Free-form technology

In the second and final part of this short series on free-form lenses, **Professor Mo Jalie** looks at the implications of the new technology for both practitioner and wearer. **Module C8065, one general CET point suitable for optometrists and DOs**

The benefits of free-form technology to the wearer can be categorised as follows:

- Free-form processing allows lenses to be made in any refractive index material with most optical characteristics the same as those to which the wearer has become accustomed when wearing normal index materials.
- Individual fitting characteristics of the wearer can be incorporated into the lens design.
- Lifestyle characteristics can be incorporated into the lens design.

The best form for an ophthalmic lens to be made in a higher refractive index material is, generally, more steeply curved than the form required for a normal index material. Normal index materials are defined as those whose refractive index is less than 1.54. When stock single vision lenses are supplied in higher refractive index materials one can assume that the manufacturer has employed best form curves for that refractive index. However, when higher refractive index lenses are made by completing the concave side of a semi-finished blank, there is no certainty that the new lens will duplicate the off-axis effects of the previous normal index design. An important advantage of free-form processing is the ability to produce lenses in higher refractive index materials, whose off-axis performance matches that of a form previously worn by the subject in a normal index material. Additionally, the former problem of the laboratory perhaps not having the correct smoothing and polishing tools for the chosen high-index material disappears with a cut-to-polish system, where the lens passes directly from the generator to the free-form polisher. The need for the traditional smoothing and polishing tools is eliminated.

It is well known that high myopes who have worn a flat-form lens in the past may not be able to tolerate a change in form to a curved best form design.[3] Even when there is no change in prescription, a change in lens form alters the effect of the lens when the wearer views through points away from the optical centre. Also, due to an altered degree of barrel distortion, the curved form may produce a change in the shape of the retinal image. This effect is particularly distressing to a subject who, after a long period of wear, has become accustomed to a given amount of distortion.

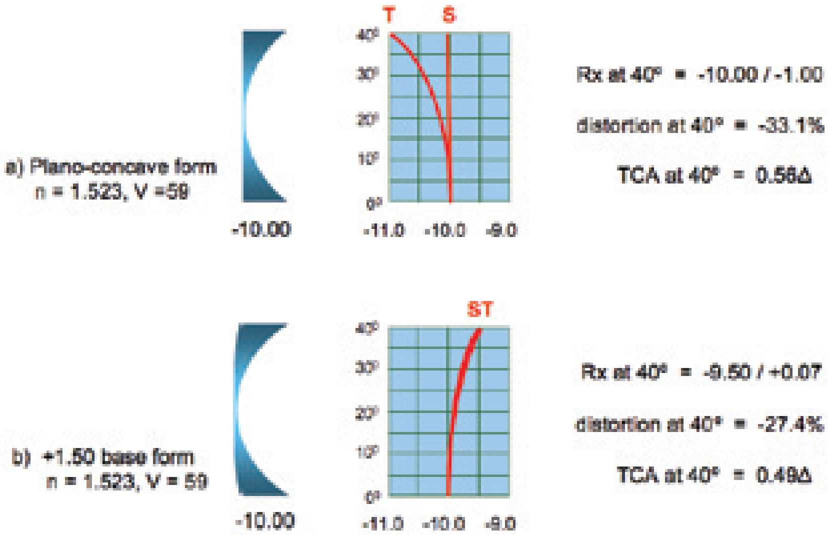

Figure 1 Field diagrams for -10.00D lenses made in crown glass S = plot of sagittal oblique vertex sphere power T = plot of tangential oblique vertex sphere power
a) plano-concave crown glass form (b) point focal form in crown glass

