# PHYSICAL AND PSYCHOPHYSICAL ANALYSIS OF PROGRESSIVE ADDITION LENS EMBODIMENTS

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# Physical and psychophysical analysis of progressive addition lens embodiments

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The extent to which the surface parameters of Progressive Addition Lenses(PALs) affect successful patient tolerance was investigated. Several optico-physical evaluation techniques were employed, including a newly constructed surface reflection device which was shown to be of value for assessing semi-finished PAL blanks. Detailed physical analysis was undertaken using a computer-controlled focimeter and from these data, iso-cylindrical and mean spherical plots were produced for each PAL studied. Base curve power was shown to have little impact upon the distribution of PAL astigmatism. A power increase in reading addition primarily caused a lengthening and narrowing of the lens progression channel. Empirical measurements also indicated a marginal steepening of the progression power gradient with an increase in reading addition power.

A sample of the PAL wearing population was studied using patient records and questionnaire analysis(90% were returned). This subjective analysis revealed the reading portion to be the most troublesome lens zone and showed that patients with high astigmatism(>2.00D) adapt more readily to PALs than those with spherical or low cylindrical(≤2.00D) corrections.

The psychophysical features of PALs were then investigated. Both grating visual acuity(VA) and contrast sensitivity (CS) were shown to be reduced with an increase in eccentricity from the central umbilical line. Two sample populations(N=20) of successful and unsuccessful PAL wearers were assessed for differences in their visual performance and their adaptation to optically induced distortion. The possibility of dispensing errors being the cause of poor patient tolerance amongst the unsuccessful wearer group was investigated and discounted. The contrast sensitivity of the successful group was significantly greater than that of the unsuccessful group. No differences in adaptation to or detection of curvature distortion were evinced between these presbyopic groups.

**Keywords** Progressive addition lenses, varifocal, physical investigation, psychophysical responses, visual performance.

## DEDICATION

To my parents

E. W. and E. W. SULLIVAN

with thanks for all your help and encouragement.

### *"Light"*

Any study in optics, indeed life on Earth itself, would be impossible without the form of energy we call *Light.* Alf McCreary of Queen's University, Belfast captures the magnificence of *Light* in his book 'This Northern Land'......

......In Genesis the creation of *Light* came first and the reality of *Light* is all around. Signs and seasons, days and years; it filters through morning mists, tumbles off hillsides and crags, sweeps across oceans and seas, cascades down deep river gorges, and shimmers through the glades of leaf and fern in the heart of the great forests. It surges in the noon-day heat, fades and dies in the last rays of the evening sun......

......Though men and women may change, empires blossom and wither, the magnificence of *Light* straining from on high has remained unaltered since time began. *Light,* like the rain from Heaven, falls on the just and the unjust, and now, as then, illuminates the lives of those who look to greater things......

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The Controller of Her Majesty's Stationery Patent Office for permission to reproduce extracts from United Kingdom patents, which are subject to Crown Copyright and the Superintendent of Documents at the US Government Printing Office, Washington, DC for permission to reproduce extracts from US patents.

All patients who acted as subjects for the psychophysical studies.....
......and finally and by no means least Dr. A. Jayne Kempster, who was the first to encourage me to embark upon this study.

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# Chapter 1

## GENERAL INTRODUCTION

### 1.1 PROBLEMS ASSOCIATED WITH PRESBYOPIA

The young human eye has the ability to change its refractive state by altering the shape of the crystalline lens. This property known as 'accommodation', has been defined by Davson (1972), as the increase in refractive power of the eye resulting when the image of a near object is brought into focus on the retina. The difference in refractive power of the eye when focusing (a)an infinite object and (b)the nearest object capable of being seen in sharp focus is called the amplitude of accommodation. Many workers have shown that the amplitude of accommodation decreases progressively with age. The resulting difficulty with near vision is known as presbyopia in older age groups. An anatomical diagram of the human accommodative mechanism is given in Figure1.1.

A number of theories have been proposed to explain the development of presbyopia(Fincham,1937; Weale,1962). It has been suggested that presbyopia may be due to hardening or sclerosis of the crystalline lens substance, weakening of the ciliary muscle and/or a loss of elasticity in the lens capsule. Paterson(1977) states that it is now largely accepted that presbyopia results due to lenticular sclerosis - a progressive hardening of the crystalline lens with age, although a reduction in capsular elasticity may also make some contribution. Duane(1922) has shown that a 10 year old child may increase the power of its eye by about 14 dioptres but by the time this subject is a 55 year old adult, the amplitude of accommodation may be less than 1 dioptre(Figure 1.2).

It is difficult to predict when any given individual will find the gradual reduction in his/her amplitude of accommodation troublesome. A number of workers(see Weale,1963) have attributed such factors as race, refractive error, sex, occupation, and general health to be significant and most people begin to notice the effects of presbyopia when in their fifth decade. A patient

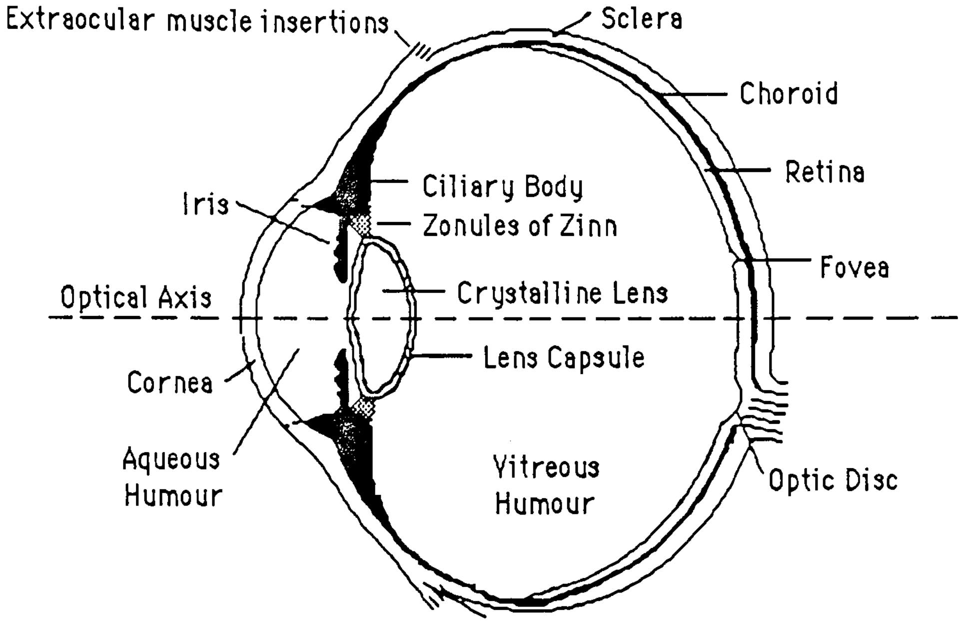


*Figure 1.1.* Schematic diagram of a human eye in cross-section, showing the important anatomical features of the accommodative mechanism.

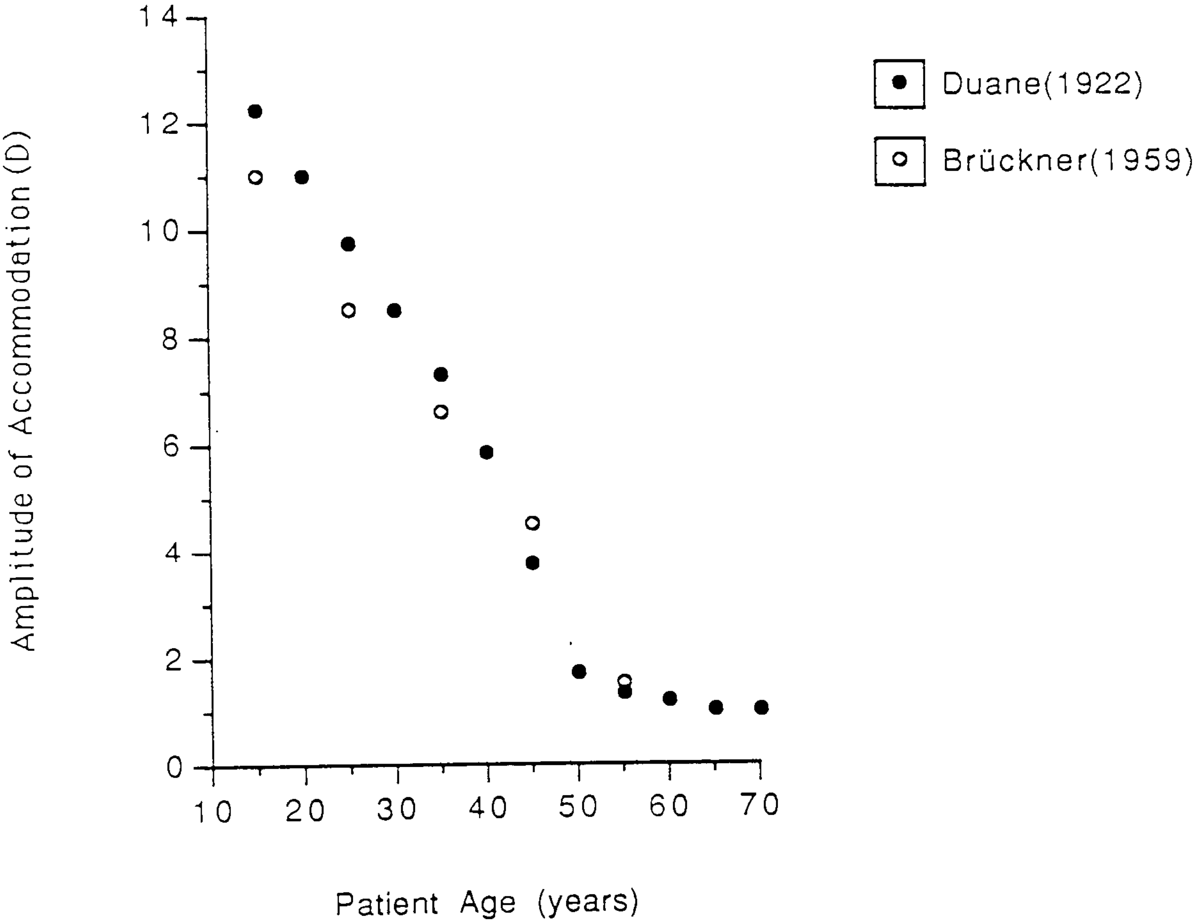


*Figure 1.2.* The work of Duane(1922) and Brückner(1959) presented together showing that the amplitude of accommodation reduces slowly but steadily with age. Most subjects first find this amplitude reduction troublesome when in their fifth decade of life.

will present with reading difficulties when the amplitude of accommodation has fallen to the point where near objects can no longer be viewed in clear focus. Before the advent of reading spectacles presbyopia was a visually debilitating condition which restricted the work of many early scholars. Early reading spectacle lenses consisted of positive powered spherical lenses which supplemented the loss of accommodation in the human eye. Later, the distance prescription was considered when arriving at the optimum reading prescription. Benjamin Franklin is thought to have been the first to incorporate the distance and reading prescription into the same pair of spectacles producing the first pair of bifocal lenses in 1784, although there is some evidence that G.Herlet may have developed a similar split lens earlier in the 18th century.

Many types of bi and trifocal lenses have been designed and produced since the early split bifocal designs. All multifocal lenses provide a number of fixed foci for the patient to view objects clearly at predetermined distances and in this respect they do not fully reproduce prepresbyopic vision for the presbyope. The prepresbyope is capable of viewing objects in focus at any distance which lies within his/her amplitude of accommodation. For a spectacle lens to allow a presbyope this facility the lens must possess a variable change in power in order to view objects from infinite to near working distances. Aves(1907) was the first to patent a 'varifocal' lens and there have been a number of different variable focus designs since his patent was granted. The majority of them have comprised an aspheric anterior surface with an intermediate progressive zone between largely spherical distance and near portions. Progressive addition lenses were developed solely with the presbyopic patient in mind and the majority of lenses prescribed are for this purpose. However, a number of clinicians (Smith,1985; Jacob *et al*,1980; Preston and Roth,1979) have found other uses for them within the field of orthoptic treatment for accommodative esotropia and pseudoaccommodation. The physical characteristics and the ability of patients to successfully wear this type of variable focus lens, known as a progressive addition lens(PAL), are the major topics of this thesis.

## 1.2 AIMS OF PROJECT

Progressive addition spectacle lenses are made with an anterior surface which comprises a complex non-rotationally symmetrical topography. This type of lens design can create adaptation difficulties for patients in addition to verification problems for the manufacturer, the prescription house and the optometrist.

The previous research undertaken in this area has largely concentrated upon qualitative methods of optico-physical evaluation for which there are no generally agreed or standardised methods of assessment. This thesis considers a number of physical parameters which may be applied to PALs and considers whether these measures are an appropriate means by which to judge and grade PAL design integrity.

One problem, associated with selecting a physical measure to grade PALs by, is that the importance of any given parameter may alter from one lens design to the next depending upon the emphasis placed upon that parameter by the manufacturer. A lower value of a chosen parameter may not indicate an inferior or less appropriate lens. The technique employed for physical assessment may also be varied. When considering literature regarding comparative analysis of PAL designs it is important to be aware of the measurement technique adopted. The study in this thesis considered the results which can arise with a number of different techniques.

Accepting the importance of the physical characteristics, both Köppen(1987) and Diepes and Tameling(1988) indicate the need to also employ psychophysical assessment techniques when considering the properties of PALs. Physical assessment may be more straightforward than psychophysical assessment because it is less time consuming, does not involve the patient, and it involves more definite values, which may be recorded to a high degree of accuracy. However, physical factors do not indicate the ability of a patient to tolerate such lenses and the final judge of an ophthalmic product must be the ability of patients to successfully wear their lenses.

The aim of this thesis was therefore not only to establish how certain physical parameters affected the overall physical characteristics of PALs but also to note the effect of these characteristics upon the psychophysical responses of PAL wearers. To undertake this investigation the properties of a sample of the PAL wearing population were studied using patient records and questionnaire analysis. It was then possible to select patients from this distribution and to compare the psychophysical responses of successful and unsuccessful patients. Any differences which exist between these groups might then be attributable factors which affect a patient's tolerance to PALs. The psychophysical factors studied in this thesis are; measures of visual performance through PALs - both grating visual acuity and contrast sensitivity evaluation, and the ability of patients to detect and adapt to optically induced curvature distortion.

Possible alternative factors for patient intolerance also need to be investigated. It is not possible to consider all the possible factors for PAL intolerance. However, such matters as dispensing anomalies and unsuccessful wearers wearing incorrectly manufactured lenses are amongst the most obvious alternative causes for patient intolerance which require investigation. Irrespective of the results of this thesis there is much work to be done in the area of PAL investigation both in the optico-physical area and especially in the psychophysical field. With this in mind, another important inherent aim in this study was the collation of a pertinent literature and patent review which might be of use to all workers in the field.

# Chapter 2

## PATENT LITERATURE REVIEW AND ANALYSIS OF PROGRESSIVE ADDITION AND VARIABLE FOCUS LENSES

### 2.1 INTRODUCTION

This chapter reviews developments in the field of progressive addition spectacle lenses and variable focus lens systems design. The first reviews in this field were undertaken by von Rohr(1916), Graham(1942), and Bennett(1970). It is the aim of this chapter to give an historical account of the development of progressive addition and variable focus lenses, and to assess and classify the recent patent literature in this field. A brief account of the work documented by the aforementioned workers is presented, however it is largely a sequel to work which has been previously documented. A largely verbal description is employed because patent literature is often devoid of mathematical models.

Ophthalmic spectacle lens systems with variable focal length have been categorised by Bennett (1970) as follows:

(1) Variable power lenses or lens systems which can be adjusted to alter their power over the whole effective aperture; for example:

   (a) systems depending on a variable separation between the component lenses,

   (b) systems depending on adjustable sliding contact between the components,

   (c) deformable lenses.

(2) Progressive power lenses with a continuous change of power over a predetermined area(Figure 2.1).

The term "progressive" may be applied to any lens surface of changing curvature. Therefore, it may apply to an aspheric lens with similar changes in all radial meridians of the lens or to a progressive addition lens with changes limited to the inferior portion of the lens.

*Figure 2.1.* Diagram showing the continuous change of power over a predetermined area of a progressive addition lens(diagram of Varilux V2 taken from Horne,1978). The front surface curvature of the lens is based upon a changing series of conic sections.

## 2.2 SUMMARY OF EARLY DEVELOPMENTS

The first patent of a progressive power lens was granted to Aves(1907). The progressive property of Aves' design resulted from the combined effect of both surfaces. One surface (with vertical section *AB* in Figure 2.2.) resembled a convex cylinder axis horizontal, with its profile forming part of the lower half of an ellipse of which the major axis was vertical. This means that the radius of curvature decreases in a vertical section towards the bottom of the lens. The second surface (with vertical section *DG* in Figure 2.2.) was a portion of the surface of a cone, axis vertical and apex downwards. The effect of this surface was to give horizontal sections with decreasing radius towards the bottom of the lens. When the two surfaces were combined the resulting biconvex lens possessed a progressive increase in spherical power from the top of the lens downwards. This design was of limited usage as it did not allow for the incorporation of cylindrical power and was only suitable for hypermetropic presbyopes.

Poullain and Cornet (1910) produced a lens with a progressively increasing surface curvature worked onto a single surface. The progressive surface had a vertical umbilical dividing the lens. Bennett (1970) likened this surface to the anatomy of an "elephant's trunk". This is shown in Figure 2.3. If the elephant trunk is bent backwards as shown in the diagram, the convex curvature along the line CS will increase continuously from the top downwards. This line, CS, is analogous to the umbilical line of an ophthalmic lens at every point of which the horizontal curvature is similar to the vertical curvature. An umbilic or umbilical point may be defined as a point on a surface at which the curvature is the same in all directions. An umbilical line is the locus of such points.

The term median line is used by many designers to describe the principal line connecting the distance and reading portions of a progressive lens. The median line bisects the intermediate portion vertically. Unlike the umbilical line definition the term median line does not indicate the nature of the lens surface. Therefore the term median line may be used in the description of an umbilical line but not vice versa.

Volk and Weinberg (1962) noted that an "elephant trunk" surface produced the same effect as a combination of two of the quasi-cylindrical surfaces of the type employed by Aves, for the anterior surface of his lens design, when their axis meridians were orientated at 45° and 135°. Figure 2.4 gives an analysis of the surface power distribution for an "elephant trunk" surface.

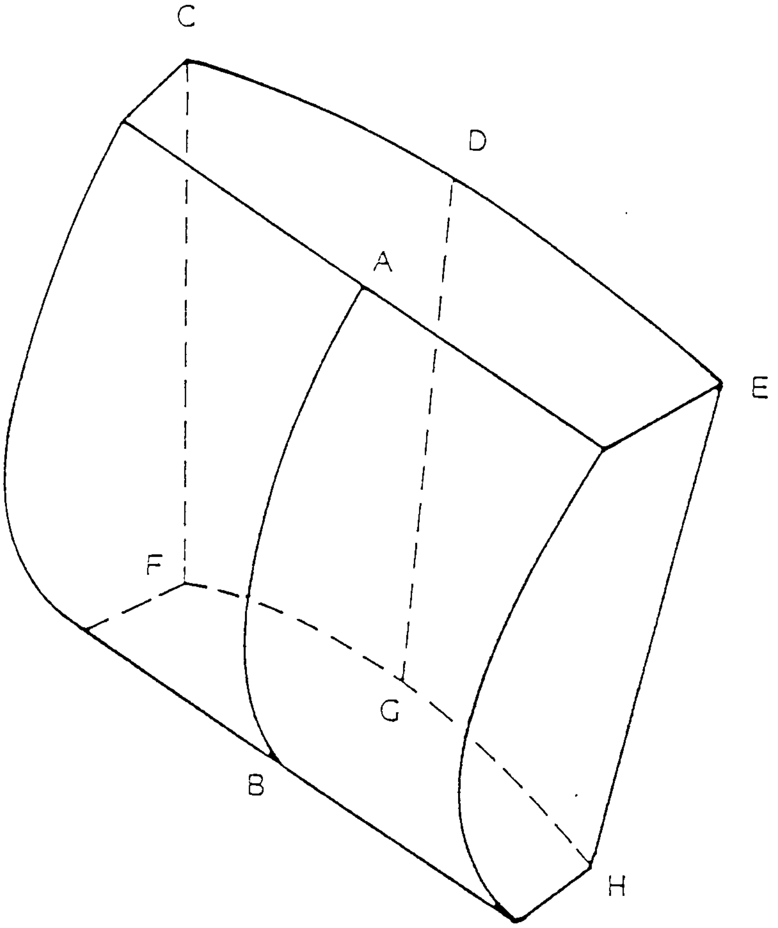


*Figure 2.2.* A schematic illustration (after Bennett,1970) showing the Aves(1907) lens. One surface is a horizontally orientated cylinder in which the power increases continuously from *A* to *B*. The second surface of the lens consists of a portion of a conical section with a vertical axis and an inferior apex. It can be seen from the diagram that the curvature of arc *FGH* is greater than *CDE*.

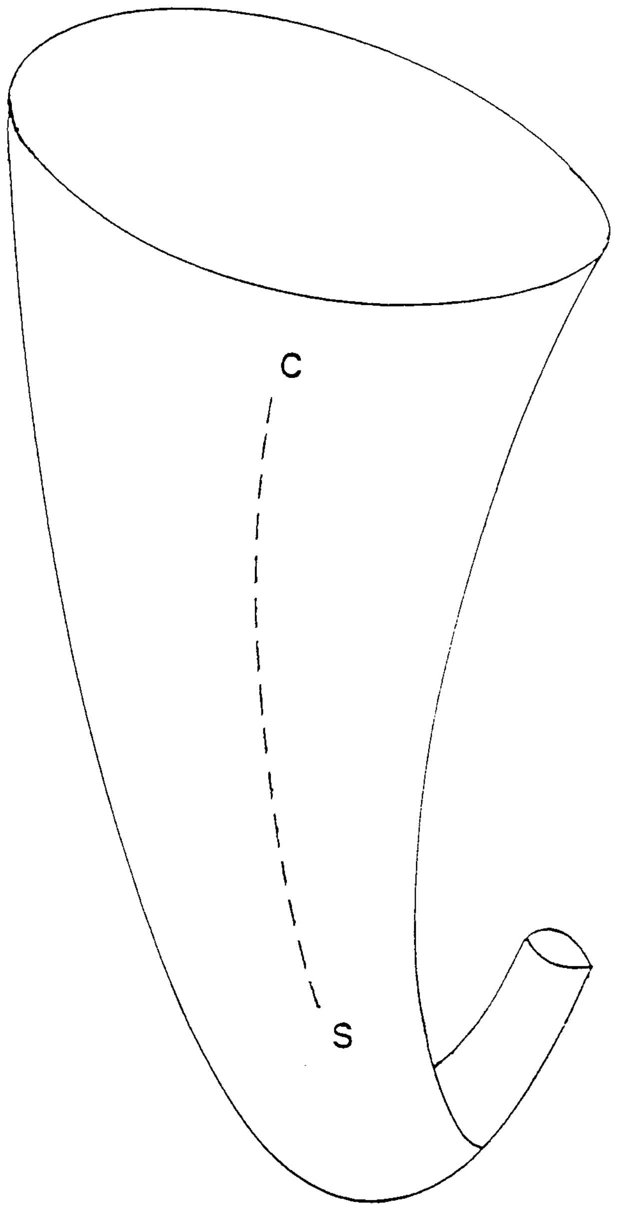


*Figure 2.3.* A sketch illustrating the concept of the "elephant trunk"surface (after Bennett,1970). *CS* denotes the umbilical line. At each point along this line the horizontal and vertical curvatures are equal. This surface cannot be produced by spinning a conic section about a central axis; hence it is not a surface of revolution.

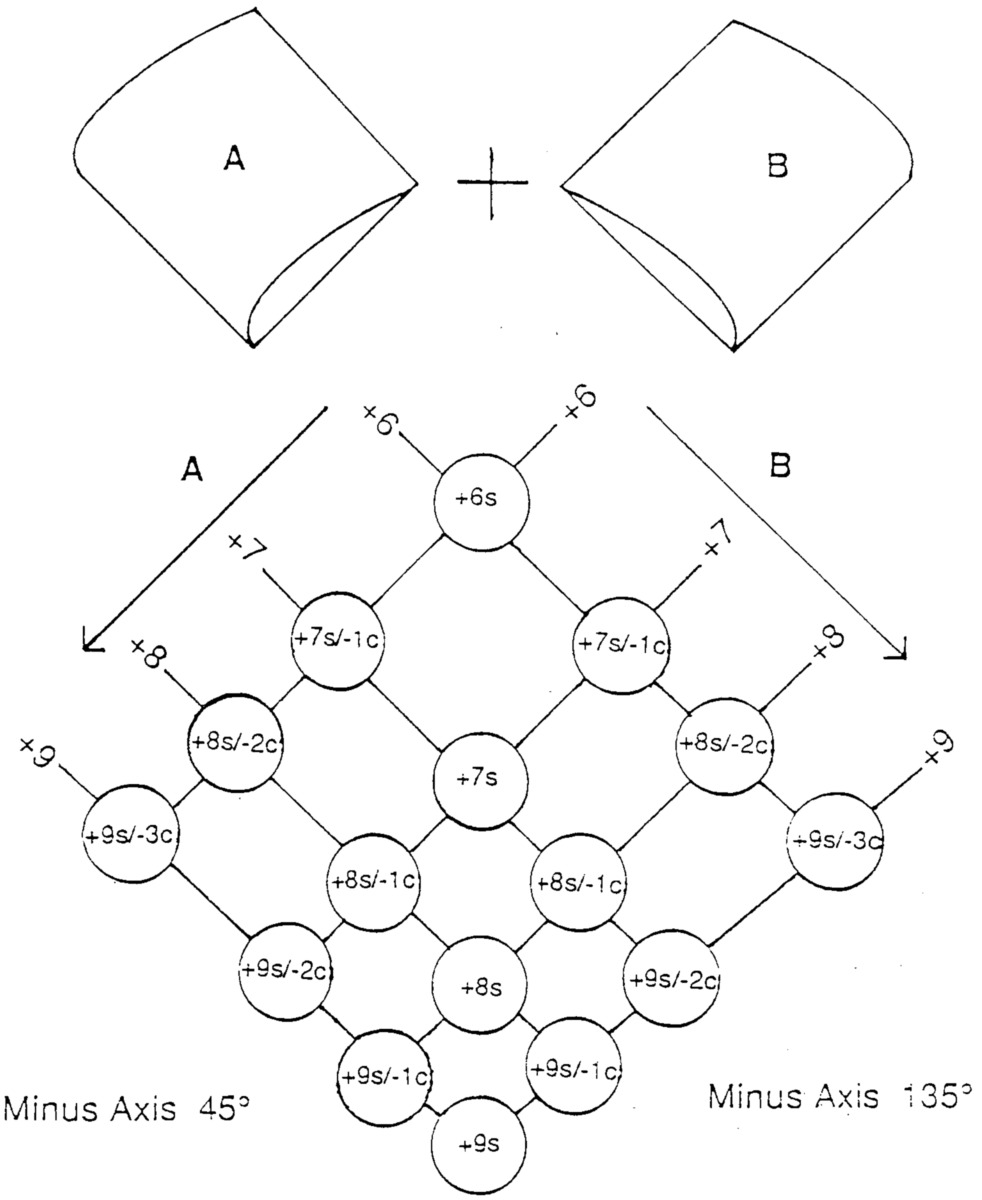


*Figure 2.4.* This diagram, reproduced from Bennett(1970), is a schematic plot of the effective power produced by two cylinders, *A* and *B* , of the type used by Aves, when situated at 45° and 135° respectively. If each cylindrical element is considered to produce a power variation from +6.00D. to +9.00D. then the sum of the resultant effect may be deduced at any point on the lens surface, as shown in the diagram. The power increases from the top of the lens downwards. In the central portion along the median line the power is essentially spherical,whilst, the peripheral portions of the lens represent the areas of greatest astigmatism.

The power which results from these two cylindrical elements is maximum perpendicular to the axis meridians. When the cylinders are combined the sum of the two elements can be expressed at any point in a sphero-cylindrical manner. Along the median line the resultant power is spherical and the power increases from the top of the lens downwards. The maximum astigmatism is found in the peripheral portions of the lens surface. The astigmatism increases with perpendicular distance from the median line at twice the rate of the power increase along the line of symmetry. Therefore, if the rate of power increase along the line free of astigmatism is 1.00D per cm at any given point on that line; cylinder power will develop at twice the rate i.e., 2.00D per cm in a direction perpendicular to the line of symmetry at the level of the said point. The advantage in this style of lens, over the Aves construction, was that it allowed the patient's prescription to be ground onto the posterior surface of the lens and this could include a cylindrical element if necessary.

It should be noted that the "elephant trunk" surface does not have axial symmetry and subsequently is not a surface of revolution. This created some difficulties for a number of manufacturers at the early part of the 20th century. Therefore a number of workers employed techniques involving a surface of revolution. Gowlland(1914) produced a lens encompassing progressive power by the use of an aspherical surface of revolution. His lens, which was the first to be produced commercially (Duke Elder,1928), consisted of an anterior toroidal surface and a posterior paraboloidal surface. This design is unusual in that the progressive surface was found on the concave surface of the spectacle lens.

An alternative method to that of Gowlland(1914), which also involved a surface of revolution was first proposed by Bach(1958) and gave a better control over astigmatism. Figure 2.5 demonstrates the design of this surface, which was classified by Bennett as homastigmatic. This name describes the uniform spread of astigmatism, in a controlled fashion, over the surface of the lens. This compares with nonhomastigmatic lenses in which the astigmatism increases continuously from the median line towards the periphery. The homastigmatic surface is produced by displacing the axis of revolution to *EE* in order to shorten the sagittal radii in such a way as to equalise (or very nearly so) the astigmatism at all points along *AD*. This astigmatism is then neutralised by incorporating an equal cylinder of opposite sign in the power of the concave surface of the lens.

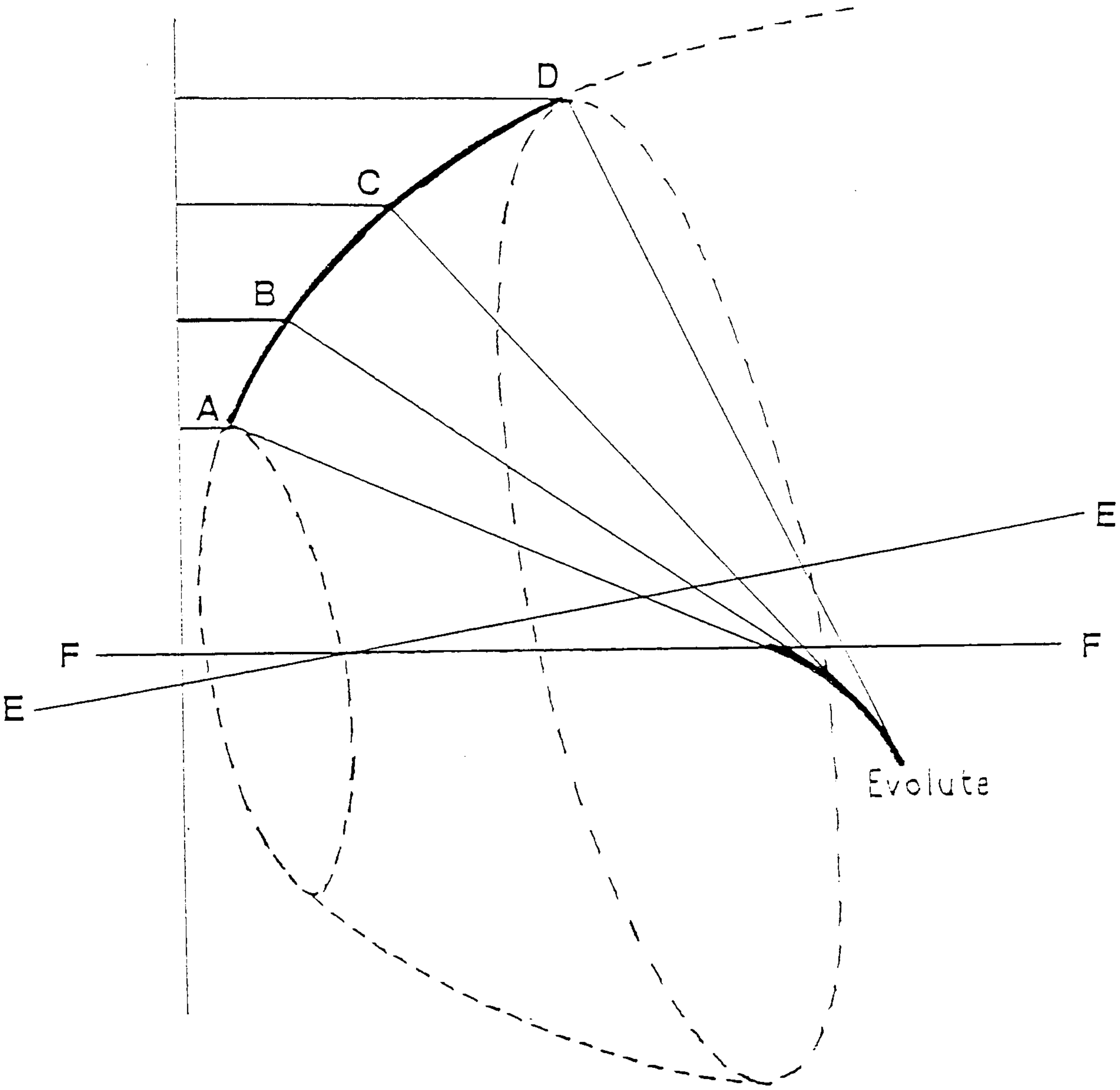


*Figure 2.5.* A geometric construction which shows the homastigmatic construction described by Bennett(1970). *AD* is a section of an ellipse with the major axis denoted by *FF* . If *EE* were chosen as the axis then the construction remains a surface of revolution. However,while the tangential centres of curvature of points *A,B,C,* and *D* remain on the evolute, the sagittal centres of curvature are now situated on *EE* rather than *FF*. This has the effect of producing a progressive surface, analogous to a surface of elephant trunk construction, but with a relatively uniform distribution of astigmatism.

