The effect of astigmatic axis on visual acuity measured with different alphabets in Roman alphabet readers

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Objective: Astigmatism produces meridional variations in the retinal blur pattern, thus interacting with object spatial detail and altering visual performance as the axis changes. This study investigates the influence of astigmatic axis orientation on visual acuity (VA) for four alphabets used worldwide.

Methods: Visual acuity was measured monocularly in 25 Roman alphabet users (mean age: 25.6 ± 7.5 years) using computer-presented logarithm of the minimum angle of resolution (log-MAR) charts with letters from four different alphabets (Arabic, Chinese, Roman, and Tamil). VA was assessed under the effect of four optical conditions: best distance correction and three astigmatic conditions (using a +2.00 cylindrical diopter trial case lens with its axis oriented at 180, 45, or 90 degrees). For each alphabet, single optotypes were presented on a monitor viewed from a distance of 4.0 m, and a matching technique was used to identify the letters.

Results: The degradation in VA with astigmatic defocus was influenced by the alphabet used (p<0.001) and by the astigmatic axis (p<0.001). Interactions in VA degradation between astigmatic axes and alphabet (p<0.001) showed differences within 0.10 logMAR. These interactions were more pronounced in alphabets with higher dominance of curves and vertical (Tamil) and horizontal (Arabic) detail.

Conclusion: Interactions between alphabet and type of astigmatism indicate that the effects of meridional blur on letter discrimination differ between alphabets. These findings have relevance in the way VA is assessed in populations using different typographies, and ultimately in the impact of astigmatic axis on their visual performance.

Keywords: visual acuity, astigmatism, meridional blur, optotypes, letter charts

Introduction
Refractive astigmatism (RA) is a common ocular refractive error in the population characterized by the cylinder modulus and its axis. Uncorrected RA of small magnitude diminishes the ability to discriminate small printing, reduces reading fluency which may affect the academic performance, and its detrimental effects increase with the modulus magnitude. In infants, high cylinders presented during the developmental period may cause meridional amblyopia. Regarding the effect of cylinder axis on visual performance, different axes produce blur patterns on retina which differ in orientation and its interaction with the object creates different distorted images. Visual acuity (VA) is more affected by oblique astigmatism and with-the-rule (WTR) astigmatism (horizontal negative corrective cylinder) tends to produce the least degradation. Contrary evidence on the dependence of axis in visual performance has been reported
in studies,16–20 which may reflect differences in sample size or methodology.17,18 The effects of astigmatic axis have been shown in reading performance,3,4,12,21 subjective tolerance to letter blur,22 and subjective quality of vision,23 using optically simulated astigmatism.

The prevalence of astigmatism has been associated with the ethnic origin of the population.24 Multiethnic studies have found differences in the prevalence of astigmatism among ethnic groups,25–28 and these differences also extend to the axis component. Huynh et al26,27 comparing East Asian, Middle Eastern, South Asian, and European Caucasian patients found a lower prevalence of WTR astigmatism in the European group compared to other ethnic groups. In Israel, Mandel et al29 reported more WTR astigmatism in a group of young Eastern, South Asian, and European Caucasian patients found differences in the prevalence of astigmatism among ethnic groups,25–28 and these differences also extend to the axis component. Huynh et al26,27 comparing East Asian, Middle Eastern, South Asian, and European Caucasian patients found a lower prevalence of WTR astigmatism in the European group compared to other ethnic groups. In Israel, Mandel et al29 reported more WTR astigmatism in a group of young Asian and African descendents than in Caucasians.

Different ethnic groups use specific alphabets. It is desirable that the optotypes used to measure the ability to discriminate letters (VA) resemble the observers’ common visual tasks30 and visual experience.31 Alphabets used across the world have different typography such as letter stroke frequency and complexity, which are relevant factors for letter discrimination.32–34 Therefore, using VA charts made with different alphabets may alter the way the optics of the eye (e.g., refractive error) interacts with the stimulus, hence influencing letter recognition.

