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Distributions of non-cycloplegic subjective refractions at Sekororo Hospital in Limpopo province, South Africa

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Background: Non-cycloplegic subjective refraction (NCSR) is useful to measure refractive errors with active ocular accommodation.

Aim: This study aimed to compare annual NCSR distributions between January 2018 and December 2019.

Setting: The study was conducted in the Optometry Clinic at Sekororo Hospital in Limpopo province, South Africa.

Methods: Data, extracted retrospectively from the clinical archive, were randomly stratified into two strata (2018 and 2019) for analysis. Stereo-pair scatter plots and polar plots of variance were used to better understand the samples concerned.

Results: Clinic patients were mostly females of African descent. Mean ages and standard deviations (± SD) for the 2018 and 2019 samples were similar (48.35 ± 20.86 years and 46.22 ± 20.36 years, respectively). For the 2018 sample, the clinical means for NCSR for the right and left eyes, respectively, were similar (R –0.44 –0.15 × 86 and L –0.46 –0.16 × 75) and similar for the 2019 samples (R –0.38 –0.17 × 77 and L –0.14 –0.05 × 99). Samples were not normally distributed and outliers were present, although uncommon. Sample variances were mainly spherical rather than astigmatic.

Conclusion: Non-cycloplegic subjective refractions were mostly classified as mild ([–2: 2 D]) compound myopic astigmatism. Severe myopia (>|6 D|) and hyperopia were uncommon.

Contribution: This article adds to current scientific knowledge of multivariate methods for the analysis of refractive states, especially when applied within rural environments. Such multivariate methods are ideally suited for the analysis of distributions of refractive state.

Keywords: subjective refractions; refractive errors; dioptric power; refractive distributions; non-cycloplegic refractions; distributional non-cycloplegic analysis.

Introduction

Non-cycloplegic ophthalmic refraction is a clinical procedure performed during subjective or objective refraction with active accommodation of the eye to measure the amount of the refractive error without drug administration.[1,2] A cycloplegic refraction is a clinical procedure used in ophthalmic care to determine the amount of refractive error by deactivating the ciliary muscles responsible for focusing the eyes using pharmaceutical agents.[1,2] During this procedure, it is essential that the eye's accommodation is in a relaxed state. It is known that children, particularly at a younger age (< 8 years), have higher levels of ocular accommodation, which can sometimes be excessive and impact upon measurement of ophthalmic refraction.[1,2]

Here the emphasis was placed upon non-cycloplegic subjective refractions (NCSR) as measures of refractive state and, in general, cycloplegia is not routinely used in the rural clinic concerned.

For effective scientific analysis, refractive errors must be converted into dioptric power matrices (see Harris[3] and others[4,5,6]) or vectors.[7,8,9,10] This allows for univariate[11] and/or multivariate methods[7,12] to be used with refractive errors and quantitative information such as means,[3,4] standard deviations (or variances)[7,8,10] become determinable. Enriched graphical output for refractive data includes three-dimensional surfaces of constant probability density (SCPD)[7,12] using stereo-pairs in Euclidean symmetric dioptric power spaces (SDPS).[8,10] Other quantitative

analyses of refractive errors in two-dimensional spaces include meridional[11] or polar profiles of dioptric power, polar profiles of variances,[11] and Mahalanobis distances for identification of outliers.[9,10,13]

Distributions for refractive errors[5,8,10,12,13] are more easily investigated, properly analysed, and understood using the aforementioned methods, and this article demonstrates this process for refractive errors from patients examined at a rural-based hospital in the Limpopo province of South Africa. In rural areas, healthcare facilities are often faced with the challenge of inadequate funding and a dearth of essential resources.[14,15,16] Given this scenario, it becomes imperative to optimise the allocation of available resources efficiently and effectively.

Limpopo province has a population of about 6 million people and is relatively underdeveloped in many regions.[17] Understanding the prevalence, nature, and variability of refractive errors over time is important for planning agencies and authorities to reduce the potentially adverse impacts of uncorrected refractive error (URE) and vision impairment (VI), thereby promoting social and economic development.

Dioptric power matrices and analysis for distributions of refractive errors

Only essential elements (for example, Equation 1) are included here as a transformation of refractive errors in clinical notation (*S C A* or $F_s F_c A$) to 2 × 2 symmetric power matrices **F** (or vectors, **f** or **h**) and analysis of a dioptric (D) power has been previously described in extensive detail.[3,4,5,6,7,8,10] (References 3, 8, and 10 will be helpful for any readers less familiar with this topic.)

$$\mathrm{F}=\begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix}=\begin{pmatrix} F_S+F_C sin^2 A & -F_C \sin \mathrm{A}\, cos\, A \\ -F_C sin \mathrm{A} cosA & F_S+F_C cos^2 A \end{pmatrix} \mathrm{m}^{-1} \text{or D} \quad \text{[Eqn 1]}$$

Notice that f_{11} and f_{22} in Equation 1 are (curvital) powers in the horizontal and vertical meridians, respectively, while $f_{12} = f_{21}$ are (torsional) powers in the reference meridian (typically horizontal but not always). Cylinders in ophthalmology and optometry are measured, of course, in relation to the horizontal meridian.