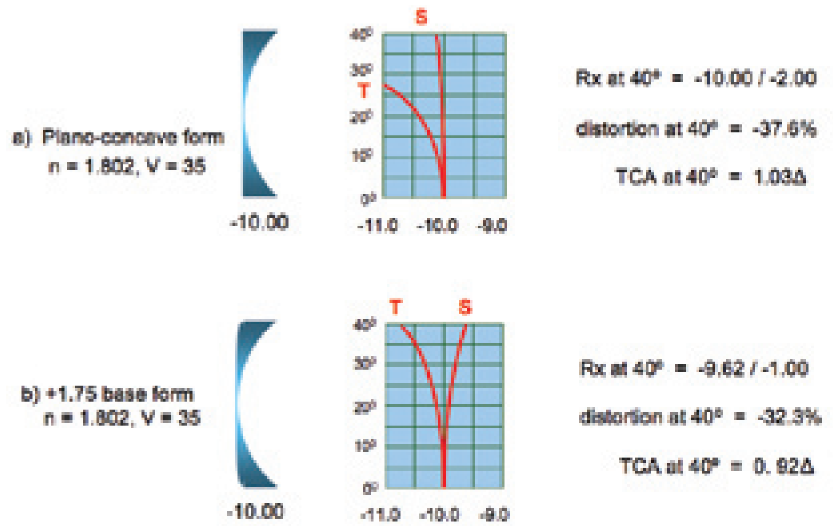

Figure 2 Field diagrams for -10.00D lenses made in 1.802 index glass
a) plano-concave form in 1.802 index glass (b) curved form whose off-axis performance matches the crown glass design illustrated in Figure 1a

Figure 1a illustrates a field diagram for a -10.00 D lens made in plano-concave form in crown glass of refractive index 1.523. The field diagram indicates how the tangential (T) and sagittal (S) oblique vertex sphere powers vary as the eye rotates away from the optical centre of the lens. Each 10° rotation by the eye is approximately equivalent to a distance of 5mm on the lens. For a 40° rotation of the eye, the real effect of the lens, some 20mm from the optical centre, has altered from -10.00 D at the centre, to -10.00 DS /-1.00 DC. The field diagram shows quite clearly that the mean oblique power of the lens becomes stronger (ie, more negative) as the eye rotates away from the optical centre and that the oblique astigmatic error reaches -1.00 D for the 40° zone of the lens. The distortion for the 40° zone is seen to be 33.1 per cent. The retinal image is noticeably barrel-shaped, an effect to which the visual system becomes accustomed, eventually learning to compensate for the alteration in shape of the image.

Figure 1b shows how the off-axis performance alters if the lens is made in a typical best form for the prescription. The design is virtually point focal with an oblique astigmatic error of just +0.07 D for the 40° zone of the lens. The lens also becomes weaker as the eye rotates away from the optical centre and the distortion decreases by some 6 per cent a value which will be noticed by the wearer.

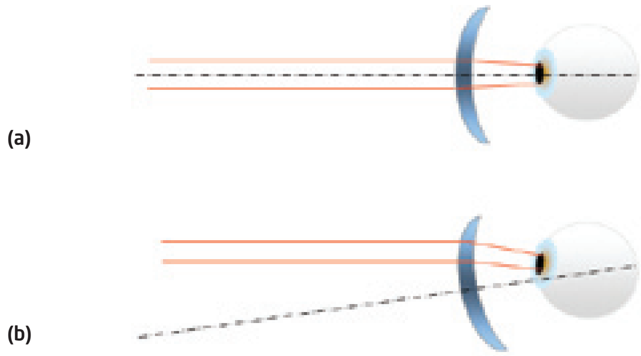

Figure 3 Measured and as-worn positions of a spectacle lens
a) lens position during refraction or as measured by the focimeter
b) typical as-worn position incorporating pantoscopic tilt and compensatory decentration

These changes in the overall effect of the lens may well be the cause of rejection of the new lenses by the wearer. The well-known rule, which is normally adopted in practice, advises that when a subject has worn a given form in the past with which they are happy, then do not alter the form, even though it may not be the best form for the prescription.

However, this rule is not valid when the refractive index of the lens material is changed. The use of a high index material for the power under consideration would result in a thinner, neater lens. Use of a 1.802 index glass, for example, would result in a lens which would be some 35 per cent thinner, a benefit which the -10.00 D myope is certain to appreciate.

Figure 2 shows what happens when the refractive index of the lens is changed to 1.802. In Figure 2a, the plano-concave lens form has been retained, the result of which is that the off-axis power becomes even greater and the oblique astigmatism is seen to have doubled from that of the crown glass design. The distortion which governs the shape of the retinal image has increased to 37.6 per cent. It is also seen that the transverse chromatic aberration (TCA) has almost doubled compared with the crown glass form, and this is due to the much lower Abbe number (35) of the very high index material.

