Progressive power lenses

A progressive power lens is designed to provide continuous vision at all distances instead of the predetermined working distances of bifocal and trifocal lenses. The lens can be considered to have three distinct zones just like a trifocal design, a distance zone, a progression zone, or simply, the progression, and a near zone. Unlike a trifocal lens, the progression provides an increase in reading addition from the distance portion to the near portion. The rate at which the power increases over the progression zone is governed by the power law for the design (Figure 1). The power law may be linear, as assumed in Figure 1, or may be more complex to provide a greater or lesser increase in power at the start of the progression (see Figure 9).

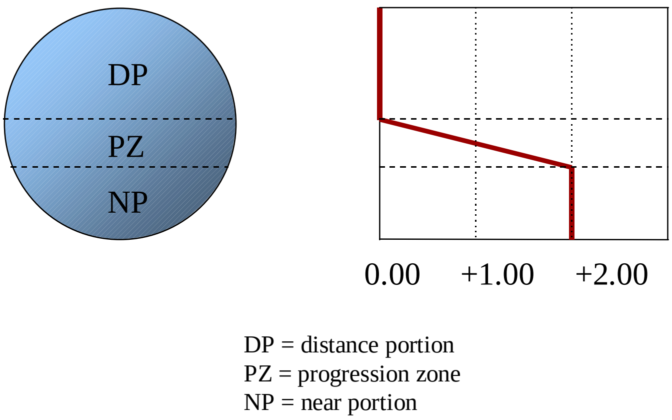


Figure 1. Progressive lens with linear power law

Compared with bifocal and trifocal designs, the progressive power lens offers:-

- vision at all distances - since the addition increases over the progression zone
- more natural use of accommodation - accommodation does not need to fluctuate when vision is transferred from one zone to another
- absence of image jump - there is no abrupt change in power
- the appearance of a single vision lens - there are no dividing lines on the lens.

The second of these benefits is immediately apparent when the accommodative demands and ranges of vision through a trifocal lens and a progressive power lens are compared.
Consider a subject who has an amplitude of accommodation of +1.00D and who is prescribed a correction of +3.00, Add +2.25 for near. The accommodative demands and ranges of vision which are obtained when this specification is dispensed in trifocal form and progressive power form are illustrated in Figures 2a and b.
Figure 2a assumes that a trifocal correction with an intermediate addition of +1.25 has been provided. This intermediate addition would provide continuous vision from 80cm, down to the near point at 31cm through the intermediate and near portions of the lens.
Figure 2b assumes that the correction has been dispensed in progressive power form and the accommodative demand is of the same form as that enjoyed by the subject before the onset of presbyopia. Naturally, the actual position of the curve depends upon which zone of the lens the subject happens to be using at the time.