From clinical notation or **F,** Equation 2 can be used for the scalar (or stigmatic) and antiscalar (or antistigmatic) coefficients of power (see vector **f** [from Harris] or **t** [from Thibos et al.[18]]):

$$\mathrm{f}=\begin{pmatrix} F_\mathrm{I} \\ F_\mathrm{J} \\ F_\mathrm{K} \end{pmatrix}=\begin{pmatrix} \frac{1}{2}\left(f_{11}+f_{22}\right) \\ \frac{1}{2}\left(f_{11}-f_{22}\right) \\ \frac{1}{2}\left(f_{21}-f_{12}\right) \end{pmatrix}=\begin{pmatrix} F_\mathrm{s}+0.5F_\mathrm{c} \\ -0.5F_\mathrm{c}\, cos2A \\ -0.5F_\mathrm{c}\, sin2A \end{pmatrix}=\begin{pmatrix} M \\ J_0 \\ J_{45} \end{pmatrix}=\mathbf{t} \quad \text{[Eqn 2]}$$

The scalar or stigmatic ($F_\mathrm{I} = M$) coefficient is essentially the spherical equivalent while the term antiscalar (or antistigmatic or sometimes '*Jacksonian*') refers to powers that are Jackson Cross Cylinders (JCC). Notice that for asymmetric power matrices (where $f_{12} \neq f_{21}$), there is another vector element (F_L) that we have ignored here. Also, $M = F_\mathrm{I}$, $J_0 = F_\mathrm{J}$, and $J_{45} = F_\mathrm{K}$.[10] These coefficients are used with basis matrices **I**, **J**, and **K**, respectively $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ and $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ for stereo-pairs plots.

Coordinate vector **f** and Equation 3 are used for plots of Mahalanobis distances (*MD*) to identify possible outliers in distributions of refractive errors.[10,13] Such plots provide estimations of the confidence level with which one can expect any specific measurement to be an outlier:

$$MD_i=\sqrt{\left(\boldsymbol{f}_i-\bar{\boldsymbol{f}}\right)^T \mathbf{S}_{\mathbf{ff}}^{-1}\left(\boldsymbol{f}_i-\bar{\boldsymbol{f}}\right)}. \quad \text{[Eqn 3]}$$

The 3 × 3 symmetric variance-covariance matrix $\mathbf{S}_{\mathbf{ff}}$ provides the necessary variances and covariances for distributions of refractive errors:[7,10,11,12,13]

$$\mathbf{S}_{\mathbf{ff}}=\frac{1}{n-1}\sum_{i=1}^{N}\left(\mathbf{f}_i-\bar{\mathbf{f}}\right)\left(\mathbf{f}_i-\bar{\mathbf{f}}\right)^T \quad \text{[Eqn 4]}$$

And

$$\mathbf{S}_{\mathbf{ff}}\begin{pmatrix} S_{\mathrm{II}} & S_{\mathrm{IJ}} & S_{\mathrm{IK}} \\ S_{\mathrm{JI}} & S_{\mathrm{JJ}} & S_{\mathrm{JK}} \\ S_{\mathrm{KI}} & S_{\mathrm{KJ}} & S_{\mathrm{KK}} \end{pmatrix}\cdots D^2 \quad \text{[Eqn 5]}$$

where S_{II} is the stigmatic variance, S_{JJ} and S_{KK} are the ortho-antistigmatic and oblique antistigmatic variances, respectively, while S_{IJ} (= S_{JI}) is the stigmatic ortho-antistigmatic covariance, S_{IK} (= S_{KI}) is the stigmatic and oblique antistigmatic covariance, and S_{JK} (= S_{KJ}) is the ortho- and oblique antistigmatic covariance. Given that $\mathbf{S}_{\mathbf{ff}}$ is symmetrical, only six entries are distinct; variances are always positive, but covariances can be positive or negative.