To date, much of the research conducted to investigate the effect of meridional blur on visual performance has used the Roman alphabet; however, this is not representative of the typography used worldwide. This leads to the question of how visual performance measured with different alphabets for a fixed amount of astigmatism changes with astigmatic axis orientation. This study measured the effect of astigmatic blur orientation on distance VA using VA charts based on the Early Treatment of Diabetic Retinopathy Study protocol35 with letter optotype derived from four different alphabets, the Roman, Arabic, Chinese, and Tamil (Indian), in a group of Roman alphabet users. Tamil, although specific from a region, has similar features to other Indian alphabets (e.g., Hindi, Gujarati, and Punjabi). We hypothesize that VA degradation will depend on the alphabet used and axis of astigmatism.

### Methods

#### Participants

The study enrolled 25 participants aged (average ± standard deviation) 25.6±7.5 years (median age =23 years; range: 19 to 51 years). All participants were subjectively refracted (spherical equivalent = 0.88 ± 2.15 spherical diopter) and achieved a VA (retro-illuminated Snellen VA chart) better than 0.0 logarithm of the minimum angle of resolution (logMAR) in at least one eye. Only participants with refractive astigmatism ≤0.75 cylindrical diopter (DC), (RA = –0.05 ± 0.26 DC) were included. The participants performed the experiment monocularly with the fellow eye occluded using a black occluder. The eye under test was the one achieving the best distance VA or randomly chosen if the VA scores of both eyes were identical. An artificial pupil (3.0 mm) was placed in the rear cell of the trial frame to standardize the entrance of the pupil of the eye and level the extent of retinal blur pattern across participants. If present, the spherical component of the subjective correction was placed in the trial frame cell immediately in front of the artificial pupil, and the cylindrical lens was placed in the next frontward cell. Four different refractive conditions were tested, which were as follows: “in-focus” (i.e., best distance correction), “WTR astigmatism” (+2.00 DC × 180), “oblique astigmatism” (+2.00 DC × 45), and “against-the-rule (ATR) astigmatism” (+2.00 DC × 90). This study protocol was approved by the Ethics Committee of the University of Bradford and all participants gave their written informed consent.

#### Chart construction

The letters used for presentation were extracted from previously validated VA charts in four different languages; Arabic,36 Chinese37, Roman,38 and Indian (Tamil)39 (Figure 1). Each VA line was generated with the same combination of letters used in the original charts to maintain similar levels of legibility per line. Four different charts using logarithmic size progression were produced for each alphabet by changing the order the letters were presented in a line. The Roman letters were electronically available (http://psych.nyu.edu/pelli/software.html) in a Sloan font type format, whereas the Arabic, Chinese, and Tamil letters were cropped from the original publication and posteriorly fitted in a 5-by-5 framework using a font creation software (FontCreator v 6.1, High Logic B.V., Utrecht, the Netherlands). A 0.0 logMAR letter viewed at 4.0 m had a width/height equal to 5.8 mm.39

#### Visual acuity protocol

The letters were generated using Psychophysical Toolbox 3 (PTB-3) supported by Matlab™ (MatlabTM 2010, The MathWorks, Inc., Massachusetts, USA) and presented individually on an LCD monitor (Nec LCD 175VXM+, resolution: 1280×1024 pixels, pixel size: 0.264 mm) at the maximum contrast level (99%) with a surround background of 292×236 arcminutes and a luminance level of 150 cd·m⁻².40 Ten visual acuity levels, with five letters per level, ranging from 0.70 logMAR to –0.20 logMAR in 0.10 steps were defined for a 4.0 m viewing distance.
Letter identification consisted of a matching visual acuity type of task. The participant was asked to carefully match the letter presented on the monitor with one of the letters presented on a template (identified with numbers from 0 to 9) which included the 10 letters corresponding to the alphabet being presented. There was no time limit to perform the match, and the participant was forced to guess when they could not identify the match. The template was laid down on a plane angled perpendicular to the participants’ line of sight at ~0.50 m from the participant. The template’s background luminance was 130 cd·m⁻² and each letter on the template subtended 1.70 logMAR units. The participant had to orally dictate to the researcher the number on the template attributed to the chosen letter. All participants were Roman alphabet users and naive to the Arabic, Chinese, and Tamil alphabets. The researcher was blind to the association between the letter presented and the number dictated. The protocol started by presenting letters of 0.50 logMAR units, progressing to smaller letter sizes when three out of the five letters were correctly matched. If, at the initial VA level (0.50 logMAR), fewer than three letters were matched correctly, a larger letter size was presented. The termination criterion for each chart was more than four incorrect letters identified in a line. The VA score was calculated by subtracting from the last VA line presented, 0.02 logMAR for each letter presented but not identified correctly. To generate a balanced random presentation, a Latin square was designed using the type of alphabet and the refractive condition.