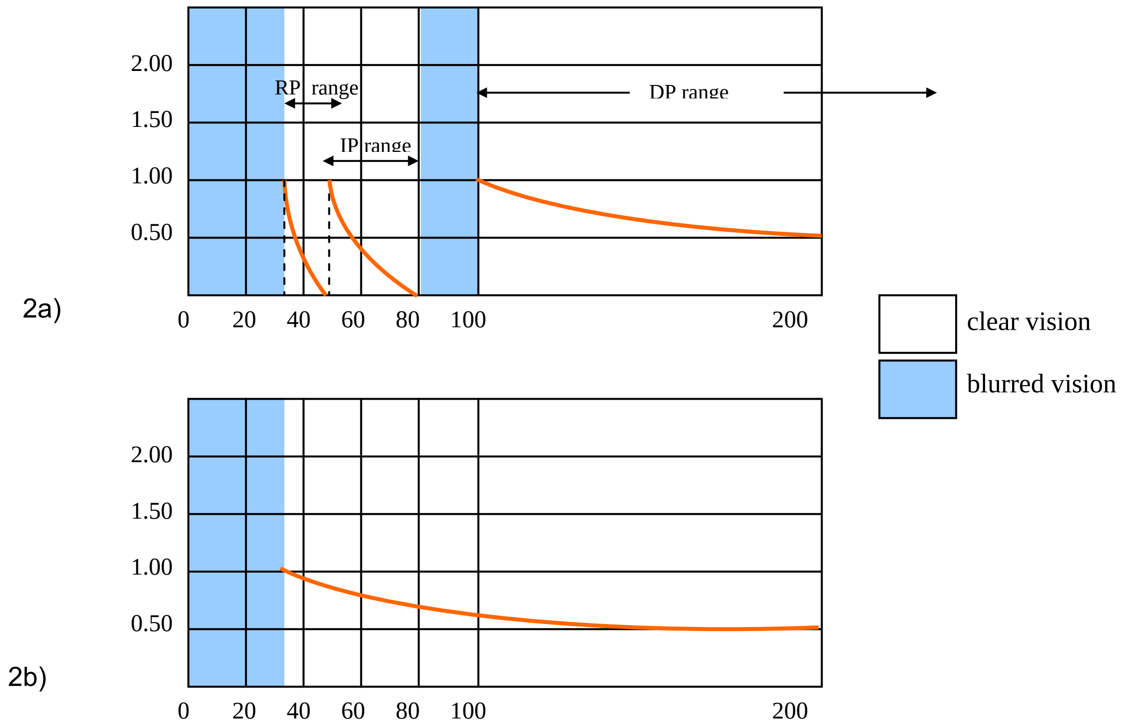


Figure 2 Comparison of accommodative demands and ranges of vision through trifocals and progressive power lenses.

In order to obtain an idea of the geometry of a progressive surface consider, first, an E-style bifocal whose bifocal surface is made from two different spherical surfaces placed together so that their poles share a common tangent at point, L (Figure 3).

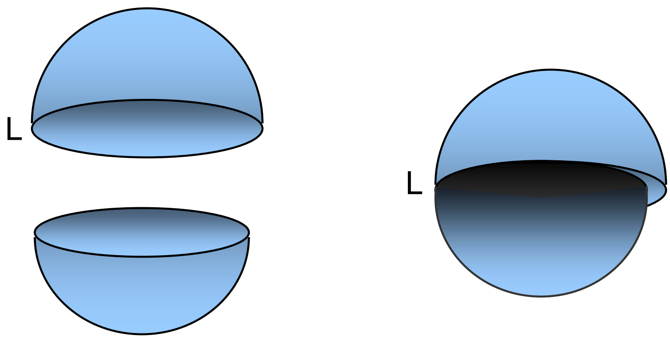


Figure 3 E-style bifocal made by placing together two spherical surfaces

Needless to say the two surfaces are continuous only at point L. At all other points there is a step between the two surfaces which increases on moving away from L. In broadest terms, if we wished to produce a truly invisible bifocal design, that is one whose dividing line cannot be detected, the two surfaces need to be made continuous by blending the two surfaces together making the DP surface and NP surfaces continuous at all points.
In principle, a progressive lens may be considered to have spherical DP and NP surfaces connected by a surface whose tangential and sagittal radii of curvature decrease according to a specific power law between the distance and near zones of the lens.
In theory, to make a surface where the curvature increases at the correct rate to satisfy whatever power law it is required to adopt, we need to be able to combine small segments of spheres of ever-decreasing radii, all tangential to one another in a continuous curve. It will be understood that these sections will only be continuous along a single, so-called, umbilic line and that at all other points on the surface the sections must be blended to form a smooth surface.

The simplest concept of this latter surface is a section taken from an oblate ellipsoid as illustrated in Figure 4 where the radii of curvature of the spherical surfaces which represent the distance and near portions are shown as r_D and r_N respectively. It can be seen that the solid ovoid which is obtained by inserting the ellipsoidal section between the two hemispheres shown in the figure will result in a surface which has no discontinuities.

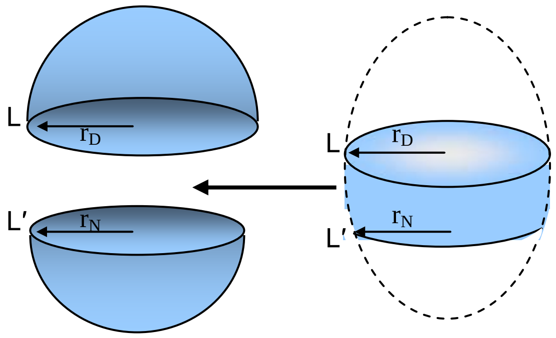


Figure 4 Concept of a progressive surface

Section of an oblate ellipsoid is inserted between two hemispheres of radius of curvature r_D for the distance portion and r_N for the near portion.