Means, variances, and covariances are essential statistics for distributions of refractive errors, and Equation 6 is the sample mean[8,10,12]:

$$\bar{\mathbf{F}}_i=N^{-1}\sum_{i=1}^{N}\mathbf{f}_i. \quad \text{[Eqn 6]}$$

The normality of refractive error distributions is assessed with meridional or polar profiles using univariate Mardia's skewness (β_1), kurtosis (β_2), and standardised mean deviation (*SMD* or *A*). The expected skewness (β_1) should be zero for a symmetric or normal data distribution, but values above or below zero are considered positively and negatively skewed, respectively.[10,13,19,20] The expected value of kurtosis (β_2) should be three (3) for mesokurtic distributions of refractive errors and values below or above three are considered platykurtic or leptokurtic.[10,13,19,20,21,22] The expected value for *SMD* (*A*) is approximately 0.7979 (≈ 0.80). (References 23–25 are useful for some of the software implementations as applied herein.[23,24,25])

The primary purpose of this study was to investigate and compare samples of NCSR over 2 years (2018 and 2019) to better understand the prevalence, type, and stability or lack thereof of NCSR for the rural clinic concerned. (Such information might be useful for planning and budgetary purposes for rural optometric and ophthalmology clinics.)

Research methods and design

Non-cycloplegic subjective refractions by an optometrist (with > 20 years of clinical experience) were collected retrospectively from the clinical archive of an optometric clinic at the Sekororo Hospital in the Mopani District of Limpopo province in South Africa (SA) for patients examined over 2 years starting from 01 January 2018 to 31 December 2019 (2020 was excluded because of the coronavirus disease 2019 [COVID-19] pandemic.).

Sampling

The clinical records were randomly selected using a probability-stratified random sampling method.[21] Sampled clinical records were spread into two strata (that is, 2018 and 2019) using the stratified formula[26] (= sample size for the whole study divided by population size × stratum size). The population size for this study comprised 1140 records over the 2 years. Of these, 706 records were for 2018 and 434 records were for 2019. The sample size for 2018 became 238 records, and 146 records for the 2019 stratum after using the stratified formula. A total of 200 records were added to each stratum to increase the statistical power of the study and to allow for the possible exclusion of incomplete records. So, records for 2018 increased from 238 to 438 records, and for the 2019 sample, 146 to 346 records. Records with incomplete information were excluded resulting in final sample sizes for the 2018 and 2019 samples of 279 records and 234 records, respectively. Thus, 513 clinical records in total and ≈134% above the calculated minimum for the whole sample from Cochrane's formula (Equation 7 below)[14,26]:

$$n = \frac{Z^2 P(1-P)}{e^2} = \frac{(1.96)^2\, 0.50(1-0.50)}{(0.05)^2} = 384 \qquad \text{[Eqn 7]}$$

where n = the required minimum sample size, P = 0.5 the percentage occurrence at 50% of the refractive error condition, and e = the margin of error or risk the researcher is willing to accept, relating to factors such as missing or incomplete clinical records in the study, and Z =1.96, the probability value at a significant level of 0.05 corresponding to the level of confidence chosen (here 95%).

Statistical analysis

The NCSR and other variables of interest such as age and gender were captured in an MS Excel spreadsheet (Microsoft 365) for Windows 11 and then imported into Matlab software (The MathWorks, USA) where NCSR were transformed into the dioptric power matrices for further analysis.

Ethical considerations

Ethical approval (REC-1170-2021) was obtained from the Research Ethics Committee in the Faculty of Health Sciences (FREC) at the University of Johannesburg (SA). Permission to conduct the study at the selected hospital was granted by the Provincial Health Research and Ethics Committee in the Limpopo Department of Health, the Senior Clinical Manager, and the Chief Executive Officer (CEO) of Sekororo Hospital.

Results

The study involved two stratified random samples (2018 and 2019) based on clinical records from the archive of the district hospital concerned from January 2018 to December 2019. Patients were of African descent and between the ages of 5– and 90 years with more females than males, that is, 346 females and 167 males. The 2018 and 2019 samples, respectively, included 279 and 234 NCSRs for the right and left eyes. Table 1 summarises the basic descriptive variables for the two samples. Clinical means (indicating mild [–2: 2 D] compound myopic astigmatism) for the right and left eyes did not differ much across the 2018 and 2019 samples. Norms of the means were similar although slightly larger for 2018 (eyes were, on average, slightly more ametropic).

Normality and Mahalanobis distances for refractive error data

Analysis of sample normality[10] and Mahalanobis distances (*MD*)[10] for the right and left eyes of NCSR for 2018 and 2019 mainly demonstrated moderate (> 4) to severe (up to 25) leptokurtosis and mild (± 0.75) negative or positive skewing (for sample normality, kurtosis is 3 and skewness is zero). For conciseness, normality plots are not included here. Given the wide range of refractive states (see stereo-pairs in Figure 1), these results were not unexpected. Outliers were infrequent in the samples, but they also contributed to departure from sample normality. Again, for conciseness, plots of *MD* are not included here (such plots are available from the first author on request).