If the high index lens is made in a curved form with a +1.75 D base curve (Figure 2b), the oblique astigmatism at 40° would reduce to the same level as that encountered with the plano-concave crown glass design and the distortion would also match that of the form to which the wearer has become accustomed. Furthermore, although the change in tangential power is not quite so great as with the original design, at least the lens becomes more negative once again as the eye rotates away from the optical centre.

Individual fitting characteristics

Stock single vision lens series are generally designed on a 'fit everyone' basis. The introduction of rapid computer processing has enabled the lens design to commence on receipt of the order from the eye care practitioner thereby introducing the possibility of individualized lenses. For example, the practitioner is now able to submit details of the vertex distance, pantoscopic and/or face-form (dihedral) angles of the lenses and from an assumption about how the practitioner fitted the trial frame or positioned the phoropter head, the lens prescription can be modified to take any changes into account.

The effect of changing the vertex distance is easy to understand and, ideally, the order should be received by the laboratory with the prescription already modified to take the change into account. Any alteration to the lens power to compensate for changes in pantoscopic or dihedral tilt of the lens are more contentious with no little debate about whether this practice is really beneficial to the wearer. The argument can be followed by comparing Figures 3a and 3b.

Figure 3a depicts an eye which is corrected by a spectacle lens which has been mounted before the eye with no pantoscopic tilt. Some manufacturers argue that this is how the practitioner mounts the lens in the trial frame or, that when refraction is undertaken with a phoropter, the refractor head may not be angled in front of the eye. Figure 3a also illustrates how the back vertex power of the lens is measured in the focimeter.

Figure 3b illustrates a typical as-worn position for the spectacle lens. It has been mounted in front of the eye with a pantoscopic tilt of about 10° and the optical centre then lowered to satisfy the centre of rotation condition that the optical axis of the lens should pass through the eye's centre of rotation.

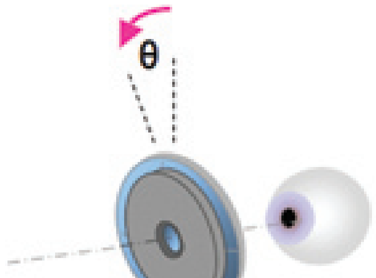

Figure 4 Astigmatism arising from oblique central refraction. Note that the lens of power F, made in a material of refractive index, n, has been tilted through an angle, θ, about the 180° meridian and has been stopped down so that refraction can only occur in the central zone of the lens. Using third-order theory, the lens becomes a sphere-cylinder with power:
$F_{SPH} = F\,[1 + \sin^2\theta/2n]$
$F_{CYL} = F_{SPH} \tan^2\theta$
axis = 180

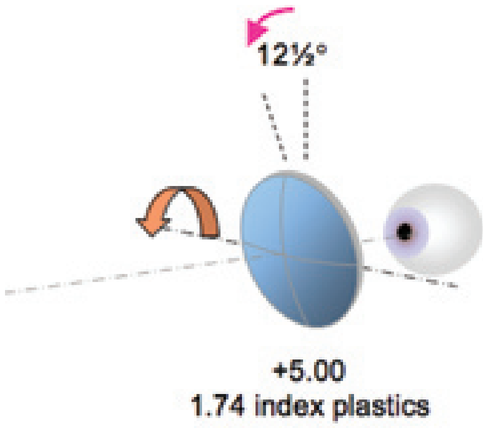

Figure 5 Astigmatism arising from oblique refraction. +5.00D lens made in a material, n = 1.74, tilted 12½° becomes +5.07/+0.25 x 180

Some manufacturers argue that in this situation, the eye is corrected by a tilted lens and that the aberrational astigmatism which is introduced by the tilt when the eye views straight ahead, alters the effective prescription of the lens. In other words, the effect of the lens in the as-worn position is not the same as that which is read by the focimeter and that for the as-worn effect to match the trial frame prescription, the power of the lens should be modified to take the change in angle into account. Therefore, they alter the prescription from that which has been ordered and inform the practitioner when the lenses are returned, of the power which should be measured in the focimeter to take the compensation for the tilt into account.

The compensation which is provided can be deduced with the help of Figure 4. When the effects of tilted and decentred lenses need to be evaluated, skew rays must be traced through the lens to determine the effects of the tilt and decentration. However, fairly close results can be obtained from the third-order relationships (Figure 4).