Along the umbilic line, LL′, a cross section through the surface would be circular and the radii of the circles in a plane parallel with either the distance or near portion circles do indeed decrease from r_D to r_N continuously.

The ability to cut surfaces of such complex nature was made possible by the arrival of computer numerically controlled grinding machines. CNC machining methods have made possible the design and production of both progressive and aspheric lens designs in the last half of this century. Basically, the CNC cutter, which today is a single point diamond tool, cuts a surface under computer control, the cutter sweeping in an arc over the workpiece with the program positioning the cutter in exactly the right place as the cutter traverses the workpiece.

The drawback to the direct machining method is that no matter how accurately the surface is generated, it must still be smoothed and polished. These final stages are accomplished by means of a floating pad system and it is essential to ensure that the pads do not remove any more glass than intended thereby maintaining an accurate surface geometry.

Slumping consists of using ceramic slumping moulds which themselves are produced by CNC cutting, upon which the glass blanks with carefully polished convex spherical surfaces are placed). The assembly is then heated to a high temperature at which the glass starts to flow. The back surface of the blank then conforms in shape with that of the ceramic mould and the convex surface of the blank, which is the progressive surface, slumps to the required geometry. The initial shape of the mould must be very carefully calculated and highly sophisticated temperature control is necessary to ensure that the glass flows correctly.

In some cases, the slumping is assisted by vacuum forming where the glass is heated to just beyond its softening point at which temperature it is incapable of flowing by gravity alone, when a vacuum is applied to the interface between the forming block and the concave surface of the blank, effectively, sucking the surface into shape.

Not the least of the difficulties which must be overcome on the production line is to select a test method which can be used to verify the accuracy of the finished surface. Unlike a rotationally symmetrical aspherical surface, mechanical measurement is useless since, even if a gauge with sufficient accuracy was available, it would mean checking every meridian in turn! Three different optical methods are employed:

- image evaluation by means of the Hartmann Test or by comparing grid patterns
- surface evaluation by interferometric methods
- computer scanning of the power distribution by a specially adapted on-line focimeter.

The actual geometry of progressive surfaces, naturally, is regarded as proprietary information by lens manufacturers but some insight into how the design of a surface might proceed can be obtained by developing the concept illustrated in Figure 4.

The CNC cutter can be programmed to cut a series of arcs each one of which is independently controlled, but which will result in a continuous surface of any geometrical configuration. For, example it is possible to cut a conicoidal surface such as the oblate ellipsoid which, in fact, looks quite promising at first sight for a progressive power surface since both tangential and sagittal surface powers increase quite rapidly as we move away from the pole of the surface. The rate of increase can be controlled by altering the asphericity of this conicoid and the change can be determined as follows. If an oblique pencil of rays is traced through a spherical lens there is likely to be an error, δT, in the tangential oblique vertex sphere power of the lens. Of course, in the case of a minimum tangential error lens form, the error, δT, may be zero. The ray-trace also yields the incidence height, y_1, on the front surface of the lens, the radius of curvature of the front surface, F_1, being denoted by r_1.
It is possible to show that for any given tangential error, there must be a conicoid which will eliminate the error. If the error is positive, a conicoid whose *p*-value is less than 1 must be employed, whereas, if the error is negative, a conicoid whose *p*-value is greater than 1 would be employed.
If the tangential error is known for a given incidence height on the front surface then the asphericity can be found from the equation:

$$p = 1 + (r_1/y_1)^2.(1 - (F_1 / (F_1 + \delta T))^{2/3}).$$

This relationship provides some of the preliminary information which we need to design a progressive power surface. In progressive power surface design we ***want*** a tangential error to occur, the error being the magnitude of the required reading addition. If we substitute the add for the tangential error in the above formula it will give us the required asphericity to reach the value of the addition in the tangential meridian at a given distance below the optical axis of the surface.
For example, for a +6.00D surface worked on a material of refractive index 1.50, an Add of +1.00 at 14 mm below the pole of the surface would require an asphericity of +4.5. For an add of +2.00 we would need an asphericity of +7.2 and for an add of +3.00, an asphericity of +9.4. These *p*-values describe oblate ellipsoidal surfaces such as the one depicted in Figure 4.
Lenses which employ oblate ellipsoidal surfaces are relatively easy to analyse using ordinary trigonometric ray-tracing techniques and in the case of a plano lens which employs a convex oblate ellipsoid whose p-value is +7.2 (which is designed to produce an Add of +2.00D, the DP power assumed to be zero), we obtain the field diagram depicted in Figure 5. It can be seen that for about a 25° rotation of the eye, which corresponds with a point about 14mm from the pole of the surface, the tangential oblique vertex sphere power is indeed +2.00D, the value which it was set out to achieve.
The ellipsoid alone, however will not produce a good progressive power surface. It will be recalled that the conicoidal surface is astigmatic, the surface astigmatism is normally chosen to eliminate the aberrational astigmatism of oblique incidence.
The field diagram depicted in Figure 5 indicates the oblique astigmatism in the refracted pencil and it is seen that the astigmatism almost matches the increase in mean oblique power of the surface. Since the field diagram indicates the amount of oblique astigmatic error in the refracted pencil it actually gives us the amount by which the sagittal curvature must be increased in order to eliminate the astigmatism. For example, at 25° where the astigmatism is -1.50D, if the sagittal power of the surface is increased by +1.50D it will go a long way to eliminating the astigmatism. The field diagram gives a first indication of the path which the CNC cutter must take as it traverses the progression zone to eliminate the increasing surface astigmatism of the simple ellipsoid.
Progressive lens design, however, does not depend only upon the astigmatism at a single point on the surface, for the power of the progressive surface changes across the refracted pencil.

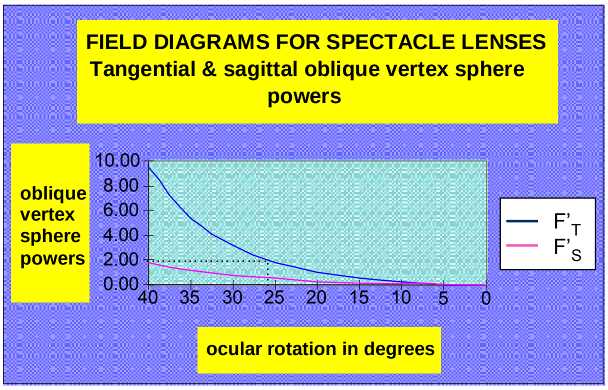
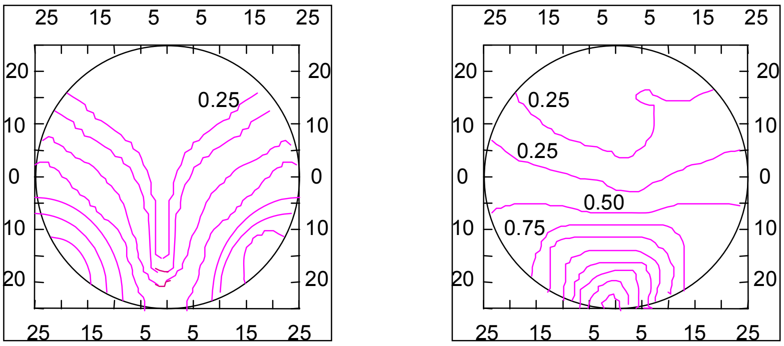


Figure 5
Field diagram for Plano lens made with a convex oblate ellipsoidal surface to provide an addition of +2.00 in the tangential meridian.

If the power law through the progression zone is linear then the change in power depends upon the near addition, *A*, and the length of the progression zone, *h*. For each 1mm of progression zone the increase in power, δF, through the zone is given by:

$$\delta F = A / h .$$

Thus, if the reading addition is +2.00D and the length of the progression zone is 10mm, the surface power through the progression zone must be changing at the rate of 0.20D per millimetre.
When the eye uses the progression zone the refracted pencil which fills the pupil must exhibit a skewed form of astigmatism, even along the umbilic line. The astigmatic nature of the pencil can be deduced by considering the tangential and sagittal fans of a narrow circular pencil of light which is limited by the eye's pupil, emanating from a region of the progression zone which is bisected by the umbilic line.
Assuming that the diameter of the beam of light traversing the progression zone is 4mm, with a surface which provides a near addition of +2.00D over a progression length of 10mm, there will be a difference in the tangential and sagittal surface powers across the zone of 0.40D. If the astigmatism across the pupil is defined as the difference in vergence between the tangential and sagittal fans across the pupil, then the astigmatism is $-2A / h$ D. This approximate but important rule tells us that the astigmatism across the pupil is proportional to the addition but inversely proportional to the length of the progression zone. In other words, the smaller the addition and the longer the progression zone, the smaller the astigmatism becomes.
As the eye moves away from the umbilic line the total astigmatism increases, approximately linearly, but of course, dependent upon the exact nature of the cross-section of the lens.
The corridor of clear vision through the progression zone is often described as the region in the zone where the astigmatism does not exceed 1.00D. It is conventional for manufacturers of progressive designs to compare the width of the corridor of clear vision either as a stated number of millimetres or by an isocylinder diagram where the contours illustrate the change in surface astigmatism in different zones of the lens. Such a diagram is illustrated in Figure 6 together with an iso-mean power diagram which shows how the power varies across the lens. On the basis of a 1.00D limit on surface astigmatism the lens illustrated would be described as having a corridor width of nearly 20mm at 10mm below the geometric centre of the lens.
The iso-mean power diagram illustrates that the surface increases in power slightly as the eye rotates upwards from the geometric centre of the lens, which is due to the method chosen to blend the surface between the distance and near portions. Also the full reading



iso-astigmatism lines iso-power lines

0.25D contour

Figure 6. Iso-astigmatism and iso-mean power lines for the progressive power lens Plano Add +2.00.

addition of +2.00D is seen to be reached at a point 20mm below the geometric centre of the lens.

A second consequence of the progressive surface is depicted in Figure 7 which compares the appearance of three vertical lines viewed through a bifocal lens and a progressive power lens. Since an increase in power is inevitably accompanied by an increase in magnification, and it is inevitable that if there is one then there must also be the other, vertical lines viewed through the progression zone exhibit skew distortion.

The directions of the lines can be illustrated by means of a vector plot which shows how their orientation can be expected to vary in a real image of the lines.

The skew effect can be minimised by decreasing the surface curvature as the eye moves away from the umbilic line. The lower down the surface, the greater the reduction in curvature needs to become.

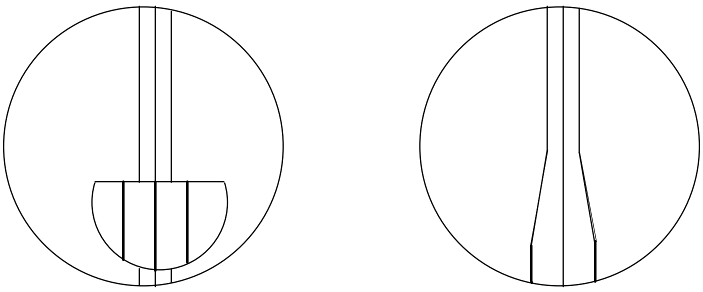


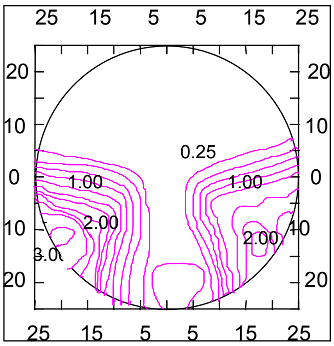
Figure 7. Skew distortion in a progressive power lens

The development of progressive lenses over the last 40 years can be discussed in terms of the way in which the CNC cutter has been employed to blend the DP surface with the NP surface. In the first commercially successful lens, the Varilux 1 design from Essel Optical

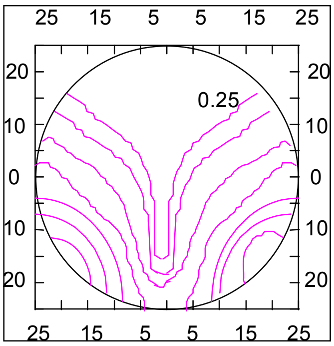
Company (now part of Essilor International), the DP and NP surfaces were spherical and the CNC followed a path which described circles of ever-decreasing radius as it traversed from the spherical distance portion to the spherical near portion. This necessitated very severe blending of the distance and near portions with large amounts of surface astigmatism at the peripheries of the progression. However the distance portion was almost completely free from surface astigmatism. The second generation Varilux 2 design used a series of conic sections of varying asphericity to reduce the astigmatic nature of the earlier design and at the same time used aspherical DP and NP surfaces to further reduce the severity of the blend. Without doubt, the Varilux 2 design pointed the way for later generations of progressive power designs.