Stereo-pair plots with 95% distribution ellipsoids

Figure 1 shows the stereo-pair plots with 95% distribution ellipsoids (DE) for the right and left eyes of 279 non-cycloplegic subjective refractive errors for the 2018 sample and another 234 non-cycloplegic subjective refractive errors for the 2019 sample. For both stratified random samples and right and left eyes (in 2018 and 2019), the plots showed vertically orientated DE along the stigmatic axes ($F_1\mathbf{I}$), and this implies that the distributions in both samples were mainly stigmatic, ranging from hyperopic to myopic eyes with mild (< 2 D) to moderate ([1.25–2 D]) astigmatism (points are mostly close to the stigmatic axis). Refractive errors (points) are more densely clustered near the sample means that are not far from the origin (0 D or 0 m^{-1}), and this

TABLE 1: Descriptive variables for non-cycloplegic subjective refractions for 2018 and 2019 stratified samples.

Descriptive variables						
Samples	**Eyes**	**Clinical means (D, D, °)**	**Matrix means (D)**	**Norm of the means (D)**	**Variances and covariances (D²)**	**Volumes of 95% ellipsoids (D³)**
2018 (279 eyes)	Right	− 0.44 − 0.15 × 86	− 0.510**I** − 0.073**J** + 0.011**K**	0.73	$\begin{pmatrix} 2.193† & -0.113 & -0.019 \\ -0.113 & 0.128† & 0.008 \\ -0.019 & 0.008 & 0.045† \end{pmatrix}$	2.80
	Left	− 0.46 − 0.16 × 75	− 0.540**I** − 0.070**J** + 0.041**K**	0.77	$\begin{pmatrix} 2.106† & -0.068 & -0.052 \\ -0.068 & 0.126† & -0.009 \\ -0.052 & -0.009 & 0.054† \end{pmatrix}$	6.75
2019 (234 eyes)	Right	− 0.38 − 0.17 × 77	− 0.466**I** − 0.076**J** + 0.036**K**	0.67	$\begin{pmatrix} 4.029† & -0.115 & -0.075 \\ -0.115 & 0.116† & 0.007 \\ -0.075 & 0.007 & 0.050† \end{pmatrix}$	3.82
	Left	− 0.41 − 0.05 × 99	− 0.433**I** − 0.026**J** − 0.008**K**	0.61	$\begin{pmatrix} 3.700† & -0.093 & 0.008 \\ -0.093 & 0.070† & -0.002 \\ 0.008 & -0.002 & 0.026† \end{pmatrix}$	2.08

Note: Scalar variances (S_{II}) are larger than antistigmatic ones (S_{JJ} and S_{KK}). Variances were similar for the right and left eyes in 2018 and 2019, but less so across the 2 years.
†, indicates variances (see Equation 5).

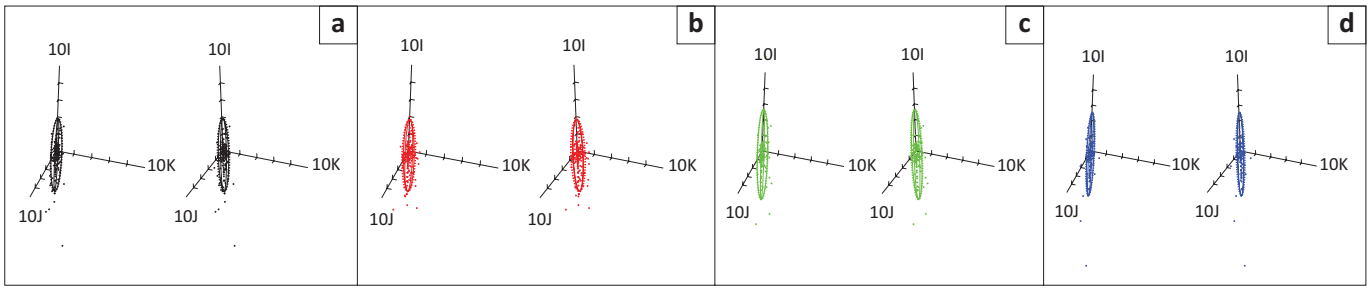

FIGURE 1: Stereo-pair scatter plots with 95% distribution ellipsoids showing non-cycloplegic refractive error data for the right and left eyes for the 2018 and 2019 samples. (a) 279 refractive errors for right eyes (black), (b) 279 refractive errors for the left eyes (red), (c) 234 refractive errors for the right eyes (green), and (d) 234 refractive errors for the left eyes (blue). The ellipsoids include about 95% of the refractive errors, while the remaining 5% are outside the ellipsoids, and some that are located far outside ellipsoids might be regarded as potential outliers. In clinical terms, the axis lengths for all stereo-pairs are 10 D with tick intervals of 2 D. The origin is 0 D or emmetropia.

indicates that there are many non-cycloplegic subjective refractive errors for the right and left eyes in both samples that are not too far off from emmetropia (reflecting the process of emmetropisation).