Another approach, first suggested by Paige(1918), but not commercially available until patented by Beach(1946), involved a surface of revolution arranged in a concentric fashion. In its simplest form this lens could be likened to a blended bifocal. However, rather than having an optically poor area between the distance and reading portions there was an annular zone of progressive power (see Figure 2.6). For the various portions to merge in a continuous fashion the lens surface was concave in the tangential meridian over a small zone at the junction of the intermediate and distance portions. However, in the sagittal direction the lens curvature remained convex which gave rise to a negative addition combined with a high plus cylinder when passing from the distance to the intermediate portion.

All the techniques of producing progressive power noted above involve a change in the vergence of light through the variation in surface power of a lens with a uniform refractive index. It has been suggested by a number of workers, for example Spiegel(1950) and Bugbee(1924), that the use of gradient index refractive material might be a suitable alternative. Charman(1982) notes that with current technology it is theoretically possible to produce sufficient magnitudes of index change to enable the creation of a varifocal lens. However, the ability to accurately manufacture index gradients for spectacle lenses without problematical aberrations, has not been tested commercially.

## 2.3 STUDY OF OPHTHALMIC PATENTS

The assessment of ophthalmic lens patents can prove to be an arduous task with few rewards. Problems arise as the standard of technical description varies greatly between patents. Some are largely verbal accounts omitting any mention of a mathematical model and those that involve an algebraic approach do so in a variety of ways and this makes comparative assessment very difficult. It is the aim of many patent applications to obtain an adequate patent without revealing detailed information concerning the lens design. These problems arise largely because of the commercial pressures inherent in any kind of marketable product. Unchallenged claims which do not tolerate detailed scrutiny are common. For example, a number of patents claim to have eliminated astigmatism, although, von Minkwitz (1963) concluded it is not possible to produce a progressive addition lens without surface astigmatism and distortion being present at some point. Furthermore, the variety of different diagrammatic representations employed often relate only to the progressive surface and ignore the oblique astigmatism and distortion inherent in all ophthalmic lenses. Therefore, it is seldom possible to evaluate the resultant aberrations apparent

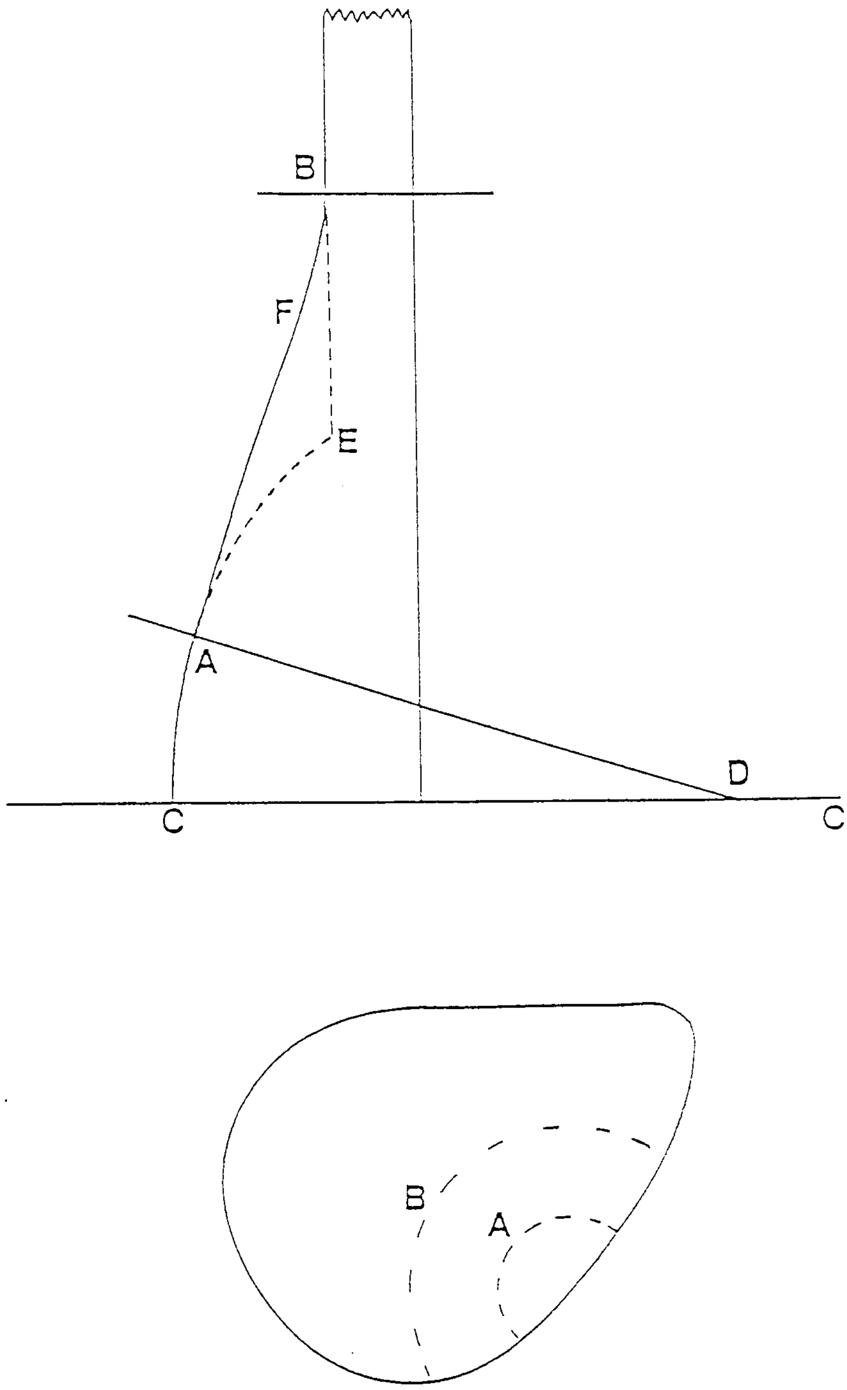


*Figure 2.6.* This diagram (redrawn from Bennett,1970) illustrates a concentric type progressive power lens. The progressive zone lies between *A* and *B*. The upper diagram represents a section through a lens blank. *CC* denotes the axis of revolution of the lens blank and *D* is the centre of curvature of the near addition. If produced the surfaces of the near and distance portions would meet at point *E* in a similar fashion to a front surface solid bifocal. *AB* represents the intermediate progressive portion. To ensure there are no breaks in the surface topography of the lens it is essential that the near and progressive zones share a common normal *AD* at their point of intersection, and that the progressive and distance zones have a common normal at *B*, where they meet. The lower diagram is a front view of the finished lens.

to the wearer by studying the ophthalmic patent.

## 2.4 THE WORK OF B.F.MAITENAZ

Maitenaz(1966) designed the first commercially successful progressive addition lens, under the proprietary name of "Varilux"in the 1950's. This lens design evolved through four stages before the commercial form with stabilised vision in both the distance and reading zones was produced (see Figure 2.7).

The progressive surface was worked on to the anterior surface of the lens and divided into three separate portions. The upper distance half of the lens was spherical, used for distance vision and was the largest of the three zones. It was bounded inferiorly by a surface of "elephant trunk" construction. This formed the intermediate zone which merged into a largely spherical near vision portion.

The Varilux 2 lens, which succeeded the aforementioned Varilux or V1 lens became the first of the 'second generation' progressive lenses (Fowler,1986). Derivation of this second lens, known hereafter as the V2 lens, resulted in a departure from many of the principles applied to the design of previously patented progressive addition lenses.

In the V1 design aberrations caused by distortion, surface astigmatism and curvature of field are well controlled along the umbilical line between the distance and near portions of the lens (Maitenaz,1966). Adjacent to the umbilical line, on either side, there was a narrow corridor with similar properties to the umbilical line in terms of reduced distortion,surface astigmatism and field of curvature but the peripheral portions of the lens were characterised by the effects of especially noticeable aberrations.

The V2 lens (Maitenaz,1972) was designed to overcome some of the problems associated with these peripheral aberrations by ensuring that the lateral reading areas were less affected by surface astigmatism and distortion. Maitenaz avoided high concentrations of surface astigmatism and distortion by spreading the aberrations more widely over the lens surface. To ensure greater comfort for the majority of wearers, Maitenaz thought it necessary to provide a reduction in the rate of variation of distortion from the umbilical line to the lateral portions of the lens. Astigmatism was less rigidly controlled in the transition zone of the V2 lens than that of the V1. Maitenaz claimed, that despite the presence of increased aberrations within the transition zone of the V2 lens, astigmatism remained below the patient's perceptive threshold. The Varilux 2

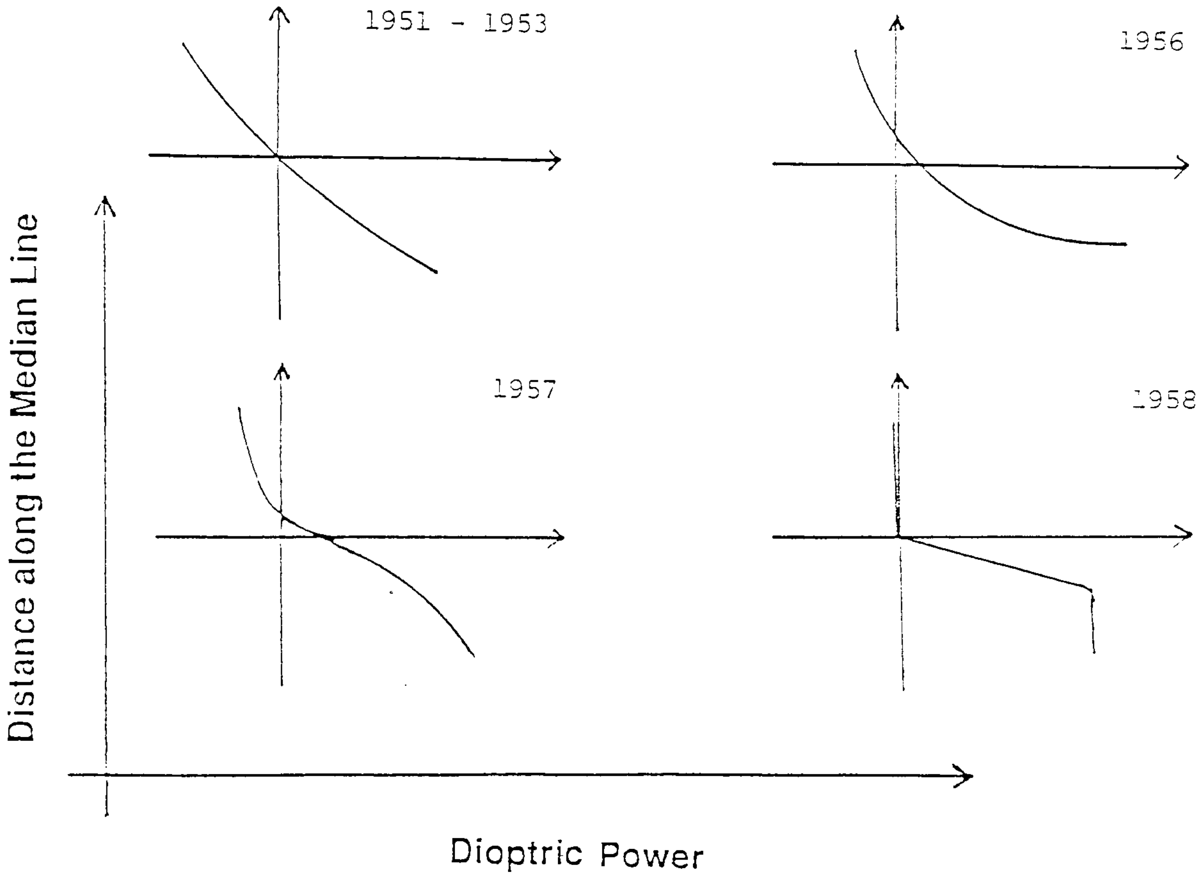


***Figure 2.7.*** A schematic diagram after Maitenaz(1966) showing the power variations obtained from the top of the lens downwards, over the four surfaces studied prior to the production of the first Varilux lens. The *x* axis represents dioptric power and the *y* axis denotes distance along the umbilical line.

(1) Virtually linear variation 1951-1953
(2) Reduced variation in distance vision 1956
(3) Reduced variation in near vision 1957
(4) Stabilised distance and near vision 1958

lens had the effects of surface astigmatism and distortion spread over a greater area of the lens in order to reduce the gradient of surface curvature.

## 2.5 DYNAMIC AND STATIC VISION

Maitenaz (1972) introduced the concept of "dynamic" vision, as opposed to "static" vision, into progressive addition lens design. Dynamic vision, the movement of the patient's eyes relative to the object of regard will occur when there is a shift in one or more of the following; the patient's head, the patient's eyes, or the object of regard. Maitenaz considered "static" vision to be a somewhat artificial idea because even if wearers move their heads to view an object of regard directly they cannot control the movement of objects within their field of view. He regarded the rate-of-change of distortion over a surface to be a more significant factor, when judging patient tolerance, than the actual numerical value of distortion at any given point. The philosophy of dynamic vision, as epitomised by the V2 lens, allowed greater comfort to the majority of wearers, but at the cost of a smaller area completely free from distortion and surface astigmatism.

Maitenaz (1974) assumed 0.3 D to be the limit of spectacle lens astigmatism tolerated by the human eye. Davis (1978) regarded 0.5 D to be the tolerable limit to surface astigmatism whilst Shinohara and Okazaki (1985) found values up to 1.00 D to be acceptable. Adopting a less stringent criterion of useful vision does not by itself worsen the performance of any lens. However, it has the effect of increasing the relative size of the "useful" distance and reading portions which may be commercially appealing.

If the region of a lens having lower astigmatism is designed to cover a greater surface area in order to obtain good static vision, the magnification changes abruptly in the lateral portions of the lens. The result of this is a deterioration in dynamic vision as distortion of images becomes more pronounced. Conversely, to improve dynamic vision the region of lower astigmatism in the distance and near portions is reduced, which adversely affects static vision.

Shinohara and Okazaki(1985) implemented a series of tests based on linear progressive portions of varying length. Controlled psychophysical studies were conducted on these sample lenses and it was by this means that they concluded the tolerable limit of surface astigmatism, within the progressive corridor to be 1.00D. Shinohara and Okazaki regarded the gradient of the surface power variation to be the most significant measure of patient tolerance. The dynamic vision design of the lens patented by Maitenaz (1972) was also based not upon the numerical value of astigmatism at any given point on the lens surface but rather upon the rate-of-change of surface power.

Atchison (1987) has described progressive addition lenses as being either "soft" or "hard"; hard lenses being similar to the static design category of Maitenaz with the aberrations confined to small areas and the soft design being analogous to Maitenaz's dynamic lens classification with the aberrations being more diffusely spread. The difference between hard and soft designs is shown schematically in Figure 2.8. The balance between dynamic and static vision is one of the most important factors in the design of second generation progressive addition lenses. Indeed, the difference between the various modern designs of progressive addition lens is essentially the difference in the degree of emphasis given to either dynamic or static vision.

## 2.6 SHORTER OR LONGER PROGRESSION LENSES

The majority of progressive addition lens research following the launch of the V2 lens has tended towards one or other of the two main techniques employed in the reduction of surface astigmatism. Firstly, it is possible to have a uniform distance portion in the upper half of the lens which allows uninterrupted distance vision. The progressive zone is shorter in lenses of this design and this results in a relatively greater degree of astigmatism, although, it is concentrated into a smaller area, as noted by Davis (1978). The aberrations are concentrated, by the designer, into the least commonly used areas of the lens on either side of the median line, in the intermediate portion. It would be unlikely for a patient wearing a pair of these lenses to find reading tasks troublesome, although, following a moving object might prove more difficult and in a few cases this task might give rise to asthenopic symptoms. Consequently, lenses of this type are best suited to the requirements of "static" vision.

Alternatively, it is possible to reduce the intensity of astigmatic aberrations by spreading them over a greater area. This approach necessitates astigmatism in the periphery of the distance portion. The V2 lens follows the broad principles of this latter design. Such lenses are characterised by having a longer and wider progressive zone than those designed for static vision. A progressive addition lens with a reduced rate-of-change of dioptric power is better suited to the needs of dynamic vision. Furthermore, a progressive addition lens with a shorter progression length, designed for static vision will tend to have a more abrupt dioptric change along the umbilical line at the distance/intermediate and

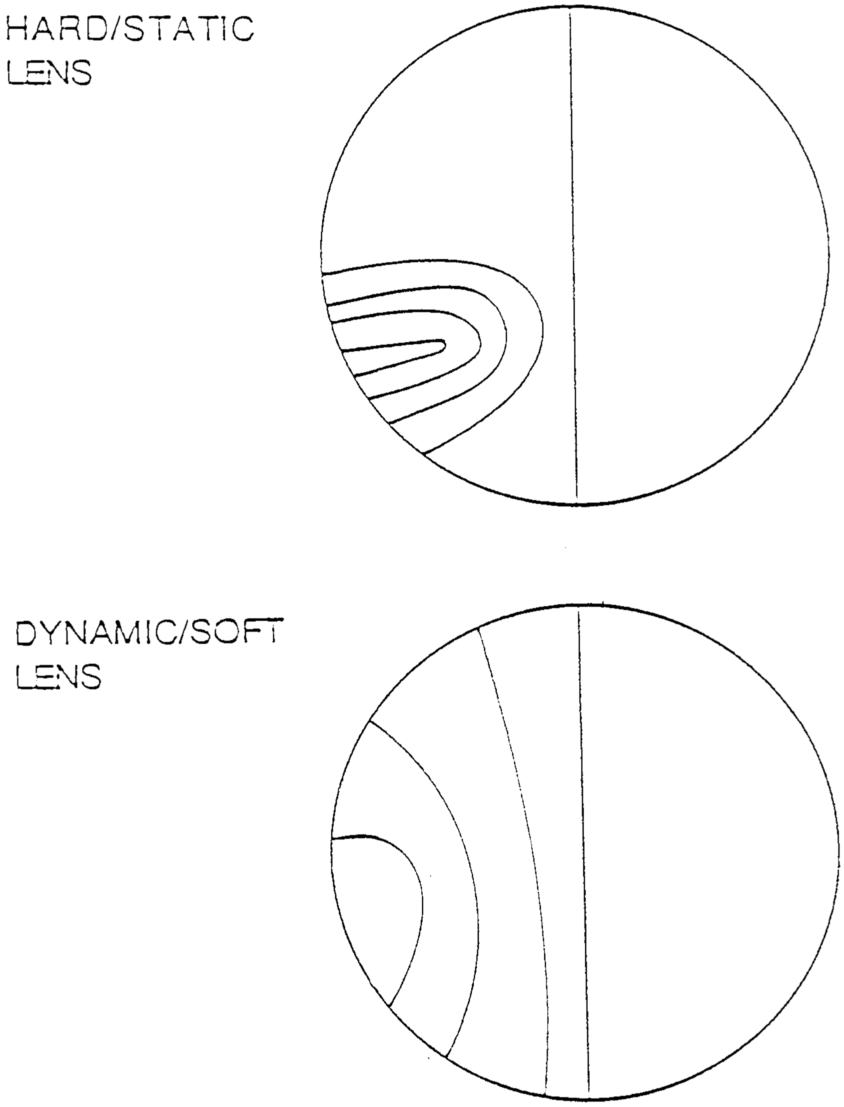


*Figure 2.8.* This diagram is a schematic representation showing the distribution of astigmatism in a contoured fashion for the two lens design philosophies. Astigmatism is shown for one half of each lens. The sketches show the relative spread of surface astigmatism: in the hard design it is concentrated into a smaller area but is subsequently of a higher degree, whilst in the soft design it is spread more widely but is of a lower order.

intermediate/reading junctions. This compares with a longer progression lens design suitable for dynamic vision, in which the zone junctions are less clearly defined.

### 2.6A Shorter Progression Lenses

Maitenaz (1974 ) patented a lens different from the V2 (see Maitenaz 1972) in which the aberrations were densely arranged in a smaller portion of the lens surface. Account was taken of the relationship between ocular convergence and accommodation. Figure 2.9 shows diagrammatically the distribution of the astigmatic aberrations in a lens rotated for a right eye, according to this patent. Maitenaz claimed that along the median line *AB* the wearer's vision was free from troublesome aberrations. This criterion also applied in the upper half of the lens above the line *XX.* At each point along the progressive umbilical line the minimum and maximum curvature were equal, thus fulfilling the criterion for a surface of "elephant trunk" construction.

Davenport(1981) patented a lens which was also based upon the static vision principle (see Figure 2.10). This lens was characterised by a very abrupt demarcation between the reading portion and those areas, that were optically inferior, adjacent to it. The patent claimed that this configuration permitted a progressive zone "totally free of astigmatism and distortion". Thus the lens could be likened to the Younger "seamless" round bifocal with a progressive zone linking the distance and reading portions. Both the Younger seamless bifocal and this lens were devised by the same manufacturer.

The optical characteristics of the distance, reading and intermediate portions were relatively good. However, gross distortion and surface astigmatism were found in an area lateral to the reading portion . These zones were optically poor and not suitable for good visual performance .

Kitchen and Rupp (1981) also patented a lens which was spherical throughout the top of the lens where the distance portion was situated. Compared to the design claimed by Davenport (1981) there was a much smoother transition from the reading portion to the lateral areas on either side. This is advantageous when considering the need to rotate the lens for either a right or a left eye. The intermediate zone was made up of constantly changing conic sections, which changed from a circle at the top to an ellipse at the bottom of the zone and then back to a circle, as the gradient reduced, towards the centre of the reading zone.

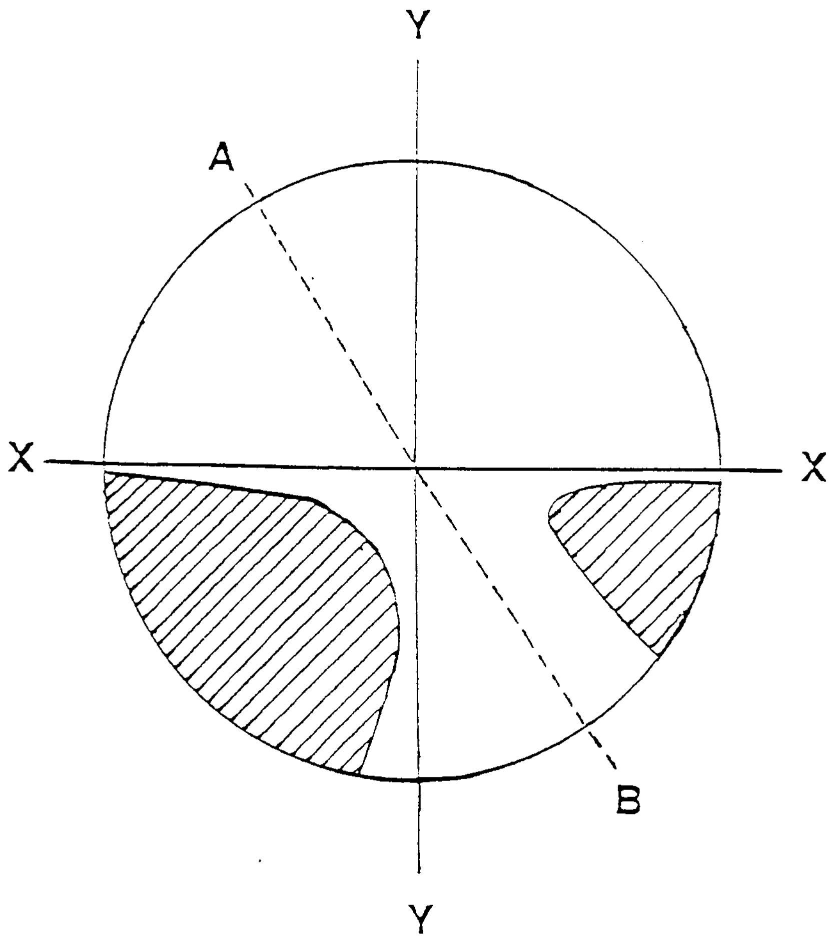


*Figure 2.9.* A schematic diagram showing the front aspect of the progressive lens (redrawn from Maitenaz, 1974). The hatched regions represent areas of "detectable" surface aberration. The distance portion is free from surface astigmatism. *AB* denotes the umbilical line when the lens is arranged for a right eye.

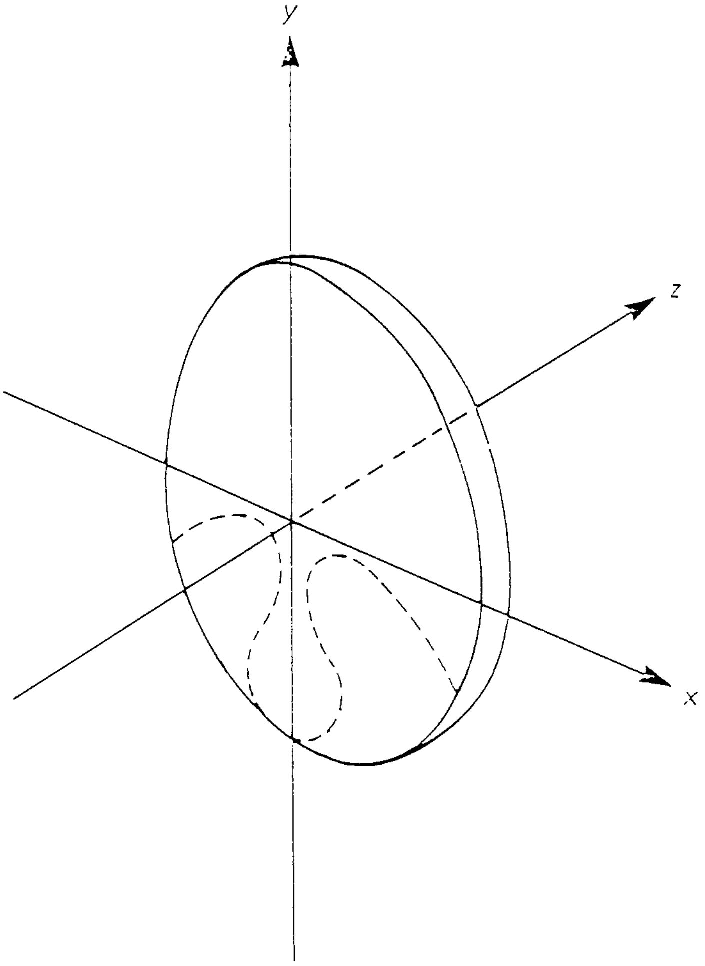


***Figure 2.10.*** A schematic diagram, after Davenport (1981), illustrating in three dimensions the limits of the optically useful areas of the lens. The *y* axis denotes the umbilical line. The axial symmetry of the umbilical line can be noted. From the diagram it will be noted that the superior section of the progressive zone is particularly narrow.

The trade-off for a lens with a reduced distortion gradient is increased astigmatism in the intermediate portion. Indeed, at the top of the progressive corridor the difference between the vertical curvature and the horizontal curvature, at any given point was up to 20% of the power of the addition, although, this reduced to almost zero where the intermediate zone merged into the reading area.

van Ligten (1982) patented a lens with an especially wide progression corridor. Rather than having a median line of zero astigmatism, the progressive zone was bounded on either side by a meridional curve of zero astigmatism. Between the two meridional curves no attempt was made to control the astigmatism, provided it was within the tolerable limit. van Ligten claimed this produced an intermediate area up to 2.5 times wider than that present in lenses with a central umbilical line.

The concession for a lens with uninterrupted distance vision and a wide progression zone was found to be a small reading area. Distortion and astigmatism were present on either side of the intermediate and reading portions.

A progressive multifocal lens which attempted to avoid astigmatic problems in the lateral areas of the lens was patented by Kitani (1984). Figure 2.11 is a front view of this lens showing the demarcation between the various zones present. The distance, intermediate and reading zones are arranged vertically along a median line *YY*. Areas *A* and *B* are usually given over to portions incorporating distortion and surface astigmatism. In accordance with the embodiments of this patent Kitani replaced such surfaces with spherical zones having a dioptric power which was the arithmetic mean of the distance and reading portions. Thus, it was claimed that surface astigmatism was eliminated and normal sight permitted in the side areas. Aberrations were certainly reduced in these otherwise useless areas, although unavoidable astigmatism was introduced along the demarcation lines between the spherical surfaces *A* and *B*, and the other portions of the lens.

### 2.6B Longer Progression Lenses

After the success of the V2 lens many subsequently patented lenses were based upon similar concepts. Winthrop (1977) patented a lens with two discontinuous power steps introduced into the intermediate progressive zone. Figure 2.12 shows a front elevational view of this lens with the boundaries

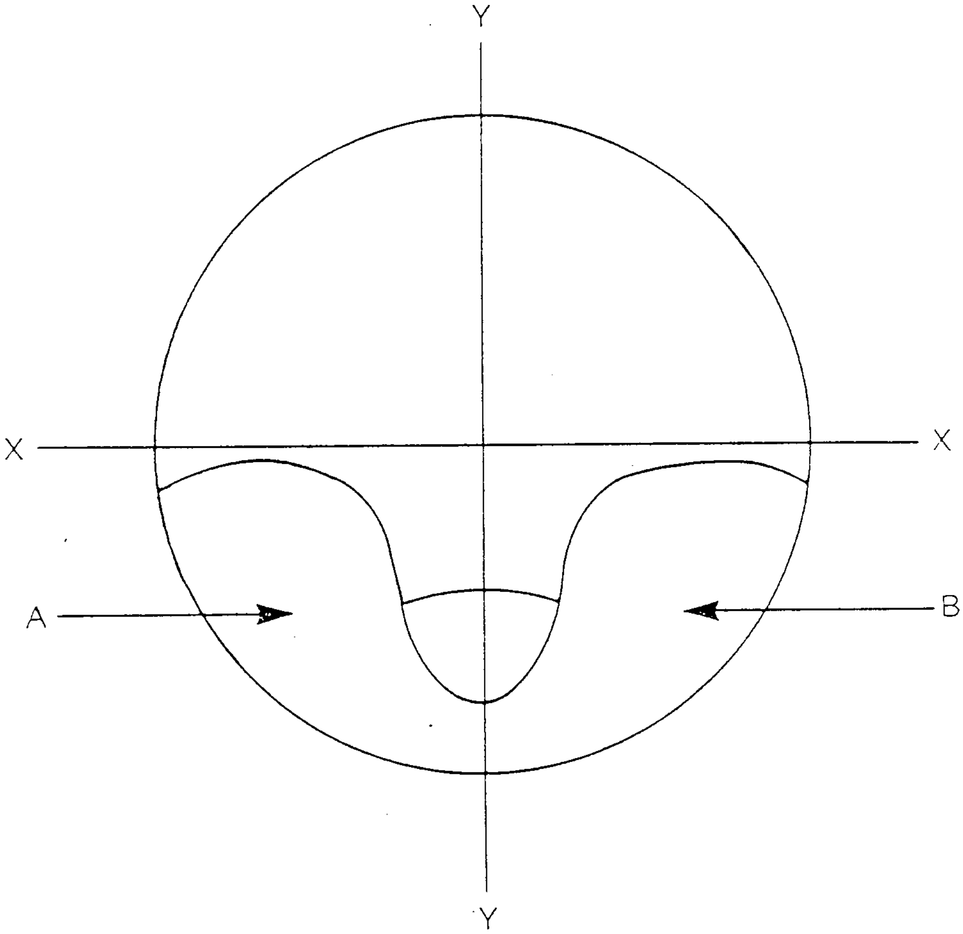


*Figure 2.11.* A front view of the lens patented by Kitani (1984). In this diagram *YY* represents the umbilical line which disects the distance, intermediate and reading portions vertically. Areas *A* and *B* signify the spherical zones unique to this style of progressive lens.

between the segments blended together to render them invisible. The rate-of-change of the addition power along the umbilical line could be reduced because of the two power steps. The aim was to limit the degree of astigmatism and distortion by reducing the rate of dioptric variation across the progressive surface, whilst maintaining the necessary power variation along the umbilical line. Offset against this was the need to ensure the power discontinuities were blended with the other portions of the lens to avoid a break in surface topography, which would otherwise result in a ridge on the lens surface. The idea of staggering the progressive zone certainly reduced the peripheral distortion. The portions of the lens which were optically inferior were concentrated into those areas of the lens (see Figure 2.12) where the stepped zones met. To preserve a smooth curve, blending the zones together was unavoidable, which resulted in a degree of astigmatism being present in the periphery of the distance portion.

Volk(1978) obtained a broad ranging patent for a number of lens surfaces which were based upon a series of conic sections. This lens was notably different from the "Omnifocal" introduced by Volk and Weinberg (1962). The anterior surface upon which the progressive portion was found is shown in Figure 2.13. This is a reproduction of a drawing from the original patent. The "great arc" divided the lens into two distinct geometric sections. Above the line the surface geometry consisted of a surface of revolution. Below the "great arc" the surface comprised a series of conic sections. The lower portion of the lens was not a surface of revolution but rather pertained to an "elephant trunk" construction.

It is difficult to generalise about a patent covering a number of separate embodiments. The lower portion of these lenses were similar to the basic principles of the V2 lens. Therefore it is possible to assume distortion and astigmatism would be of a comparable nature. To what extent peripheral areas of the distance portion were affected by astigmatism would depend upon the surface of revolution employed.

Okazaki (1981) patented a progressive lens which he claimed was something of a compromise between a lens where the aberrations are distributed uniformly over the whole surface, to reduce the distortion (Maitenaz 1972) and a design in which the aberrations are concentrated at the periphery of the clear viewing zones (Winthrop 1977). The aim was to produce a lens which was suitable for 'daily general use' in that astigmatism was dispersed so as not to concentrate in a particular portion whilst maintaining an umbilical line free from astigmatism.