Third generation designs, such as the Truvision Omni design, combined aspherical DP and NP surfaces which spread the blending further into the distance portion, softening the definition in the distance portion but considerably reducing the astigmatism in the lateral portions of the lens. The power profile of lenses such as the Omni can be compared with that of an up and downcurve trifocal design with the full distance prescription being obtained near the top of the lens and the near prescription at the bottom. Such a long progression, of course, enabled the lens to exhibit remarkably low levels of surface astigmatism in the "intermediate", periphereral zones.

The latest generation have combined the features of low-power aspheric lenses with progressive surface design and also adopted different power laws for different near additions. This feature of progressive lens design, being able to control in which areas of the lens the blending between the DP surface and the NP surface occurs, has enabled manufacturers to decide which areas they should prioritise for optimum vision. If the designer requires a large distance portion with the surface astigmatism confined to the lower portion of the lens, rather like the earliest progressive lens designs, the result is a *hard progressive design*. The arrangement of the surface astigmatism in a hard design is shown in Figure 8a. It is seen that this design enables a large DP area and a relatively large NP area to be obtained but there are rapid discontinuities in the astigmatism in the lower portion of the lens.



a) Hard progressive design



b) Soft progressive design

iso-astigmatism lines 0.25D contour

Figure 8. Comparison of iso-astigmatism lines for progressive power lens Plano Add +2.00.

If the designer wishes to reduce the amount of astigmatism which occurs in the lower portion of the lens, to speed subject's adaptation to progressive lens wear, it can be spread into the distance portion as indicated in Figure 8b. This arrangement results in a *soft progressive design*, and there can be no doubt that when the addition is low and, hence, the surface astigmatism is low, the soft progressive design has proved to be the most successful in enabling rapid wearer acceptance of progressive design.

Some manufacturers produce progressive lens series which are deliberately soft in design for the low addition lenses in the series, the design tending to become harder as the additions increase. These are known as *multi-design* series. Figure 9 illustrates how the power law differs with a multi-design series for the additions, +1.00, +2.00 and +3.00D. It can be seen how the length of the progression zone reduces as the addition increases for these series.

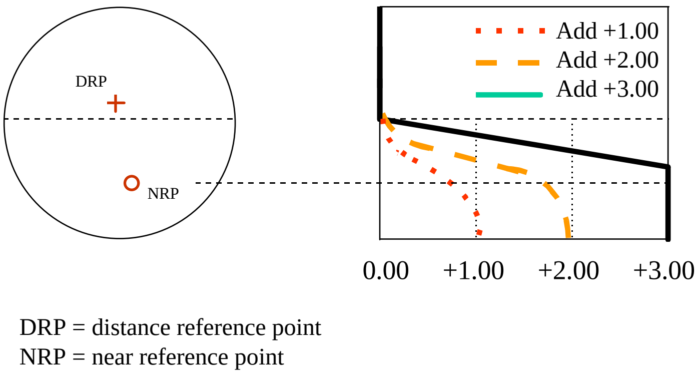


Figure 9. Power laws for +1.00, +2.00 and +3.00D additions for a Multi-Design series of progressive power lenses. Note the designs tend to become harder as the reading addition increases.

Another important feature of progressive power lens design relates to the symmetry of the power distribution across the lens. In Figure 10, the eyes are supposed to be viewing an object at B, the visual axes intersecting the lenses at P in the right eye and P′ in the left eye.
If the surface power at point P differs much in magnitude or orientation from the surface power at P′ there will be different prismatic effects at the two points. For ease of fusion in all directions of gaze the vertical prismatic effects at corresponding points must be approximately equal. This is more likely to be the case if each lens is individually designed for the right and left eyes rather than producing a single design which is rotated inwards in opposite directions for the two eyes. Progressive lens designs which exhibit approximately equal vertical prismatic effects at corresponding points are said to possess horizontal symmetry.