Rotated stereo-pair scatter plots with 95% distribution ellipsoids

Figure 2 shows the same plots as in Figure 1, but rotated (0, –90°) so that the data are viewed along the stigmatic axis with the antistigmatic (or Jacksonian) plane viewed in the plane of the page, and the further a measurement is from the origin, the greater the antistigmatic powers (F_J and F_K), and also cylinder (F_c) or astigmatism present for any eye (The term antistigmatism is synonymous with JCC and F_J and F_K are equivalent to J_0 and J_{45}).

Polar profiles of variances for the refractive errors (for non-cycloplegic subjective refraction)

Figure 3 shows polar profiles for curvital variances for the refractive states (after transformation to power matrices – see Equation 1) for the right and left eyes in the 2018 and 2019 samples. The profiles represent the three variances, namely, f_{11} and f_{22} for the curvital coefficients of power, and f_{12} (=f_{21}) for the torsional coefficients of power. Profiles for curvital variances (f_{11} and f_{22}) are represented on the same profiles but shifted by 90°. The origin of each polar plot is at zero squared dioptres (0 D²) meaning no variance. So, profiles closer to the origin show smaller variation and profiles further away from the origin show greater variation. The radial scale in the polar plots shows the magnitude of variance (in D²). Variation can be either uniform (completely or partially uniform) or non-uniform across the meridians of the eyes concerned.

Figure 3A indicates that curvital variances in the samples for 2018 were ≈ 2 to 2.5 D² and less than for the 2019 samples (see Figure 3B where the range was ≈ 3.75 D² to 4.25 D² depending on meridian). In 2019, refractive errors were more variable for the right eyes than for the left eyes (compare the outer profiles in green and blue). The curvital profiles are almost uniform or constant, that is, variation is roughly similar for all meridians across the eyes concerned. Torsional variances (innermost profiles and see also Figure 4) were smaller than curvital variances and similar irrespective of the year (2018 or 2019).

In Figure 4, the profiles for the torsional variances are shown with dashed lines and they have a resemblance to '*rabbit ears*'. Irrespective of laterality (right or left eyes), the torsional variances are small (< 0.125 D²). This suggests that astigmatism for the eyes in the samples was not very variable, although cylinders (F_c) ranged from –0.25 D to –4 D. By contrast, spherical powers (F_s) ranged from –18 D to 12 D for the samples for 2018 and 2019.

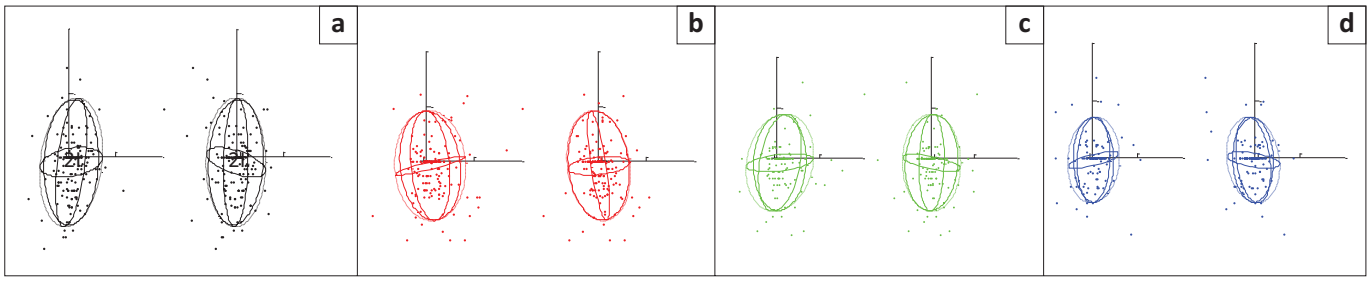

FIGURE 2: Rotated (0, – 90°) stereo-pair scatter plots with 95% distribution ellipsoids for the non-cycloplegic subjective distance refractive errors for the right and left eyes for the 2018 and 2019 samples. (a) and (b) represent rotated ellipsoids for the right (black) and left (red) eyes for the 2018 sample, while (c) and (d) represent rotated ellipsoids for the right (green) and left (blue) eyes for the 2019 sample. In clinical terms, axis lengths are 2 D and the origins are at 0 D (or emmetropia). Thus, most eyes exhibited mild (< 1 D) or moderate (1.25 to 2 D) astigmatism.