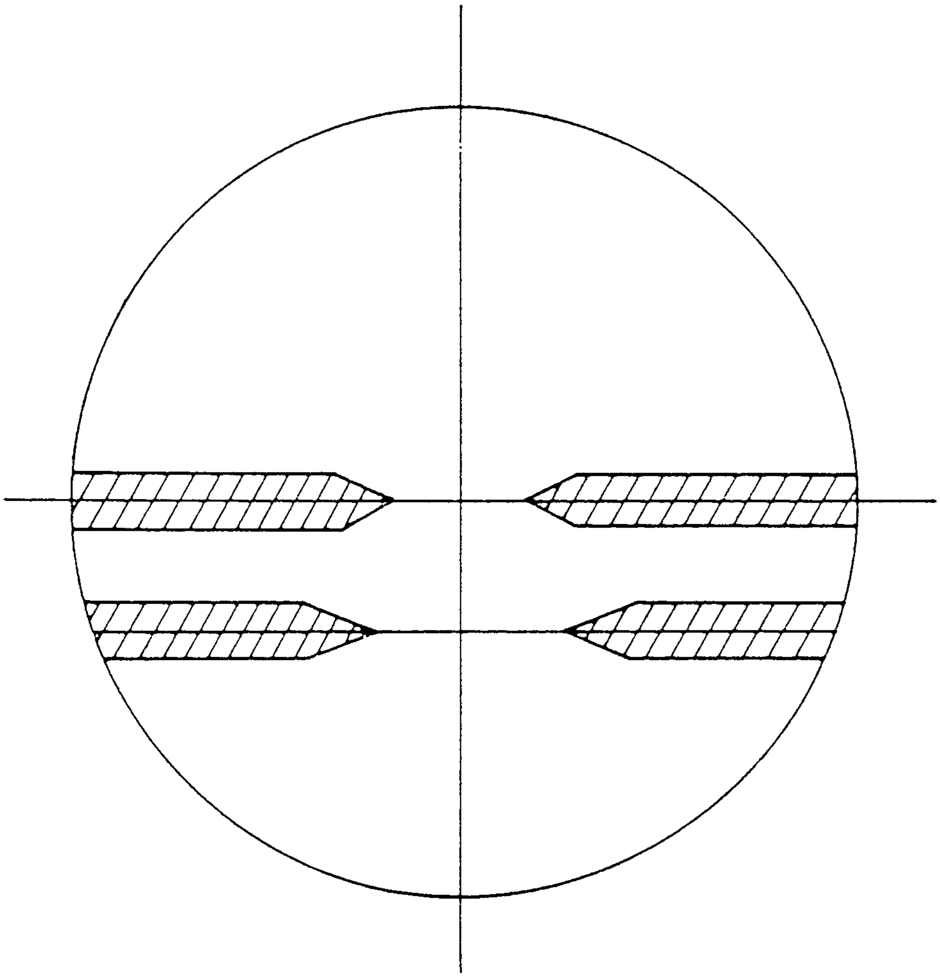


*Figure 2.12.* A diagrammatic representation of the front elevational view of the Winthrop (1977) lens. The illustration shows the location, within the progressive corridor, of the two power steps. The boundaries between these segments are blended together to render them invisible. The hatched areas represent those optically inferior areas where blending occurs.

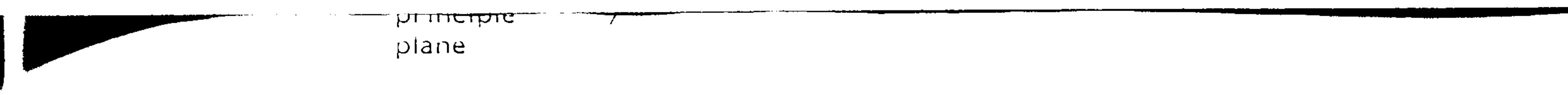


*Figure 2.13.* An illustration taken from the Volk (1978) patent. Above the "Great Arc" the lens surface was either spherical or another surface of revolution. Below this line there was an area of "elephant trunk" construction. The "Great Arc" was situated perpendicular to the umbilical line or "Principal Curve".

The progressive zone consisted of a portion of "elephant trunk" construction. The curvature along the median line was constant in the far and near zones and changed in the manner of a sine wave throughout the progressive zone. Okazaki chose a non-linear power progression in the intermediate portion in order to reduce the skew distortion in the periphery of that said zone. Figure 2.14, which is taken from the patent, was intended to show the effect of distortion when viewing a grid pattern through the lens according to this invention. One attribute of this patent was the low level of distortion, nevertheless, this diagram is clearly an inadequate method of representating the degree of distortion present. The grid pattern would suggest that the level of distortion is negligible and of equal value over the whole lens surface. However, the distortion can not be uniform in a lens with an intermediate portion which is made up of "elephant trunk" construction.

Criticism could be made of the narrowness of the upper section of the progressive zone which arose in an attempt to reduce the extent of the areas of concentrated astigmatism. However, in keeping with other lenses of a similar design, this solution led to astigmatism being present in the periphery of the distance portion.

Wilkinson (1981) designed a lens with a reduced degree of peripheral distortion in the distance zone which, he considered, would nevertheless be suitable for "dynamic vision". In keeping with Jeffree's idea (1957), this was achieved by the utilisation of a non-umbilical progression line between the distance and reading portions. With a non-umbilical meridian the vertical and horizontal power values at any given point were unequal resulting in astigmatism. Figure 2.15 shows the power law for this design. The difference between the horizontal and vertical power began at the junction between the intermediate and distance portions. The power differential increased initially but further down the lens the horizontal and vertical co-ordinates converged. There was a point within the reading portion where the two dimensions met and were of equal value. The lower part of the lens blank which is shown in Figure 2.15 was removed during the edging process. Wilkinson's lens was never produced commercially although a number of prototypes were manufactured.

Guilino and Barth (1980) patented a lens which is to-day produced commercially as the Progressiv R lens. This lens was based on the V2 principle of spreading astigmatism more widely over the surface. A subsequent patent (Guilino and Barth, 1982) described a lens based upon similar principles to

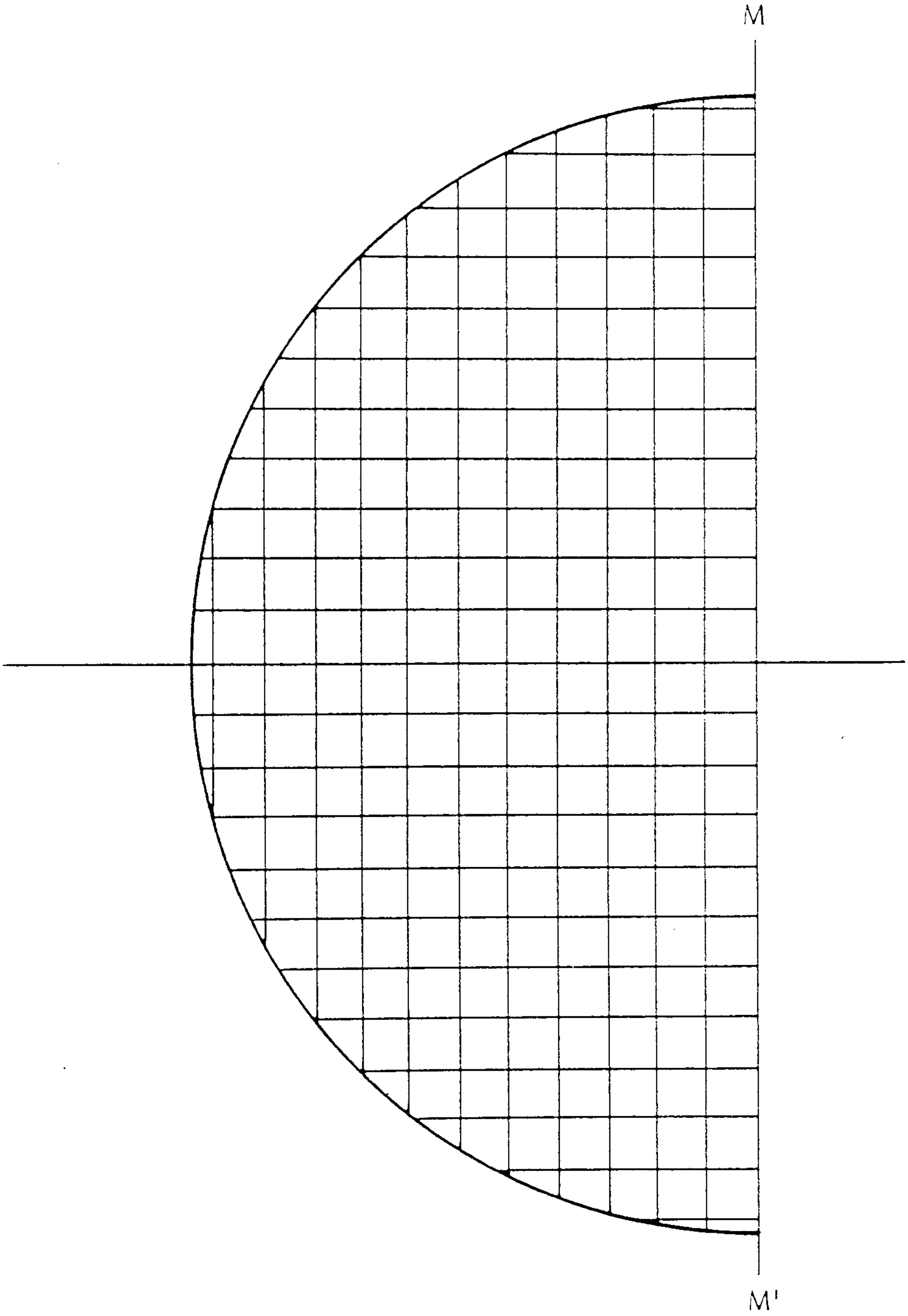


*Figure 2.14.* A grid pattern designed to show the distortion present in Okazaki's (1981) lens patent. This illustration, reproduced from the patent, shows the left-hand half of the lens blank. *MM'* denotes the median line. This diagram is a good indication of the limitations of grid pattern assessment.

*Figure 2.15.* A sketch showing the power distribution in Wilkinson's (1981) lens design. The area labelled " lower part of the lens" is removed during the edging process. It will be seen that the horizontal and vertical curvatures along the median line are different, save in the distance portion. This illustration is taken from the patent granted to Wilkinson (1981). The $x$ axis denotes the dioptric power of the lens while the $y$ axis represents distance along the median line. The dashed line represents the horizontal component, and the unbroken line corresponds to the vertical component, of the median line.

that of the previously patented Progressiv R . Figure 2.16 shows a comparison between these lenses in regard to the surface astigmatism present with a 3.00 D addition lens. The lens covered by Guilino and Barth(1982) falls somewhere between the Progressiv R and the V2 in the extent to which astigmatism is diffusely spread.

van Ligten and Kee(1984) produced a varifocal lens which they claimed had a wide transition corridor and an improved balance between astigmatism and distortion in the field of peripheral vision. The merits of this design were attributed to the blending of the transition corridor with the peripheral area, using a cosine function. In a lens design with a cosine function the distortion reduces more rapidly towards the umbilical line, from the periphery, than in some other lenses with wide corridors.

Davenport (1984) obtained a patent on behalf of the Younger Manufacturing Company which was based on a meridian line of "elephant trunk" construction. If this line were sectioned successively in an orthogonal fashion a series of gradually changing conic sections would be produced. The upper portion, for distance vision, could be either spherical or an aspheric surface of revolution. Astigmatism was present in the periphery of the distance portion in keeping with designs analogous to the V2 lens concept. Patents often cover a number of separate embodiments. Davenport included in this patent several different power variation formats for the progressive meridian line. These included linear and parabolic power variations.

In 1985 Winthrop obtained a patent for a lens which was designed to produce a uniform distribution of the unavoidable aberrations. The V2 principle of spreading the aberrations was employed in order to produce a lens suitable for dynamic vision. However, the plan behind this patent went one step further to produce the aforementioned uniform distribution of aberration. Winthrop describes the power distribution by analogy to the "Dirichlet principle" which relates to thermal conduction. If a thin sheet of copper is taken, with similar dimensions to a lens blank, and two points on the surface are held at 0° and 100°, then the resulting isotherms create a highly regular pattern (see Figure 2.17). Winthrop positioned the power distribution of this patent along similar contours in order to ensure a uniform flow of optical power and to minimise aberrations.

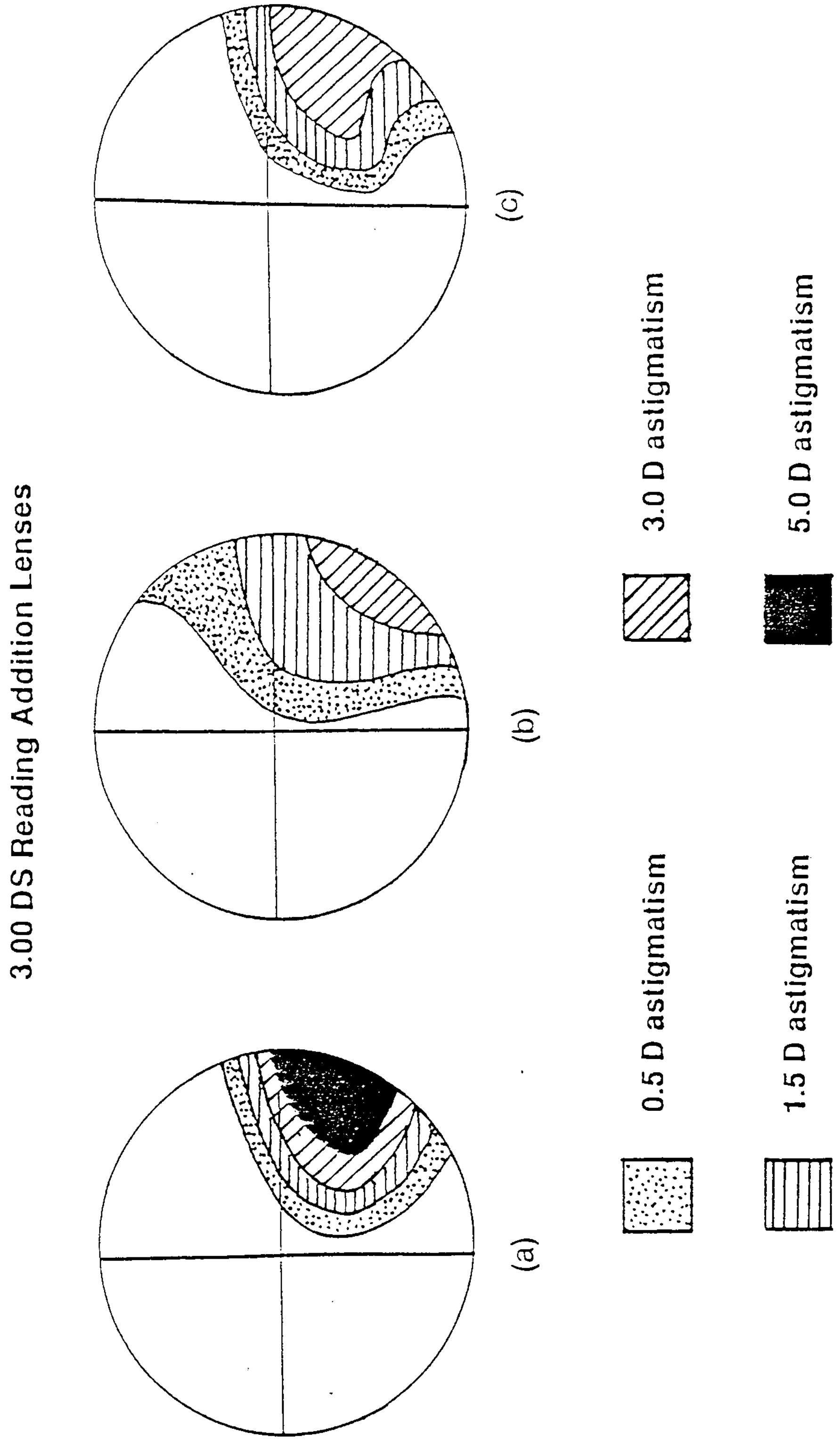


*Figure 2.16.* A comparative analysis of surface astigmatism present in one half of three different lens designs. Each lens is considered to be a plano distance with a +3.00DS reading addition .The shaded areas denote the situation of astigmatism in a contoured arrangement with steps of 0.5D, 1.5D, 3.0 D, and 5.00 D.

This diagram is redrawn after Guilino and Barth (1982):

(a) Progressiv R (Guilino and Barth,1980)

(b) V2(Maitenaz,1974)

(c) patented lens of Guilino and Barth(1982).

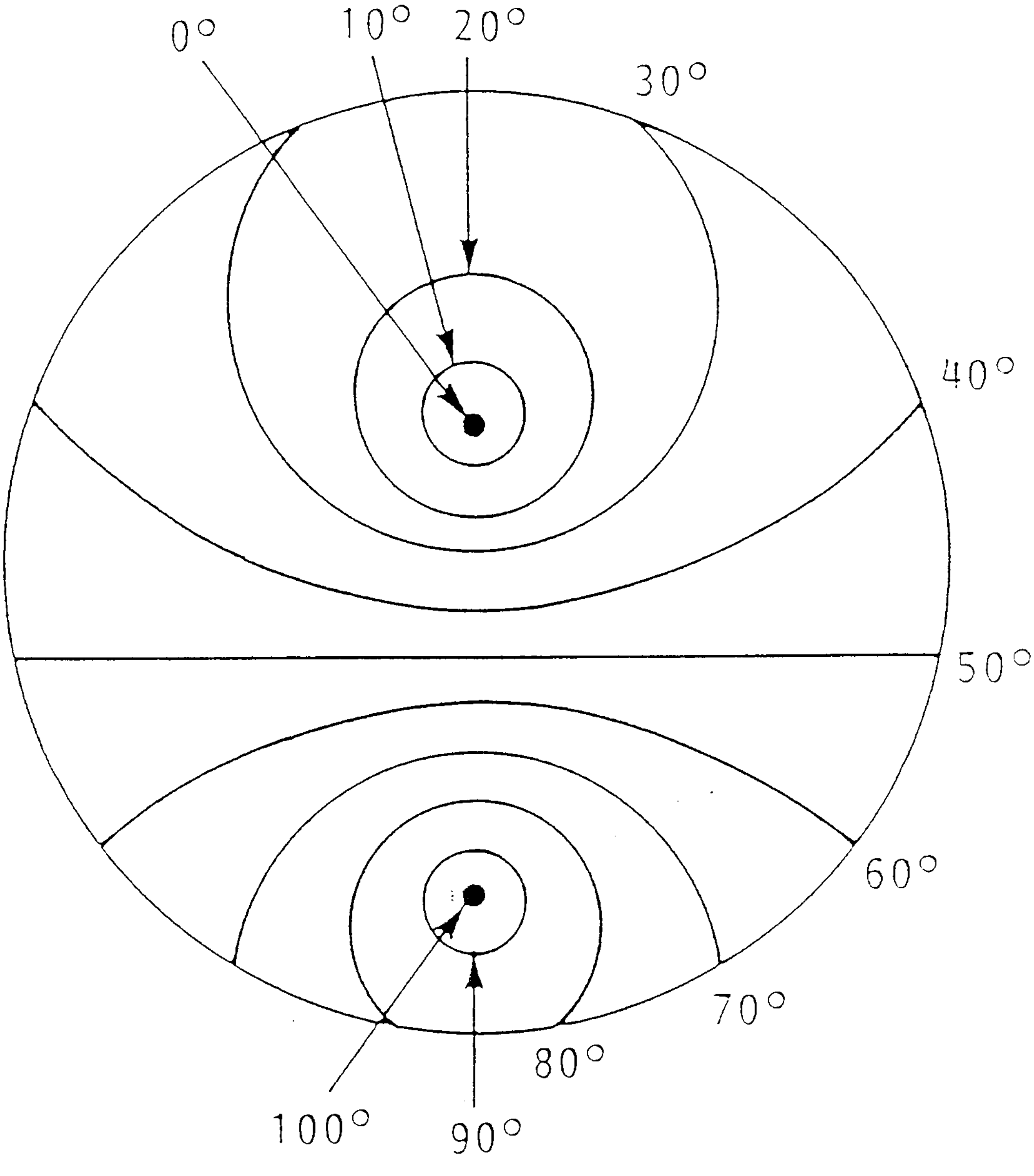


*Figure 2.17.* A schematic diagram, after Winthrop, relating the "Dirichlet Principle" of thermal conduction to Winthrop's (1985) lens design. Bipolar isotherms are produced which surround a point heat source held at 100° and a point heat sink held at 0°. These points represent the near and distance centres respectively.

Shinohara (1986) patented another lens based upon the principle of dynamic vision. Astigmatism was situated along the median line, between the near and intermediate zones. There was also a fairly significant degree of astigmatism in the distance portion. However, in keeping with other lenses of this design, there was a reduction in the apparent shaking of the image caused by movement of the wearer's head. Another patent, Shinohara (1987), was taken out in order to extend the range of base curves for the above design.

Fuëter and Lahres(1986) designed a pair of progressive lenses (for Zeiss in West Germany) which were designed to take account of the relationship between ocular accommodation and convergence, essential for binocular vision. These lenses were constructed with a non-linear principal line of sight. The corridor through which the eye passed was designed to be vertical in the distance portion, inclined towards the nose in its course through the progressive zone and again vertical in the reading zone. It is accepted in the patent that some degree of astigmatism is present along the principal line of sight. This results because the median line is not straight, although, the designers have attempted to keep this to a minimum by distributing the inherent aberration over the entire lens.

Barkan and Sklar(1987) in a recent patent produced a lens which, it was claimed, came somewhere between the "static" and "dynamic" design models. This design consisted of an almost linear progression in focal power, along the median line, from distance to near. Along the eye path corridor, which was relatively wide, there was up to 0.5 D of astigmatism present. This would suggest that the Barkan and Sklar lens (marketed by Sola as the 'Graduate' or 'V.I.P') is best classified within that group of lenses with less clearly defined divisions and long progression zones. Another patent which proved difficult to classify into either group is that granted to Shinohara and Okazaki (1985). The literature covering this patent contained a series of separate embodiments including those for dynamic and static vision.

### 2.6C Multiple Design

Dufour(1989) notes that the range of reading additions of a PAL design are mostly arranged in one of two groupings. In one design the length of the progressive umbilical line is constant with increasing reading addition powers resulting in a steeper power law and greater dioptric gradient between the distance and reading segments of the lens. An example of this would be the Maitenaz(1974) design. An alternative approach is to have a constant gradient for all reading additions with the length of the umbilical progression line increasing with the power of the reading addition(Deguchi *et al*, 1989). The Dufour(1989) patent comprised an aspheric surface with a different surface topography design for each reading addition. The progressive zone was subdivided into three areas, in which, the central portion had a constant length and power law irrespective of the reading addition, and the upper and lower sections altered in length depending upon the reading addition. This design is shown in Figure 2.18, where M is the umbilical line, B the distance portion and N the reading area. The distance D, between A1 and A2, is constant for each of the 13 lenses in the series. However, the distances d1 and d2 decrease with an increase in the reading addition (Figure 2.19). This lens design is marketed as a 'multiple design' lens.

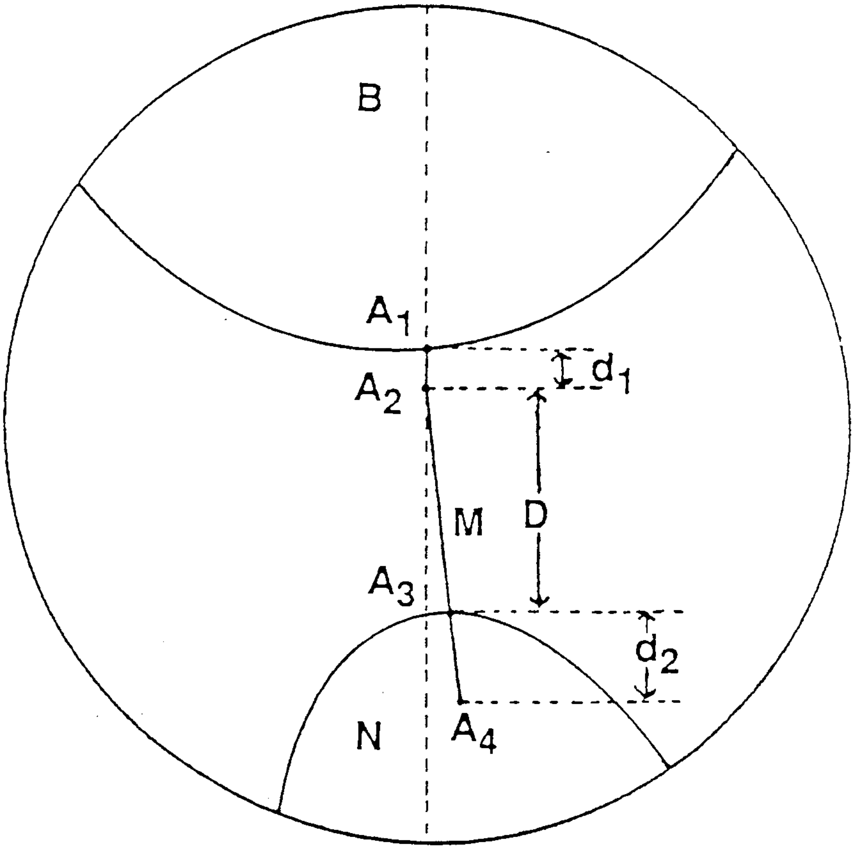


*Figure 2.18.* A schematic diagram(after Dufour,1989) of the Varilux Multiple Design lens. The umbilical line M , which links the distance portion B with the reading zone N, is divided into three zones between the points $A_1$, $A_2$, $A_3$, and $A_4$. Distance D, between $A_2$ and $A_3$ remains constant for each of the 13 lenses in the series, whilst the distances $d_1$ and $d_2$ decrease with an increase in the reading addition power.

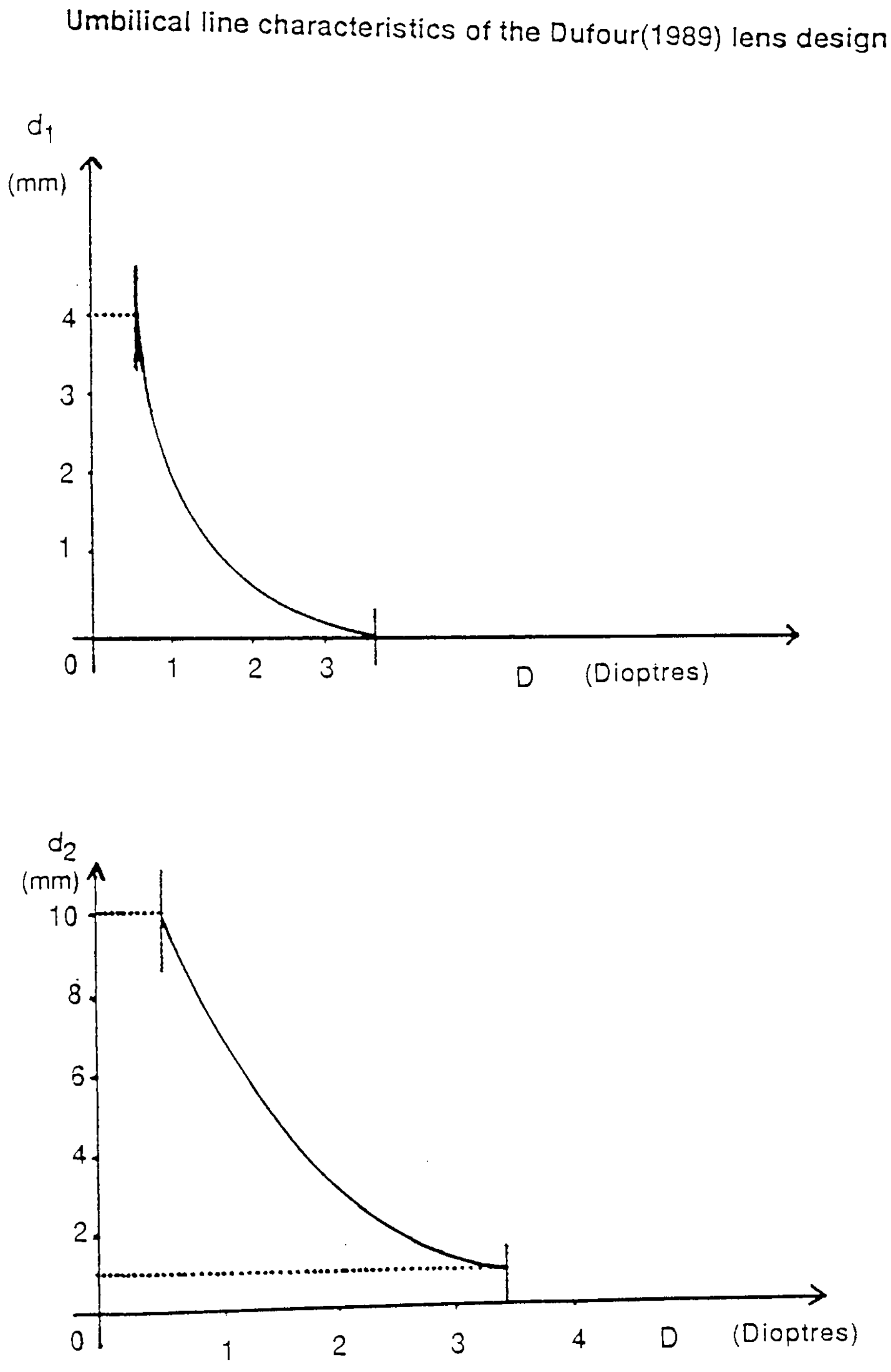


*Figure 2.19.* Two graphs from the Dufour(1989) design showing the manner in which the distances d1 and d2 (mm) decrease with an increase in the power of the reading addition (D).

## 2.7 VARIABLE FOCUS LENSES

Most recently patented lenses can be classified under the broad principles of one or other of the two lens groupings described above. However, there are a number of lenses which defy straightforward classification. Under this heading a wide range of patented, progressive and variable focus, lenses are covered. Few of the patents listed below have reached commercial fruition.

Wright (1971) patented a variable focus lens based upon a transparent liquid sandwich construction. This concept was not new, indeed Bennett (1970) cited a number of lenses founded upon a similar principle. Wright's arrangement comprised of two rigid outer lenses and sandwiched between these was a polyvinyl butyral interlayer. A cell, fed with a viscous liquid via a duct from the spectacle frame, was worked centrally into the interlayer. Figure 2.20 is a diagram taken from the original patent showing the construction of this spectacle lens system. A piston assembly relayed an aqueous solution, made up of calcium bromide with glycerol and having a similar refractive index as the two outer layers, through the duct into the cavity as required. The front rigid layer was a conventional spectacle lens, the anterior surface of which could be worked to correct a specific patient's ametropia. The rear component was a sheet of thin glass approximately 0.15mm thick. The thin rear layer was made to bulge, when the liquid was forced into the central cavity, by the piston assembly.

One criticism of this lens relates to the fact that the focusing range was little more than one dioptre; this would limit the degree of presbyopia which could be assisted. An alternative embodiment of this patent provided for the variable focus construction to be incorporated into a fixed focus lens. This would allow distance and reading areas with a variable intermediate zone.

Wylde(1972) also patented the design of a variable focus lens system with a liquid film chamber. This optical system consisted of two pieces of a synthetic plastics material which had been worked to produce a centrally situated sealed recess, when they had been adhered together. A communicating duct led from the liquid filled chamber through the lens periphery and via the spectacle frame to the piston assembly (see Figure 2.21). Increasing the volume of the liquid in the chamber caused the thin central portion of the rear surface to flex thus increasing the dioptric power of the optical system.

Wylde produced a number of prototypes in CR 39 plastic, which is a better material than glass when the factor of safety is considered. The focusing range

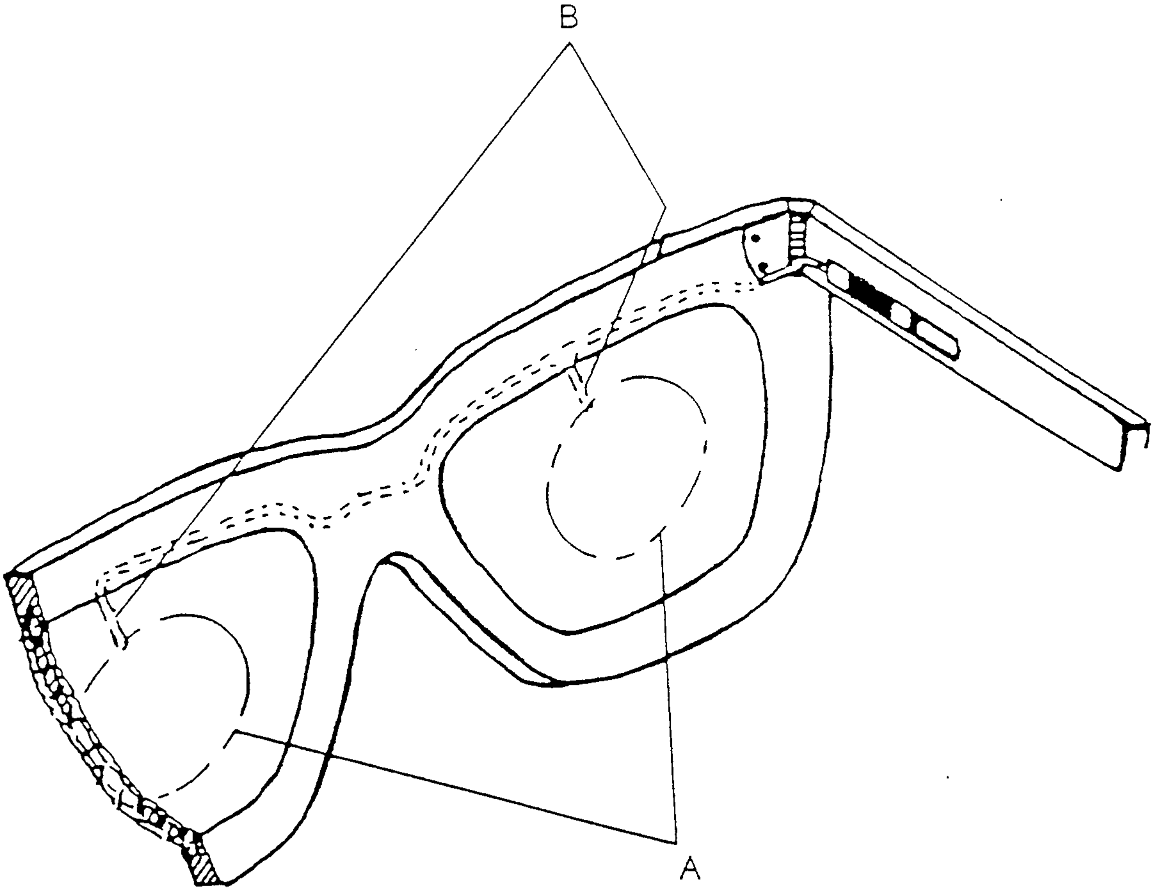


*Figure 2.20.* A diagram, after Wright (1974), showing the variable focus lens arrangement which was based upon a transparent liquid sandwich construction. *A* denotes the cavity filled with a viscous liquid and *B* is the duct through which the lens was supplied. A viscous liquid with a similar refractive index to the other elements of the optical system was fed from a reservoir through the spectacle frame and via the lens duct into the centrally situated cavity.

