Achieving Emmetropia in Extremely Short Eyes with Two Piggyback Posterior Chamber Intraocular Lenses

Jack T. Holladay, MD, James P. Gillis, MD, Jane Leidlein, MD, Myra Cherchio, COT

Purpose: To examine the refractive results and limitations of current intraocular lens power formulas when implanting two posterior chamber lenses in-the-bag to achieve emmetropia in extremely short eyes.

Methods: Preoperative measurements (corneal diameter, axial length, keratometry, anterior chamber depth, and lens thickness) and postoperative measurements (refraction, corneal vertex to iris depth, and iris to front anterior lens surface) were taken in six eyes from three patients, with axial lengths ranging from 15.09 to 19.95 mm. These data were used to calculate the prediction error for three current third-generation formulas (Holladay, Hoffer Q, SRK/T) and two older formulas (SRK2 and SRK1).

Results: None of the formulas accurately predicted the refractions using the optimized lens constants for normal eyes. The third-generation formulas were not different (P ≥ 0.602) and averaged 5 diopters (D) of absolute error (Hoffer Q = 4.64 ± 1.57 D; Holladay = 5.07 ± 1.28 D; SRK/T = 5.12 ± 1.43 D). The older formulas were significantly worse (P = 0.0006), with average mean absolute errors of 10.83 ± 5.09 D for the SRK2 and 13.33 ± 5.09 D for the SRK1. When the formulas were optimized for these six eyes, the mean absolute errors were Holladay = 1.33 ± 1.25 D; SRK/T = 2.10 ± 1.31 D; Hoffer Q = 4.54 ± 2.00 D; SRK2 = 4.71 ± 1.94 D; and SRK1 = 4.71 ± 1.94 D. The Holladay and SRK/T formulas were statistically better (P = 0.0088) than the Hoffer Q and the two older formulas.

Conclusion: Current third-generation formulas are better than older formulas for extremely short eyes, but still are not acceptable for the desired clinical accuracy. Newer formulas that will use additional anterior segment measurements (corneal diameter, anterior chamber depth) and lens thickness will be required for improved accuracy, because the anterior segment often is not proportional to the axial length.

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Achieving emmetropia in extremely short eyes (<20 mm) after cataract removal is a difficult challenge clinically for several reasons. First, ultrasound axiometers are calibrated with average velocities for normal-length eyes (23.5 mm) that are incorrect for short eyes causing significant measurement errors. Second, any measurement error in the axial length of a short eye will have a much greater effect on the final refraction, because a given measurement error is a much larger percentage of the axial length in a short eye. Third, the current third-generation intraocular lens calculation formulas are not consistently accurate in
short eyes.13-27 And fourth, lenses above 34 dipters (D) are not readily available, must be custom manufactured, and require Food and Drug Administration approval with long-term monitoring.

We have analyzed the refractive results after cataract surgery of six eyes from three patients whose axial lengths ranged from 15.09 to 19.95 mm. Each of these patients had final refractions ranging from -0.12 to -3.37 D using two posterior chamber lenses in-the-bag to achieve the necessary dioptic intraocular lens power. In this study, we discuss the optical consequences of "piggyback" lenses and the limitations of our current intraocular lens power formulas.

Materials and Methods

Preoperatively, the axial length, keratometry readings, horizontal and vertical white-to-white corneal diameters, anterior chamber depth, and crystalline lens thickness were obtained for each eye. Postoperatively, the power of the two implants, the stabilized refraction (4-6 weeks postoperatively), the distance from the corneal vertex to the iris and the distance from the iris to the anterior vertex of the front intraocular lens were recorded. These values are shown in Table 1.

All six pairs of lenses were in-the-bag with the haptics parallel to each other. The intraocular lenses were biconvex with 1:1 front-to-back surface powers (equiconvex) with personalized lens constants (for JPG) of A-constant = 119.0, anterior chamber depth = 5.37 mm and a Surgeon Factor of 1.81 mm. The personalized lens constants had been determined previously on 100 consecutive patients using the same surgery and intraocular lens. The data from each of the eyes were used to calculate the predicted refraction using the three current third-generation intraocular lens calculation formulas: Holladay,17 SRK/T,22 and the Hoffer Q,23 and two earlier formulas the SRK28 and the SRK1.29 The prediction error then was calculated as the difference between the predicted refraction from the formula and the actual postoperative refraction. The results are shown in Table 2. Each of the formula constants then were optimized for the six eyes to achieve zero average error, and the optimized values are shown in Table 3.