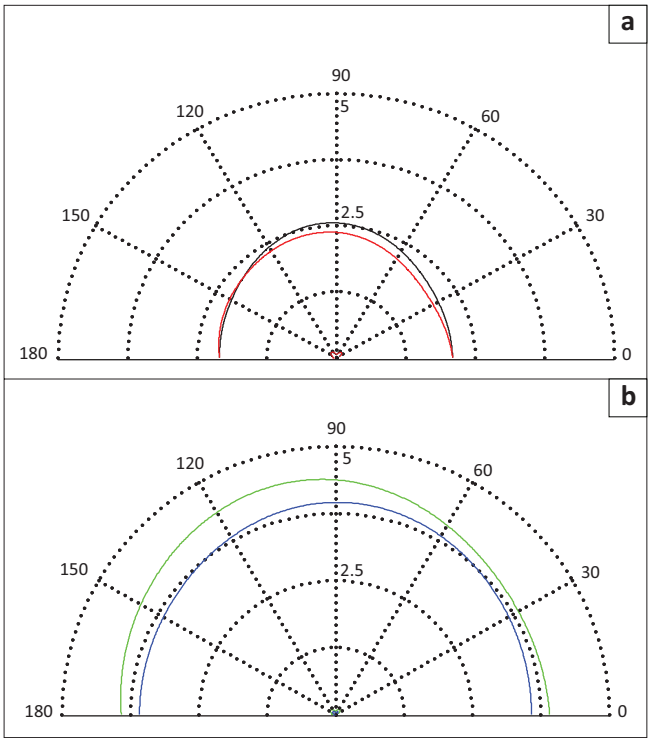

FIGURE 3: Polar plots of variance for the 2018 and 2019 distance refractive error samples. The figure includes profiles for curvital (f_{11} and f_{22} [+90°]) and torsional (f_{21}= f_{12}) variances, respectively. However, the inner torsional variances (almost at the polar origins) in (a) and (b) are not easily visible because of the scale necessary to represent the curvital profiles. (a) Variances for refractive errors (2018) for the right and left eyes are shown with black and red curves, respectively. (b) Variances for refractive errors (2019) for the right and left eyes are shown with the green and blue curves, respectively. The radial scale in both (a) and (b) ranges from 0 to 5 D^2 with intervals of 1.25 D^2. The meridional scale is from 0 to 180° with 30° intervals. There are four profiles per polar plot, but the inner profiles at the polar origins are redrawn in Figure 4 after adjusting the radial scale to improve their visibility.

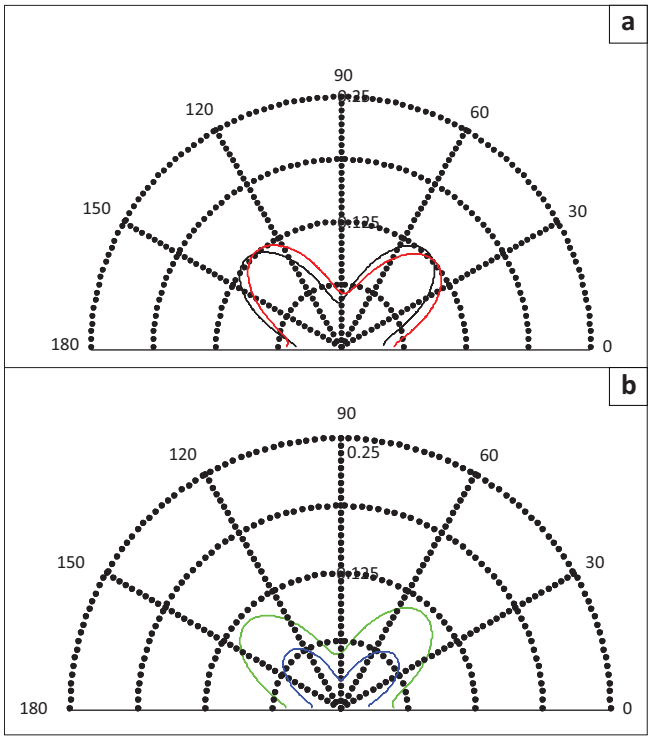

FIGURE 4: Polar plots for the torsional variances for the 2018 and 2019 refractive errors. (a) The 2018 sample with black and red, respectively, representing the right and left eyes. (b) The 2019 sample with green and blue representing the right and left eyes. The radial scale is 0.25 D^2 with intervals of 0.0625 D^2 (the polar origin is the same as in Figure 3 and is 0 D^2).