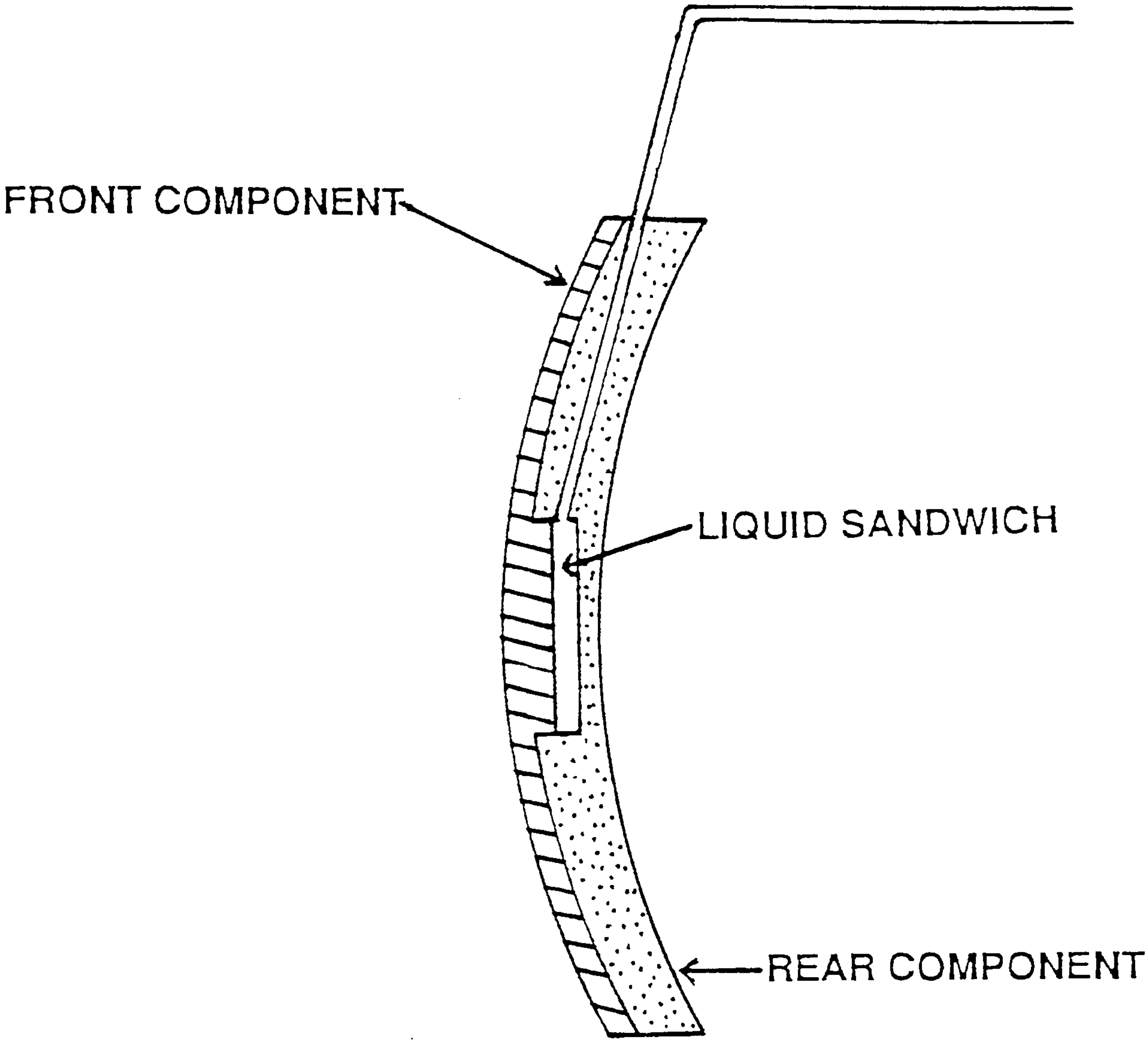


*Figure 2.21.* A schematic diagram, taken from the patent, of the variable focus lens patented by Wylde(1972). The drawing shows the two outer layers of synthetic plastic material with the central cavity. The power of the lens system is increased when addition fluid is introduced via the duct to the central cavity. This causes the rear rigid component to bulge.

could extend up to 5.00D, if the central aperture in the rear component was sufficiently large, when a liquid of 1.5 refractive index was employed (Wylde, unpublished observations).

A lens system based upon the Alvarez principle was patented by Plummer (1974). The Alvarez system consisted of two identical lens elements each with a complex surface curvature that produced power variations by lateral translation of one element relative to the other(Bennett,1970). Although used successfully in refraction instruments, the Alvarez system was not the ideal basis for a variable power lens. Most notably, there was a need to manually adjust the variable lens construction every time the wearer's working distance changed. Furthermore, debris could collect between the two lens components which would degrade the resultant image. The Plummer system, described as an 'azygous' ophthalmic lens because it was not a doublet nor an axial set of lenses but comprised a single element(see Figure 2.22), produced a refractive power changing continuously from the top of the lens system to the bottom. The posterior surface of the lens had a non-spherical topography of decreasing curvature(increasing power) towards the bottom of the lens, whilst the anterior surface was toric. The anterior surface was designed to combine with the posterior surface to allow the wearer's optometric prescription to be incorporated. The resultant power of the azygous lens was zero along a line of sight coaxial with the optical axis, progressively negative above this point and progressively positive below it. This polyfocal lens of constant refractive index was curved about the eye in order to arrive at a suitably shaped spectacle lens and to minimise distortion.

Glorieux (1979) patented a variable focus liquid lens, different from Wright (1971) in that the transparent walls were of fixed curvature. Between the sides of this outer casing was a capillary space into which a liquid of known refractive index had been drawn under pressure. The dioptric power of the reading portion was dependent upon the angle at which the spectacle lens was tilted, as shown in Figure 2.23.

The schematic diagram, which is taken from the patent, is a little puzzling because the volume of liquid appears to increase substantially when the lens is tilted; however it is assumed this was not so. The area of reading zone increased in size as the patient looked down. The distance correction was provided by the anterior and posterior surfaces of the system; the near correction was dependent upon the aforementioned liquid. The patent obtained collectively covered a

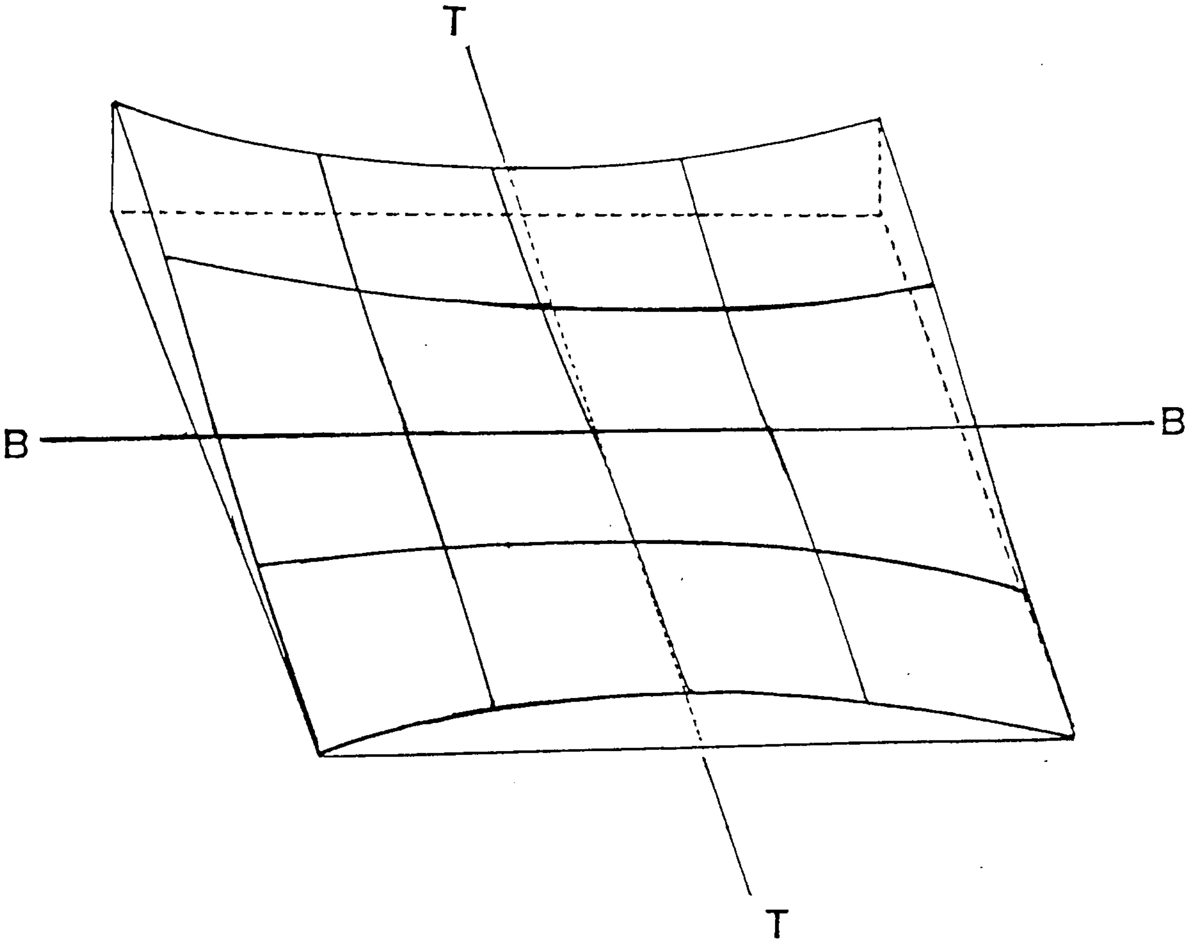
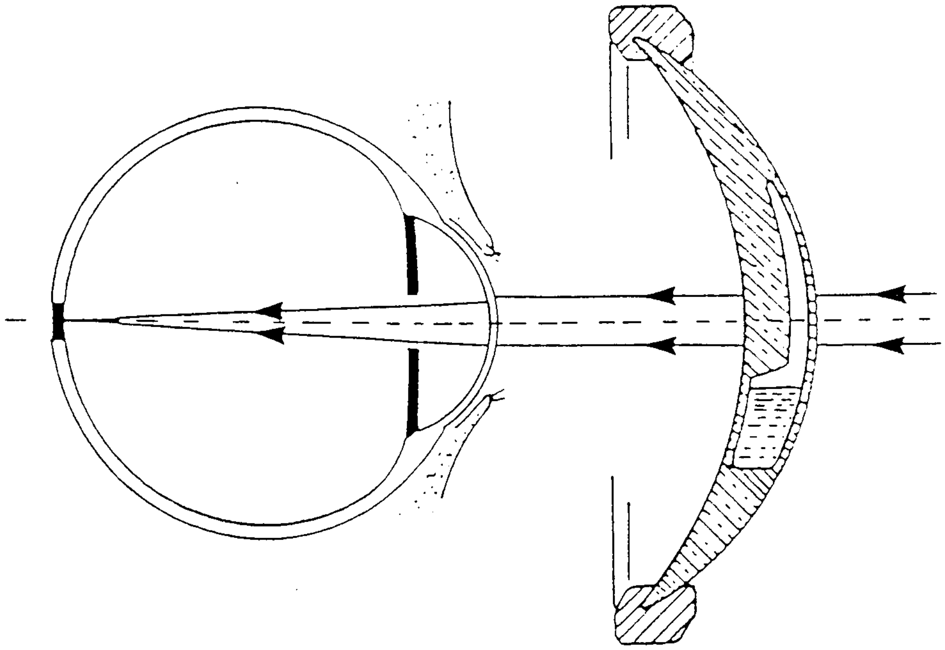


*Figure 2.22.* A schematic diagram redrawn from Plummer's (1974) design showing the posterior (progressive) surface of the "azygous" ophthalmic lens. The power along median line *TT* increases continuously from the top of the lens to the bottom. The surface power of the rear surface along line *BB* is zero. The lens surface shown in this diagram combined with an anterior toric surface to produce the patented polyfocal spectacle lens.

Distance vision



Reading/intermediate vision

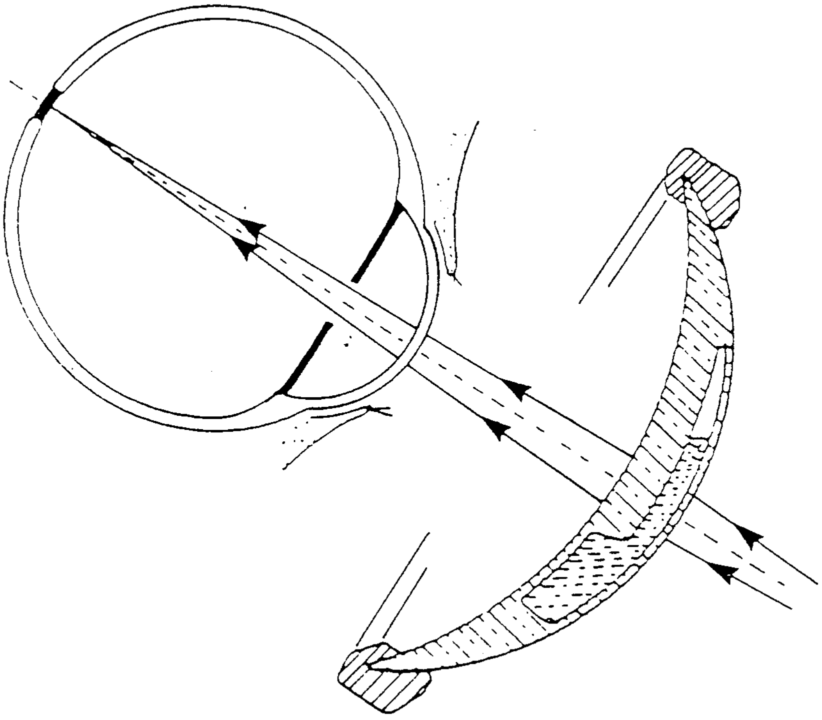


*Figure 2.23.* This schematic diagram shows two positions of the lens system resulting from the Glorieux (1979) patent. The size of the reading and intermediate portions was dependent upon the angle at which the spectacle frame was tilted. When depressed, the intermediate and reading portions enjoyed a relative increase in segment area.

variety of embodiments to allow for any form of bifocal, trifocal and varifocal arrangement, including a contact lens. The patent is devoid of mathematical explanation which makes assessment of potential optical aberrations difficult.

The progressive lens design patented by Freeman (1984b) may prove to be very significant in the future. Another embodiment of this patent, a contact lens (Freeman 1984a), is already available but production costs for a progressive addition spectacle lens are currently prohibitive. The variable refractive properties of this design arose from the introduction of a transmission hologram. This creates negative diffractive power which produces positive longitudinal chromatic aberration to add to the natural longitudinal chromatic aberration of the human eye and increases the range of the chromatic effect. Figure 2.24 compares in a schematic fashion the chromatic viewing properties of the human eye with and without the patented lens. This lens design has diffractive power up to approximately -3.4 D, which would be sufficient for the addition value of a progressive lens.

The phenomenon of diffraction occurs because an image of a point object forms not a point but rather a concentric pattern. This effect is most noticeable when the wavelength of light approaches the aperture size within the diffraction grating. The progressive lens embodiment allows for a variable hologram with the residual power of the spectacle lens resulting from the refractive surfaces.

One valid criticism of this lens would relate to the efficiency of diffraction across the visible spectrum. Freeman claimed there was no more than 20% between the maximum and minimum values of efficiency. The maximum being over 70% and the minimum above 50%.

Legendre (1984) patented a lens which comprised both bifocal and progressive power. Legendre's proposal was to reduce the effects of image jump, caused by a bifocal segment, while maintaining a clear and uniform reading portion. A number of different embodiments were encompassed in this patent including both fused and solid bifocals.

The Legendre patent was not the first recorded progressive lens of this type. Bennett(1970) noted this idea in his review of progressive lenses. He suggested a downcurve bifocal segment for the reading portion situated below the intermediate progressive zone, which would be an area of elephant trunk construction. This design would involve a break in surface topography between

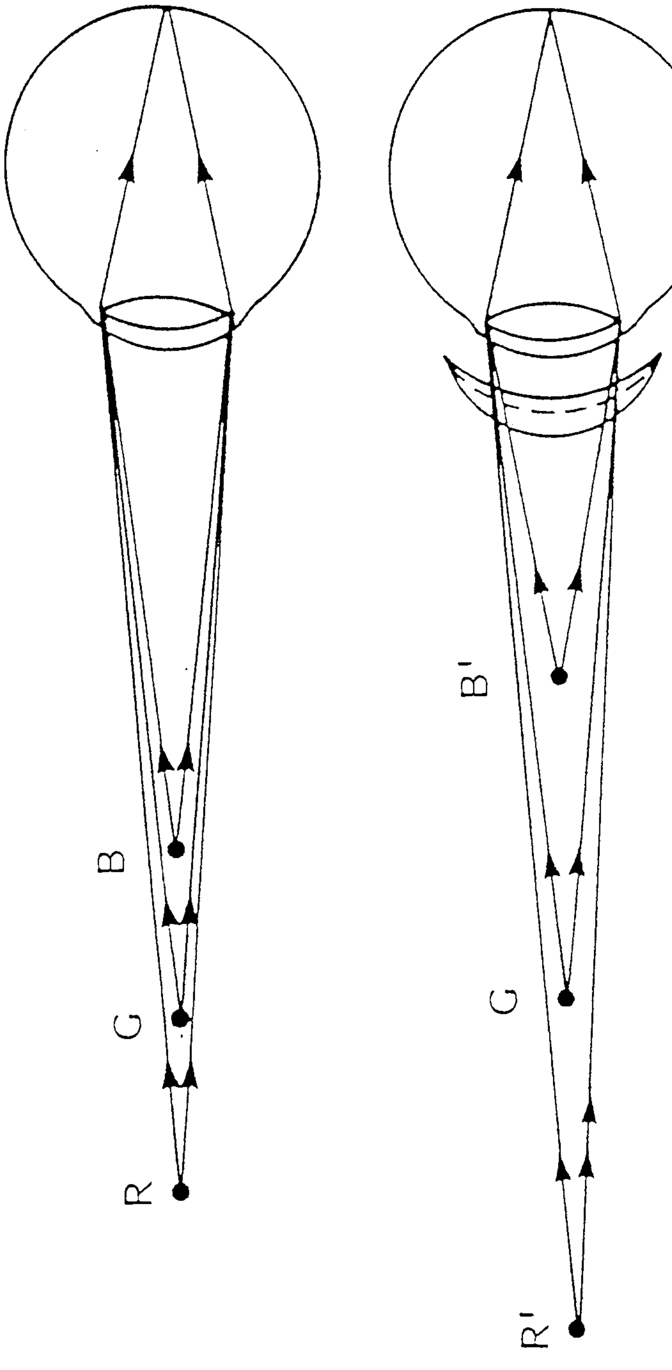


*Figure 2.24.* A schematic diagram of the diffractive power spectacle lens taken from Freeman's (1984b) patent, which shows the chromatic viewing properties of the human eye and how these are increased by the introduction of the patented article. *R, G,* and *B* represent the foci of red, green and blue light respectively when the eye's natural longitudinal chromatic aberration is considered. *R'* and *B'* denote the relative shift in the red and blue foci when Freeman's lens is introduced.

the segments, in order to avoid image jump. Fowler (1985a) also described a pair of spectacles based upon the combination of a progressive lens and a spherical reading portion. This construction was based upon a split-bifocal technique. The upper segment consisted of a V2 progressive lens, involving the distance and intermediate areas, while the lower segment for reading was taken from a single vision lens blank. It is worth noting the patient's reactions were favourable to this design.

# Chapter 3

## OPHTHALMIC SPECTACLE LENS DESIGN

### 3.1 INTRODUCTION

A lens, such as that used in spectacles for the correction of ametropia, has been described by Tunnacliffe and Hirst(1981) as a single element optical system of two refracting interfaces where one or both of these is curved. The refractive power of such a system is derived from the combined effect of the two surfaces and the lens thickness. In some cases spectacle lenses are considered as "thin" lenses, in which case the thickness is deemed to have a negligible effect upon the total refractive result and the power of the lens is regarded simply as the sum of the front and rear surfaces.

Bennett(1968) noted that when considering manufacturing standards very few ophthalmic lenses can be thought of as thin if the back vertex powers are to be kept within the tolerances permitted by the British Standards Institution. Furthermore, in a study which regards the accurate nonparaxial assessment of progressive lenses it is inappropriate to consider a spectacle lens as a thin lens.

### 3.2 SEIDEL ABERRATIONS

The resultant image created by a spectacle lens may be degraded by the presence of optical aberrations. Such aberrations are the consequence of Snell's Laws of Reflection and Refraction at spherical surfaces and are quite separate from image degradation which may arise from a fault in the construction of the lens surfaces or the matrix of the lens material. Bennett(1974) has grouped these into two categories depending upon the area of the spectacle lens from which they result;

| AXIAL | OBLIQUE |
|---|---|
| Lateral Chromatic | Transverse Chromatic |
| Spherical | Coma |
| | Distortion |
| | Astigmatism (oblique or radial) |
| | Curvature of Field |

The two forms of chromatic aberration(CA) arise by the variation of the refractive index of the material with wavelength. The others, which are present in monochromatic light, are known as the Seidel (or third order) Aberrations after von Seidel(1856), who first described them. The overriding factor which effects the degree of CA present is the constringence and this is dependent upon a suitable material being chosen. Chromatic aberration is not a great problem with progressive addition lenses because to date the materials used have had sufficiently high constringence(V) values. Spherical Aberration(SA) results because light from a point object passing through the periphery of the lens comes to a focus nearer the lens than paraxial rays. Coma, which has been named as "off-axis" spherical aberration, is an aberration that results from obliquely incident rays. In a similar manner to S.A., Coma results from the failure of the lens to image paraxial and marginal rays at the same point. Both these aberrations arise with large aperture optical systems. Whilst an ophthalmic lens constitutes a large aperture system when taken in conjunction with an eye the pupil acts to produce a small aperture system. Therefore, irrespective of the angle of gaze, only a small zone of the lens is used for viewing objects. Conventional ophthalmic spectacle lens design does not take account of the effects of S.A. and coma.

### 3.2.A Distortion

This defect in image quality arises due to a variation in magnification at different distances from the axis of the lens. To be free from distortion an optical system must have the same magnification over the whole field, such a condition is called orthoscopic. When an image is distorted, the value of the magnification differs from the paraxial value in the outer parts of the field. Therefore the image points may be in sharp focus but due to distortion they occupy positions either closer to or farther away from the axis, than would be the case were the objects magnified uniformly. If the resultant image point is closer to the axis than it would be by uniform magnification the distortion is said to be positive and of a barrel type. The converse condition where the image point lies beyond its ideal position is said to be negative and be of the pincushion type.

Figure 3.1 shows the manner in which distortion arises. If a single thin lens is considered to be essentially free from distortion it can be seen that the introduction of a stop into the optical system may produce a distorted image. If the stop is placed between the object and a positive thin lens the distance CO is increased by the new ray path to CO'. This increase in object distance results in

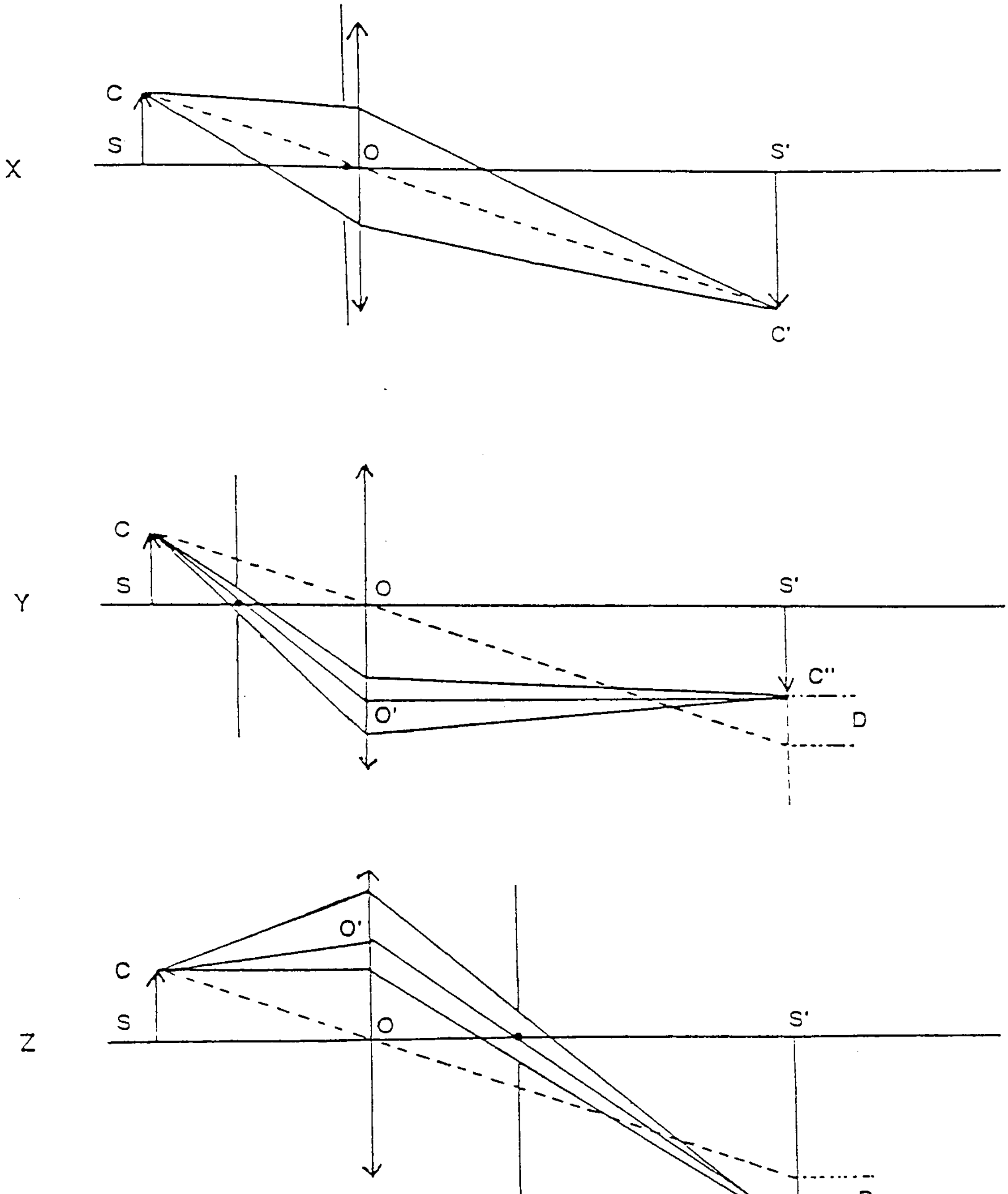


*Figure 3.1.* Diagram showing how distortion may arise when a stop is introduced into an optical system previously free of distortion (X). Either barrel(Y) or pincushion(Z) distortion may be produced depending upon the position of the stop. The human eye has a stop(pupil) lying behind the location of the spectacle lens. A positive spectacle lens will therefore produce negative distortion(Z) and a negative lens will create positive distortion.

a reduced image distance, from OC' to O'C", therefore producing barrel distortion. Conversely, if the stop is located between the positive thin lens and the image, the ray CO decreases in length to the new ray CO', the result of this is to produce ray path O'C" in place of OC', which gives rise to pincushion distortion. When considering spectacle lenses it is the pupil of the human eye which acts as a stop. The eye views the virtual image produced by the spectacle lens and because the pupil lies behind the spectacle lens a positive lens produces negative (pincushion) distortion and a negative lens creates positive (barrel) distortion.

### 3.2B Oblique Astigmatism

When light from a point source is obliquely incident upon a spherical surface, the result is essentially similar to normal incidence upon a cylindrical or toric surface, if the aberration coma is ignored or reduced by the presence of an appropriately placed stop. Thus, the resultant beam is astigmatic and rather than forming a point image two images(which may be considered to be short lines perpendicular to one another) are produced, as is shown in Figure 3.2.

O is the pole of a refracting surface which has a centre of curvature at C. The horizontal meridian of the refracting surface is denoted by SS' and the vertical meridian by TT'. The plane of the paper(which contains TT') upon which the diagram is printed forms the tangential plane of the diagram, while the plane at right angles to the paper plane ( in which SS' is located) forms the sagittal plane of the figure. Within the tangential plane both the axis of symmetry of the surface, OC, and the auxiliary axis through P, PC, are situated. A narrow pencil ( exaggerated greatly in the diagram) of light emergent, from the point object P, in the tangential plane will strike the refracting surface along DE and be refracted to form a tangential image , labelled $P_t$. In a similar fashion, a narrow pencil of light emergent from P, in the sagittal plane will strike the refracting surface along GH and be refracted to form a sagittal image , labelled $P_s$. The distance between $P_s$ and $P_t$ is called the *astigmatic difference* and when expressed in dioptres it is referred to as the *oblique astigmatic error.*

### 3.2C Curvature of Field

When a lens is free from Spherical Aberration, Coma, and Oblique Astigmatism each point object should be represented by a point image. However, the image points may lie on a curved, paraboloidal surface called the Petzval surface(Figure 3.3). This defect is known as Petzval Field Curvature after

TANGENTIAL AND SAGITTAL IMAGES FOLLOWING OBLIQUE

INCIDENCE UPON A SPHERICAL SURFACE

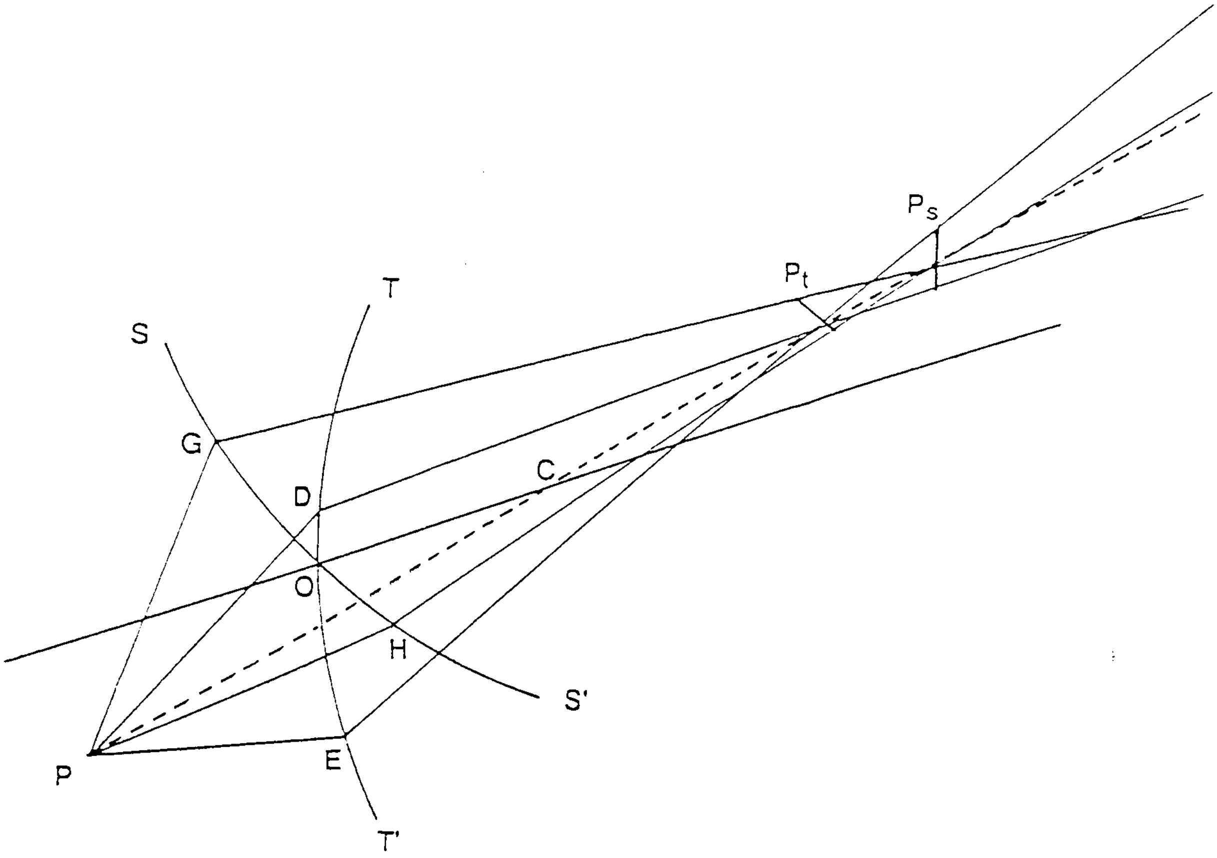


*Figure 3.2.* Light from a point object P which strikes a lens surface eccentrically will produce an astigmatic image in a similar manner to when light from a normally located object strikes an astigmatic surface. The resulting difference between the images $P_t$ and $P_s$ are due to this phenomenon which is called oblique astigmatism. The clearest image will be found at the circle of least confusion, which is located at the dioptric midpoint of the foci of the SS' and TT' meridians.

