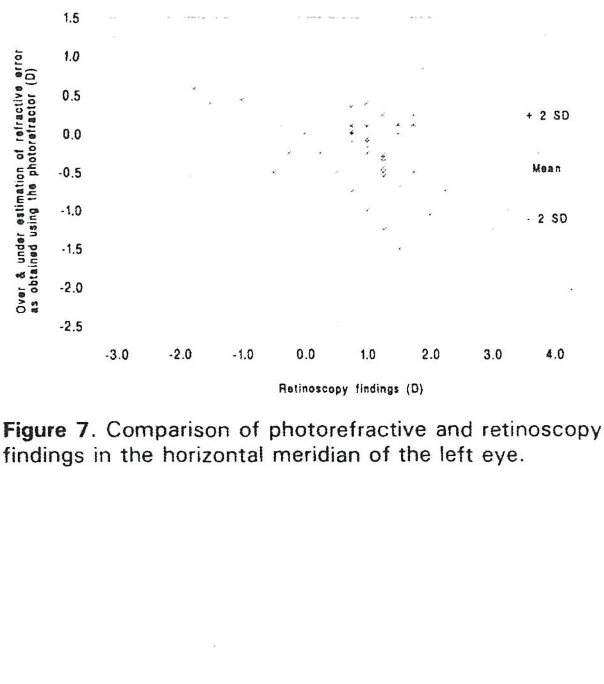


Figure 7. Comparison of photorefractive and retinoscopy findings in the horizontal meridian of the left eye.

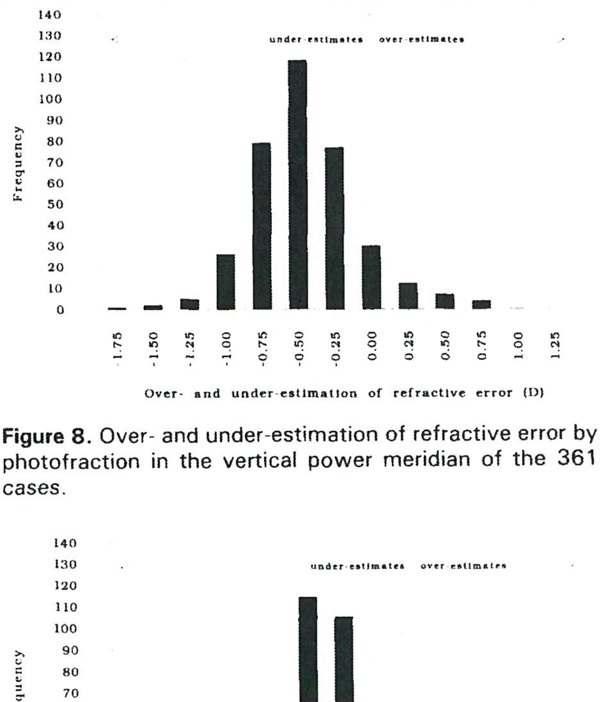


Figure 8. Over- and under-estimation of refractive error by photofraction in the vertical power meridian of the 361 cases.

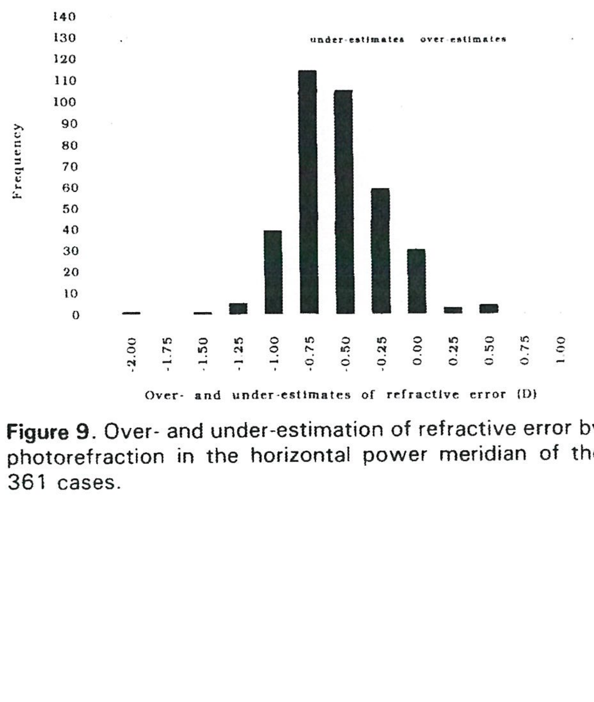


Figure 9. Over- and under-estimation of refractive error by photorefraction in the horizontal power meridian of the 361 cases.