Discussion

This study involved two (2) stratified random samples (for 2018 and 2019). Data collection was performed retrospectively based on case records extracted from the clinical archive of the Sekororo District Hospital for the patients at this rural Optometry Clinic over 2 years starting from 01 January 2018 to 31 December 2019. The samples for 2018 and 2019, respectively, included 279 and 234 non-cycloplegic subjective refractive errors for the right and left eyes. Both samples were of African descent, with more females (≈ 69% in 2018 and ≈ 65% in 2019). Although ages ranged from 5 years to 90 years, patients were mostly adults with a mean age of ≈ 47 ± 21 years (that is, 48.35 ± 20.86 years and 46.22 ± 20.36 years, respectively, for 2018 and 2019). For the purpose of this article, the decision was to analyse both samples separately rather than combine them into a single sample. This was performed specifically to compare the two annual samples to get an idea of the type and stability of the two distributions of NCSR over the period involved, and Figure 1 to Figure 4 and Table 1 provide clear indications of the similarity of the two annual samples in terms of mean NCSR and SCPD, despite slightly greater variation in NCSR for both the right and left eyes in 2019 (A future article might combine the two samples for further analysis).

Previous studies[13,27,28,29,30,31,32,33,34,35,36,37] of distributions of refractive state in different parts of the world including the African continent, and sub-Saharan African region, and/or local studies in South Africa (SA) have differed in sample

sizes and other variables such as age, gender, and ethnicity. Comparisons of the results here to previous studies are not simple given differences in primary aims, population or sampling methods, and study designs and methodology. The sample sizes (279 and 234 eyes) for the years 2018 and 2019 are consistent with that of another study by Hasrod[13] in the Department of Optometry at the University of Johannesburg (SA).

Previous studies have used smaller or larger samples and in some studies[28,34,36] participants were selected with random sampling methods (such as for this study), while others used convenience or non-probability sampling.[9,13,27,29,30] This study naturally has a clinical bias because of the nature of the data concerned, and this might limit generalisation to the broader population.

Table 1 showed similar clinical means for the refractive errors for the right and left eyes for both samples (2018 and 2019). For the 2019 sample, the clinical mean for the right eyes was slightly less myopic and astigmatic compared to the left eyes. The magnitude or norms (the Euclidean distance of the sample mean concerned from emmetropia) for the right and left eyes were also similar (Table 1), albeit slightly smaller for the left eyes. These findings support the basic principle of emmetropisation that is common to many distributions for the refractive state in eyes that are not affected by conditions, such as, say, keratoconus or ocular or systemic disease.[27] The clinical means, and norms of the means for the right and left eyes for this study are comparable to that for previous work.[9,10,13,20,30] The clinical means for the right and left eyes of this study indicate mild compound myopic astigmatism (CMA) (sphere and cylinder: > 0.25 D),[37,38] consistent with that of previous studies, but the magnitude of the means for the right and left eyes of this study are not the same as that of other studies reported by Mathebula and Rubin,[9] MacKenzie,[28] Unterhorst,[30] Moalusi,[29] Hasrod,[13] and Chetty.[27] However, Chetty included both controls and eyes with keratoconus but in separate samples.[27] Hasrod included different samples in her research, including presbyopes and non-presbyopes, as well as both cycloplegic and non-cycloplegic results. Moalusi, as for the other researchers above including Hasrod also, included apparently healthy individuals only, but MacKenzie, Mathebula and Rubin were mainly interested in comparing results for the reliability of subjective refractions.

Departures from the normality of refractive state for the right and left eyes revealed mainly mild negative and/or positive skewing of data and more profound leptokurtosis that support similar findings from previous studies.[9,13,28,29,30,33] Mahalanobis distances suggested that outliers were relatively uncommon (with five or less per sample or, at worst, 5/234 ×100 = 2.1%), and this again largely agrees with previous work reported in different settings, or geographical areas, or with different participants including some (see Chetty) with keratoconus.[9,13,28,29,30,33] Although not included here for brevity, plots of Euclidean distances can be calculated and are useful in terms of identification of outliers.[9,10,13]

Polar profiles for variances (Figure 3 and Figure 4) revealed similar variation across samples (2018–2019), although the right eyes for the 2019 sample had slightly larger variation than that for the left eyes. Further studies with much larger samples and perhaps also with and without cycloplegia would be useful to investigate this aspect further. The graphical and quantitative (Table 1) methods used herein are well-suited to such studies and specifically apply to the stereo-pair scatter plots with 95% distribution ellipsoids, which are important to understand the distributions of refractive errors more thoroughly. Much of the variation in the refractive state was spherical (stigmatic or scalar) irrespective of laterality or the year of consultation at the rural clinic involved. Astigmatism varied across samples and the rotated plots in Figure 2 are especially helpful to visualise antistigmatic (JCC) variation.