IMAGE SHELL RESULTING DUE TO THE PRESENCE OF CURVATURE

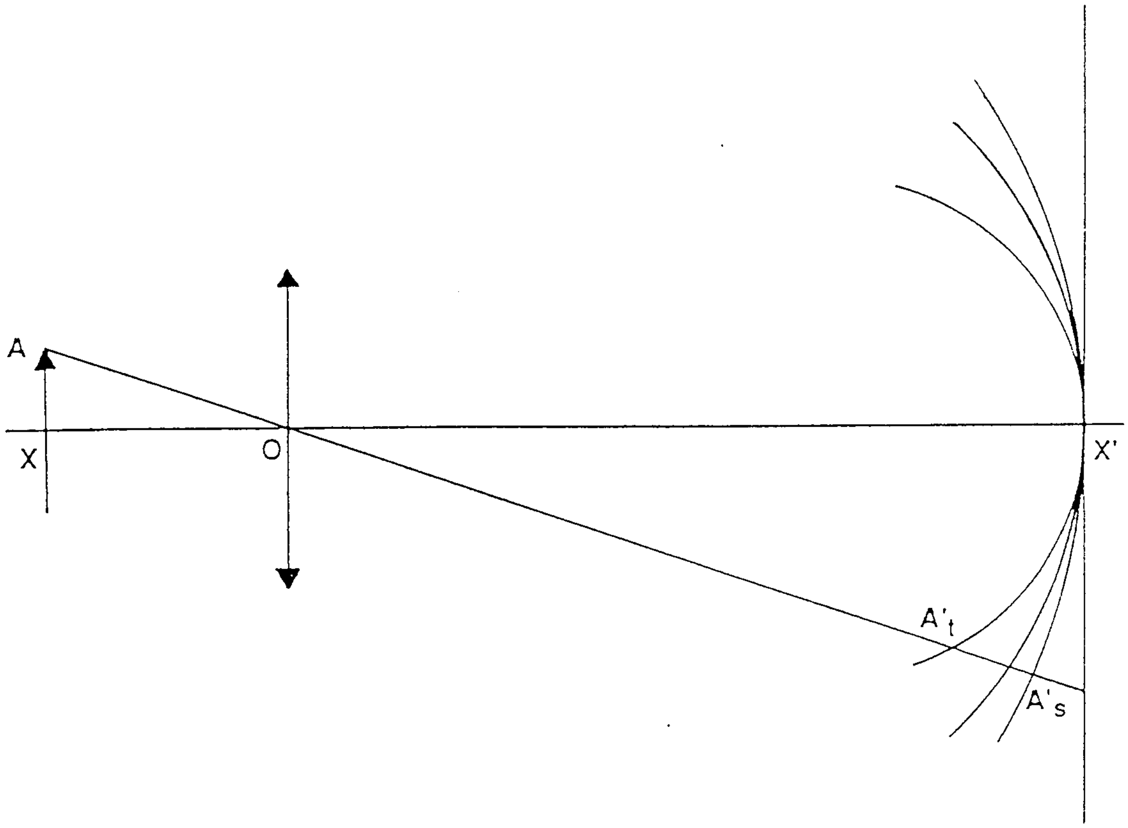


*Figure 3.3.* If oblique astigmatism, coma and spherical aberration were eliminated the images of AX shown as $A'_tX'$ and $A'_sX'$ would appear on a single paraboloidal surface due to the presence of curvature. With ophthalmic spectacle lenses this reduced image shell will not coincide with the far point sphere and a compromise must be sought between either having some residual astigmatism or accepting a difference between the residual image shell and the far point sphere.

Petzval(1843). Joseph Petzval showed that when SA, coma and oblique astigmatism have been corrected, the curvature of the image surface depends upon the refractive indices and the ratio of the lens surfaces. The radius ( $r_p$ ) of the Petzval surface is given by;

$$r_p = \frac{(1-n)}{nr_1} + \frac{(n-1)}{nr_2}$$

$$= n f_1 + nf_2$$

For the curvature to be eliminated $r_p$ must be equal to zero; this is known as the Petzval condition. A degree of curvature is desirable with ophthalmic spectacle lenses, unlike most other types of lenses, because the far point locus must focus upon a curved surface - the retina. The problem arises when trying to match the curve of the image plane to the far point sphere.

### 3.2D Spectacle Lens Design

The above aberrations play a significant part in the ultimate design of an ophthalmic spectacle lens. The most troublesome are oblique astigmatism, curvature and distortion. The spectacle lens designer has the following variables to juggle with;

(a) thickness of the lens,
(b) refractive index of the lens material,
(c) the two surface powers, provided the back vertex power remains unaltered,
(d) the distance from the back vertex of the lens to the centre of rotation.

Distortion does not alter the the position of the image but merely its shape, and for this reason the aberrations of oblique astigmatism and curvature take priority.The ideal situation would be to have the sagittal and tangential image shells collapsed together and for this astigmatic free image shell to be coincident with the far point sphere. The choices available to the lens designer(Figure 3.3) are either:

(a) Point Focal - this design eliminates oblique astigmatism, but accepts a residual power error between the image plane and the far point sphere.

(b) Percival - this design accepts some residual oblique astigmatism, but places the locus of points corresponding to the mean of the tangential and sagittal powers (the mean oblique powers) coincident with the far point sphere.

## 3.3. IMAGE QUALITY

Image quality is dependent upon a number of factors. With an ideal lens all the rays emanating from a point on an object will be brought to a focus at the corresponding point on the image. The ideal lens would also produce an image which is to the same scale as the object. However, as a simple lens, a spectacle lens is subject to a number of aberrations(von Seidel,1856) which will impair the quality of the resulting image. The degree of each aberration is dependent not only on the power of the lens but also the form in which the lens is made. Changing the form of a lens may decrease the effect of one type of aberration at the expense of increasing another. The wearer may not notice the aberrational effects whilst looking through the centre of a lens but they may become apparent when looking obliquely with the use of nonparaxial rays of light. This is especially true in multifocals and progressive addition lenses where specific off axis portions of the lens are used for viewing objects at near and intermediate distances.

At one time spectacle lenses were made up in a flat form but nowadays these have been largely superseded by a variety of curved forms. The best curve for a given lens will not be purely dependent upon the required prescription. It will also depend upon which aberration is considered to be the most troublesome and hence is given the greatest consideration. In practice manufacturers tend to have a series of around 6 but possibly up to 12 different base curves with which to cover the range of necessary back vertex powers.

The optical performance of a spectacle lens may be dependent upon the presence of physical defects. Jalie and Wray (1983) divided the possible defects into two categories; (a) surface defects, and (b) defects in the lens material.
This subject has been comprehensively documented by Jalie(1984), and Jalie and Wray (1983). Such imperfections are quite separate from image degradation due to Seidel aberrations and they may arise from a fault in either the matrix of the lens material or the construction of the lens surfaces. It is important from the point of view of quality control that manufacturers and prescription houses inspect the finished product prior to their usage in spectacle frames.

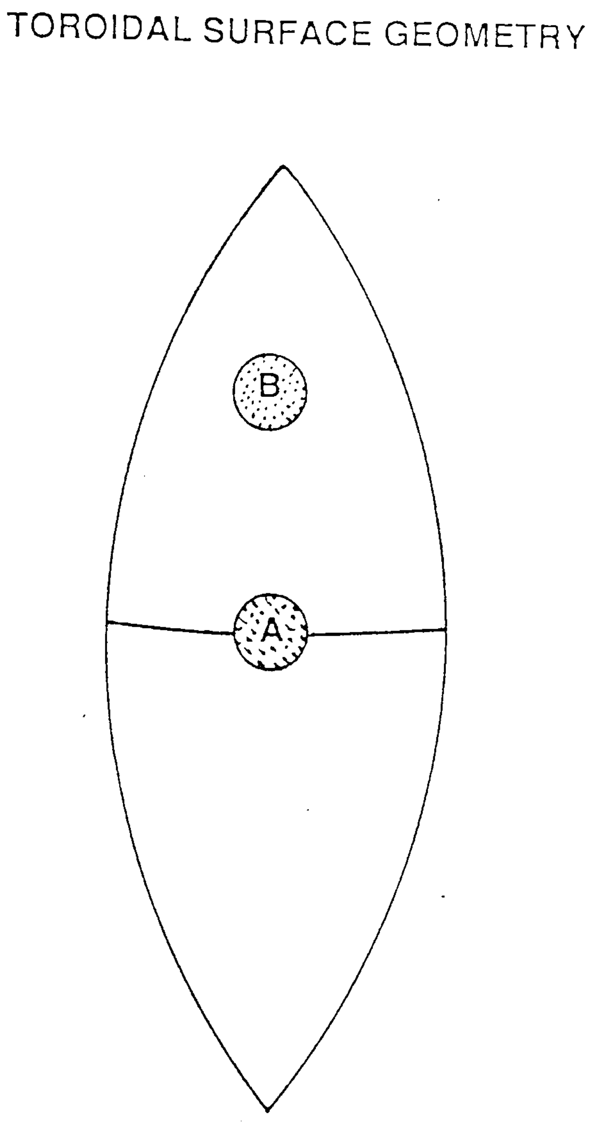


*Figure 3.4.* A schematic diagram showing that, when working on a toroidal surface, a tool which makes perfect contact with the surface at the equator(A) no longer fits the surface when moved to a transverse position(B).

## 3.4. SURFACE GEOMETRY

Surface geometry may be difficult to reproduce accurately. Bennett and Blumlein (1983) note that it is hard to produce a toroidal surface of really good quality which is free from waves or surface irregularities. Unlike a cylindrical surface, a toroidal surface is not the same throughout its length. Figure 3.4 shows that if a tool is moved along the equator it will maintain true contact but when moved across the surface the tool cannot maintain perfect contact. This is because the later clearly has a different shape at this point.

By calculated manipulation of the surface curves a designer will produce a spectacle lens in a toric form most suitable for the minimisation of the aforementioned aberrations in order of relative importance. The design may depend upon the material of the lens, the prescription, the relative importance the designer attaches to the each aberration, and the range of the base curves employed. If the use of aspheric surfaces is introduced into the spectacle lens design then the optical engineer has additional parameters, to alter, to allow the minimisation of aberrations. The additional control of aberrations afforded by aspheric spectacle lenses is particularly useful in the case of high prescriptions. In most aspheric lens designs the lens consists of one aspheric surface, usually the anterior surface, and this allows a much better control of distortion and oblique astigmatism than would otherwise be the case with spherical surfaces.

Smith and Bailey(1981) noted that it is not possible to correct a spherical +12.00DS lens for primary oblique astigmatism, irrespective of the degree of bending which might be employed. Distortion may be corrected but very steep front curvatures would be required for this which will in turn lead to high levels of magnification. Atchison and Smith(1980) have concluded that the peripheral surface power of an axially symmetrical aspheric lens surface should be less than the central surface power for improved image quality. In a series of diagrammatic representations they have shown that front surface flattening will reduce distortion, curvature-of-field, and astigmatism. In addition, these lenses are thinner and consequently lighter.

TYPES OF CONIC SECTION

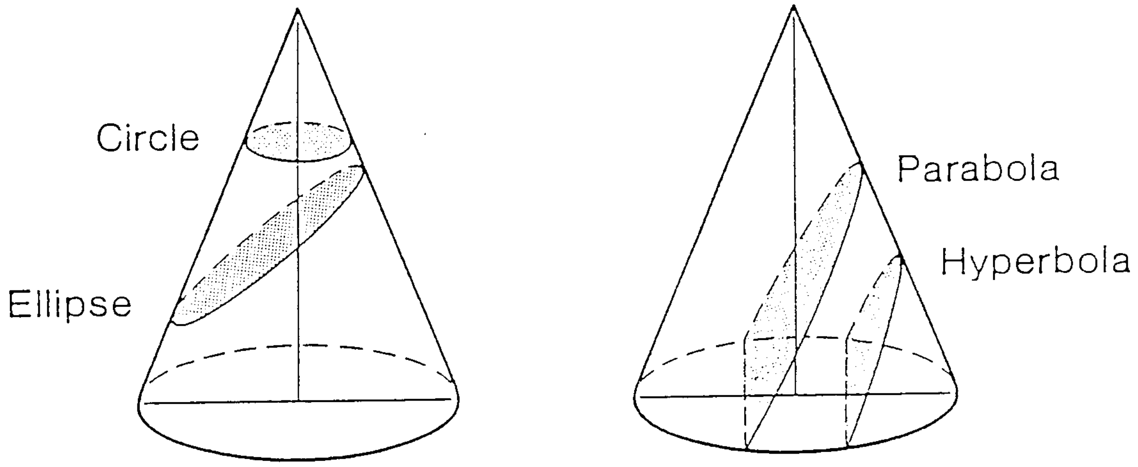


*Figure 3.5.* Slicing through a solid cone at various orientations will produce a number of different conic sections. Four different types of section may arise depending upon the angle of the division through the cone. These are a circle, an ellipse(either prolate or oblate), a parabola and a hyperbola.

### 3.5. CONIC SECTIONS

When a section is taken through a solid cone, four different types of section may arise depending upon the angle at which the cone is cut(Figure 3.6). If the section is taken at right angles to the vertical pole of the cone - then the resulting section will be a circle, otherwise a complete section will result in an ellipse. A section, may also be taken which cuts through the base of the curve; when the cut is parallel to the side of the cone then the resulting section will be a parabola and when not parallel a hyperbola is produced. If these resulting curves are rotated about their axis of symmetry a set of solid three dimensional structures are produced, namely, a sphere, an ellipsoid, a paraboloid, and a hyperboloid. The collective name for these solids of revolution is conicoid. The curve of each conic section may be shown graphically, as in Figure 3.6. If the vertex of each curve is taken as the origin (x=0, y=0.) the equation for a conic section is:

$$y^2 = 2rx - px^2$$

Where $r$ is the vertex radius,

and $p$ is a constant the value of which dictates the type of curve as shown below:

| | |
|---|---|
| Paraboloid | $p = 0$ |
| Hyperbola | $p < 0$ |
| Ellipsoid rotating about its major axis | $0 < p < 1$ |
| Sphere | $p = 1$ |
| Ellipsoid rotating about its minor axis | $p > 1$ |

The smaller the value of $p$, the flatter the conic curve will become when moving away from the vertex of the curve. The curves shown in Figure 3.7 have the same value of surface power at the origin because they share the same vertex radius, r. The surface power will depart increasingly from that of the circle with distance from the origin. In the case of the oblate ellipse the surface power will be relatively greater than the circle, whilst with the prolate ellipse, parabola, and hyperbola it will be less.

## 3.6. CONICOIDS

As noted above, the geometrical term conicoid is used to describe those aspheric surfaces of revolution which are derived from a conic section. The following relationship is quoted by Malacara(1978) to denote the three dimensional topography of an optical surface, which is a surface of revolution.

$$z = cS^2 / \{1 + [ 1 - ( K + 1 ) c^2 S^2 ]^{1/2} \} \qquad (3.1.)$$

where,

Z is the *z* axis co ordinates,

$S^2 = x^2 + y^2$

c = 1/ r , where c is the radius of curvature.

K, is a constant determined by the location of the focus and the directrix of a conic surface.

Expression (3.1.), noted above, is a specific form of the equation which describes any polynomial expansion;

$$z = cS^2 / \{1 + [ 1 - ( K + 1 ) c^2 S^2 ]^{1/2} \} + A_1 S^4 + A_2 S^6 + A_3 S^8 + A_4 S^{10} \qquad (3.2.)$$

$A_1$, $A_2$, $A_3$, and $A_4$ are the aspheric deformation constants.

Expression (3.1.) results because the aspheric deformation constants are zero when the curve which generates the three dimensional structure arises from a conic section and thus the relationship may be simplified.

Substituting r for 1/c, then equation (3.1.) may be changed to

$$z = \{ r - [ r^2 - ( K + 1) S^2 )^{1/2} \} \ / \ K + 1 \qquad (3.3.)$$

in the case of the above noted conicoids except for the parabola which simplifies to

$$Z = S^2 / 2r \qquad (3.4.)$$

because K = -1. It is from equations (3.3.) and (3.4.) that the proper and simplified expressions for the sag formula, of a spectacle lens are produced. The proper expression for a spherical lens is equation (3.3.) which simplifies because K = 0.

$$Z = r - (r^2 - s^2)^{1/2} \qquad (3.5.)$$

The simplified form, shown in equation (3.4.), should only apply when the surface is parabolic and K = -1. However, the simplified form is commonly used as a "quick" method over the central portion of a lens, because often the discrepancy, between a sphere and a paraboloid, is relative small and within the range of measurement error, e.g.; for a 10.0 D curve the sag differs only by 0.01mm.

## 3.7. POLYNOMIAL ASPHERIC LENSES

Jalie(1984) notes that the most common type of aspheric lens in use to-day is a conicoid type which incorporates a convex ellipsoidal surface. However, often the lens design of aspheric lenses involves a more complex structure than a simple conicoid surface of revolution. Aspheric lenses may involve the blending together of more than one aspheric surface. These lenses are described as Zonal Aspherics. The first such lens was the Welsh 4 -Drop(1978), which was so called because it comprised of four concentric zones in which the surface power dropped off by 4.00D from the centre of the lens to the periphery. The advent of computer controlled surface grinding has resulted in the production of lens moulds with surfaces of a higher order than that of the conicoid.

Davis and Fernald (1965) were the first to design an aspheric lens with a polynomial convex surface. This lens, called the Aolite Aspheric, had a front surface with a three term polynomial lenticular aperture. The resulting aspheric surface was not greatly different from that of an ellipsoid, however this was bettered by the Fulvue Aspheric lens, (Whitney, Reilly, and Young; 1980) which is described by a five term polynomial expression. These extra terms were introduced to allow peripheral flattening of a lens and thus enhance the cosmetic appearance rather than to improve the optical quality. To date, there are a number of aspheric spectacle lenses of this order available, which exhibit a useful field of view extending to around 30° before oblique astigmatism becomes troublesome.

CROSS-SECTION THROUGH THE CONICOIDS

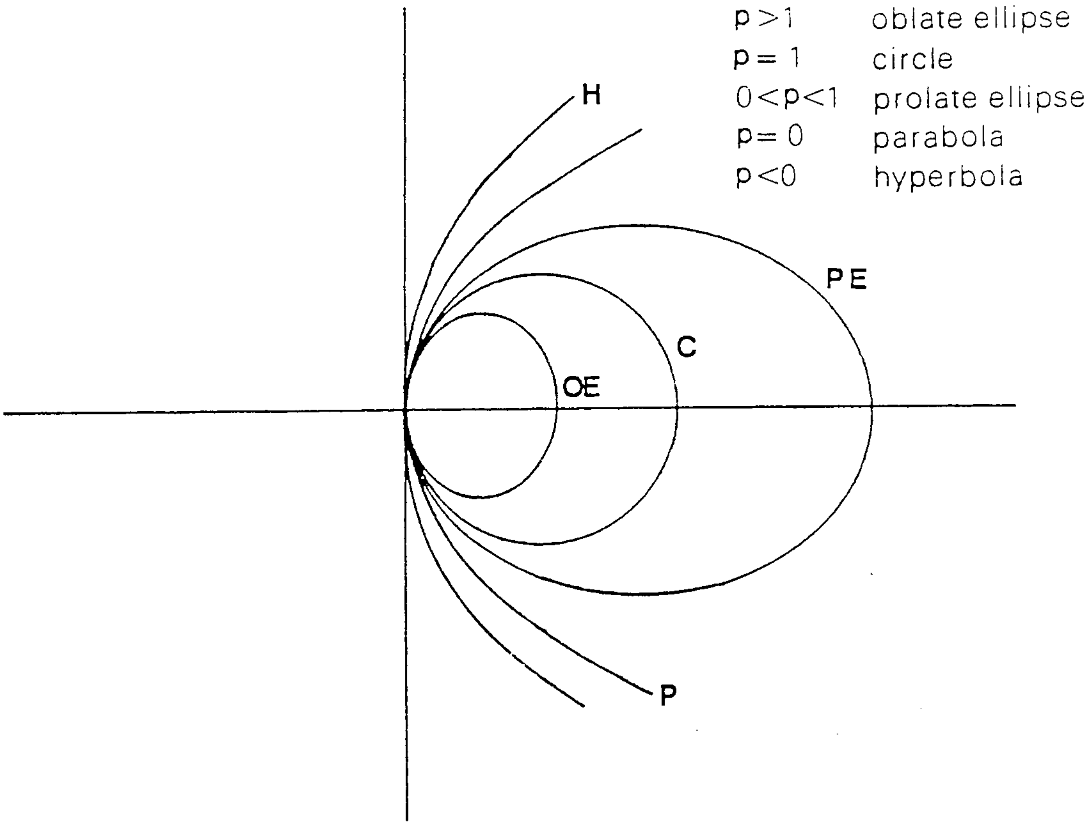


*Figure 3.6.* The conic sections produced in *Figure 3.5.* may be spun around a common axis of symmetry. Lens manufacturers may employ the surfaces of these three dimensional structures(surfaces of revolution) in their ophthalmic products. An aspheric lens surface resulting from an ellipsoid, a paraboloid or a hyperboloid.

## 3.8. PROGRESSIVE ADDITION LENSES

A progressive addition lens may be classed as a specialised form of aspheric lens. The progressive surface unlike those described above does not possess rotational symmetry and the only meridian of the lens which is truly compatible to an aspheric lens is the umbilical line. Elsewhere the lens surface is affected by the presence of surface astigmatism and distortion due to the controlled progression of surface power within the intermediate corridor.

If the meridian from a progressive addition lens along which the umbilical line lies is compared to a meridian from an axially symmetrical aspheric lens there is one very notable difference. In the case of the progressive addition lens the surface power increases towards the periphery in order to give an increase in lens power for the necessary reading addition. With an axially symmetrical aspheric lens the power decreases as noted by Atchison and Smith(1980).

Therefore in the case of the PAL the effects of curvature-of-field, distortion, and astigmatism can only be increased by this design. Nevertheless, the polynomial relationship (3.2.) may be applied to this umbilical line, as a means of denoting the surface topography in that meridian. Elsewhere on the lens surface the topographical geometry will be affected by the distribution of surface aberrations and a mathematical description will be more difficult. Curve fitting equations may however be applied to empirical results.

With the exception of the Aves(1907) lens patent and the more recently patented Freeman(1984b) design, progressive addition lenses are structured with an aspheric surface and a toric sphero/cylindrical surface. Most commercially available lenses are designed with the anterior surface being progressive. Lenses are supplied in a semi- finished blank form from the manufacturers to the prescription house, where an individual patient's requirements are worked onto the posterior surface.

It is the aim of every optical engineer to produce a progressive lens free from surface astigmatism and distortion. In reality it is not possible to produce such a lens due to the aspheric requirements of the progressive zone. Torgersen(1987) notes that the aim of a designer is to produce a lens which:

(1) provides a wide, clear distance portion,
(2) provides a wide, clear near portion,
(3) provides usable intermediate vision,
(4) minimises peripheral distortion, and
(5) provides invisible segment boundaries.

In order to satisfy these five criteria simultaneously a compromise is necessary. Each PAL design varies from its commercial rivals by the emphasis placed upon each criterion by the individual lens designers. Guilino and Barth(1982) state that surface astigmatism of 0.5 dioptres, which corresponds to a deficient spherical correction of 0.25 dioptres is not perceived as very bothersome. However, Shinohara and Okasaki(1985) state that most people can tolerate up to 1.0 dioptres of astigmatism, which corresponds to 0.5 dioptres of spherical correction.

When considering mathematical models of the meridian line through the progressive zone, surfaces can be subdivided into two groups. These are as follows:

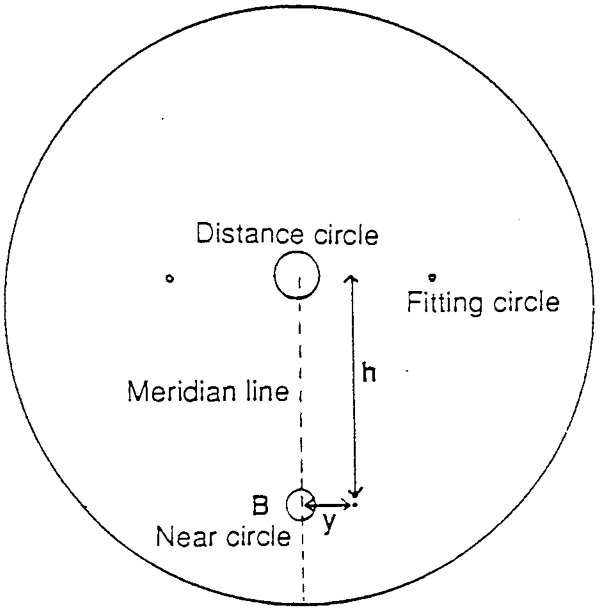
(a) linear progression,
(b) non-linear progression.

For lenses with a linear progression,i.e., a constant rate of addition, the surface astigmatism will increase with perpendicular distance from the principal vertical meridional line. von Minkwitz(1963) stated that the dioptric value of astigmatism increases with perpendicular distance from the median line at twice the rate of power increase along the line of symmetry(Figure 3.8). Therefore if $B$ denotes the power of the add and the height of the intermediate zone is $h$ ,then the astigmatism $A$ at a distance $y$ from the median line is given by;

$$A = 2By / h$$

From this equation it is possible to calculate the width of the "corridor of clear vision", depending upon the criterion of acceptable astigmatism, and it can be seen that lenses with short progressions and high reading additions are subject to more surface astigmatism. Astigmatism can also be altered by changing the reading portion width. Subsequently, manufacturers produce their lenses in a number of base curves to produce the optimum form for any given reading addition.

CALCULATION OF PAL SURFACE ASTIGMATISM



Astigmatism (A) = 2By/h

*Figure 3.7.* Astigmatism (A) at a point on a PAL surface(von Minkwitz,1963) will depend upon the power of the reading addition B, the distance down the umbilical line h, and the lateral displacement from the umbilical line y.

Lenses with non-linear progressions may have a number of stepped progressive sections. The above expression can then be adapted for the appropriate number of power discontinuities, e.g., if $b_1$ and $b_2$ are added, to represent two discontinuous power steps then the equation will become;

$$A = 2(B - b_1 - b_2)y / h$$

The Winthrop(1977) progressive lens design incorporated two discontinuous power steps introduced into the intermediate progressive zone (see *Figure 2.12*). The rate-of-change of dioptric power along the umbilical line can then be reduced. This design limits the degree of astigmatism and distortion, whilst maintaining the necessary power variation along the umbilical line. Offset against this advantage is the need to ensure the power discontinuities are blended with the other portions of the lens to avoid a break in surface topography, which would result in a ridge on the lens surface. To preserve a smooth curve, blending the zones together was unavoidable, which resulted in a degree of astigmatism being present in the periphery of the distance portion. This type of progressive addition lens may be considered analogous to a zonal aspheric spectacle lens due to the necessary blending which is present in the lens design.

# Chapter 4

## THE INTRODUCTION OF PROGRESSIVE ADDITION LENSES TO THE HUMAN VISUAL SYSTEM

## 4.1 ADAPTATION

### 4.1A Adaptation to the Optical Distortion of Form

Adaptation to optically altered transformations of the retinal image has been widely studied since the pioneering work of Stratton (1897). However, Stratton's research involved inverting the retinal image which clearly led to extreme disruption of visually guided behaviour and is not characteristic of prescription spectacle lens adaptation. Rock(1966) lists the different kinds of image transformation which have been studied . These include, inversion or tilting of the retinal image , alteration of the direction or rate of movement of the image across the retina with head movements, magnification or minification of the image, lateral displacement of the image, and unequal displacement of different parts of the image resulting in curvature induced distortion. When considering the distorting effects of PAL's a number of the optical transformations listed above may be present simultaneously.

Gibson(1933) performed, what is now considered to be a classic experiment on adaptation to optically altered form. Gibson used wedge prisms to create optically induced curvature distortion. When a straight line is viewed through a plano prism the image is deviated towards the apex, it will also appear curved because the effective prism power increases with an increase in oblique incidence. When the subjects viewed the straight line initially it appeared to be quite curved. However, Gibson noted that his subjects reported an adaptation to the curvature of a straight line, so that the curved lines appeared less curved following a period of adaptation. When the prisms were removed a straight line was perceived as being curved in the opposite direction. Gibson noted that there was a measurable decrease in the apparent curvature of a prismatically distorted straight line after 10 mins and that there was an equivalent increase in the curvature of straight lines when viewed immediately after removal of the prisms.

Bales and Follansbee(1935) confirmed the effect noted by Gibson. They verified the negative after effect which Gibson had noted. They also showed that there is a notable variation in the effect reported by different subjects. Indeed 5 of the 22 subjects involved displayed no adaptation to the changed retinal image. Bales and Follansbee also showed the phenomenon was present when the straight line was substituted for a curved one and confirmed Gibson's findings that the negative after effect was strongest immediately following the inspection period. They noted that following curvature adaptation a period of 'reading' as opposed to a period of 'fixing' the line preserved the after effect longer.

In a follow up study , Gibson(1937) showed that adaptation and the subsequent negative after effect were also present with a bent line as opposed to a curved line, provided that the subjects gaze was confined to the section of line where the bend appeared. In these subsequent experiments Gibson established that the effect is localised to the area of the retina upon which the image falls, that much of the adaptation effect is transferred from one eye to the other, and that the effect is present with both static and kinetic straight line images. Pick and Hay(1964) claimed that adaptation to line curvature produced by a prism occurred rapidly and completely whereas adaptation to certain shape distortions occurred slowly and was incomplete. They concluded that the degree of adaptation varied with a variety of different shape distortions.

Kohler(1964) showed that, in addition to a change in curvature, a prism will create a variable amount of displacement depending upon the angle of incidence. Objects to the left or right will be deflected more than those straight ahead. This effect is shown in Figure 4.1a. When the prism is located base left then there will be a compression of objects on the left and an expansion on the right(see Figure 4.1b). Furthermore, horizontal lines located above eye level will slope upwards away from the base of the prism and those below eye level will slope downwards away from the prism base. This effect was named a 'situational aftereffect' by Kohler. This additional property of prismatic optical disturbance is not evident with a single dimension test line but it is clearly of importance when dealing with everyday objects of regard.

Kohler(1964) also found that adaptation to a two dimension object such as the test grid shown in Figure 4.1b does occur, but this adaptation is slower and less complete than in the case of a single dimension straight line. He further reported that when the wedge prisms were removed the apparent size and shape of objects varied with the direction of gaze. Pick and Hay(1966) produced quantitative

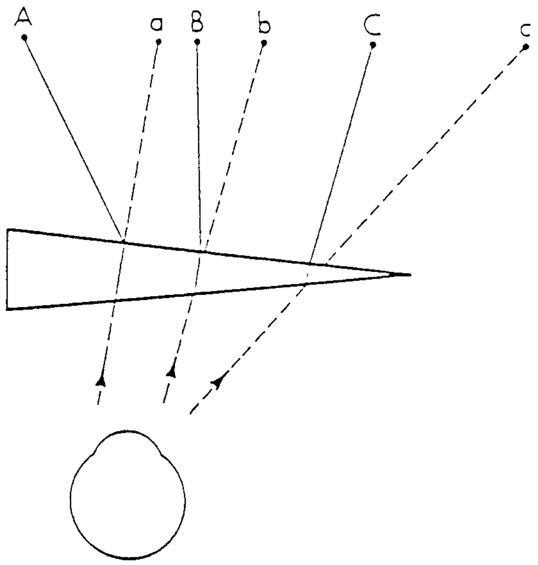


*Figure 4.1.(a).* This diagram shows how a prism creates a variable degree of displacement depending upon the angle of gaze through the prism. The images of points A, B and C are located at a, b, and c respectively. The introduction of the prism produces a smaller amount of movement for the image of B than for A and C, due to the lateral displacement of A and C from B.

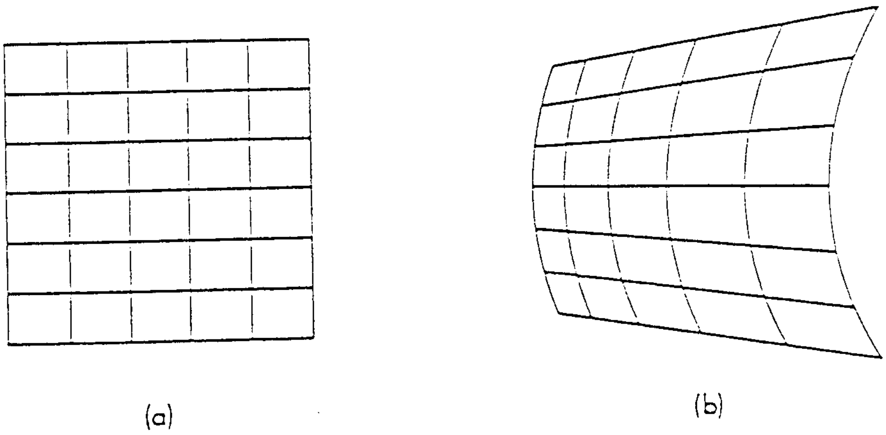


*Figure 4.1.(b).* When this variable degree of prism displacement is applied to a two dimensional object, such as a grid, the effect is to transfer grid(a) into the distorted image shown as (b).

results which stated that a reduction in compression and expansion occurred, with head rotation, of between 5 and 10 per cent after over 40 days wear. The same study showed that over the same period the tilt effect reduced by around 25 per cent.

Ross(1970) studied adaptation to curvature distortion in an underwater situation. Her two dimensional study involved sub-aqua divers and showed that a smaller degree of adaptation occurred with experienced divers than with novice divers. She concluded that experienced divers had undergone a process of 'perceptual learning' because they were aware of their surroundings. Experienced PAL wearers may also undergo a similar process. Ross and Lennie(1972), in another underwater study stated that the adaptation which occurred to counteract three dimensional distortion was of a highly complex nature. Their work suggested that adaptation in one dimension could produce an apparent increase in distortion in another direction. However, this 'trading' effect which they noted was found to be incomplete and there was in addition some overall adaptation in all dimensions.

Wallach and Barton(1975) studied adaptation to optically produced curvature. They found adaptation was more rapid when the subject nodded their head during the exposure period. However, the rate of adaptation was not enhanced when the object was moved and the head remained stationary. They concluded that head movements are not necessary for adaptation to become manifest it would appear that they reduce the time interval necessary for adaptation to occur.

Vernoy and Luria(1977) showed that significant adaptation to three dimensional curvature distortion occurred after 5 mins, in an underwater environment. For this study a skeleton cube made of flexible rods was constructed and this was adjusted by the subject whilst underwater so as to form, what the subject considered to be, a perfect cube. They noted that the type of task undertaken by the divers whilst underwater did not affect the amount of adaptation, which they found to be significant in each of the three dimensions. Vernoy and Luria observed that the amount of distortion perceived whilst notable, was less than that which would be predicted optically in each dimension. This finding is in agreement with Ross's observations(Ross,1970). Vernoy and Luria found that the subjects did not adapt totally - they measured values of up to 63.75% adaptation. Their results demonstrated percentage adaptation values over twice that found by both Ross(1970) and Wallach and Barton(1975).

Kohler(1964) also used prisms that covered only the upper half of the field of view, the lower half being unaffected. When looking at a straight vertical line, at first it appeared to be split with the upper half also being curved. After a period of adaptation subjects perceived the line to be straight and unbroken, despite the discontinuous retinal image. Kohler (1964) suggests that the wearing of bifocals is in some ways an analogous, albeit less radical, situation.