It can be shown[2] that when a lens of power, F, is tilted through an angle, θ, it becomes sphero-cylindrical with power

$$F_{SPH} = F\,[1+\sin^2\theta / 2n]$$
$$F_{CYL} = F_{SPH} \tan^2\theta$$

Axis – parallel with the axis about which the lens is tilted.

Thus a +5.00 D lens made in a material of refractive index 1.74, which has been tilted about the 180 meridian to provide a pantoscopic tilt of 12½°, becomes +5.07/+0.25x180 (Figure 5).

If the practitioner orders a +5.00 D lens and the manufacturer assumes that the finished lens is to be mounted with a pantoscopic angle of 12½°, the manufacturer will make a lens of power +4.93/-0.25x180 and inform the practitioner that this is the correct value which the focimeter should read when the lens is returned. This compensated prescription can be confirmed by substituting +4.93 for F in the above equation for the change in spherical power (with θ = 12½° and n = 1.74) and assuming that no change in power needs to be considered from the tilt of the -0.25D cylinder. The +0.25DC x 180 which arises from the tilt of the +4.93 component is neutralised by the -0.25DC x 180 which has been added to the compensated prescription. If the ordered prescription includes a cylinder with an oblique axis direction, then the axis direction of the compensated prescription will also need to change, when the effect of the induced cylinder with its axis at 180 is taken into account.

The source of the contention which arises from this automatic prescription compensation is that the eyes are not stationary behind spectacle lenses but roam about the field of vision using many different visual points all over the lens area.

Consider the compensation which is provided for the prescription +5.25/+0.25 x 30 (Figure 6).

Using the same method as before, the compensated prescription which the manufacturer should provide is

+5.05/+0.25 x 60. Note that in this case the axis direction has changed to 60 from the ordered value of 30.

When the eye views straight ahead the effect of the lens is indeed, +5.25/+0.50 x 30 as required by the subject. However, if the lens has been correctly fitted with its optical centre lowered by the correct amount to satisfy the centre of rotation condition, the optical axis of the lens will now pass through the eye's centre of rotation. When the gaze is lowered by 12½°, so that the eye is viewing along the optical axis, the effect of the lens becomes the same as its back vertex power, +5.05/+0.25 x 60. This change in the axis direction with the direction of gaze may well be a source of complaint about the off-axis vision which is experienced with this lens.

Lifestyle characteristics

With rapid computational facilities now available at the order-entry stage, some lens manufacturers now offer to redesign the lens form to take into account the actual way in which the lens is to be used. For example, it is well known that lenses required only for near vision should be made in a form which is some 2.00D shallower than the form which would be employed for distance vision. The difference which the change in form makes is shown in Figure 7 which illustrates by means of field diagrams the difference in the off-axis performance for a lens of power +6.00D which is made in a point focal form for distance vision (front curve +12.18 D, t_C=4.0mm, CRD=27mm). In Figure 7a, the field diagram for the lens performance confirms that the design is point focal when used for distance vision but in Figure 7b, the performance of the same form when used for near vision at -33.3cm is no longer point focal but, instead, is seen to be afflicted with aberrational astigmatism. The paraxial vergence leaving the lens in near vision is about +2.80D owing to the near vision effectivity error that is exhibited by this form for near.

To improve the design for near vision, the front curve should be flattened to +9.75 when the design now becomes point focal for near, as is shown by the field diagram in Figure 7c. If this +6.00 D lens is to be used only for near vision, then, supplying the wearer with this personalized form is truly bespoke dispensing.

In the case of progressive lenses, not only can individual fitting characteristics be taken into account, but also the progressive surface can be modified to take account of how the wearer uses the lens, such as the preference for head or eye movements which is incorporated into Essilor's Varilux Ipseo design.