The age range for this study was wide (from 5 years to 90 years) and included children and adults and because cycloplegia was not used at the clinic concerned, this could be an important factor that may have affected the refractive state of some of the younger participants. However, most of the patients were adults with a bias towards older adults (> 40 years) and thus this is not believed to have been a critical factor. Generally, means, variances, covariances, and SCPD are relatively robust to outliers, and even to the absence of cycloplegia in some younger eyes (provided there are not too many such eyes). Therefore, the data for NCSR and analysis of refractive error herein provides useful information that can be used to modify and improve clinical services at the rural clinic involved and that may also be helpful for similar clinics in other parts of the world, particularly for less-developed regions where limitations in the availability of eye care professionals and, for example, instrumentation and/or diagnostic pharmaceutical drugs such as mydriatics, cycloplegics, and others might occasionally be factors.

Classifications of refractive error differ across authors,[35,36,37] organisations,[37] and types of refractive errors[38] but for the analyses herein, and using magnitudes, mild refractive errors (in terms of stigmatic powers, $F_1 = M = F_{ns}$) are < 2 D, moderate in the range from 2.25 to 5.75 D (or [2.25: 5.75 D]) and severe is a magnitude > 6 D (see Equation 1 for astigmatism and cylinder, F_c). Although there are other qualitative and quantitative methods[38] (not included here for brevity) to specify the magnitude of refractive error, Figure 1 and Figure 2 allow for a clinical and mainly qualitative assessment of such distributions or refractive errors. For example, Figure 1 and its distribution ellipsoids suggest that approximately 95% of the sample refractive errors (or NCSR) were mainly spherical ranging from about −4 D to 4 D for the right and left eyes in 2018 and −5 D to 4 D for the right and left eyes in 2019. Severe hyperopia or severe myopia were uncommon in these samples. Figure 2 indicates that most eyes (see the 95% distribution ellipsoids) had cylinders with magnitudes ≤ 1 D, irrespective of laterality (the right or left eyes) (OD or OS) or the sample year (2018 or 2019). Thus, most eyes had a mild astigmatism and larger cylinders were rare in these samples. Assuming that these samples are representative of the geographic region

concerned, this might also be true for the population itself. However, given the presence of outliers in some samples and departures from normality observed, one needs to exercise caution with the previous assumption, and studies with much larger samples remain necessary for future confirmation.

This study reports on the refractive powers, primarily of mild compound myopic astigmatism, measured without the administration of cycloplegic agents. Presbyopia was also commonly found but has not been included in this article that involves distance refractive errors as determined with NCSR.

Possible limitations

The design of this study was a cross-sectional retrospective study based on historical records extracted from the clinical archive of the Sekororo Hospital, Limpopo, South Africa for the patients who consulted at the Optometry Clinic over 2 years starting from 01 January 2018 to 31 December 2019, and this design could not establish the causality of the subjective refractive errors. As a result of the COVID-19 pandemic, records for 2020 were not included in this study because of disruptions in clinic visits and booking schedules. Although the study's sample sizes were relatively small, and cycloplegia was absent, which may have had an impact on the results, they were sufficient for the study's aims. It is worth observing that the small sample sizes may limit the generalisability of the findings. However, given the study's specific research aim and objectives, the results still provide valuable insights. Moving forward, it may be beneficial to consider including larger sample sizes and cycloplegia to further validate these findings. In future studies, the analysis could be augmented by including autorefraction and/or retinoscopy, in addition to the subjective method. For this study herein, methods such as retinoscopy were used before NCSR and this increases the potential reliability of the NCSR as determined for analysis. Random selection (extending beyond the limitations of a single clinical environment) would also be useful to form an improved understanding of the population distributions of URE in the geographic region concerned. Such approaches could lead to a more comprehensive understanding and knowledge about the general topic of refractive error and potentially also the probability of correctable and uncorrectable vision impairment (UVI) in relation to refractive error.

Possible strengths

All measurements of refractive state were obtained via a single optometrist with extensive clinical experience. Randomisation was used to select participants from the larger populations that utilised the optometric refractive services at the clinic concerned. The study provides results for refractive errors in African eyes, and this article amply illustrates multivariate methods that are important for the analysis of such data. These methods have not been used previously to any great extent, particularly involving samples that include African eyes and participants only. Thus, this article provides original and important information in this field of study.

Recommendations

The researchers suggest that future studies relating to refractive errors be conducted in other primary high-level public (or state-owned) hospitals such as regional, provincial, and national hospitals, and private optometric facilities for comparison of results. Where possible, samples should be increased in size and cycloplegia should be incorporated in the studies involving refractive state especially those involving children.

Conclusion

The results here can be applied to plan for improvements in clinical refractive services (namely, the provision of evidence-based optometric care, and allocation of adequate resources including the provision of corrective lenses to reduce spectacle backlog) across rural-based optometric clinics in South Africa and elsewhere.

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

K.D.M., N.H., and A.R. have contributed equally during the planning process and writing of this article, but K.D.M. was the principal investigator of this study.

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Data availability

The data that support the findings of this study are available on request from the corresponding author, K.D.M.

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