### 4.1B Adaptation to the optically distorting effects of PALs

Whilst research has been directed at ascertaining the properties and performance of progressive addition lenses, both physically and psychophysically. There has been relatively little work which has considered adaptation to the distortions induced by the design of progressive addition lenses. An analogy has been drawn between Kohler's work with split prisms and bifocal wear. The non-uniform nature of PAL asphericity may further complicate the adaptation process and delay the onset of visual comfort.

Thorn *et al* (1985) measured the amount of perceived image movement induced by head rotation before, during and after PAL wear. Their apparatus comprised a computer driven VDU, upon which two vertical lines were displayed, one above the other. One of these lines could be adjusted by the subject with the use of a joystick, whilst the other was fixed. When the subject rotated their head, the movable bar of light moved either with or against the motion of the head. The subject then responded indicating the apparent movement of the vertical bar image. The computer used these responses to derive, using a staircase approach, a psychophysical threshold indicating the point at which there was just no apparent motion. Unfortunately, their study only involved two subjects; one subject appeared to adapt to the extra image motion resulting from the induced prism effect of PAL's in the inferior visual field. The other adjusted to the disturbances present with the PAL but showed no adaptation of the sensory visual system. These findings led them to conclude that the response of a PAL wearer may take one of two forms; subjects being classed as either 'adapters' or 'adjusters'. This thesis includes a study of the problems related to PAL adaptation and questions the factors which may govern patient tolerance.

### 4.1C Oculomotor Adaptation

The flexibility of the human oculomotor system, possessed by subjects with normal binocular vision, has been demonstrated by a number of workers. Ogle and Prangen(1953) studied the nature of hyperphoria whilst the eyes were forced into vertical divergences using prisms. They found most subjects were able to compensate or adapt completely for vertical prism divergences up to at least 6Δ. They also noted that the original oculomotor balance was maintained following the period of adaptation, in those cases where there was no underlying hyperphoria. With such subjects the prism was accepted by the amount required to correct the hyperphoria and the remainder was adapted or compensated for, as in the manner of those subjects without a hyperphoria.

Carter(1965) reported similar results with horizontally orientated prisms(both base in and base out). Prisms from 10Δ base in to 32Δ base out were used and he showed that subjects with normal binocular vision adapt to them by a change in the tonicity of the extraocular muscles. These findings have been confirmed by Henson and North(1980) who found that adaptation could be completed after only 2-3 mins of binocular vision when they separately, used prisms of up to 2Δ vertically and 6Δ horizontally. Henson and North(1980) also found that adaptation was quicker for a 6Δ base out prism than for a 6Δ base in prism, at distance vision. They found no significant difference at near between base in and base out prism. They also considered the effect of lens -induced phorias upon the oculomotor system(North and Henson 1985), with largely similar results.

It is a little paradoxical that presbyopes who by definition have reduced accommodation ability do not appear to have major asthenopic symptoms despite the increased exophoria exhibited through a reading correction. Sheedy and Saladin(1975) have considered this paradox. They compared two population groups. One, a group of presbyopes, showed an average near phoria measure of 8.7Δ when corrected, whilst the other group, comprised of non presbyopes, indicated an average near phoria of 2.8Δ. Sheedy and Saladin also measured the two groups for fixation disparity. They found both groups exhibited no fixation disparity, for near, under binocular conditions. Whatever the best measure for phorias/fixation disparities, it is evident that the normal human oculomotor system is very flexible. Miles and Judge(1982) further demonstrated this by fitting a number of subjects with a periscopic device which had the effect of doubling their apparent interpupillary distance. Within 30 mins the oculomotor system had adapted and the subjects were able to converge more for near objects without increasing the convergence for distance objects.

## 4.2. CASE HISTORY STUDIES

In a study of the performance of progressive addition lenses it must be noted that there are many reasons for patient failure other than a physical rejection of the lenses themselves or the patient's inability to adapt to a particular design. Indeed, the slow acceptance of progressive addition lenses by optometrists and patients alike is often attributed to the relatively large number of possible complications which may arise with these lenses.

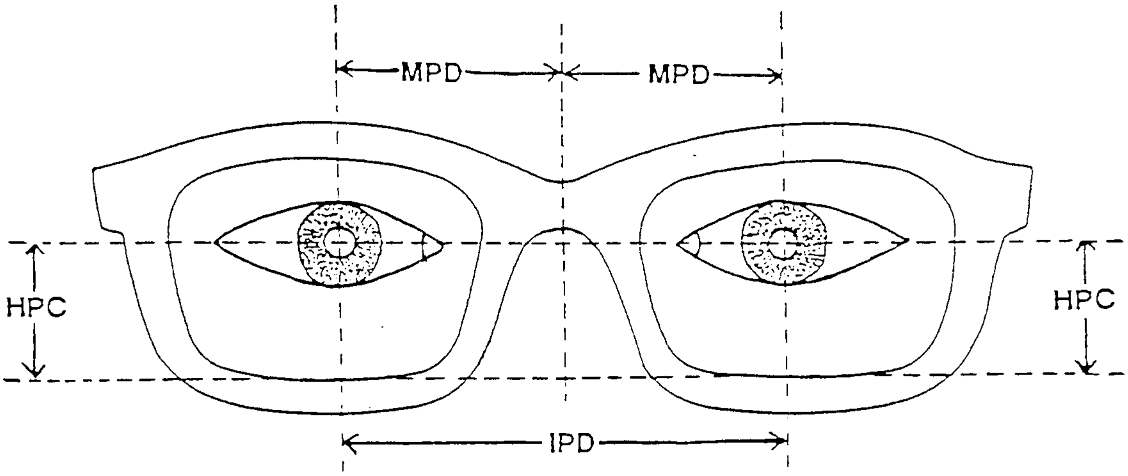
There have been many instances when progressive lenses have been dispensed incorrectly to patients or when they have been prescribed to inappropriate patients. It is essential to consider the necessary constraints placed upon progressive lens dispensing before a comparative analysis of the physical and psychophysical properties of these lenses may be undertaken. A psychophysical study which encompasses faulty or inappropriate dispensing will give rise to the introduction of variables which may mask the underlying results. The succeeding sections of this chapter review the documented guidelines which have arisen from previous clinical studies and case histories.

### 4.2A Dispensing Precautions

The non-rotationally symmetrical nature of these lenses means that to avoid faulty dispensing a number of special precautions must be undertaken. It is necessary to specify the monocular pupillary distances to ensure each lens is placed in the correct lateral position should any facial asymmetry be present(Figure 4.2). Hubler (1976) noted that it is not uncommon for a patient's monocular P.D.'s to differ by up to 4 mm. Innes (1982) stated that accuracy to within 0.5 mm is required. Therefore, as indicated by Hoeft, Martin and Lee (1980), an ordinary facial rule is not sufficient for the recording of pupillary distances. Another important measure which also requires accuracy to within 0.5 mm is the position of the pupil centres relative to the frame location. The majority of progressive addition lenses are designed to have the distance centres 2-4 mm below the pupil centre, in the absence of a prismatic element being present. Any vertical asymmetry between a patient's eyes must also be recorded. Hubler(1976) has stated that vertical asymmetry (≥0.5mm) occurs in 10% of cases.

In order for the whole length of the umbilical line to be incorporated into the spectacle frame it is necessary, according to Brooks (1976) and Innes (1982), for the depth of the frame to be no less than 22 mm below the position which coincides with the pupil centres. A suitable spectacle frame must therefore be

Necessary Dispensing Precautions



M P D = Monocular Pupillary Distance

H P C = Height of Pupil Centres

I P D = Interpupillary Distance

*Figure 4.2.* Diagram showing the monocular pupillary distances (MPD) and the height of pupil(HPC) measurements which must be accurately recorded for successful PAL dispensing. The monocular pupillary distances for each eye combine to produce the total interpupillary distance(IPD).

selected which is deep enough to encompass the whole length of the progressive corridor.

In a similar fashion to bifocal lenses, progressive lenses must not be glazed too low or too high. Lenses set too low will result in a need for the eyes to be excessively depressed in order to read whereas when they are set too high the patients distance vision will be blurred by the top section of the progression zone. Failure to align the lenses properly will also result in the eyes not following the corridor of the umbilical line when they converge, which may give rise to asthenopic symptoms. An asymmetrical glazing of lenses which is not justified by an underlying facial asymmetry is another source of possible complication.

Progressive addition lenses are designed to be dispensed at a particular vertex distance and with the spectacle frame fitting at the correct angle of side and pantoscopic tilt(Figure 4.3). Innes (1982) reported the ideal vertex distance to be 12-14 mm. The closer the eyes are to the lenses, without touching the eyelashes, the wider the field of view will be. Alexandre (1977) suggested it is best not to chose frame designs which "push" the lenses away from the face as this will increase the vertex distance. Brooks (1976) also considered a small vertex distance and the correct pantoscopic tilt (around 5° -10°, but this will depend upon the style and size of the frame) to be essential to allow a suitable field of view for reading. Daley (1979) reckoned that too great a value for the vertex distance was the single most common reason for patient rejection of progressive addition lenses.

### 4.2B Patient's Physical Features

Aspects of the patient's facial and physiological features may also be of importance when assessing potential problems. The patient's pupil size is a factor which may be attributed to unsuccessful patient adaptation. Sasieni(1984) noted that those patients with large pupils may find the inherent aberrations more noticeable. This may arise as the difference in vergence of light entering the top of the pupil and that entering the bottom will be greatest with large pupils. This is shown in Figure 4.4.

Innes (1982) stated that people with especially high cheekbones, flat nose bridges, and deep set eyes can prove difficult to dispense successfully. This is due to the problem of selecting a suitable frame to allow a small vertex distance with an appropriate degree of pantoscopic tilt. Brooks (1976) noted that the

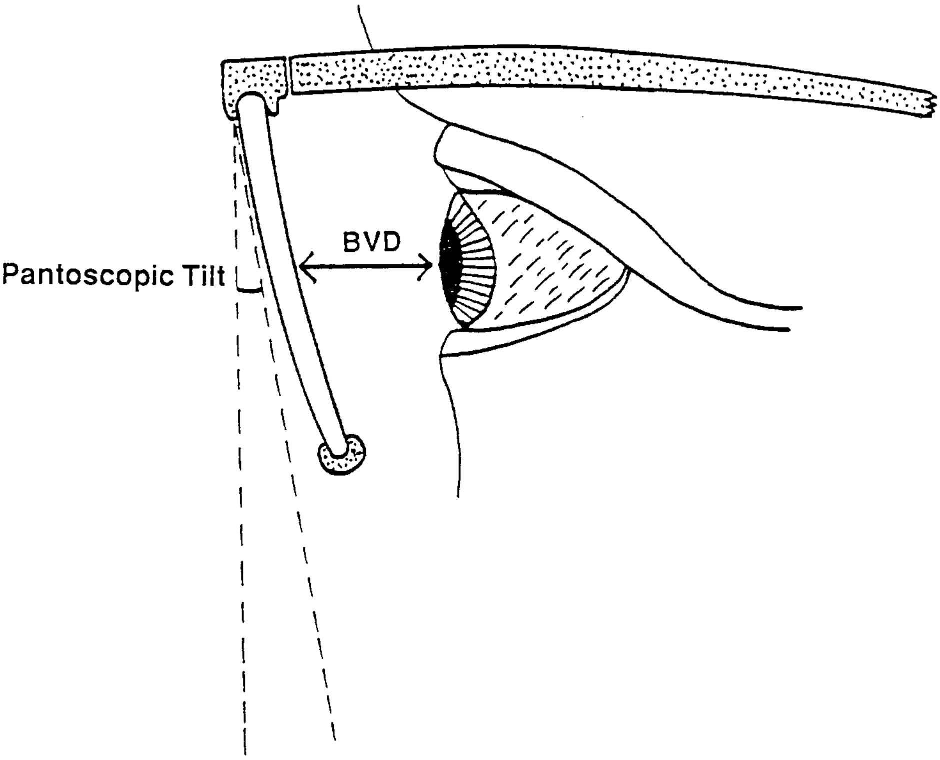


*Figure 4.3.* Cross section diagram of the pantoscopic tilt and back vertex(BVD) measurements. Values of between 5° - 10° for the pantoscopic angle measurements and 12 - 14 mm for the BVD are suggested for successful PAL dispensing.

patient's height may also be an important factor when positioning the lenses vertically in the frame. Facial asymmetry, such as one eye higher than the other, may also be the source of problems; if these factors are not accounted for by the spectacle dispenser.

### 4.2C Patient's Refractive Error

The patient's underlying ametropia may also be of significance in relation to the success rate of these lenses. Hubler (1976), Runninger (1980), and Mullins (1981) have all stated that the emerging presbyope with a low addition requirement makes one of the best candidates. Two reasons for this may be; firstly, the patients are relatively younger and secondly, the reading addition being smaller should result in a wider intermediate corridor being present.

Hubler (1976) further stated that myopes produced a high rate of success as did high hypermetropes. Runninger (1980) confirmed that there is a relatively good success rate with myopes. Tsujimura and Moore (1979) performed a study upon randomly selected aphakics. They found that aphakic patients preferred progressive addition lenses to either bifocals or trifocals. Innes (1982) remarked that patients whose prescriptions incorporated moderate to high cylinders often did better than those with purely spherical corrections. Wittenberg(1978) has also suggested that patients wearing a high cylindrical correction were more likely to succeed than those with low cylindrical or spherical correcting lenses. Innes(1982) further noted that early presbyopes were a group which often succeeded. This, he supposed, was due to the low addition required and that this population did not need to be retrained after bifocal wear. Runninger (1980) stated that it was best to avoid cases with more than 1.50 D of anisometropia due to the differential prism introduced; present designs of progression addition lens cannot be slabbed off.

### 4.2D Ophthalmological Contraindications

These lenses have been used for the treatment of some forms of orthoptic anomaly and they have been shown to have some success in this when used as as an alternative to bifocals(see Smith,1985; Jacob *et al*, 1980; and Valentino, 1982). Nevertheless, it is best to avoid fitting patients who for ophthalmological reasons may find adaptation especially difficult. A number of cases have been specifically mentioned in the literature. Innes (1980) noted that it is best not to fit patients who suffer from nystagmus. He further remarked that patients with macular problems do not make suitable candidates. Good macular vision is essential for the successful use of progressive addition

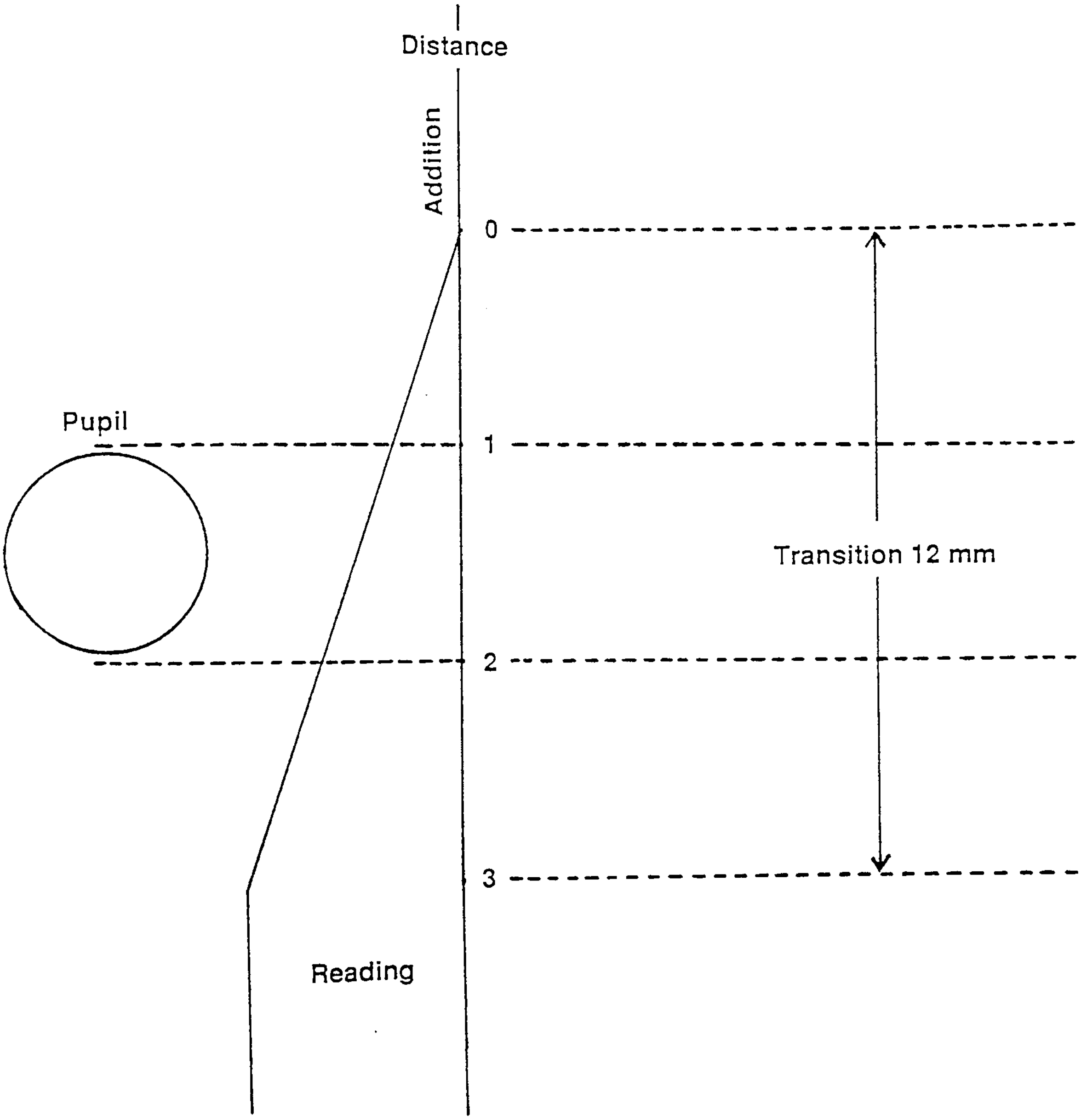


*Figure 4.4.* A schematic diagram( after Sasieni,1984) showing the manner in which the vergence of light alters across a 4mm pupil due to the progressive nature of a PAL.

lenses. North and Henson(1982) noted that patients with orthoptic problems, other than those being treated with PALs, often showed a reduced adaptational ability, thus it might be best to avoid the use of progressive addition lenses with these patients. Chapman (1978) found patients with convergence insufficiency to be unsuitable candidates.

### 4.2E Patient's Personality and Lifestyle

Bétournay(1979) found that successful adaptation to progressive addition lenses was similar for males and females. Fowler (1982) also found no sex bias in his results. Augsburger *et al* (1984) found a slightly higher success rate with women than with men. A number of workers have noted that a particular aspect of a patient's lifestyle whether that be a type of employment or specific hobby may result in these lenses being unsuitable. Sasieni (1984) noted that patients who require accurate intermediate vision do not make successful candidates for progressive addition lenses. Patients who undergo extensive near vision tasks may also find progressive lenses are inappropriate.

A patient's temperament is somewhat difficult to assess scientifically. Psychological testing is not something ordinarily undertaken by the optometrist. Apart from being a little disconcerting to the patient, quantifiable character testing is very time consuming. However, Young (1984) cites personal temperament as being an important factor when considering the reasons for failure. Innes(1982) made a similar point when he noted that those patients who were 'relaxed and flexible' proved to be better patients than those who were 'complaining and inflexible'. Tucker (1981) also applied a classification to potential progressive lens wearers covering such factors as their intellectual and psychological nature.

Fowler (1982) did not make this type of assessment prior to fitting these lenses and achieved a comparable success rate to those who did. However, Wittenberg (1978) stated that when personality traits were considered he was able to increase his success rate by around 20%. Sasieni (1984) considered there to be no satisfactory method of accurately assessing those patients who might be classed as psychologically unsuitable. He further stated that when the other reasons for failure are taken into consideration then the probability of temperament being the reason for rejection was very small.

### 4.2F Success Rate

The above criteria might suggest that there are few ideal candidates for progressive addition lenses. One valid criticism of optometrists and dispensers is that they have been over cautious on occasions when progressive lenses would have been appropriate. Bennett (1966) claimed a success rate of between 90%-95% in a study which involved 30,000 lenses. Bétournay (1979) stated an acceptance value of 96% and Wittenberg (1978) achieved a value of 96.5% in a study that involved 25,000 lenses. Augsburger *et al* (1984) rated their success as 93.5% in a final year university clinic with "first time" dispensers. These studies define successful patients as those who were still wearing their lenses after a set period of time when the patients were reassessed. Another method of assessing successful wearers would be to ask patients if they would be happy to have another pair. The results of this type of assessment might indicate a number of wearers who are persevering with their PALs but would not choose another pair when they return to their optometrist. The above mentioned success rates from documented studies may account for the increased usage of PALs within the United Kingdom over the last few years.

# Chapter 5

## METHODOLOGY EMPLOYED IN PREVIOUS STUDIES OF PROGRESSIVE ADDITION LENS ASSESSMENT

### 5.1 INTRODUCTION

Empirical analysis of Progressive Addition Lenses can be divided into two groups. These are physical and psychophysical. Physical assessment relates to a mechanical evaluation of the lenses in isolation from the patient. Indeed, to study the progressive surface alone it may be sufficient to have the lens in the semi-finished state. This form of evaluation is especially useful for assessing the reproducibility of a particular design and also for a comparative analysis of the physical properties amongst designs. However, it is not possible to derive information regarding the influence of the progressive addition lens on the visual system, or the visual performance obtained through the lenses, by using this technique.

Psychophysical assessment entails an evaluation of the patient's visual perception whilst the lenses are being worn. Such a response judges the quality of the progressive addition lens by rating the degree to which the natural vision of a pre-presbyope is reproduced for the presbyopic patient, in addition to the correction of any ametropia. Psychophysical assessment is particularly useful for the study of adaptation to and patient tolerance of PALs.

When a practitioner is faced with a non-tolerant patient the lens/patient incompatibility may be attributed to one of three reasons:

(a) The PAL's may have been dispensed incorrectly or they may have been dispensed to an inappropriate patient on the basis of previously recorded case histories. This subject was dealt with in the previous chapter.

(b) The patient's visual system may not be sufficiently flexible to adapt to this type of lens design. This area is the perogative of psychophysical lens assessment.

(c) There may be shortcomings with the lenses themselves. Physical assessment of the lenses should reveal an incorrectly manufactured article.

## 5.2 PHYSICAL ASSESSMENT

A number of different techniques have been employed. They vary in the degree to which they are either quantitative or qualitative. Physical assessment of progressive addition lenses may be divided into two types of evaluation. Those methods which involve the finished lens and those which consider the semi-finished lens blank.

### 5.2.A Finished Lens Assessment

*Conventional Focimeter*

The focimeter is the most commonly used instrument in the assessment of progressive lenses. It has been employed in a number of different ways. The conventional use of the focimeter involves measuring the Back Vertex Power (B.V.P.) at the distance and near viewing circles and is the technique employed by the optometrist in daily practice. The focimeter may of course be used outside those areas specified by the manufacturers to measure any area of the lens in this fashion. This technique does not take any account of the eye position in relation to the glazed spectacle lens. Measures of the lens periphery, with the above method, do not consider the increased vertex distance and oblique incidence of light which result with eccentric viewing.

*Morgan Rotating Mount Focimeter*

It is possible to simulate the effect of the moving eye behind a fixed spectacle lens with the use of a specially designed rotating lens mount attached to a conventionally designed focimeter. Morgan (1961) was the first to propose this type of adaptation, although his work was not related particularly to progressive addition lenses. Simonet, Papineau and Gordon(1983) adapted a projection focimeter in this manner for the assessment of progressive addition lenses. They choose the use of a projection focimeter due to the large number of measurements necessary to provide a thorough examination of a progressive lens. Sheedy *et al* (1987) and Atchison (1987) are two examples of the use of this type of lens mounting with an automatic focimeter. Sheedy *et al* (1987) reported that they took around 700 measurements from each lens. Figure 5.1 is a diagram showing a modified focimeter similar to that used in the technique described by Morgan(1961).

Fowler(1981) noted, with high powered positive(>10.00D) lenses, that when a conventional focimeter is adapted measurement of angles up to about 25°-30° can usually be taken before either mechanical constraints due to the focimeter design or optical aberrations, besides oblique astigmatism, prevent a clear focal image from being located. The range of possible measurements will increase if a rotary compensating prism is included in the focimeter design, as this allows the image of the focimeter target to be placed centrally within the viewing telescope. Simonet *et al* (1983) constructed a lens holder for a projection focimeter which allowed lens rotation up to 45°. However, they found measurement of high powered lenses difficult beyond 25° due to the above noted aberrations.

### *Grid Patterns / Checkerboard Patterns*

Assessment of these lenses can also be undertaken, on a largely qualitative basis, using a grid pattern arrangement. A uniform pattern is viewed through a lens and the resultant pattern gives some indication of the skew distortion and oblique astigmatism present within the design. A variety of different patterns have been used but they all give roughly similar information. The more compact the pattern used, then the more detailed the information which can be received from the final plot. One common technique is to place the lens upon the grid with the progressive surface uppermost. It most be noted that when this method is employed that the viewer is looking through the lens the wrong way and at the wrong vertex distance (see Figure 5.2).

A more quantifiable use of grid patterns to indicate distortion, was utilised by Heath *et al* (1987). Their technique involved the comparative analysis of a photographed rectilinear grid through a number of Varilux V2 lenses with different reading additions. A camera with a pinhole aperture was used in order to ensure a large field free from any magnification effects caused by the camera optics. The pinhole also enabled the magnification effect of the lens to be recorded whilst allowing a sufficient depth of focus to eliminate the effect of changes in lens power upon the clarity of the image. Heath *et al* also included a rotating lens mount to allow for proper simulation of eye rotation for all positions of gaze. The resulting field covered by the instrument extended 40° to either side, 20° superiorly and 60° inferiorly, although this area could be extended if the effects of magnification were ignored (Figure 5.3).

### *Hartmann Test*

A technique, which has been used for the evaluation of astronomical telescopes, is the Hartmann Test. This was first introduced into the field of applied optics by J. Hartmann in 1904. Statton *et al* (1981) applied this test to a variety of spectacle lenses including progressive addition lenses. They produced a series of

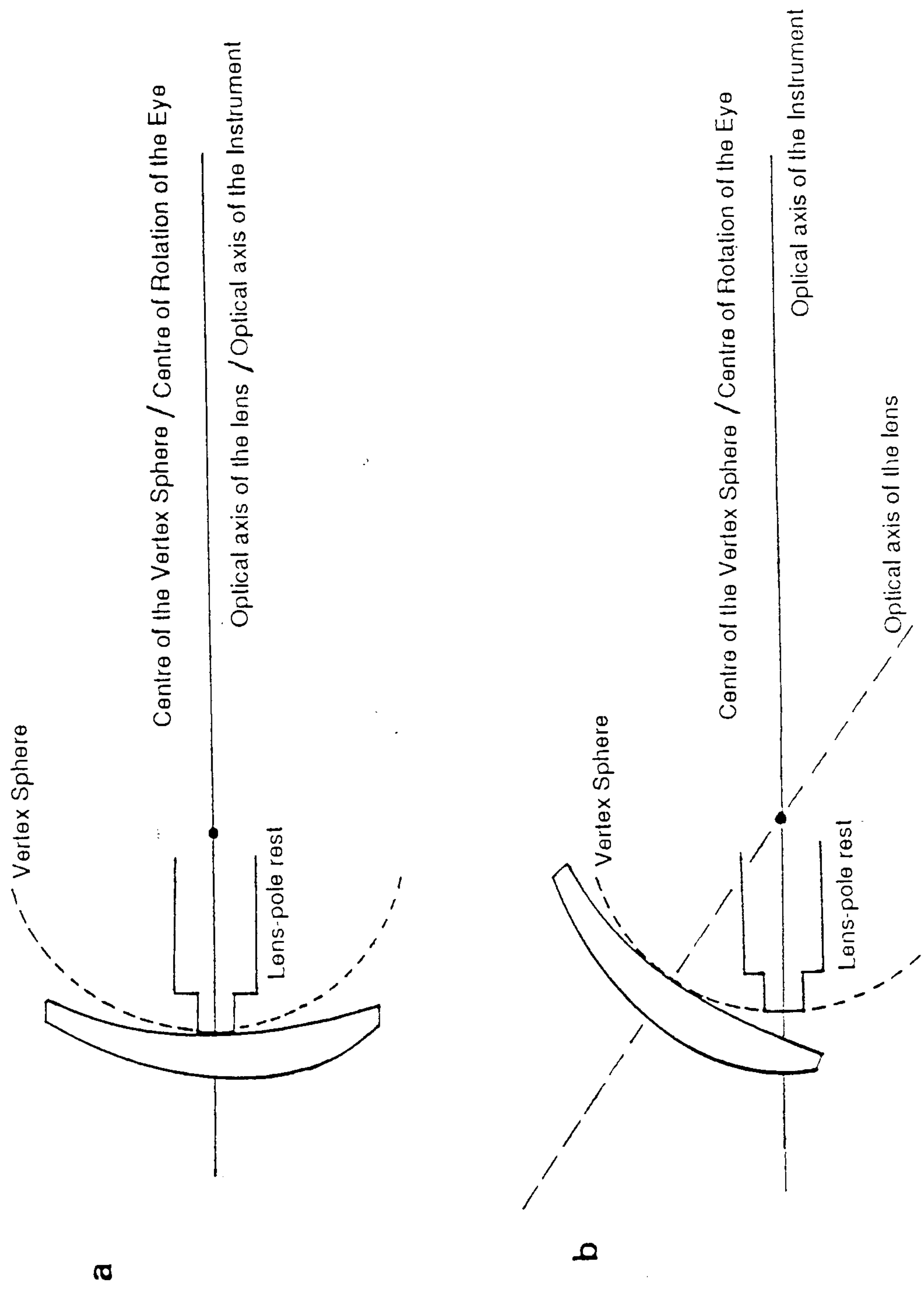
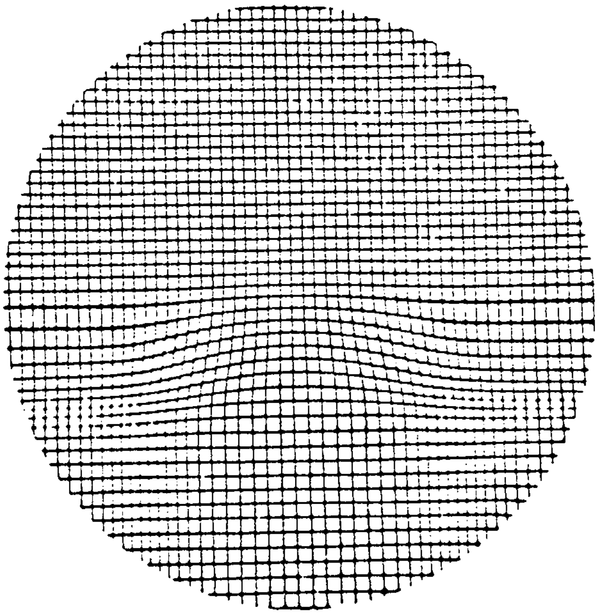


***Figure 5.1.*** Schematic diagram showing (a) the on axis and (b) the off axis positions of a PAL when tested using the Morgan rotating mount focimeter. This instrument takes account of the vertex distance being greater than the vertex sphere radius( r = 27mm) for eccentric angles of gaze.

a



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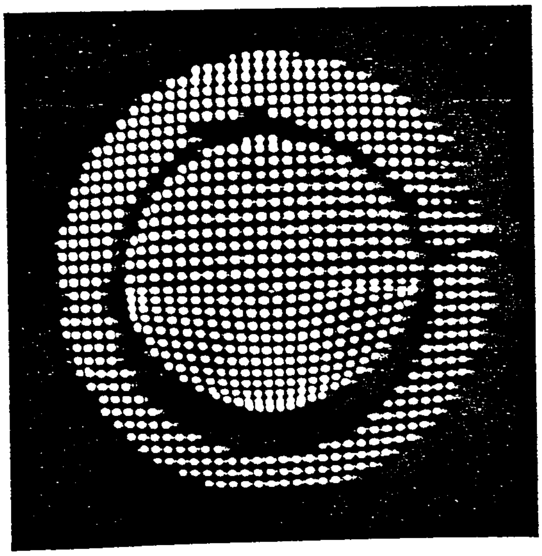

*Figure 5.2.* Diagram showing the results of viewing (a) a grid pattern and (b) a dot matrix pattern through a PAL. Resulting distortions in the grid and dot matrix patterns are qualitative methods of PAL assessment. The Hartmann test is a method of quantifying the dot matrix results.