**Statistical analysis**

The effect of the fixed astigmatic defocus on VA was analyzed by the intra-individual change in VA from the in-focus condition for the three astigmatic axes; this difference was defined as VA degradation. The normality of the VA and VA degradation was verified using the Shapiro-Wilk test. Repeated measures analysis of variance (ANOVA) (one-factor: alphabet) was used to analyze differences in VA (logMAR) across the charts in the in-focus condition. The influence of the astigmatic axis on VA was analyzed using repeated measures ANOVA (two-factors: alphabet and astigmatic axis). Post hoc analysis using repeated measures ANOVA (one-factor) was applied to analyze the differences in VA degradation induced by the VA charts for each astigmatic condition and the differences in VA degradation induced by the astigmatic conditions within each VA chart. Statistical analysis was performed using SPSS (IBM SPSS 23).

**Results**

Table 1 presents the VA scores for the four alphabets in the four refractive conditions.

**In-focus visual acuity**

For the in-focus condition, VA varied depending on the alphabetic chart presented $F(3,72)=24.7, p<0.001$. Compared to the VA measured with the Roman chart, with which participants exhibited best VA, VA measured using the Arabic and Chinese charts was ~0.05 logMAR line poorer (difference [logMAR]: Arabic vs Roman $0.04$ [CI: $0.01, 0.08$], $p=0.040$; Chinese vs Roman $0.06$ [CI: $0.02, 0.10$], $p=0.050$). Among the four VA charts, VA measured with the Tamil chart was the poorest, with approximately one logMAR line difference compared to the Arabic and Chinese charts (difference [logMAR]: Arabic vs Tamil $0.16$ [CI: $0.12, 0.20$], $p<0.001$).
VA dependence upon axis of astigmatism
The VA degradation induced by the three astigmatic conditions for each alphabetic chart is shown in Figure 2. Two-factors repeated-measures ANOVA showed differences in the magnitude of VA degradation induced by the three astigmatic conditions on each alphabetic chart (main factor: alphabet) $F(3,72)=12.1, p<0.001$. Across all three axes of astigmatism, the average VA degradation obtained with the Roman chart was the lowest (VA degradation [logMAR]; Roman $-0.23$ [CI: $-0.28$, $-0.17$]) compared to other three VA charts (Arabic vs Roman, $p<0.001$; Chinese vs Roman, $p<0.001$; and Tamil vs Roman, $p=0.006$). The Arabic, Chinese, and Tamil charts showed similar levels of VA degradation (VA degradation [logMAR]; Arabic $-0.36$ [CI: $-0.42$, $-0.31$], Chinese $-0.35$ [CI: $-0.40$, $-0.29$], Tamil $-0.36$ [CI: $-0.42$, $-0.31$], all pairwise comparisons $p>0.05$). Post hoc repeated-measures ANOVA one-factor (astigmatic axis) applied for each alphabet showed statistically significant influence of the astigmatic axis on the four charts (Table 3). In general, the magnitude of the VA degradation between different astigmatic axes are also reflected in the percentage of participants presenting clinical significant differences in VA defined as differences equal to or higher than ±0.1 logMAR between orientations (Table 2).43

The alphabet and astigmatic axis showed significant interactions ($F(6,144)=4.1, p<0.001$), suggesting that the VA degradation between different astigmatic axes differed among the four charts (Table 3). In general, the magnitude of the interactions calculated as the difference in VA degradation between two astigmatic axes for two alphabetic charts was smaller than one logMAR line. The strongest interactions (0.1 logMAR) show that VA measured with Arabic and Chinese charts is more affected by a rotation in astigmatic axis from WTR to oblique astigmatism than the Roman chart. Similarly, the Chinese chart was more sensitive to whether the axis was WTR or ATR compared to the Roman chart. Between the Arabic and Tamil charts, altering the axis orientation from ATR to oblique induced a higher change in VA for the Arabic alphabet.