Results

In Table 2, we see the prediction error and the absolute prediction error for each of the five intraocular lens formulas tested along with the average and standard deviation. The two best measures of a formula are the standard deviation of the prediction error and the average absolute prediction error, because prediction errors of opposite signs will not cancel out. The standard deviation weighs larger errors more heavily because it squares the error before averaging, whereas the average absolute error weighs all errors equally. Statistically, these are both valid measures, but the standard deviation may be more mean Mayweather et al.
Table 2. Prediction Errors (diopters) for the Five Formulas Using the Personalized Lens Constant for Normal Eyes

<table>
<thead>
<tr>
<th>Case No./Eye</th>
<th>Holladay (absolute)</th>
<th>Holladay (absolute)</th>
<th>SRK/T (absolute)</th>
<th>HOFFER Q (absolute)</th>
<th>SRK2 (absolute)</th>
<th>SRK2 (absolute)</th>
<th>SRK1 (absolute)</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/OD</td>
<td>-5.56</td>
<td>5.56</td>
<td>-6.28</td>
<td>-4.78</td>
<td>4.78</td>
<td>-7.19</td>
<td>7.19</td>
<td>-9.59</td>
</tr>
<tr>
<td>2/OD</td>
<td>-6.06</td>
<td>6.06</td>
<td>-6.81</td>
<td>-4.76</td>
<td>4.76</td>
<td>-8.83</td>
<td>8.83</td>
<td>-11.23</td>
</tr>
<tr>
<td>2/OS</td>
<td>-4.01</td>
<td>4.01</td>
<td>-4.68</td>
<td>-2.78</td>
<td>2.78</td>
<td>-7.23</td>
<td>7.23</td>
<td>-9.63</td>
</tr>
</tbody>
</table>

Mean ± SD = -5.07 ± 1.28, 5.07 ± 1.28, -5.12 ± 1.43, 5.12 ± 1.43, -0.59 ± 4.86, 4.64 ± 1.57, -10.93 ± 5.09, 10.93 ± 5.09, -13.33 ± 5.09, 13.33 ± 5.09

D = diopters; OD = right eye; OS = left eye; SD = standard deviation.

Table 3. Prediction Errors (diopters) for the Five Formulas Using the Optimized Lens Constant for Six Eyes

<table>
<thead>
<tr>
<th>Case No./Eye</th>
<th>Holladay (absolute)</th>
<th>Holladay (absolute)</th>
<th>SRK/T (absolute)</th>
<th>HOFFER Q (absolute)</th>
<th>HOFFER Q (absolute)</th>
<th>SRK2 (absolute)</th>
<th>SRK2 (absolute)</th>
<th>SRK1 (absolute)</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/OD</td>
<td>-1.77</td>
<td>1.77</td>
<td>-2.35</td>
<td>2.35</td>
<td>4.28</td>
<td>3.74</td>
<td>3.74</td>
<td>3.74</td>
<td></td>
</tr>
<tr>
<td>1/OS</td>
<td>-0.48</td>
<td>0.48</td>
<td>-1.08</td>
<td>1.08</td>
<td>-2.89</td>
<td>2.89</td>
<td>4.58</td>
<td>4.58</td>
<td></td>
</tr>
<tr>
<td>2/OD</td>
<td>-1.63</td>
<td>1.63</td>
<td>-2.23</td>
<td>2.23</td>
<td>-4.19</td>
<td>4.19</td>
<td>2.10</td>
<td>2.10</td>
<td></td>
</tr>
<tr>
<td>2/OS</td>
<td>-0.09</td>
<td>0.09</td>
<td>-0.62</td>
<td>0.62</td>
<td>-2.27</td>
<td>2.27</td>
<td>3.70</td>
<td>3.70</td>
<td></td>
</tr>
<tr>
<td>3/OD</td>
<td>3.71</td>
<td>3.71</td>
<td>4.69</td>
<td>4.69</td>
<td>8.48</td>
<td>8.48</td>
<td>-5.91</td>
<td>-5.91</td>
<td></td>
</tr>
<tr>
<td>3/OS</td>
<td>0.27</td>
<td>0.27</td>
<td>1.60</td>
<td>1.60</td>
<td>5.15</td>
<td>5.15</td>
<td>-8.21</td>
<td>-8.21</td>
<td></td>
</tr>
</tbody>
</table>