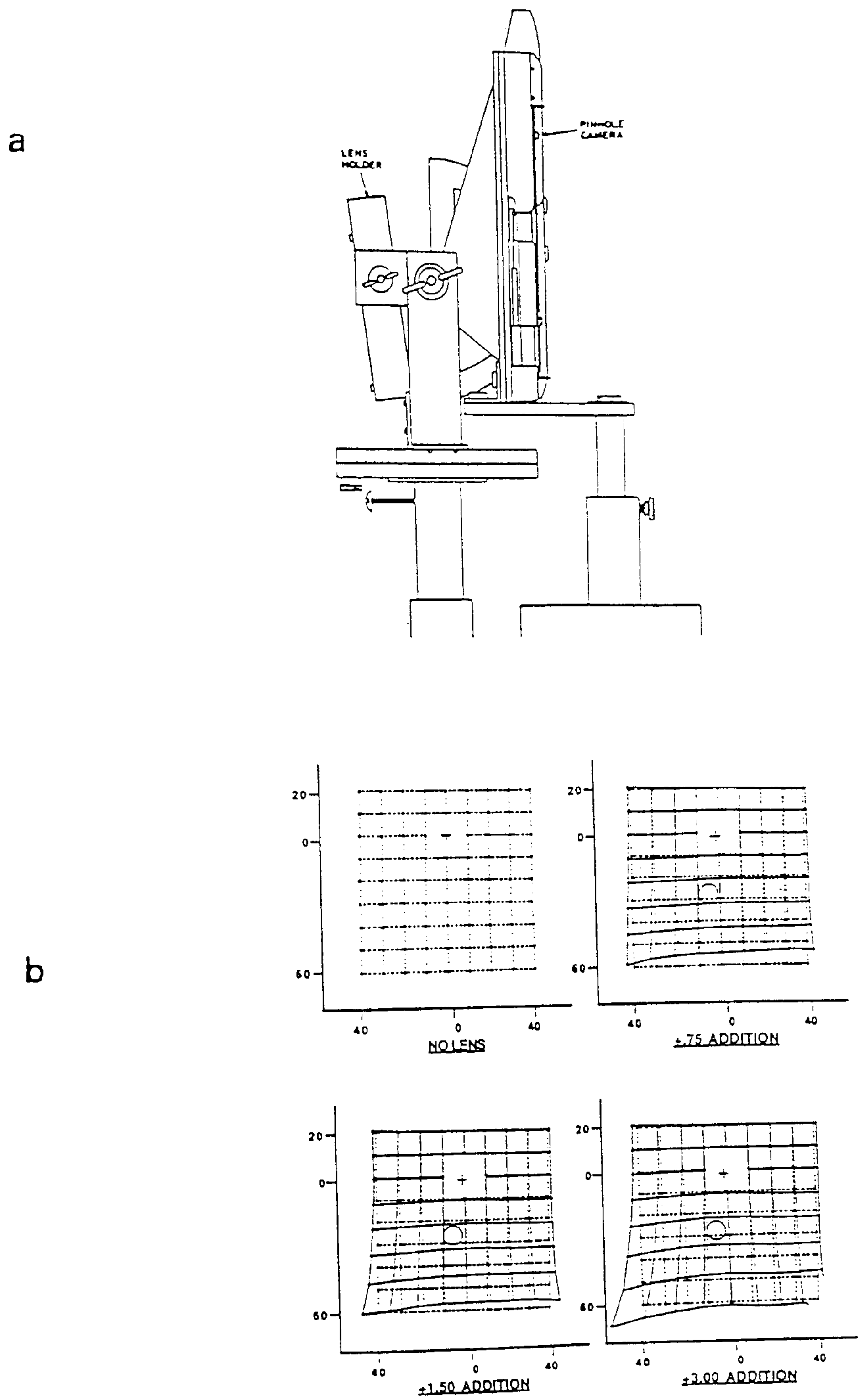

*Figure 5.3.* A photographic method of recording PAL distortion ( after Heath *et al*, 1987). Diagram (a) shows the apparatus employed with a rotating mount lens holder and a pinhole camera attached to an adjustable table. Diagram (b) shows the grid patterns which result following the introduction of +0.75, +1.50, and +3.00 D addition PALs. The grid pattern when no PAL was present is also represented for comparative purposes.

dot matrix patterns which are analogous to the above mentioned grid patterns. This pattern could be produced onto a screen or photographic plate. Statton *et al* (1981) concluded it was possible to identify between various types and powers of progressive addition lenses. However, they made no attempt to relate distortion and other aberrations to patient asthenopia.

*Interferometry*

An optical interferometer is an instrument which uses interference patterns or fringes to allow accurate measurements of wavelengths, wave velocity, and distance. From the interference pattern produced it is possible to note the type of aberration present( Figure 5.4 after Malacara, 1988). The closer the lines of the interferogram are together then the greater the departure there is between the test lens and the master.

The use of interferometers for the assessment of progressive addition lenses is becoming increasingly popular. Optical components may be tested using the Twyman-Green interferometer (Twyman and Green,1916). Figure 5.5 shows a schematic diagram of this instrument. Light from a monochromatic source is collimated by the lens $L_1$ to produce flat wave fronts which are then divided by the beam splitter BS. Light is reflected from BS through the test lens and is reflected back to BS by an accurately worked convex spherical mirror, m. Light also passes through BS to a plane mirror M where it is reflected back to BS and then focused by $L_2$ on to a screen, S. If the surfaces of the test lens are free from aberration and the material of the test lens is perfectly homogeneous - a uniform field of illumination will be seen by the eye, or photographed at S. If the lens is not free from aberration or the lens material is not homogeneous then the image at S will be made up of a 'contour map' of interference fringes.

One problem with interferometric PAL assessment is that interpretation difficulties may arise due to the simultaneous presence of several different aberrations. Torgenson(1987) presented his interferometric evaluation of a progressive lens with the use of photographs. This technique will also allow a more quantitative approach and it is possible to calculate the lens surface parameters. Guilino(1988) has developed an interferometric method of quality control for aspheric surfaces, which allows a rapid evaluation of a given lens. Mohr(1989) showed the value of this instrument for PAL assessment. The instrument used by Rodenstock is an adaptation of the Mach-Zehnder interferometer. Both the Twyman-Green and the Mach-Zehnder designs are two

## INTERFEROGRAM INTERFERENCE PATTERNS

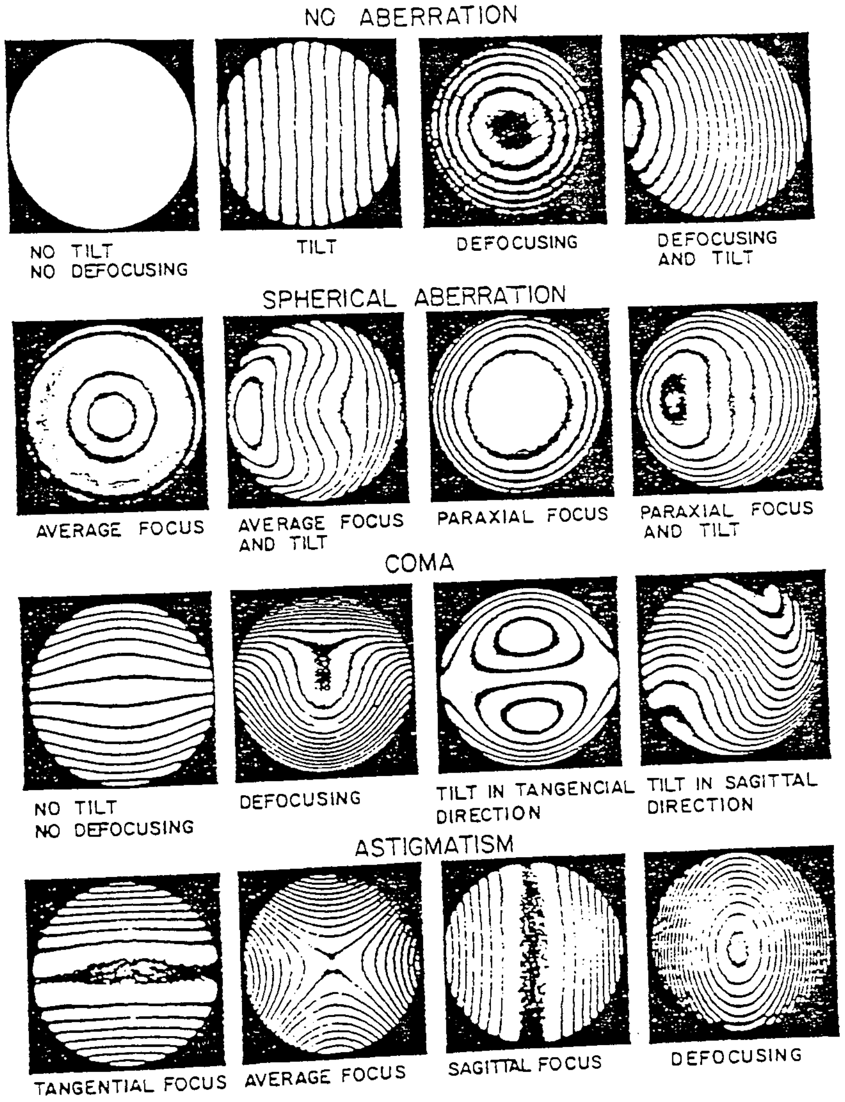

*Figure 5.4.* The interference patterns( after Malacara,1988) which arise using an optical interferometer. The presence of various aberrations will give rise to notably different patterns which helps in the differential interpretation of an optical system under examination.

# The Twyman-Green Interferometer

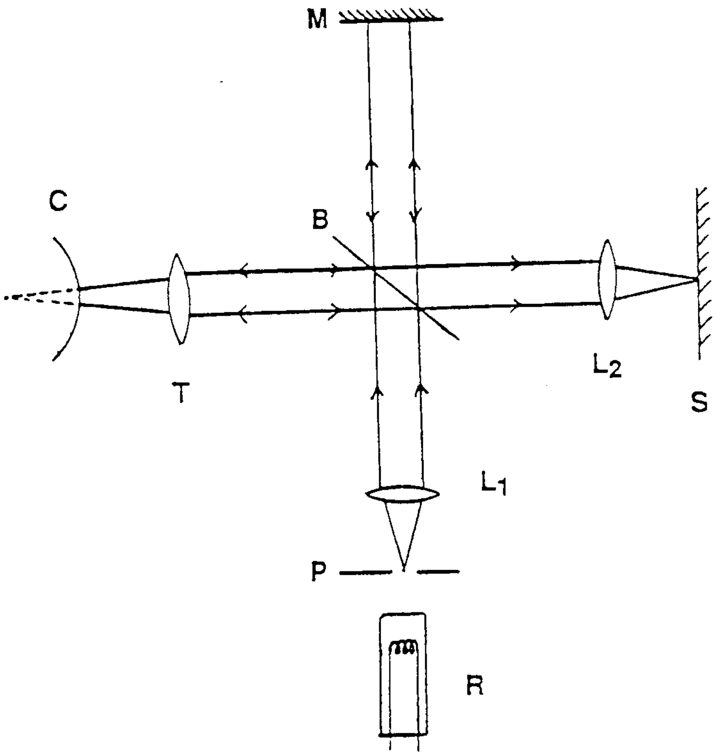

*Figure 5.5.* A schematic diagram of the Twyman-Green interferometer. The light source R emits monochromatic light which is collimated by lens $L_1$ and then divided by a beam splitter BS. From the beam splitter light travels in two directions; (a) through the test lens T and back following reflection at a convex mirror C, and (b) to a plane mirror where it is reflected back to the beam splitter. The wave fronts which meet back at BS are reflected through lens $L_2$ on to a screen S, where any resulting interference pattern may be noted.

beam variations of the Michelson interferometer. Unlike the Twyman-Green interferometer, the light source of the Mach-Zehnder need not be monochromatic. The Essilor Lens Company(1989) also make use of a laser interferometer for quality control purposes. The 'master' lens is compared to the production lenses.

### *Ray Tracing*

Ray tracing schemes for spectacle lenses allow for the checking of image quality against the accepted design of ophthalmic lenses. Modern calculators allow for a fairly quick method of checking the aberrations of astigmatism, curvature and distortion. Computing schemes for spherical lens surfaces have been available for many years(Conrady,1929). The development of aspheric surfaces led to the need for suitable ray tracing schemes. Emsley(1956) and Bennett(1968) give equations which are suitable for ray tracing through conics sections. Whilst, Smith and Bailey (1981) have produced a modified version of the computing scheme suggested by Bennett and Edgar(1979) suitable for conic sections. A computing scheme for polynomial ray tracing is given by Feder(1951)and a modified version of this is described by Smith(1966). A ray tracing method was employed for the assessment of single vision aspheric lenses by Smith and Atchison (1983). They were able to show(Atchison and Smith,1983) that commercial claims relating to the reduction of distortion amongst some types of aspheric aphakic lenses are exaggerated. Such a technique could also be used for progressive addition lenses but it would be more complex due to the non-rotationally symmetrical nature of these lenses.

### *Modulation Transfer Function Measurement*

The optical modulation transfer function (MTF) may be measured for PALs as with other types of spectacle lenses. Loshin(1988) has described a technique for measuring the MTF of progressive lenses by moving a small diameter analyser across the lens aperture. This overcomes the major problem associated with MTF assessment of spectacle lenses; namely, that although the MTF is normally given for the whole lens, the eye does not use the whole lens at any one time for foveal vision.

## **5.2.B Semi-Finished Lens Assessment**

This approach allows assessment of the progressive or aspheric lens surface while the lens is in the form of a semi finished lens blank.

### *Scanning Instruments*

Manufacturers are able to assess the surface of an aspheric or progressive lens with great accuracy using complex scanners. Köppen(1987) notes that these instruments are capable of assessing the sag to within 0.1μm. Guilino(1988) has described the scanning device employed by the Rodenstock Optical Works, Munich for quality control. This instrument comprised an *x/y* table upon which the lens rested and a probe(*z* axis) which touched the lens surface. The apparatus was driven by computer and could be programmed to make evaluations of a single meridian or a whole-surface. The Essilor Lens Company(1989) have a scanning device with a ruby tipped sensor which can measure the accuracy of a progressive surface to one quarter the wavelength of visible light.

### *Travelling Microscope*

The use of a suitably adapted travelling microscope was employed by Fowler(1985b) for the measurement of aspheric surfaces. Figure 5.6 shows, in a schematic fashion, the device that was used. It may be noted that the instrument was only arranged for two dimensions because of the rotationally symmetrical nature of an aspheric surface and if this technique is employed for progressive lenses then a three dimensional arrangement would be required. A variation of this method is to replace the microscope with a probe which touches the lens surface, thus producing a scanning instrument as noted above.

### *Surface Reflection*

Another method of analysis is to use a technique involving the phenomenon of surface reflection. This approach treats the progressive surface as a convex mirror and may involve either qualitative or quantitative assessment. Fowler(1981) proposed a speedy method of qualitative assessment using an annular target. He suggested that a series of concentric rings would be a suitable target. A large number of rings would be necessary to undertake a detailed study. The spherical portions of the lens surface would produce a circular image but the aspheric areas would give a distorted image. The annular picture could be photographed for quantitative analysis the results being calculated in a manner similar to the method used for anterior corneal surface recordings with the Wesley Jesson keratoscope.

### *Other Techniques*

Fowler(1981) proposed a number of other techniques for the determination of the surface curves of aspheric single vision spectacle lenses. Although less appropriate for the measurement of progressive lens surfaces than aspheric

TRAVELLING MICROSCOPE SURFACE MEASUREMENT

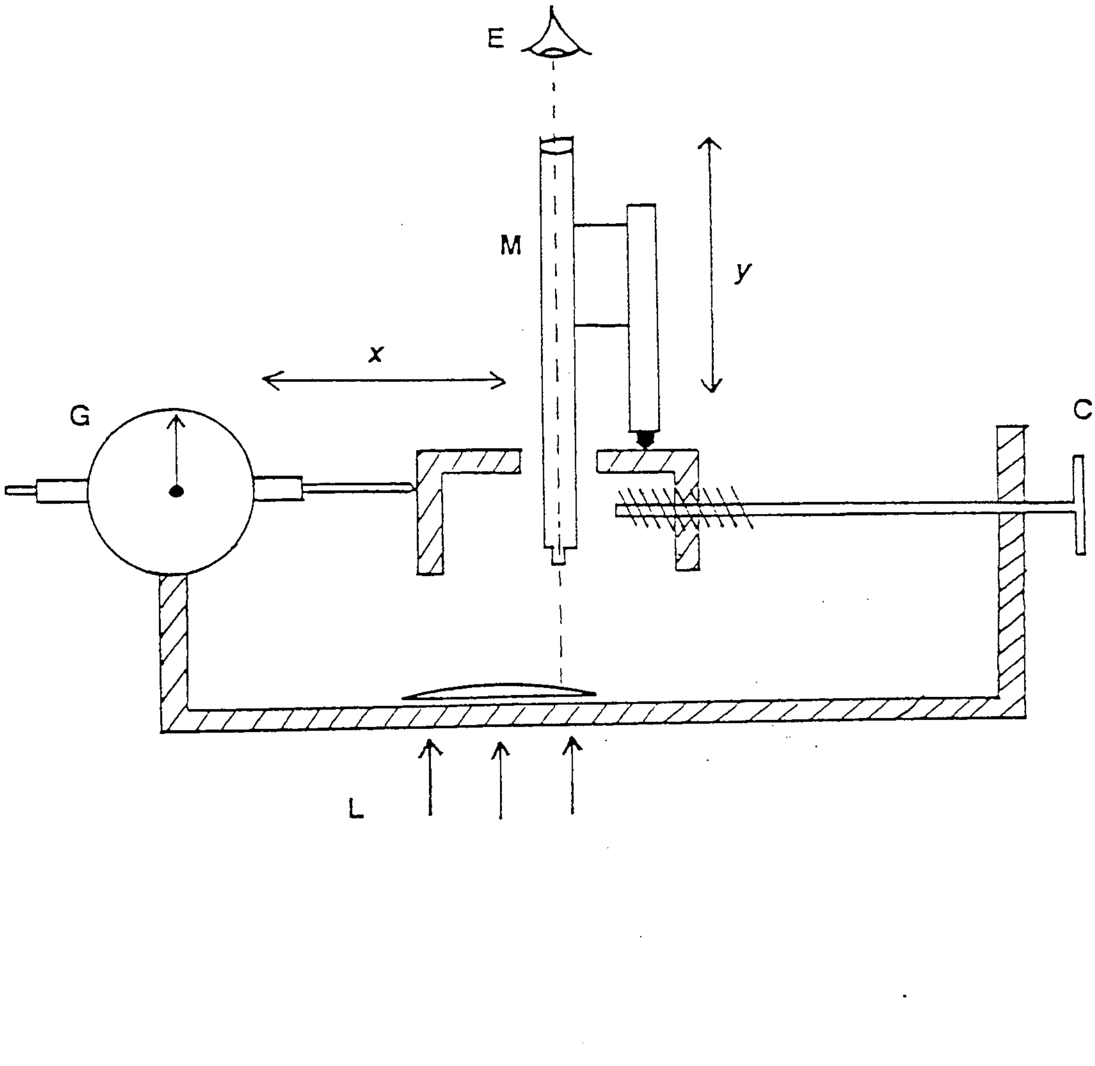

*Figure 5.6.* The adapted travelling microscope employed by Fowler(1985b) shown in a schematic fashion. Lateral movements *x* could be controlled by screw C and recorded with the dial gauge G. Light L illuminated the lens to enable the viewer E to focus microscope M, hence determining the value of the *y* co-ordinate. This two dimensional measuring device was used for aspheric lenses; a three dimensional instrument would be required for PAL assessment.

they are nevertheless worth noting. It is possible to check a surface with the use of graduated templates. This approach is only of limited value in the case of progressive surfaces because unlike spherical and aspheric surfaces the lens surface is non rotationally symmetrical. The use of a suitably adapted shadowscope is another technique proposed. A number of these instruments are available for the assessment of contact lens surfaces. As with the templates, a shadowscope is of limited use when considering the non rotationally symmetrical anterior surface of a PAL.

## 5.3 PSYCHOPHYSICAL ASSESSMENT

All psychophysical assessments must be carried out with finished lenses which have been made up into spectacles for the patient to wear. Köppen(1987) and Diepes and Tameling(1988) consider psychophysical techniques to be essential when evaluating the suitability of progressive addition lenses. A purely optico-physical review gives no indication of patient tolerance to the tested lens. Indeed, ultimately the quality of a progressive lens will be judged not with physical measures but by the degree and manner in which it restores pre-presbyopic vision for the presbyope. It is therefore essential for manufacturers to run clinical trials or 'wearer' tests before lens suitability can be conclusively assessed.

### *Amsler Grid*

This method tests a patient's ability to detect visible distortion through PALs. Borish *et al* (1980) placed an enlarged grid at 1 metre from the patient. Patients were asked to report the distortion which they could appreciate, when they kept their head steady and viewed the centre of the grid. This test was undertaken, in a double masked study, with both the patients and clinicians being unaware of which type of PAL (either the Varilux 2 or the Ultraview PAL) was being worn. Borish employed this apparatus in two ways. In the first instance, patients reported the degree of distortion present whilst they kept their head and eyes still and fixed on the centre of the grid pattern. Borish also recorded the distortion noted when the patient moves their head from side to side and reports a "swimming" motion.

### *Visual Acuity / Contrast Sensitivity Tests*

The assessment of visual acuity is the most common test for the suitability of spectacle lenses and this test is employed by refractionists in every day practice. Hitzeman and Myers(1985) recorded visual acuity at three different distances; 4m, 100cm, and 40cm to grade the distance, intermediate, and near portions of a progressive lens. They also recorded the acuity obtainable through the periphery of a progressive lens. Contrast sensitivity may also be assessed through different portions of a PAL. Garcia and Loshin(1988) measured the contrast sensitivity function(CSF) through six different portions of a PAL. They showed that the CSF is not greatly affected along the umbilical line, compared to the CSF present in a single vision control lens. However, when the peripheral areas of a PAL are assessed a considerable reduction in contrast sensitivity is observed.

*Perimetric Field Plots*

Borish *et al* (1980) measured the breadth of the reading field with the use of a specially constructed perimeter. This instrument had four different target sizes which corresponded to near snellen acuities of 6/6(1.0), 6/9(0.666), 6/12(0.5), and 6/15(0.4). The patient's head rested in a chin rest which could be adjusted for the required height and distance from the screen. Borish and Hitzeman(1983) used the same equipment for a comparison between progressive addition lenses and blended bifocals, and reported a similar field of usable vision in the two lens types.

## 5.4 OTHER TECHNIQUES

Under this section are listed a variety of methods of PAL assessment which do not neatly fall into either the category of optico-physical measurements or subjective psychophysical responses.

*Questionnaires*

A number of the 'wearer' test studies have been compiled in the form of a questionnaire completed by the patients once they had worn progressive lenses for a specified period. Many of these studies were not structured upon properly controlled experimental standards and others have a very clear commercial bias, nevertheless, they are of interest in revealing the reactions of patients to progressive lenses.

*Eye Movement Sensors*

A number of workers have employed objective eye movement monitors to investigate the usable field of vision for the progressive lens wearer. Afanador and Aisebaomo(1982) used a technique which involved a trial frame and head band apparatus fitted with sensors to record head and eye movements. The target was a board held horizontally at arms length on to which a series of light emitting diodes located at 2° intervals were placed in a line. Each diode was lit successively and the degree of eye movement prior to head turning was recorded. Afanador and Aisebaomo later changed the target symbols (Afanador, Aisebaomo and Gertsmann,1986) from light emitting diodes to Landolt C's because it was not necessary to view the diodes in focus. This may have reduced the incentive for the patient to turn their head when the image degraded due to optical aberrations from the periphery of the spectacle lens.

### *Electrophysiological Eye Movement Recording*

In the study by Borish *et al* (1980), involving a perimeter method of near reading field analysis, a number of the subjects were also tested using an electrophysiological technique to determine the amount of angular eye movement present before the head was turned. This arrangement consisted of a variable current device which registered the point at which the eyes stopped moving across a page of writing and head turning was introduced.

# Chapter 6

## SAMPLE ANALYSIS OF A PROGRESSIVE ADDITION LENS POPULATION

### 6.1 PREAMBLE

A number of workers have studied the success and usage of Progressive Addition Lenses(PALs) using questionnaire analysis and by compiling information from clinical records. Wittenberg(1978) investigated by survey the success of the Ultravue PAL. The study used 158 subjects, of which 115 (72.8%) were happy to continue wearing the lenses. The Wittenberg study questioned whether factors such as age, sex, occupation, patient prescription, and personality were relevant to a patient's success with PALs. Whilst he noted that varying success rates due to differences in age, sex, occupation, and personality were not statistically significant; he did show that certain aspects of a patient's prescription such as the spherical mean power and the near addition did have a significant effect upon the success rate.

Fowler's(1982) survey is relevant to the present study because it was also undertaken at the Aston University undergraduate teaching clinic. A high return rate of 86.5% was achieved. Using both free-response and forced-choice questions, it was shown that patients considered the progressive nature of PALs to be a greater asset than their cosmetic appeal. In another study involving the Ohio State University undergraduate teaching clinic, Augsburger *et al* (1984), an even higher success rate of 93% was achieved. Tucker(1981) studied the usage of PALs and showed there to be a great variation in their usage between individual practitioners. Tahran(1984) considered usage in terms of the sales figures for the Varilux V2 lens and showed there to be a difference between the mode and mean of add powers used in Canada and USA to those used in France. This, he concluded, was due to the V2 lens being generally accepted later in North America than in Europe and as a result fewer elderly patients wear PALs in North America.

There have been a number of studies which have compared the acceptance of PALs to already established multifocal designs (Borish and Hitzeman,1983 and Hitzeman and Myers,1985). Both these studies compiled data by comparing visual acuity and visual field measurements in addition to questioning the patient. These papers both concluded that patients preferred wearing PALs to bifocals. Borish, Hitzeman and Brookman(1980) was a study which compared the acceptance of two different PALs in a double-blind evaluation. Their work was also divided into two parts with, survey questions to determine the subject's preferred choice, and the subjective assessment of visual fields and acuity measurements.

## 6.2 METHODOLOGY

### 6.2A The Sample

The sample consisted of 110 presbyopes who had been prescribed and dispensed Varilux V2 progressive lenses within a period of one year (1st August 1987 - 31st July 1988), in the Aston University undergraduate optometric clinic. The figure of 110 was 4.33% of all those patients dispensed in the clinic within that period and consisted of 65 females (59%) and 45 males (41%).Three types of V2 lenses were employed in the sample; 7 (6.4%) were wearing V2 clear glass lenses, 32(29.1%) were wearing photochromatic V2 glass lenses, and the remaining 71 (64.5%)had V2 plastic lenses. It became apparent that one subject had died whilst the questionnaire was being undertaken (October 1988), giving a survey sample of 109 possible replies.

### 6.2B Social Survey Techniques

A number of social survey techniques are available and are designed to maximise the response of subjects to questionnaires. Some workers have suggested, for example, the use of incentives to increase the number of responses received (Greenberg and Mannfield,1957). Although no incentives were offered with this study, a prepaid envelope was included with each questionnaire. First-class gummed stamps were used because Kephart and Boston (1958) have shown that head stamped envelopes produce a greater response than envelopes sent with prepaid franked markings. Shackleton, Wild, and Wolfe(1980) have shown that the use of follow up letters is an effective method of increasing the number of questionnaires returned. The return rate was closely monitored and a follow up letter was sent to those outstanding replies when the reply rate began to diminish (Figure 6.1). It has been suggested by some workers that a second follow up letter should be sent with another copy of the questionnaire, when again the numbers being returned begins to decline. In this study such a strategy was not thought to be necessary due to the high rate of response. The follow up letter was carefully worded (Goode and Hatt,1952; Dillman,1972; Shackleton *et*

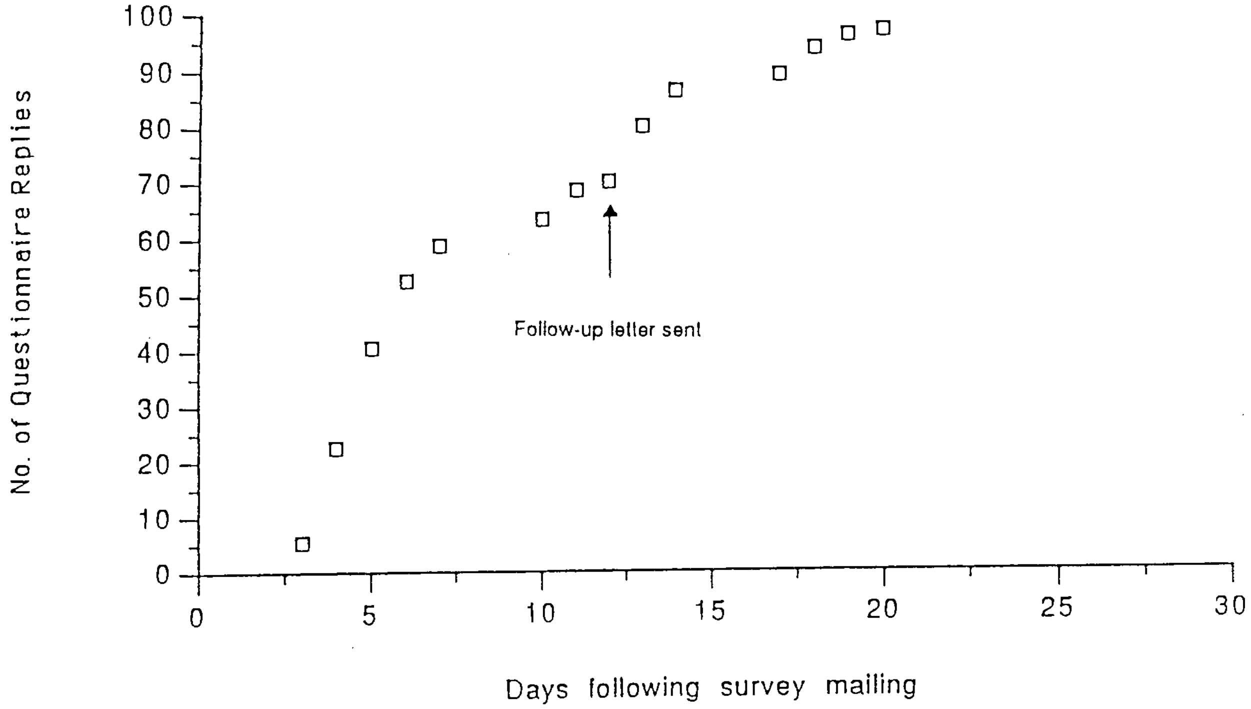

*Figure 6.1.* A scatter graph of the accumulation of questionnaire replies. These replies are plotted against the number of days following the sending of the survey to patients. The first replies were returned on Day 3 and the gaps in the cumulative number represent the weekends when no questionnaires were delivered to the University. The arrow indicates the point (Day 11) when the follow up letter was sent to patients. An increased return rate may be detected two days later on Day 13. The survey was closed to any further replies on Day 21, three weeks after the questionnaires were first posted.

*al*,1980) in order to maximise the response rate.

Oppenheim(1966) notes that conclusions from questionnaire surveys are only valid if the respondents are representative of the total survey sample. Indeed, one problem with surveys involving poor response rates is that the characteristics of the respondents may be different from the non-respondents. Of the 109 possible replies, 98 were returned which represented a final response rate of 89.9%. This is above the expected return rate for such mailed questionnaires which Goode and Hatt (1952) noted could be anywhere between 20 and 70 %. The high return allows a level of confidence to be attached to the results which is not normally possible with most questionnaire surveys.

### 6.2C The Questionnaire

The questionnaire consisted of three pages with 14 questions. Both "open" and "closed" questions were used in this questionnaire. Oppenheim(1966) considers this to be necessary in a properly designed questionnaire. Patients were asked to read the whole questionnaire before answering the questions shown in Table 6.1. The open or free response questions have the advantage of not imposing a choice upon the subject, however one disadvantage, is that they require more thought from the subject and are more difficult for the investigator to quantify. The converse is true of closed or forced choice responses. Oppenheim(1966) further notes that mailed questionnaires are a better approach than subject interviews because they avoid interviewer bias and in addition they are also cheaper. An explanatory covering note was included in the questionnaire, which politely encouraged patients to reply promptly.

## 6.3 RESULTS

Analysis of the 98 completed replies is presented under the following subsections.

### 6.3A Patient History

Patients were asked to indicate the primary reason why they chose to wear PALs. The response is shown in Figure 6.2. This question was also asked in the Fowler (1982) study and the two sets of results have been presented together. It may be noted that the two population groups have a very similar distribution despite being taken 6 years apart and with no subjects common to both surveys. The current study indicated that approximately half (52.1%) of the patients were advised by their optometrist to wear PALs, whilst 32.3% had been encouraged by other varifocal wearers and a third group of 15.6% had learnt of them by

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(1) Did you decide to have varifocals as a result of:
  (a) Advice from the optician ?
  (b) Recommendation from another varifocal wearer ?
  (c) Reading about the lenses, for example, in an advertisement or magazine article ?

(2) What sort of optical appliance did you wear before you had your varifocals ?
  (a) Distance and/or reading spectacles
  (b) Bifocal spectacles
  (c) Contact lenses
  (d) None

(3) Do you still wear varifocal spectacle lenses?

(4) Would you have another pair of varifocal spectacle lenses ?

(5) How long did it take you to get used to wearing varifocal spectacle lenses?

(6) In general, have you found your varifocal lenses ... ?

Very good  Good  Satisfactory  Poor  Very poor

(7) Do you find the DISTANCE vision through the lenses to be ... ?

Very good  Good  Satisfactory  Poor  Very poor

(8) Do you find the INTERMEDIATE vision through the lenses to be ... ?

Very good  Good  Satisfactory  Poor  Very poor

(9) Do you find the NEAR vision through the lenses to be ... ?

Very good  Good  Satisfactory  Poor  Very poor

(10) What do you like most about varifocals ?

(11) What do you like least about varifocals ?

(12) If you no longer wear varifocal spectacle lenses, what sort of optical appliance do you wear now ?
  (a) Distance and/or reading spectacles
  (b) Bifocal spectacles
  (c) Contact lenses
  (d) None

(13) When were you first fitted with varifocal spectacle lenses?
(14) How many pairs of varifocal spectacle lenses have you worn?

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***Table 6.1.*** The progressive addition lens questionnaire. Free response or open and forced choice or closed questions are included.

*Figure 6.2 .* The reasons why patients chose to wear PALs. This diagram allows a comparison of the results of the current study with those from the similar study undertaken by Fowler(1982).

*Figure 6.3.* The different types of optical correction, worn by the patients of the survey prior to commencing PAL wear. The results of a similar study (Fowler, 1982) are presented for comparison.

reading, seeing or hearing an advertisement or other article.

The type of optical correction worn by patients prior to wearing PALs was also investigated. The response to this question is illustrated in Figure 6.3. There was a small majority in favour of patients (55.1%) who had worn multifocals (bi or trifocals) prior to wearing progressive addition lenses. Previous wearers of single vision lenses (distance and/or reading) amounted to 42.2% of the total. Contact lens wearers represented 1.6% and there was only one subject (1.0%) who had not previously worn any form of optical correction. As with the question above these results may be directly compared to those of the Fowler(1982) study. However, unlike the previous question where the two surveys produced roughly similar results, the Fowler(1982) questionnaire showed multifocals to account for 40.6% of the total. The previous wearers of single vision lenses represented 56.3%, there were no previous contact lens wearers and only one patient (3.1%) who had worn no previous optical correction. Of the 98 patients who replied, 64 (65.3%) had not worn PALs previously, 22 (22.4%) had worn one pair previously, and the remaining 12 (12.2%) had worn 2 or more pairs of PALs. When the survey was taken the majority of patients questioned, 68 (69.3%), were in their first year of wearing PALs. Six (6.1%) were in their second year, and the remaining 24 (24.2%) had worn PALs for over 2 years. Nine patients (9.2%) had worn lenses for over ten years.

### 6.3B Patients Records

Data for this population was also derived from the patient's clinical records. Information regarding their age, sex, and refractive prescription was obtained from this source.