Table 1 Visual acuity scores for the different alphabet charts and refractive conditions

<table>
<thead>
<tr>
<th>Alphabet</th>
<th>In-focus</th>
<th>WTR-astigmatism (2 DC)</th>
<th>Oblique astigmatism (2 DC)</th>
<th>ATR-astigmatism (2 DC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arabic</td>
<td>$-0.04 \pm 0.07$ [CI: $-0.07$, $0.01$]</td>
<td>$+0.24 \pm 0.13$ [CI: $0.19$, $0.30$]</td>
<td>$+0.44 \pm 0.10$ [CI: $0.40$, $0.48$]</td>
<td>$+0.30 \pm 0.11$ [CI: $0.25$, $0.34$]</td>
</tr>
<tr>
<td>Chinese</td>
<td>$-0.02 \pm 0.09$ [CI: $-0.06$, $0.01$]</td>
<td>$+0.22 \pm 0.11$ [CI: $0.17$, $0.26$]</td>
<td>$+0.41 \pm 0.12$ [CI: $0.36$, $0.46$]</td>
<td>$+0.34 \pm 0.09$ [CI: $0.30$, $0.38$]</td>
</tr>
<tr>
<td>Roman</td>
<td>$-0.08 \pm 0.07$ [CI: $-0.11$, $-0.05$]</td>
<td>$+0.11 \pm 0.12$ [CI: $0.06$, $0.16$]</td>
<td>$+0.20 \pm 0.10$ [CI: $0.16$, $0.25$]</td>
<td>$+0.13 \pm 0.09$ [CI: $0.09$, $0.16$]</td>
</tr>
<tr>
<td>Tamil</td>
<td>$+0.10 \pm 0.13$ [CI: $0.05$, $0.15$]</td>
<td>$+0.36 \pm 0.15$ [CI: $0.30$, $0.42$]</td>
<td>$+0.46 \pm 0.11$ [CI: $0.43$, $0.53$]</td>
<td>$+0.44 \pm 0.14$ [CI: $0.39$, $0.50$]</td>
</tr>
</tbody>
</table>

Notes: Values represent mean visual acuity score, standard deviation, and the 95% confidence intervals for the mean.
Abbreviations: ATR, against-the-rule; DC, cylindrical diopeter; logMAR, logarithm of the minimum angle of resolution; WTR, with-the-rule.
**Figure 2** VA degradation induced by the astigmatic conditions for each alphabet. The VA degradation values represent the average of the intra-individual reductions in VA relative to the best-corrected VA. The gray box indicates the 95% confidence interval limits for the mean, the light gray line represents the mean, and the bars indicate the standard deviation.

**Abbreviations:** ATR, against-the-rule; logMAR, logarithm of the minimum angle of resolution; VA, visual acuity; WTR, with-the-rule.

**Figure 3** VA degradation induced by the astigmatic conditions for each astigmatic condition. The gray box indicates the 95% confidence interval limits for the mean, the light gray line represents the mean, and the bars indicate the standard deviation. Pairwise comparisons between Arabic, Chinese, and Tamil alphabets (all \( p > 0.200 \)) are omitted for the sake of clarity.

**Abbreviations:** logMAR, logarithm of the minimum angle of resolution; VA, visual acuity.
Participants exhibiting a VA difference of $\pm 0.10$ logMAR or less achieve the abilities of an experienced observer. Familiarity with unfamiliar alphabets requires training to recognize the letters. The first is lack of familiarity with the Arabic, Chinese, and Tamil alphabets, since letter recognition of unfamiliar alphabets requires training to achieve the abilities of an experienced observer. Familiarity might explain the difference in VA between Roman, Arabic, and Chinese charts, since these alphabets have similar letter stroke frequency and complexity (Table 4). The Chinese chart is similar to a Roman chart when tested in a population familiarized with both alphabets. For the Tamil chart, the lack of familiarity might have had a stronger effect due to higher complexity of Tamil letters. The second and third factors are letter stroke width and letter complexity, both contributing for Tamil letters with a $\sim 15{\%}$ thinner stroke (corresponding to $-0.07$ logMAR). The thinner letter stroke width matches the difference in VA reported for the Tamil and Gujarati chart compared to the Roman chart for a population familiarized with both alphabets. Therefore, the present in-focus VA results indicate that lack of familiarity with optotypes decreases VA on average between 0.05 and 0.1 logMAR.