Mean ± SD = 0.00 ± 1.82, 1.33 ± 1.25, 0.00 ± 2.47, 2.10 ± 1.31, 0.00 ± 4.96, 4.54 ± 2.00, 0.00 ± 5.09, 4.71 ± 1.94, 0.00 ± 5.09, 4.71 ± 1.94

D = diopters; OD = right eye; OS = left eye; SD = standard deviation.
ingful clinically, because the larger prediction errors are much more problematic and deserve a greater weight than the smaller errors. All $P$ values for our statistical analysis were determined using the Duncan multiple-range test. 29

The standard deviation for the three third-generation formulas ranged from a low of 1.28 D for the Holladay formula to 1.43 D for the Hoffer Q formula. The standard deviation of the SRK I and SRK2 regression formulas were 5.09 D, more than three times greater. The mean absolute prediction errors were also not significantly different for the third-generation formulas ($P \geq 0.60$), with the Hoffer Q having the smallest of 4.64 D and the SRK/T the largest of 5.12 D. The SRK2 and SRK1 had mean absolute prediction errors that were significantly worse ($P = 0.0006$) at 10.93 and 13.33 D, respectively. Although the third-generation formulas were two to three times better, they are still clinically unacceptable with errors from the desired refraction, averaging 5 D.

Optimizing each of the five formulas for these six eyes is accomplished by determining the constant that forces the mean prediction error to zero. In Table 3, we see that the mean prediction error for each of the five formulas is zero, with the corresponding standard deviations and mean absolute prediction errors. The standard deviations, using the optimized constant for the five formulas, ranged from a low of 1.82 D for the Holladay formula to a high of 5.09 D for the SRK2 and SRK1. The mean absolute prediction error was 1.33 D for the Holladay, 2.10 D for the SRK/T, 4.54 D for the Hoffer Q, and 4.71 D for the SRK2 and SRK1. The mean absolute errors for the Holladay and SRK/T were not different ($P = 0.363$), but were better than the Hoffer Q, SRK2, and SRK1 ($P \leq 0.0068$).

Although these values are superior to the nonoptimized values in Table 2, they are still unacceptable clinically, with the smallest average formula error of 1.33 D for the Holladay formula and the largest formula error for a single eye ranging from 3.71 D for the Holladay to 8.48 D for the Hoffer Q in the right eye of case 3.

Discussion

Implanting two posterior chamber lenses to achieve emmetropia in nanophthalmic eyes was first performed by Gayton, 30 in 1993. He used the SRK/T for his intraocular lens calculation, which required a 46-D lens. Based on these calculations, a 25-D lens was placed posteriorly and a 20-D lens was placed anteriorly in the capsular bag, for a total of 45 D. Similar to our results, he had an 8-D hyperopic surprise requiring replacement of the anterior lens with a 30-D lens, which still left the patient with a +2.25 spheroequivalent refraction.

As with many new developments, necessity was the mother of invention. Because Gayton was unable to get any of the lens manufacturers to make a 46-D lens, his only choice was to implant two lenses. Although Gayton was unaware at the time, using two lenses to achieve these high dioptic powers is superior optically to a single lens of the same total power if the two lenses are optically aligned (optical centers aligned). 31 The reason for the superior optical quality of the piggyback lenses is due to less spherical aberration than a single lens at these high dioptic powers. This factor is one of the reasons manufacturers chose 34 D as the upper limit of their available lens powers. Lenses that are significantly stronger required such steep radii that the lens begins to look more like a sphere than a lens. For a 3-mm pupil, the manufacturers could not pass the current resolution requirements for lenses above 44 D. 32 Clinically, it is similar to looking through a sphere where the image quality is severely distorted, such as a fish-eye lens or glass sphere.

Our results, as with those of Gayton, were achieved empirically by the surgeon (JPG). Similarly, the initial case required lens exchange because of a significant hyperopic surprise. In analyzing these three patients, we see that cases 1 and 2 have normal anterior segment dimensions for the corneal diameters, keratometry, and anterior segment length (anterior chamber depth + lens thickness). The only apparent abnormality is the foreshortened axial length, which is totally due to the shortened posterior segment. In contrast, case 3 truly has nanophthalmic eyes with corneal diameters, K-readings, and anterior chamber depth that indicate a very small anterior segment, as well as a very short posterior segment, which is almost proportional to the front. Only case 3 has symmetrically “small” eyes and cases 1 and 2 have asymmetrically “small” eyes, with normal anterior segments and short posterior segments.

