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On-Eye Power Characteristics of Soft Contact Lenses

The recent article by Plainis and Charman[1] was a commendable study looking at the age-old problem that was first encountered almost 2 decades ago. Why does the power of a soft lens change when placed on the eye? Why does the positive soft lens tend to supply less plus power than originally anticipated? In the introductory part of their article, the authors present a review of soft lens bending models. In Table 1, there is one main error: the beam-bending model should be credited to Bibby,[2] not to Janoff and Dabezies.[3] The authors reviewed several models, each of which has its own intrinsic limitations and conditions. They mentioned the constant arc length model attributed to Wallace-Williams and Magabilen and the constant volume model credited to Bennett. The authors did not mention a particular model that combined the attributes of both the constant volume and the constant arc length models.[4] Without performing any further calculations at this stage, if the authors had reviewed that model they might have found that the results of computations described therein fit very nicely with the experimental data they encountered, especially for the plus lenses. The authors do say that Bennett's constant volume model and the constant arc length model make predictions that closely follow the clinical data, but it must not be forgotten that these two models have fundamental flaws. Bennett's model was not an exact constant volume model at all, and this point was stressed elsewhere.[4] Plainis and Charman did not report on any simple rule that could help the clinician calculate the typical change in power of the lens after it is flexed when placed on the eye, but they did report in their Figure 9 that change in back optic zone radius and change in front optic zone radius are functions of *in vitro* lens power. Using a contact lens wet cell and immersing the lenses in a high refractive index liquid medium (cinnamaldehyde of refractive index of 1.62),[5] it was found that the change in lens back vertex power caused by flexure was a function of (1) the initial back vertex power; (2) the initial back optic zone radius; and (3) the actual change in back optic zone radius. This relationship held for both positive and negative lenses except for differences in relevant indices. It would be interesting to see if the results reported by Plainis and Charman either supported or refuted the relationship discovered in the *in vitro* study.

The problem of contact lens flexure is not just confined to the soft lens. When RGP lenses are either sufficiently thin or made of a material in which the modulus of elasticity renders the lens "flexible," it is not surprising that the prescribed lens does not quite supply the eye with the intended power. In a controlled environment in which an RGP lens is flexed by applying specific weights to the edge of the lens, thus reducing its overall diameter along the direction of the applied force, the change in lens power is a function of original lens power, applied force, and material.[6] Perhaps pressure from the eyelids also contributes to soft lens flexure *in vivo*. The problem is, how can we incorporate eyelid pressure as well as the other factors listed by Plainis and Charman with the intention of producing a more comprehensive model for *in vivo* lens flexure?

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Authors' Response

We are grateful to Dr. Patel[1] for his helpful comments on our paper.[2] We agree that Bibby's priority[3] in formulating the beam-bending model deserves to be fully recognized. Our text did make this clear, and we regret if our Table 1 gives a different impression.

We were aware of Dr. Patel's own interesting theoretical model[4] but did not discuss it because it is only stated in terms of effects for positive lenses and we were unsure how to relate its results to our own measurements, which were made on both positive and negative lenses. The basic model involves three assumptions about the lens changes on bending: that the arc of the back surface remains constant; that the volume remains constant; and that a plus spherical lens is monocurved and has zero edge thickness. Implicit also is the assumption that both front and back surfaces of the lens remain spherical throughout any bending. The model is then extended to toric lenses and positive spherical lenses, in which bending occurs only in one meridian but arcs of the lens across a diameter remain circular. Unlike some other models, Patel's model suggests that the center thickness of the lens will change on bending. Presumably, the restriction to knife-edge positive lenses is necessary because of uncertainty regarding what happens to the edge geometry when a negative lens or a positive lens of finite thickness flexes.

The form of Patel's equations makes it difficult to make simple, generalized predictions of the effects of lens bending, and the knife-edge positive lens geometry used is not very realistic. It is possible, however, to simplify the model to give an approximate idea of its predictions. We use our own notation that the initial front and back surface radii r_1 and r_2 become r_1' and r_2' after bending, and Patel's terminology that the lens diameters before and after bending are 2x and 2x', respectively. Following Patel, the volume of the spherical cap of radius R, diameter 2x, is $\pi(RS^2 - S^3/3)$, where S is the sag. It is evident that for small sags where $S \ll R$, the volume approximates to πRS^2. Furthermore, for such small sags $S \approx x^2/2R$. Thus, for positive lenses with the geometry considered by Patel the condition that the lens volume remains equal before and after bending becomes:

$$\pi r_1(x^2/2r_1)^2 - \pi r_2(x^2/2r_2) = \pi r_1'(x'^2/2r_1')^2 - \pi r_2'(x'^2/2r_2')^2$$

Simplifying, this becomes:

$$x^4(1/r_1 - 1/r_2) = x'^4(1/r_1' - 1/r_2') \quad (1)$$

We can now use Patel's equation 2, i.e.,

$$x' = r_2' \sin[(r_2/r_2')\sin^{-1}(x/r_2)]$$

subject to the approximation that $r_2/r_2' \approx 1$, i.e., that the change in back surface radius is small. This yields:

$$x' = xr_2'/r_2$$

Introducing this in equation 1:

$$x^4(1/r_1 - 1/r_2) = (xr_2'/r_2)^4(1/r_1' - 1/r_2')$$

i.e.,

$$(1/r_1' - 1/r_2') = (r_2/r_2')^4(1/r_1 - 1/r_2) \quad (2)$$

However, assuming that the lens is thin, the change in power on flexure is

$$\Delta F = (n-1)(1/r_1 - 1/r_2) - (n-1)(1/r_1' - 1/r_2')$$

Replacing the last bracket by expression 2 gives:

$$\Delta F \approx (n-1)(1/r_1 - 1/r_2)(1 - (r_2/r_2')^4)$$

Evidently, the first two brackets correspond to the original, unflexed power of the lens, F, so that:

$$\Delta F \approx F(1 - (r_2/r_2')^4) \quad (3)$$

It is convenient to write $r_2' = r_2 + \Delta r_2$, where Δr_2 is the change in back radius on flexure. Then:

$$(r_2/r_2')^4 = (r_2/[r_2 + \Delta r_2])^4 = (1 + \Delta r_2/r_2)^{-4} \approx 1 - 4\Delta r_2/r_2$$

because Δr_2 is assumed to be small compared with r_2. Introducing this in equation 3:

$$\Delta F \approx 4F\Delta r_2/r_2 \quad (4)$$

Thus, the change in power is a function of the initial back vertex power, the initial back optic zone radius, and the change in back surface radius as stated by Dr. Patel in his letter.

For a steeper postflexure BOZR, as found in our study, Δr_2 is negative, so that ΔF is also negative, i.e., positive lenses become less positive on eye, as found experimentally. Thus, qualitatively the model is in agreement with our findings. From the quantitative point of view, use of the experimental parameter changes given for positive lenses in Tables 2 and 3 of our paper in conjunction with equation 4 above gives a mean value of about 1.2 D, not too much greater than the observed value of about 0.5 D and of similar magnitude to the predictions of several other models. Because equation 4 was derived for positive lenses, it is not surprising to find that its prediction of a mean change of +0.67 D for our negative lenses fails to agree with the experimental finding of 0.01 D.

In principle, it ought to be possible to make direct experimental measurements to determine whether the arc of the back surface of the lens remains invariant in length as a lens is flexed, although with today's thin lenses it may be difficult to distinguish between this possibility and the constancy of the length of the strain-free boundary predicted by beam-bending models. Finally, we fully agree with Dr. Patel that much work is still needed on the development of more refined models incorporating the full range of factors that might influence on-eye lens power changes.

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