**Discussion**

The present study evaluated the effect of meridional blur variation, produced through optically simulated simple myopic astigmatism, on distance VA assessed with charts built with letters from different alphabets, in a population of Roman alphabet users (Figure 4). The main findings are that in-focus VA and VA degradation depended on the type of alphabet used, astigmatic axis influenced the amount of degradation, and differences in VA degradation between astigmatic axes differed between charts, indicating that the effects of meridional blur depend on typography.

**In-focus visual acuity**

The VA attained with Roman letters was the highest and within the values expected for fully corrected young adults. The differences in VA between the Roman chart and the remaining three charts can potentially be explained by a combination of factors. The first is lack of familiarity with the Arabic, Chinese, and Tamil alphabets, since letter recognition of unfamiliar alphabets requires training to achieve the abilities of an experienced observer. Familiarity might explain the difference in VA between Roman, Arabic,
Accounting for the lowest degradation is the use of a 3.0 mm pupil limiting the extent of blur on the retina. Also, the matching technique used might have facilitated letter recognition by allowing observers to carefully match the letter presented from a fixed set of 10 letters, instead of mentally choosing a letter from the full alphabet. These intra-chart differences are further evidenced by interactions between astigmatic axis and alphabet, revealing that the combination of typography and astigmatic axis influence VA degradation. For the Roman alphabet, the effects of astigmatic axis on VA were found to agree with previous studies that used simple myopic astigmatism. Wildsoet et al found an average of 0.20 logMAR difference in VA between 2.00 DC of WTR and ATR against oblique astigmatism, for Bailey-Lovie chart and other pictorial charts. The data in Kamiya et al’s study showed a consistent lower effect of WTR astigmatism on VA compared to ATR. Miller et al reported that oblique and ATR astigmatism induce higher dissatisfaction compared to WTR astigmatism. Using an adaptive optics system, Guo and Atchison found 18% higher tolerance to blur created by WTR astigmatism compared to oblique astigmatism, and Vinas et al found a lower effect of WTR astigmatism on VA compared to oblique and ATR astigmatism. The effect of axis orientation extends to

Table 4 Letter stroke frequency and letter complexity for the individual four alphabets used

<table>
<thead>
<tr>
<th>Alphabet</th>
<th>Arabic</th>
<th>Chinese</th>
<th>Roman</th>
<th>Tamil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>1.6; [1; 2]</td>
<td>1.8; [0; 3]</td>
<td>1.5; [1; 2]</td>
<td>2.7; [1; 4]</td>
</tr>
<tr>
<td>Horizontal</td>
<td>2.0; [1; 3]</td>
<td>2.0; [0; 3]</td>
<td>1.7; [1; 3]</td>
<td>1.9; [1; 4]</td>
</tr>
</tbody>
</table>

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</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>62.9±5.4</td>
<td>67.1±11.8</td>
<td>69.5±14.4</td>
<td>113.4±17.6</td>
</tr>
</tbody>
</table>

Notes: Vertical and horizontal letter stroke frequencies were determined by the number of times a horizontal or a vertical crossed a letter stroke. The letter width/height was constant for the four alphabets. Letter complexity was calculated by measuring the perimeter of the letter outline (pixels) divided by the area occupied by the letter (pixels).

Dependence of VA upon astigmatic axis

The degradation in VA depended on the type of simulated astigmatism; WTR astigmatism being the least degrading axis and oblique the most. The effect of ATR astigmatism varied between charts; for the Arabic and Roman charts the degradation was closer to that induced by WTR astigmatism, whereas for the Tamil chart its effect was similar to oblique astigmatism. The effects of ATR astigmatism on the Chinese chart differed from those of WTR and oblique astigmatism. These intra-chart differences are further evidenced by interactions between astigmatic axis and alphabet, revealing that the combination of typography and astigmatic axis influence VA degradation. For the Roman alphabet, the effects of astigmatic axis on VA were found to agree with previous studies that used simple myopic astigmatism. Wildsoet et al found an average of 0.20 logMAR difference in VA between 2.00 DC of WTR and ATR against oblique astigmatism, for Bailey-Lovie chart and other pictorial charts. The data in Kamiya et al’s study showed a consistent lower effect of WTR astigmatism on VA compared to ATR. Miller et al reported that oblique and ATR astigmatism induce higher dissatisfaction compared to WTR astigmatism. Using an adaptive optics system, Guo and Atchison found 18% higher tolerance to blur created by WTR astigmatism compared to oblique astigmatism, and Vinas et al found a lower effect of WTR astigmatism on VA compared to oblique and ATR astigmatism.
reading tasks with oblique and ATR astigmatism producing worse reading performance compared to WTR.\textsuperscript{3,5–21} For Roman letters, differences in visual performance have been associated with the low dominance of oblique detail in letters and with the vertical stroke dominance in lower-caps letters which favors the interaction with vertical blur patterns as happens in WTR.\textsuperscript{9,22}