error was under-estimated in 324 cases, over-estimated in 7 cases and correctly estimated in 30 cases. Under-estimation of refractive error of over 1.0 D was found in only 7 of the 361 cases. In the remaining 98% of the cases, the difference in the estimation of refractive error was within 1.0 D. The maximum under-estimation of refractive error (2.0 D) was found in a case with hyperopia of +4.25 D.

The results of *Figures 8* and *9* show that the photo-refractor under-estimated refractive error in 88% of the cases and over-estimated refractive error in only 4% of the cases. The under-estimation of refractive error could perhaps be explained by the use of film which was insufficiently sensitive to pick up all the light returning from the eye. As a result, the size of the reflex measured from the slides may be smaller than the theoretical size. The refractive error obtained using the photorefractor based on the size of the reflex was, therefore, less than the actual amount. In addition, the retinoscopy results were measured through a pair of binocular fogging lenses. For photorefraction, however, the photographs were taken of the naked eye. Consequently, the refractive error measured using retinoscopy revealed a fuller amount of hyperopia when compared with photorefraction and thus the photorefractor seems to have under-estimated the hyperopia.

Although the photorefractor tends to under-estimate refractive error, the mean error was −0.45 D (SD 0.38 D) and −0.55 D (SD 0.33 D), respectively, in the vertical and horizontal power meridians. In 98% of the cases, the difference between retinoscopy and photorefraction results was less than 1.0 D.

Validity of the photorefractor

The validity of a vision screening is the ability of the test to identify children with and without a visual problem, and is defined in terms of sensitivity and specificity. Sensitivity indicates the percentage of affected individuals who are identified by the test as affected and specificity indicates the percentage of non-affected persons who are identified as unaffected (Allen, 1976).

Using the referral criteria developed by Chan and Edwards (1994), 59 (16.3%) of the 361 children failed the clinical examination and were considered as having a visual problem. This is, so far, the best estimate of the prevalence of visual problems in Hong Kong Chinese preschool children. Since colour vision was not assessed, the prevalence value quoted above does not include children with colour vision defects. *Table 2* summarizes the abnormalities found in these 59 children.

The referral criteria were then applied to the results obtained by photorefraction. The corneal reflexes were assessed to determine the presence of heterotropia.

Photorefraction correctly identified 44 of the 59 cases who failed the clinical examination, failing to identify 15 cases. Of the 302 children with no visual problems, photorefraction also falsely identified 11 cases. The results are summarized in *Table 3*.

Table 4 summarizes the validity of photorefraction in identifying children with visual problems; 74.6% of the children who failed the clinical referral criteria were identified using photorefraction and 80% of the children identified photographically had failed the clinical referral criteria. The results also showed that 96.4% of the children who passed the clinical referral criteria also passed the photorefraction and 95.1% of the children identified as having passed the photorefraction screening were actually free of visual problems.

The above results show that the false-positive and false-negative rates for photorefraction were 3.6% and 25.4%, respectively. The false-positive rate was satisfactory; however, the false-negative rate was not. Of the 15 false-negative cases, three failed only the referral criterion for visual acuity and had bilateral visual acuity of 6/18; however, their refractive errors passed the criteria for referral and could not account for the poor visual acuity scores. The

Table 2. Combinations of visual problems found in the 59 subjects who failed the clinical tests

Criterion/criteria failed	*No. of cases*
Visual acuity only	3
Refractive error only	25
Heterotropia only	2
VA + Refractive error	27
VA + Heterotropia	0
Refractive error + Heterotropia	0
VA + Refractive error + Heterotropia	2
Total number of cases	59

Table 3. Contingency table showing the breakdown of photorefractive and clinical referrals

Photorefractive results	*Results of clinical tests*		
	Abnormal	*Normal*	*Total*
Failed	44	11	55
Passed	15	291	306
Total	59	302	361

Table 4. Summarized results showing the validity of photorefraction

Sensitivity	74.6%
Specificity	96.4%
Predictive value of a positive test	80.0%
Predictive value of a negative test	95.1%
False-negative rate	25.4%
False-positive rate	3.6%
Phi coefficient	+0.73

photorefractive results of these three children did not reveal any excessive refractive errors (according to the referral criteria), abnormalities in the external eye or ocular media. The poor acuity found in these children may have been due to poor cooperation in the clinical test because they were all very young (aged three years). The findings from the remaining 12 false-negative cases are listed in *Table 5*.