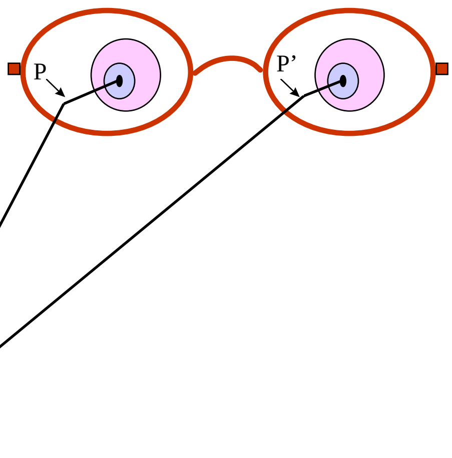


Figure 10. Horizontal symmetry at corresponding points on the lens

Although isocylinder and vector diagrams are informative it is foolhardy to suppose that they can be used to predict wearer adaptation and acceptance of the lens.
Despite the consequences of the progressive surface, the brain quickly adapts to the effects of surface astigmatism and skew distortion. The adaptation required of the visual system is

probably no greater when a subject wears their first pair of progressive lenses than when they wear their first pair of bifocals. Indeed, if progressive power lenses are introduced at the onset of presbyopia when the reading addition is low, the adaptation period is probably smaller than it would be for a first pair of bifocal lenses. In an attempt to evaluate the performance of new progressive designs, most manufacturers submit the lenses to clinical trials, the information which the wearers report being fed back into the design loop.
Subjects who, typically, find it difficult to adapt to progressive lenses are those with high reading additions who have successfully worn bifocal lenses in the past and have become accustomed to a wide reading field of view through a large segment.
Problems with adaptation to progressive lenses are almost always due to either an incorrect prescription or poorly fitted lenses.

Prism thinning
When a progressive lens is worked to individual prescription by surfacing the concave surface of the blank it is usual for the workshop to incorporate a thinning prism in the specification of the back surface. The purpose of the thinning prism is to equalise the edge thickness of the finished lens and its magnitude depends upon the power of the lens, the cylinder axis direction if the lens is astigmatic and the position of the distance reference point with respect to the box centre of the lens (Figure 11). Typically for plus spherical lenses, the magnitude of the thinning prism is about two-thirds of the reading addition and its base usually lies at 270°.

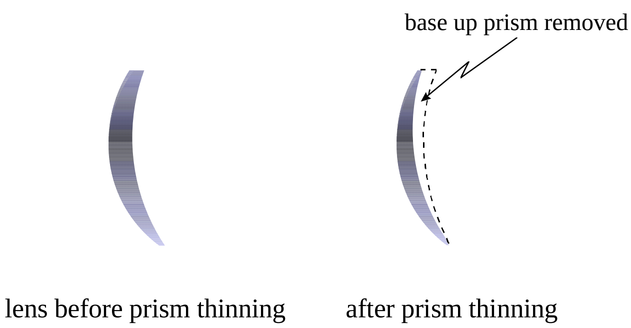


Figure 11. Prism thinning a progressive power lens

It is sensible to apply an antireflection coating to any lens which incorporates prism in order to eliminate the possibility of the ghost image which is formed by total internal reflection at the lens surfaces being of annoyance to the wearer.

Fitting progressive power lenses
A suggested fitting routine for progressive power lenses is as follows.
1. Select the final frame that the subject is to wear and adjust it to fit properly. As a general guide, the frame should be closely fitting with the smallest possible vertex distance and the correct pantoscopic angle and should provide adequate depth beneath the centre of the pupil to accommodate the reading zone of the lens. A minimum depth of 22mm is often suggested.
2. If the frame is empty, attach vertical strips of transparent adhesive tape to each eye to enable reference points to be marked, otherwise the fitting cross positions can be marked on the existing lenses.
3. With the correctly adjusted frame in position, ask the subject to look straight into your eyes. If necessary, adjust the height of your stool to ensure that your eyes are on exactly the same level as that of the subject.

4. Direct the subject to look straight into your open left eye and using a fine-tip marking pen and, preferably, a light coloured ink, place a dot in front of the centre of the subject's right pupil.
5. Direct the subject, without moving their head, to look straight into your right eye and place a second dot in front of the centre of their left pupil.
6. Remove, and replace the frame on the subject's face and repeat the above procedure, this time without making any marks, to ensure that the dots which you have marked do lie in front of the centres of the pupils.