Among the three unfamiliar alphabets, the pattern of VA degradation with astigmatic axis resembles that observed with the Roman alphabet, mainly due to the low prevalence of oblique detail. However, the different spatial features of the letters among alphabets create differences in this pattern of VA degradation. When using the Tamil chart, nearly 15% of the participants performed better with oblique astigmatism compared to ATR astigmatism (Table 2), contrasting with the absence of participants performing better with oblique astigmatism against ATR in the Arabic alphabet. The explanation might lie in the presence of oblique detail and dominance of horizontal detail in the Arabic letters, contrasted to the vertical stroke dominance and curvy layout of the Tamil letters. This favored the interaction with oblique blur patterns in the Tamil letters and with horizontal blur patterns for the Arabic letters. In general, when compared with WTR and ATR astigmatism, oblique astigmatism was better tolerated with the Tamil alphabet than with Arabic or Chinese. Interactions between letter typography and meridional blur orientation were suggested by Kobashi et al to explain the lack of significance in reading performance between WTR and ATR using the Japanese reading chart.\textsuperscript{12} Although the magnitude of the interactions found in the present study are generally lower than one logMAR line within the clinical variability expected in VA assessment, the influence of astigmatic axis on VA is dependent on the nature of the object and should be taken into consideration.

Limitations
This study exhibits a number of limitations. One is the fact that our participants were familiar with one of the alphabets (Roman) but not with the others, which might have unbalanced the ability to recognize letters from the different alphabets. Based on the present findings, further work including common users of different alphabets could confirm the present results using VA charts and using more realistic tasks (e.g., reading). Another limitation regards the single-letter presentation method,\textsuperscript{18,22} which did not account for the effects of adjacent blur as would happen in a line of letters.\textsuperscript{22} Also related to the letter presentation method, the application of a methodological approach based on numerically simulated defocus\textsuperscript{59} could have facilitated the investigation of additional astigmatic conditions and increasing the number of repetitions per condition to improve the reliability of the study. The authors opted for using an optical simulated method since it is a more common experimental approach (given in detail in studies of Wolffsohn et al, Kamiya et al, and Remon et al\textsuperscript{1,13,17}), resembles more the ocular defocus effect, and previous work has shown differences between numerical and simulated defocus.\textsuperscript{18} A third limitation was the use of optically simulated blur which differs from uncorrected refractive astigmatism, due to magnification effects produced by the defocusing lens and the lack of long-standing neuronal adaptation to the astigmatic error.\textsuperscript{54} The sample included in the study did not present significant RA, minimizing the effects of any meridional long-term blur adaptation,\textsuperscript{53,55} and the effects of blur adaptation on the optical conditions were balanced throughout the sample by randomization.

Conclusion
The present results demonstrate that astigmatic axis influences letter discrimination which may vary depending on the alphabet in use. Considering the ethnic variations in prevalence of type of astigmatism reported, the assessment of visual performance using letters as optotypes should take into consideration the commonly used typography/calligraphy to weigh the effect of astigmatism on the day-to-day visual function of the patient. The new electronic VA assessment devices\textsuperscript{56} are versatile tools which can have incorporated optotypes adapted to different ethical backgrounds.

Acknowledgment
The authors would like to thank Dr Brendan Barrett for helpful discussions during the manuscript preparation.

Disclosure
CMC is employed by Topcon Eye Care Company as Senior Manager for Global Education and Clinical Affairs. The authors report no other conflicts of interest in this work.

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