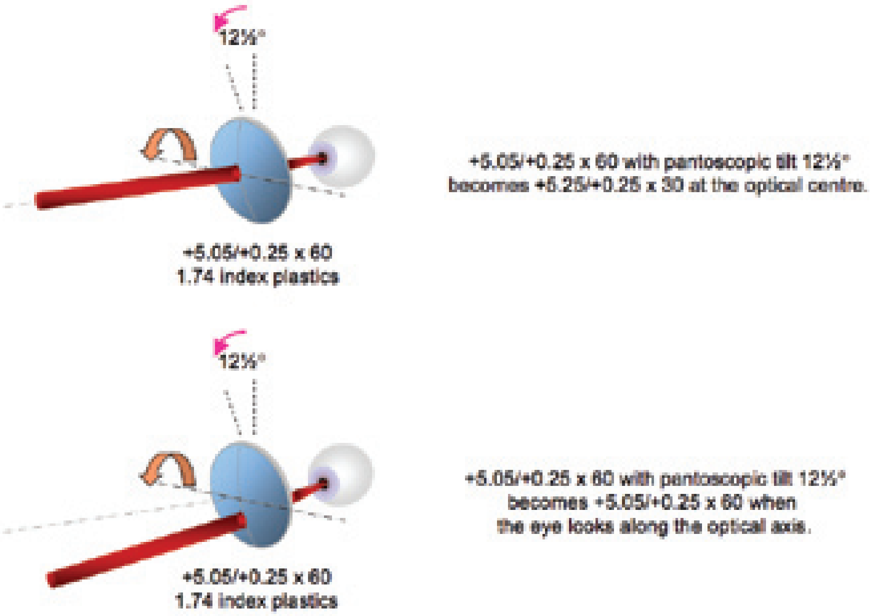

Figure 6 Compensated prescriptions

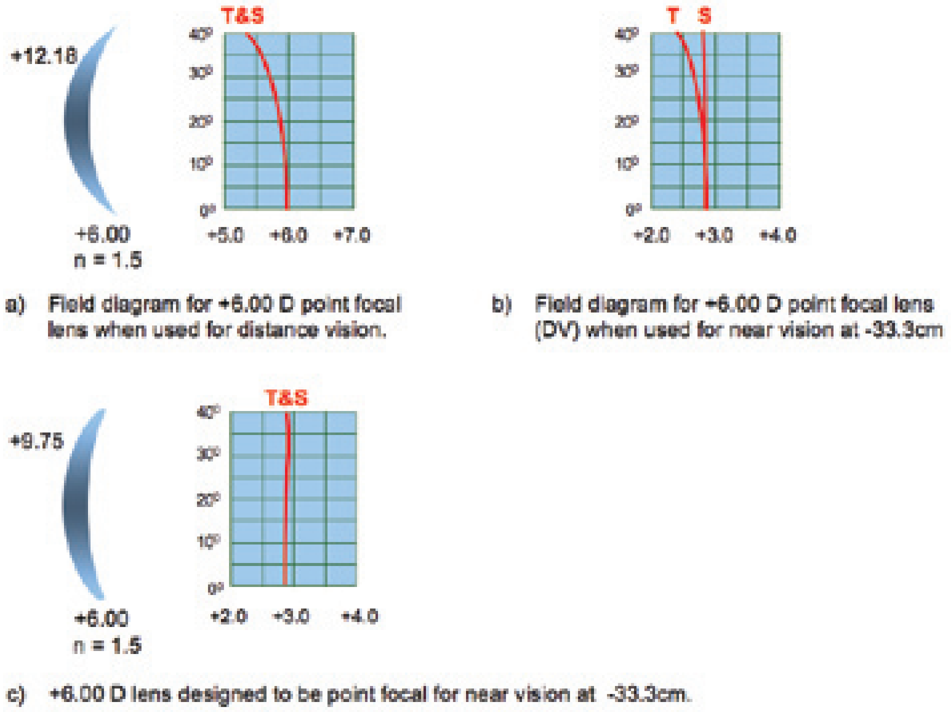

Figure 7 Field diagrams for +6.00 D point focal lens used in near vision

In addition, lens designs which have convex progressive surfaces and have been supplied to the laboratory in semi-finished form can have their basic configuration altered by means of free-form surfacing on the concave side of the blank. For example, the progression length of the design can be shortened by incorporating extra additional power on the concave surface. A design with an add power on the convex surface of +2.00D, which becomes fully operative over a progression length of 14mm will have its progression length reduced to 12mm by the incorporation of a progressive +0.25 addition on the back surface of the lens (Figure 8).

Some manufacturers already use this expedient to offer progressive designs with a range of different progression lengths.