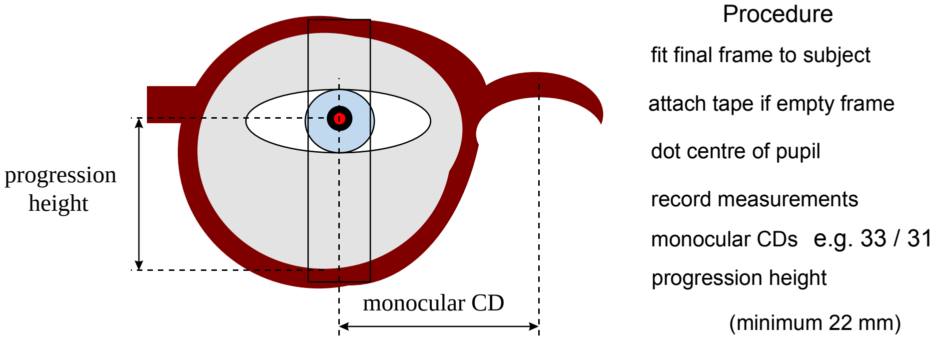


Figure 12. Fitting progressive power lenses

Record the positions of the fitting cross positions and check by means of an appropriate blank sizing chart that the lenses can be obtained from the available blank diameters given by the charts. When ordering the lenses it is necessary to give the progression heights (the heights of the fitting crosses) together with the monocular CDs measured from the centre of the bridge of the frame, which is the reference point for the glazing department. It is very common for the monocular CDs to differ between the right and left eyes, and the specification should be written, for example, as **34/32** which indicates that the right eye monocular CD is 34 and the left eye monocular CD is 32. The heights of the pupil centres may also differ for the right and left eyes. Ideally the progression heights should be specified from the horizontal centre line of the frame, such as 4mm above HCL. There should be a minimum progression height of 22mm to ensure that the near portion is large enough to provide an adequate field of vision.
It is sensible, whenever possible, to dispense a frame which allows some vertical adjustment of the height of the distance reference point at, or subsequent to, the final fitting. This enables the lenses to be raised or lowered, if this is found to be necessary, to aid adaptation.

Verification of progressive power lenses
When the lenses have been mounted they are normally returned with stickers attached to assist in verifying the powers of the lenses and the progression heights. Typically, the lenses will appear as shown in the Figure 13.

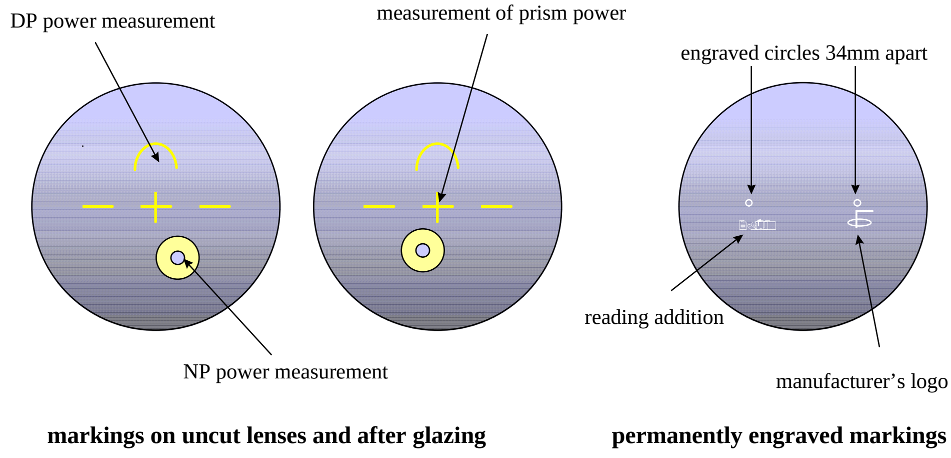


Figure 13. Markings found on progressive power lenses

The upper painted circular line is for the measurement of the distance prescription. The circular sticker at the bottom of the lens is for checking the power of the near portion. The prismatic effect of the lens is checked at the painted cross at the geometrical centre of the lens which is the usual prism reference point. Normally, any prism found at this point is thinning prism that has been incorporated to equalise the thickness at the top and bottom edges of the lens.

When these lines are removed, the progression height and orientation of the surface can still be determined by locating two small circles which have been engraved on the convex surface 34mm apart on the horizontal centre line of the blank. The geometric centre of the original blank lies midway between these two circles. The reading addition of the lens is also permanently engraved under the temporal circle and the manufacturer's identifying mark is engraved under the nasal circle. These markings are easiest to detect by reflected light from a strong source above the lens and with the lens being held in front of a black background. In the case of plastics lenses the engravings are often made easier to detect by the application of a fluorescent dye to the engravings which fluoresce when illuminated with ultra violet radiation from a UV source.