Case numbers 1 to 8 in *Table 5* failed only the criterion for refractive error; however, the astigmatism in each of the cases was only 1.0 or 1.25 D and the only case that failed the criterion for hyperopia had hyperopia of +2.0 D. These cases had just failed the referral criteria for astigmatism and hyperopia and their vision had not failed the criterion for visual acuity. They were, in fact, borderline cases.

Case numbers 9 and 10, like those of the first eight cases, just failed the criterion for astigmatism; however, they also failed the criterion for visual acuity.

Case number 11 had compound myopic astigmatism. Although the amount of myopia and astigmatism did not cause the subject to fail the refraction referral criteria, the vision in this subject failed the referral criterion for visual acuity. In fact, myopic photorefractive reflexes had been found in the photograph of this child; however, the size of the reflex was not large enough for the child to fail the refraction referral criterion.

Although the refractive error and visual acuity of the child in case number 12 passed the criteria for referral, the child showed an intermittent heterotropia that dissociated under a cover test. Since the heterotropia was intermittent and the corneal reflexes on the photograph were perfectly symmetrical, this child was not identified using photorefraction.

Although the sensitivity of photorefraction was 74.6% and 15 of the 59 cases were under-referred, none of the under-referred cases had astigmatism of over 1.25 D, hyperopia of over +2.0 D and/or visual acuity of worse than 6/18. These 15 cases had just failed the criteria for referral. All the cases with higher ametropia were identified.

Table 5. The 12 false-negative cases of photorefraction

Subject	*Age (months)*		*Sph. (D)*	*Cyl. (D)*	*Visual acuity*
1	55	R.	+0.75	−1.25	6/12
		L.	+0.75	−0.50	6/9
2	36	R.	+0.50	−1.00	
		L.	+0.50	−1.00	Not measurable
3	47	R.	+1.00	−1.00	6/12
		L.	+1.00	−1.00	6/12
4	52	R.	+0.75	−0.75	6/9
		L.	+0.50	−1.00	6/12
5	46	R.	+1.00	−1.25	6/12
		L.	+1.00	−1.25	6/12
6	47	R.	+0.50	−1.00	6/12
		L.	+0.25	−0.50	6/9
7	51	R.	+0.25	−1.00	6/12
		L.	+0.50	−0.75	6/12
8	65	R.	+2.00	−1.00	6/12
		L.	+1.50	−0.75	6/12
9	61	R.	+0.50	−1.00	6/18
		L.	+0.25	−1.25	6/18
10	51	R.	+0.50	−1.00	6/18
		L.	+0.75	−1.00	6/18
11	59	R.	−0.25	−0.75	6/18
		L.	−0.50	−0.50	6/18
12*	62	R.	+1.00	0.00	6/9
		L.	+1.50	−0.50	6/9

*Decompensated heterophoria shown on cover test.

Summary

Using the optical analysis of photorefraction, a nomogram was developed to convert photorefractive reflexes into refractive errors. Although the photorefractor used in the present study tends to under-estimate refractive error, there is good agreement between the retinoscopy and photorefraction results as reflected by the slope of the regression lines. The mean error obtained using the photorefractor compared with retinoscopy was 0.45 and 0.55 D. In 98% of the cases, the difference was within 1.0 D.

The photorefractor used in the present study is a reliable tool when used to screen preschool children according to the referral criteria developed by Chan and Edwards (1994). In screening for amblyopia and abnormal refractive errors, the photorefractor has a sensitivity of 74.6% and a specificity of 96.4%. The rate of under-referral is high but the rate of over-referral seems satisfactory. The advantage of having a low over-referral rate is that the existing health care system would not be loaded with a large number of unnecessary referrals. Analysis of the under-referred cases showed that all the cases with high refractive error were identified and only children with refractive error which just failed the criterion for referral were missed.

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