Since all of the third-generation formulas shorten the expected anterior chamber depth to the lens as a function of the axial length, they would all predict the position of the lens to be too far anterior, which results in a hyperopic error. The Holladay and SRK/T formulas made a hyperopic error in all six of the eyes, ranging from 2.37 to 7.11 D. The Hoffer Q formula attenuates the scaling of the predicted anterior chamber depth by approximately one half of the Holladay and SRK/T formulas. Therefore, the Hoffer Q formula made slightly smaller hyperopic errors on cases 1 and 2, but actually made significant myopic errors on case 3 by predicting a much larger anterior chamber depth in this nanophthalmic eye.

Another factor that caused the hyperopic errors is the actual position of the piggyback lenses in-the-bag. Before measuring the distance from the iris to the anterior intraocular lens vertex, it was expected that the anterior intraocular lens would be more anterior in the posterior chamber than a single lens. Our measurements demonstrated that the anterior lens was in the normal position and the posterior lens was one lens thickness deeper than normal. In retrospect, we should have predicted this because the elasticity of the posterior capsular bag easily can accommodate another lens that is only approximately 1-mm thick. The lens thickness before cataract extraction averaged 4.8 mm in the cataract age group. 31-33 In fact, we now have one patient (JPG) who has four standard intraocular lenses in the capsular bag.

If we are to achieve results that are comparable to normal eyes in these extremely short eyes, we first must determine the size of the anterior segment using the horizontal white-to-white corneal diameter, anterior chamber
Table 4. Clinical Conditions Demonstrating Independence of Anterior Segment Size and Axial Length

<table>
<thead>
<tr>
<th>Anterior Segment Size</th>
<th>Axial Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
</tr>
<tr>
<td>Small</td>
<td>Small eye nanophthalmia</td>
</tr>
<tr>
<td>Normal</td>
<td>Axial hyperopia</td>
</tr>
<tr>
<td>Large</td>
<td>Megalocornea + axial hyperopia</td>
</tr>
</tbody>
</table>

depth, and lens thickness as well as the K-readings and axial length, i.e., determine whether the eye is nanophthalmic (symmetrically small anterior and posterior segment) or simply a short posterior segment with a normal anterior segment. This is analogous to measuring the height of two very short people—one pituitary dwarf (symmetric dwarf=++) and one achondroplastic dwarf (asymmetric dwarf=+).36 The pituitary dwarf is comparable to nanophthalmia, where the all of the body parts are proportionately small (short crown-to-rump and short limbs). In the achondroplastic dwarf, however, the trunk and head are normal, only the limbs are short (normal crown-to-rump with short limbs). The independence of the anterior segment size and the axial length can be seen by the clinical conditions shown in Table 4.

With these additional measurements of the anterior segment (horizontal white-to-white, anterior chamber depth, and lens thickness), newer intraocular lens formulas can use these dimensions to distinguish between the different types of short eyes, making a better prediction of the actual position of the intraocular lens within the anterior segment of the eye and resulting in much smaller prediction errors. Distinguishing between these types of short eyes is also important surgically, because intraocular procedures in the nanophthalmic eye with the small anterior segment frequently are complicated by choroidal effusion, nonhegmatogenous retinal detachment, and angle-closure glaucoma.37,38

References


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FIG. 62.—ATROPHY OF THE EYEBALL. IN PART AFTER WEED-BACK.

The eye is smaller and of irregular shape, chiefly from the folding of the sclera behind the points of attachment of the ocular muscles, the rectus internus, pt, and the rectus externus, pr. The cornea, c, is diminished in size, flattened, and folded especially on its posterior surface. At its inner border is bears the depressed cornea, k. which was produced by the injury. The anterior chamber is shallower; the iris, i, is thinned and forms an uneven surface, because the pupil is closed by exudate. Behind the iris lies the choroid, ch, and behind this is the great shell of ciliary membrane, r, the shrinking of which is the adventuring iris, the ciliary process, p, the pigment-layer of which has not increased. The ciliary process, p, is drawn in toward the center, and together with the adjacent choroid, ch, are detached from the sclera, s. Between the two structures are seen the divided laminae of the superciliary membrane, a. The retina, r, is detached from the cornea, c, and folded in the form of a funnel, which includes the remains of the degenerated vitreous. The subretinal space, s, is filled with a fluid rich in albumin. The optic nerve, o, is thinner than usual and atrophic.

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