The optical performance of progressive lenses in general has improved enormously since the first generation ▶

designs of 50 years ago. However, we are reminded by the Minkwitz theorem[5] that in order to obtain progressive power, the refracted pencil through the progression zone must be afflicted with aberrational astigmatism which depends upon the total power of the addition and the length of the progression zone. It will be noted that it does not depend upon which side of the lens incorporates the progressive surface or how the addition might be distributed between each surface. Some new designs have the addition distributed between the two surfaces either in spherical form or even in cylindrical form with the axes of the cylinders at right angles to one another. What is important is that any undesirable, but unavoidable, characteristics of the progressive surface are modulated as far as is possible by careful design of the other surface. New lens designs with convex progressive surfaces and optical modulation provided by free-form production of the concave surface are certain to feature prominently in the next generation of progressive lenses from the major ophthalmic lens manufacturers.

It is hoped that this paper has helped to clarify some of the mystique which surrounds the term free-form. There is no doubt, that in the hands of major manufacturers who already have the support of lens design teams to specify free-form surfaces and software engineers to digitise the specifications to drive free-form machinery, this new technology can be fully utilised to produce state-of-the-art lenses for the 21st century. It goes without saying, that the smaller manufacturer who has invested in free-form machinery but does not have the ability to redesign software is only able to reproduce lens designs for which the software has been made available.

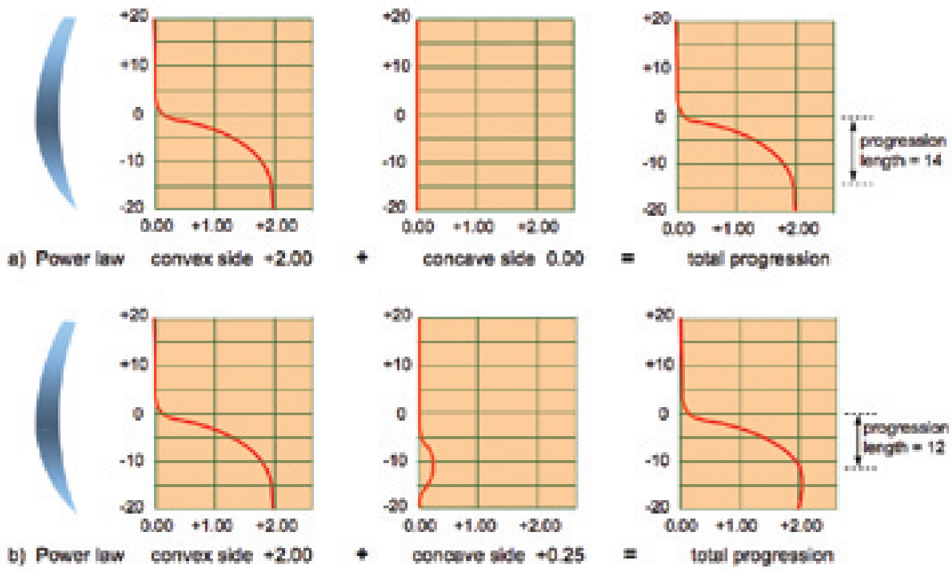

Figure 8 Power laws for each surface of progressive lenses of power 0.00 Add +2.00 with different corridor lengths
a) The concave surface has no progressive power and the total add is provided by the convex surface. The progression length is 14mm
b) The concave surface provides a progressive addition of +0.25, the effect of which is to shorten the progression length of the design by 2mm

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MULTIPLE-CHOICE QUESTIONS

1 Which of the following statements about lens form is false?
A Patients respond better to thinner lenses irrespective of form
B Refractive index will not influence lens form
C The best form for higher refractive index is generally steeper
D Higher refractive index lenses duplicate the off-axis effects of the normal index design

2 For a positive sphere power ordered for a pantoscopic angle of 12 degrees, what will the manufactured sphere power be?
A Bigger positive power
B Reduced positive power
C The same power
D Different depending on manufacturer preference

3 Which of the following does not improve optical performance at near?
A Flattening the base curve
B Increasing pantoscopic angle
C Flattening the front curve
D Steepening the front curve without changing the refractive index

4 Normal index lenses are taken to be those with a refractive index of lower than what value?
A 1.51
B 1.54
C 1.66
D 1.80

5 Each 10 degree eye rotation roughly approximates to what distance covered on the lens surface?
A 1mm
B 2mm
C 5mm
D 10mm

6 What impact would a 20mm rotation have upon the lens power for a plano-concave lens of -10.00DS of index 1.523?
A No effect for this refractive index
B An increase in negative tangential power
C An increase in negative sagittal power
D An increase in tangential and sagittal powers of equal amount

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