The mean spherical error of each patient was calculated (Figure 6.4a)and it may be seen from this representation that the majority of this population of PAL wearers are low hypermetropes. A Kolmogorov-Smirnov one sample test was undertaken to investigate if the mean sphere was normally distributed. Normality tests are undertaken in order to ascertain if parametric statistics can be employed, however, in this case the result($p = 0.064$) would suggest that the distribution was not normal at a 5% level. This is confirmed by regarding the graph which indicates that the distribution is skewed or possibly even bimodal. The mean cylindrical power may be plotted in a similar fashion (Figure 6.4b) and it was shown to be normally distributed ($p = 0.018$). Information regarding, the age and reading addition of patients is presented in Figure 6.5.

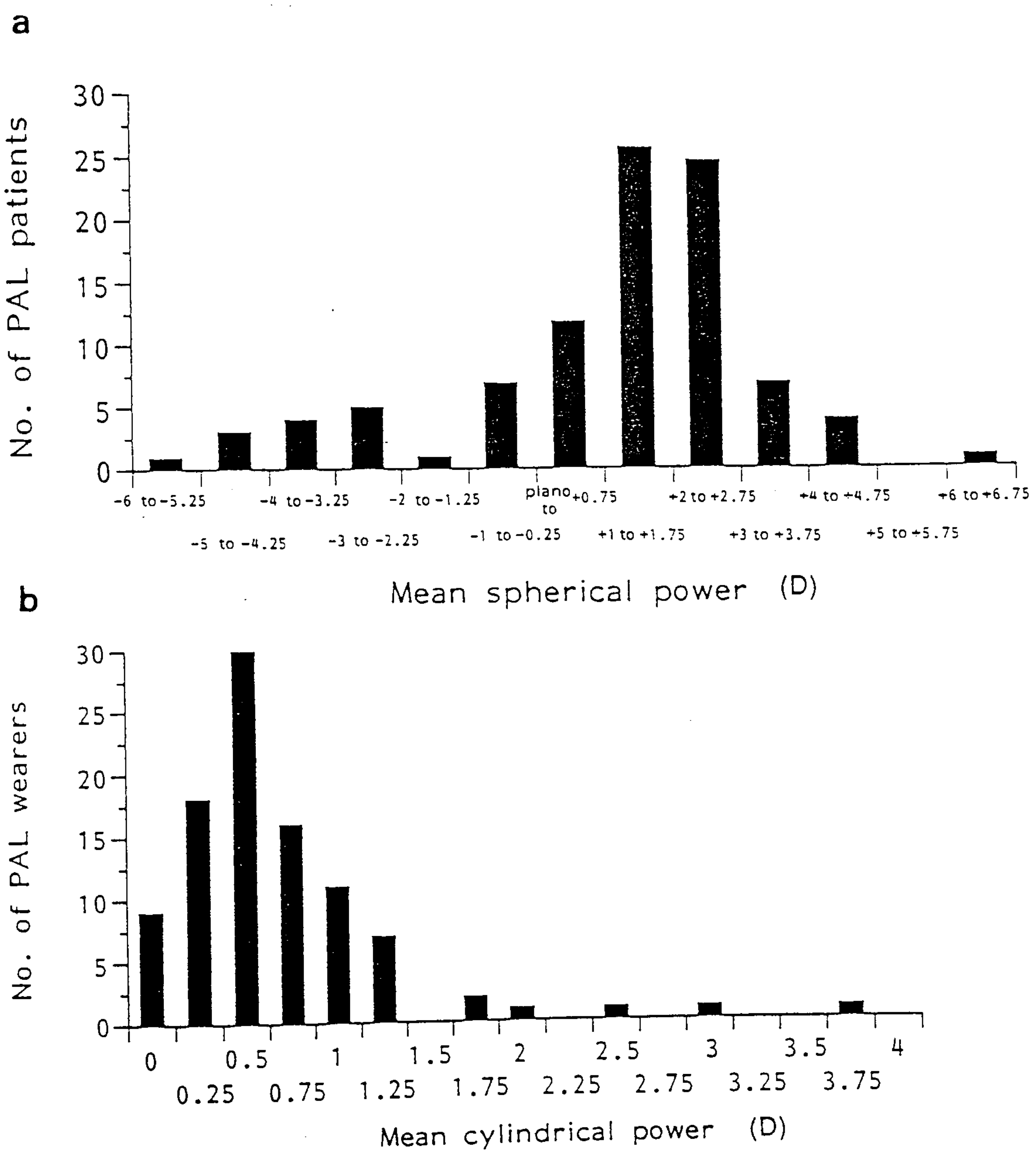


***Figure 6.4.*** The spread of (a)Mean Spherical Power and (b)Mean Cylindrical Power for the 98 patients who replied to the PAL questionnaire.

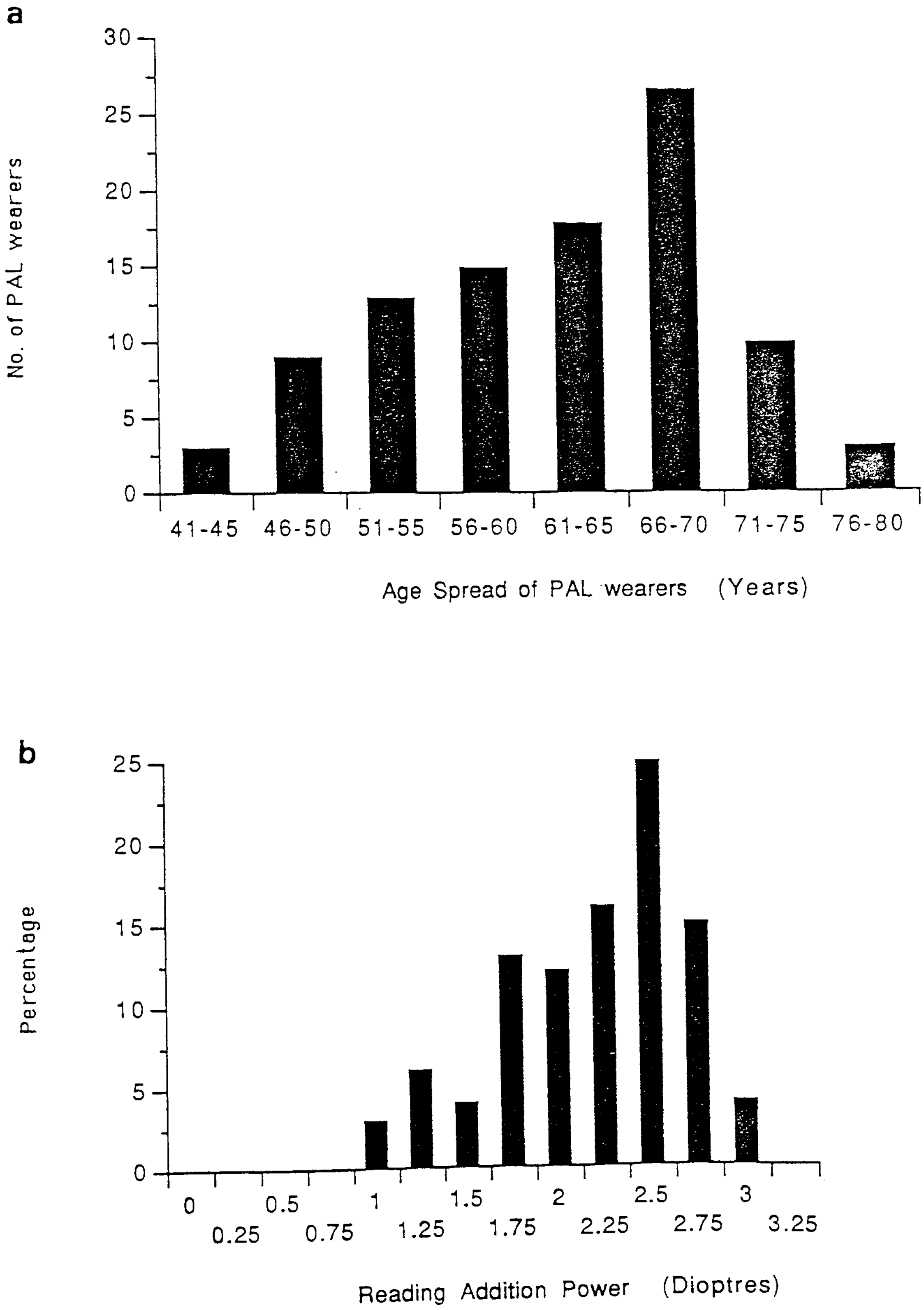


***Figure 6.5 .*** The distribution of (a)Patient Age and (b)Reading Addition Power for the PAL population of 98 patients who participated.

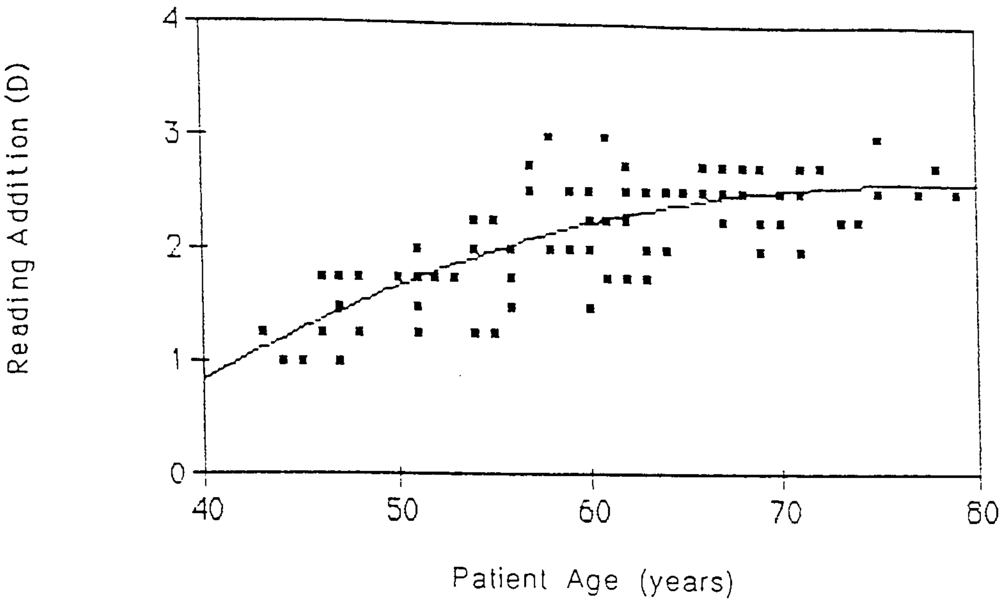
The age spread of this presbyopic population was tested for normality ($p = 0.146$), as were the reading additions present with this population ($p = 0.036$). It may be seen from Figure 6.5 that the reading addition spread is skewed towards the higher reading addition powers with a mode of 2.50 D. It was also hoped to list and group the occupations of the patients included in this study. However, this information was incomplete and therefore it was thought best to exclude such an investigation.

Statistical analysis, using a chi squared test, showed there to be a highly significant ($p < 0.001$) relationship between the patients age and their reading addition which is of course to be expected. However, one interesting point is the nature of the correlation between these two variables. The best straight line (simple regression) through the scatter plot produced a coefficient of correlation (r) of 0.752. When the best fitting polynomial was chosen a coefficient of correlation (r) of 0.781 was produced (Figure 6.6). The results of this PAL study are compared to the data quoted by Borish(1970), who cites mean reading addition against patient age for the two working distances of 40 and 33 cms.

### 6.3C Success Rate

How successful patients are with their PALs may be judged in a number of different ways. Patients were asked if they still wore their lenses. 85.7% responded positively, whilst 11.2% had changed to another form of optical correction and 3.1% stated that they still wore their lenses occasionally. An alternative way of considering successful wear is to ask patients if they would chose to wear another pair of PALs, when they next change their spectacles. Response to this question showed that 80.6% were happy to have another pair, whilst 16.3% would chose another type of optical correction and 3.1% were undecided. The results of these two questions are shown together in Figure 6.7. The success rate for the clinic will depend upon how patient success is defined.

To determine whether males or females are more successful the PAL population was divided into the two groups of 40 men and 58 women. The questions put to the whole population above were applied to these two groups and the results highlight the difference between considering the success rate to be either a measure of those who continue to wear their PALs or a measure of those who are happy to have another pair. When success is judged by considering those who are still wearing their lenses, the results showed 87.5% males and 84.5% females to be successful. However, when success is judged as a measure of those who are



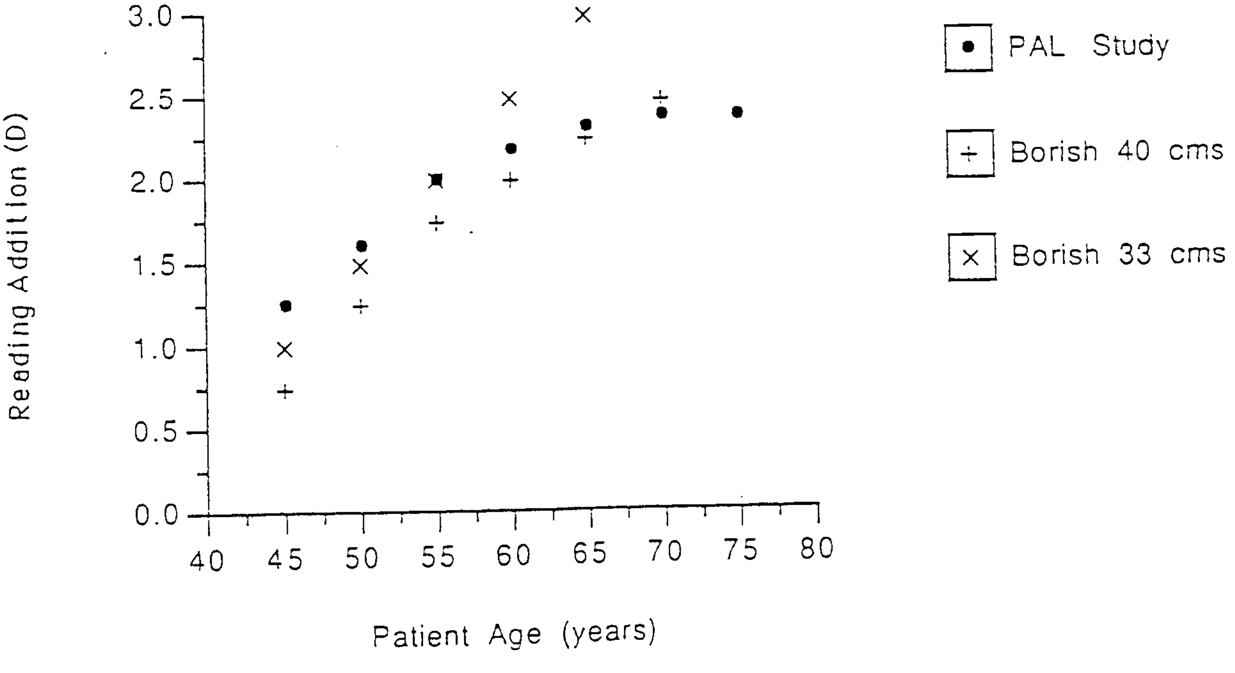


*Figure 6.6.* A comparison of patient age to reading addition. A scatter plot and correlation curve indicating the results for 98 PAL wearers is presented, in which, the best fitting curve has the equation, $y = -0.001x^2 + 0.197x - 5.020$ ($r = 0.781$, $p < 0.001$). Below the polynomial regression plot, a comparative graph is presented which shows the results of this PAL study and the data quoted by Borish(1970) for the working distances of 33 and 40 cms.

prepared to have another pair, 77.5% of the males are successful and 82.8% of the females. Chi-squared testing (Still worn,p = 0.334; Wear again,p = 0.105) showed the patients' sex and their success with PALs to be independent variables, at the 5% level.

When age is studied the results are contradictory and depend upon which measure of success is considered. A chi squared test showed that age, and whether the patient still wears the lenses, to be independent of one another (p = 0.259). However, when the patients age is considered against the measure of whether patients were prepared to have another pair the chi squared test produced a significant result (p= 0.048). Older patients(≥61 years) being more inclined to chose another pair of PALs.

Chi squared analysis which compared success to various aspects of the patient's prescription such as; the reading addition, the mean spherical power, and the mean cylindrical power showed these factors to be independent of the success obtained by patients. Nor was any relationship apparent between the patient's success and the number of PALs worn.

### 6.3D Patient Adaptation

Success for each patient depends upon their ability to adapt to wearing PALs and the inability of some patients to adapt is an area of concern to optometrists, dispensing opticians and lens designers. Patients were asked, in a free response question, how long it had taken them to adapt to their PALs. The results were tabulated in groups of weeks. Thirteen of the 98 patients never adapted to their lenses. Figure 6.8 shows a frequency response diagram for this question. Analysis of the adaptation time for those who successfully adapted, using the Kolmogorov-Smirnov normality test, produced a significant result (p = 0.023), showing adaptation time to be normally distributed. A normal distribution allows t-testing to be employed. This was done and no significant difference( p = 0.293) was revealed when the reading additions of those who adapted, and those who did not, were compared using an unpaired t-test. The adaptation time, estimated by patients, was further investigated using chi squared testing.

The reading addition and mean spherical power were shown to be independent of the variable of adaptation time. However a significant relationship was shown to exist between the mean cylindrical power and the adaptation time when a chi squared test was employed. The result (p = 0.014) was significant but

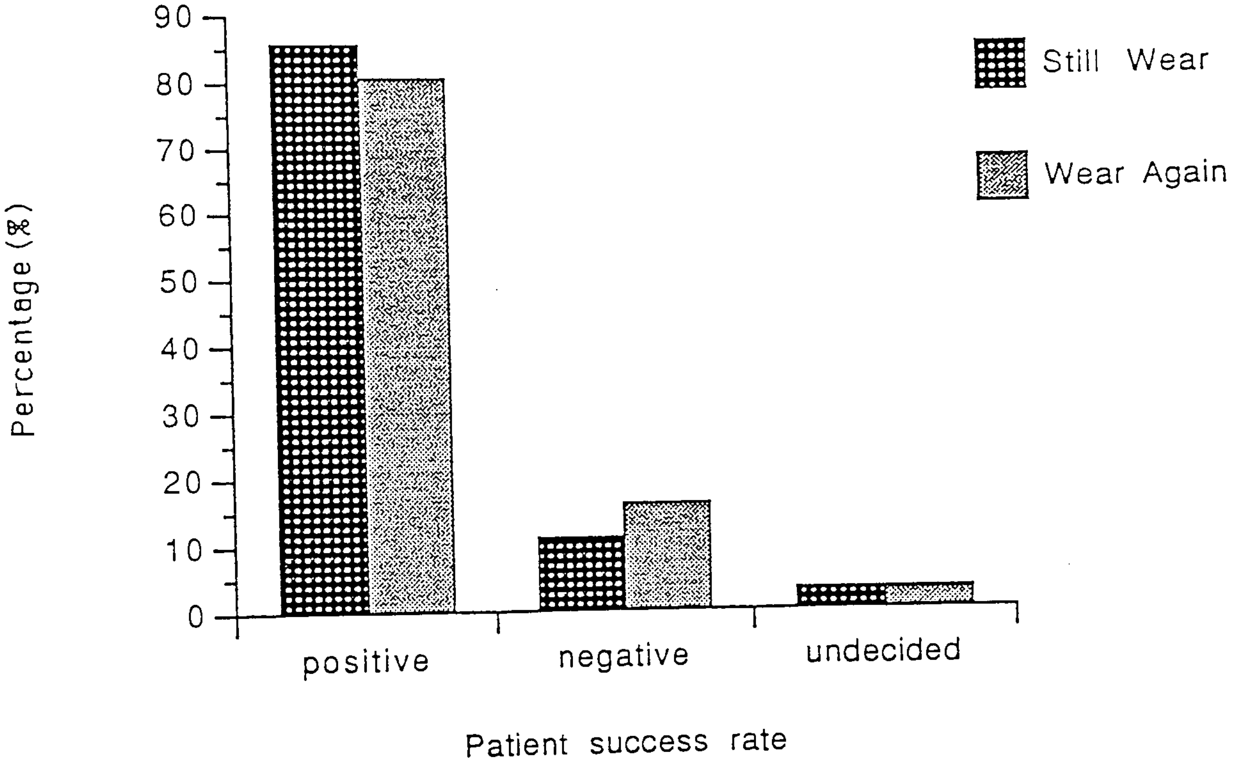


*Figure 6.7.* The results of the success rate study. Success was judged by (a) asking patients if they still wore their lenses and (b) if the patient was prepared to wear another pair of PALs. Both questions produced positive replies from over 80% of the PAL population.

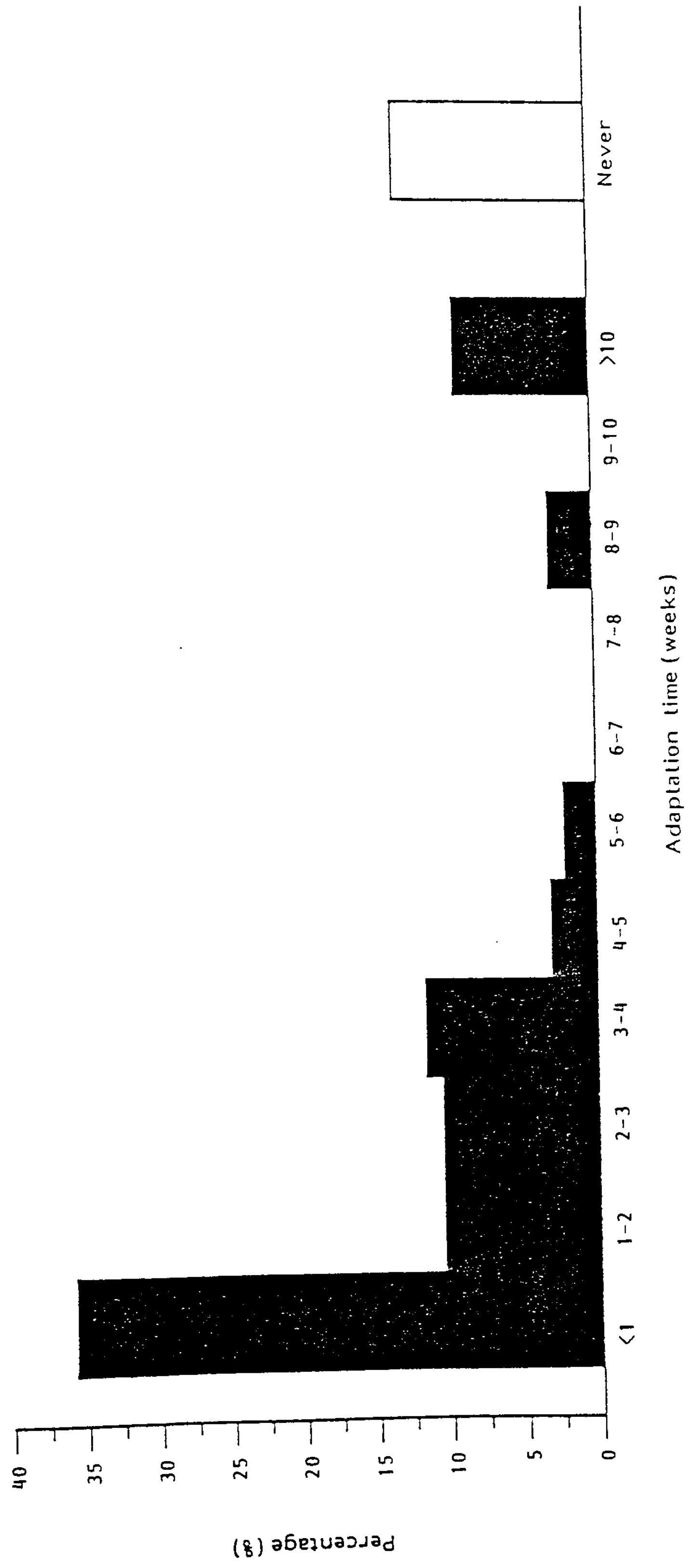


***Figure 6.8.*** The time taken by the patient population to adapt to wearing PALs. The results are derived from a 'free response' question in which patients were asked to state the time they felt was necessary for them to 'get used to' wearing PALs. Thirteen patients failed to adapt to PALs and this category of non-adapters is shown detached from the adapting category.

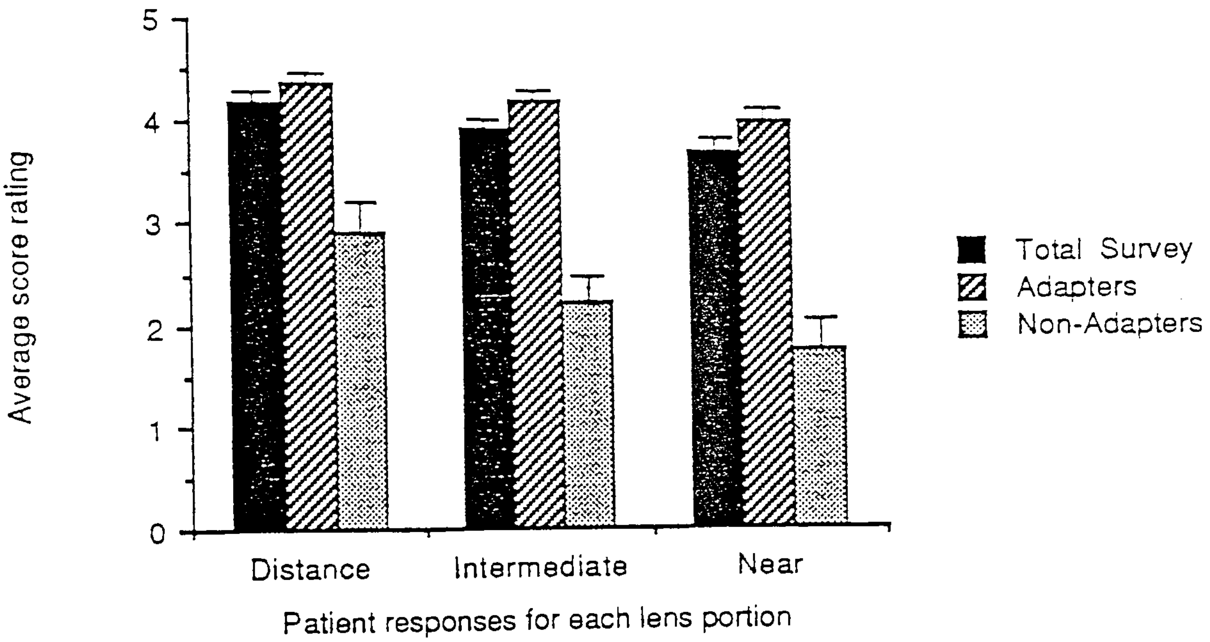


*Figure 6.9.* Patients were asked to give a score, on a scale from one to five, to denote their satisfaction with the distance, intermediate, and reading portions of PALs. One represented very poor and five represented very good. The mean scores (and the standard errors of the mean) are shown in the bar graph above.

caution must be attached to these results as the number of patients falling into the high cylinder category was relatively small. Patients with high cylindrical corrections(>2.00DC) appeared to take less time to adapt to PALs than those with small cylindrical or spherical prescriptions. No sex bias was evident with adaptation time - of those patients who adapted to their lenses there was no significant difference between the time taken for males and females. This was established using an unpaired t-test. However, when those who failed to adapt are considered it may be noted that 21.3% of the female patients failed to adapt compared to only 7.9% of the male patients. A chi square test(p=0.566) showed the time taken for patient adaptation to be independent of patient age.

### 6.3E Patient Preference

Patients were also asked to complete a number of forced choice questions. They had to grade the distance vision, intermediate vision, and near vision obtained through the lenses on a scale of one to five; with one representing very poor and five denoting very good. The mean values for the distance, intermediate, and reading portions are 4.174, 3.950, and 3.725 respectively. These figures (and the standard errors of the mean) from the 98 completed replies, for each portion of the lens, are presented in Figure 6.9. The data suggests that it is the reading rather than the intermediate (or 'progressive') portion which patients find to be the most troublesome area of a PAL; with the distance portion being the least troublesome. The results noted above are for the whole population sample of 98 completed replies which includes both adapters and non-adapters.

For the adapting wearer group the mean scores for distance, intermediate and near were 4.366, 4.220 and 4.037 respectively. These figures may be compared to the mean scores obtained for the non-adapting wearer groups which were 2.923, 2.231, and 1.769 for the distance, intermediate, and reading portions respectively. Patients were also asked to give an 'overall' score, again on a scale of one to five, in which one represented very poor and five denoted very good. The 'overall' scores obtained were assessed in terms of age, sex, and refractive prescription differences. Nonparametric analysis, using chi squared tests, showed that patient preference is not related to the variables of age, sex, reading addition, the mean spherical power, nor the mean cylindrical power.

## 6.4. DISCUSSION

Social survey techniques which are described in the method, allowed a representative sample to be obtained. Patient records are another important source of information. The results showed that the sample of patients are spread throughout the presbyopic years. Reading additions were shown to be normally distributed. However reading additions seldom go higher than 3.00D despite the increasing age, because at this level of correction objects at near may be seen in focus even when patients have minimal amplitude of accommodation. Therefore one would expect the relationship between patient age and reading addition in a presbyope to be polynomial rather than linear and this was confirmed in this study, as the best fitting curve was a second order polynomial with a correlation coefficient (r) of 0.781. It is suggested by some manufacturers and dispensers that the reading addition prescribed for a PAL wearer should be an extra +0.25 DS more positive than would otherwise be prescribed. The results of this study were compared to the figures cited by Borish(1970) for working distances of 33 and 40 cms. The comparative plot showed that for young presbyopes(40 - 55 yrs) the PAL reading additions were a little greater than the figures quoted by Borish.

The success of a dispensing clinic may be judged in a number of ways. Other studies, such as Augsburger *et al* (1984 ) and Wittenberg (1978), have considered the success rate to be measured by the continued participation of the patient with their PALs. However, this method of assessment fails to take account of the fact that patients whilst being unhappy with their lenses may persevere due to the inconvenience or expense of making a change. One might expect such a category of patient to chose another type of optical correction at a subsequent visit to the dispensing clinic. For this reason the questionnaire approached the subject of successful fitting in two ways. The success rate for the clinic may be claimed as either 85.7% or 80.6% depending upon whether a favourable outcome is judged by the patients continued use of their PALs or by a patient being prepared to have another pair.

The time taken for patients to adapt to their lenses was shown to be normally distributed. However, it was also shown that there was a notable category of 13 (13.3%) who failed to adapt. Chi squared analysis indicated that patients with high cylindrical corrections appeared to adapt more quickly than those with low cylindrical or spherical corrections. Wittenberg(1978) has also noted that patients wearing a correction with a high cylinder may be more likely to succeed with PALs. This finding may be explained in a number of ways. It may be the case that patients with a high cylindrical correction have a poorer standard of vision and are therefore less able to appreciate the deterioration in vision due to the introduction of PALs. Alternatively, it might be suggested that patients with high astigmatic corrections are better able to adapt to PALs because of their prior experience of wearing highly astigmatic sphero-cylindrical corrections.

This study showed the spread of reading addition powers to have a mode of 2.50 D. The frequency response for reading addition may be compared to the results recorded by Tahran(1984) who plotted the percentage usage of PALs according to the reading addition. He showed the mode to be 2.25 D in the United States, 3.00 D in France, with a worldwide mode of 2.50 D. The reason given for the higher mode in France was that PALs had been prescribed for a longer period in Europe than in North America and subsequently there was a cumulation of more elderly PAL wearers who required higher reading additions. If the sample involved in this study is representative of United Kingdom dispensing habits it may be suggested that the UK reading addition mode lies somewhere between that of France and the United States.

The ranking system, used to determine the patient preference for PALs showed, that both adapters and non-adapters found the reading portion to be the most unsatisfactory area. Although PALs are known to be aspheric in their 'progressive' intermediate zone, it would appear that most patients have difficulty with the reading zone, which purports in most PAL patents to be spherical along the umbilical line. Patient dissatisfaction may be due to the relatively greater usage of the reading portion compared to the intermediate portion. Furthermore, whilst the reading portion may be spherical along the umbilical line, the lateral areas on either side of this meridian are often highly astigmatic. Many patients are in the habit of moving their eyes rather than turning their head when reading printed material and a patient who reads in this manner is likely to become more critical of lens aberrations.

## 6.5 CONCLUSION

The clinical survey assessed aspects of a progressive addition lens population. Statistical analysis of the age, sex, and prescription details was undertaken in order to investigate if there were any trends or relationships between these variables. The study showed the success rate of the undergraduate clinic to be either 85.7% or 80.6% depending upon the criterion for successful wear. In addition it shown that, using a chi squared test, patients with high cylindrical corrections appear to adapt more quickly than those with a lower cylindrical or spherical correction. A study of patient preference revealed that patients find the reading portion of a PAL most troublesome and the distance portion of the lens to be most satisfactory.

# Chapter 7

## THE PHYSICAL ASSESSMENT OF PROGRESSIVE ADDITION LENSES

### 7.1 PREAMBLE

The anterior surface power distribution of a PAL is a most significant factor in determining the optical properties of the whole lens. Surface power analysis is essential to establish the extent of the aberrations and to construct a comprehensive picture of the complex nature of progressive addition lens topography. Physical assessment also helps to determine the features which differentiate a given lens from those of other designers, to test lens reproducibility, and to study the factors which may affect a patient's visual performance.

### 7.2 METHODS EMPLOYED

A number of the previously employed methods of PAL power distribution assessment(described in Chapter 5), have been used in this study in addition to a new surface reflection technique not previously documented and a fully automated form of BVP analysis.

### 7.2A The Conventional Focimeter / Lateral Movement Technique

The focimeter is a very useful instrument for the quantitative analysis of ophthalmic spectacle lenses. The conventional use of a focimeter, as a measure of vertex power, is a technique readily available to many optometrists as most practices will be equipped with a focimeter. Smith(1966) notes there are two optical bench methods of measuring focal length. These are;

(a) a nodal point technique(equivalent power measurement), and
(b) a focal collimator technique(vertex power measurement).

The focimeter is an adapted and enclosed form of the 'focal collimator' approach and was first devised as an instrument to measure back vertex power by Troppman(1914). A focimeter is designed so that irrespective of the power($F'_v$) of the test lens(T) the light leaving the instrument is parallel. To ensure this the target may be moved away from or towards the standard lens(S) depending upon whether the lens under test is negative or positive(Figure 7.1.). If the distance the target moves from its zero position is denoted by x, which is

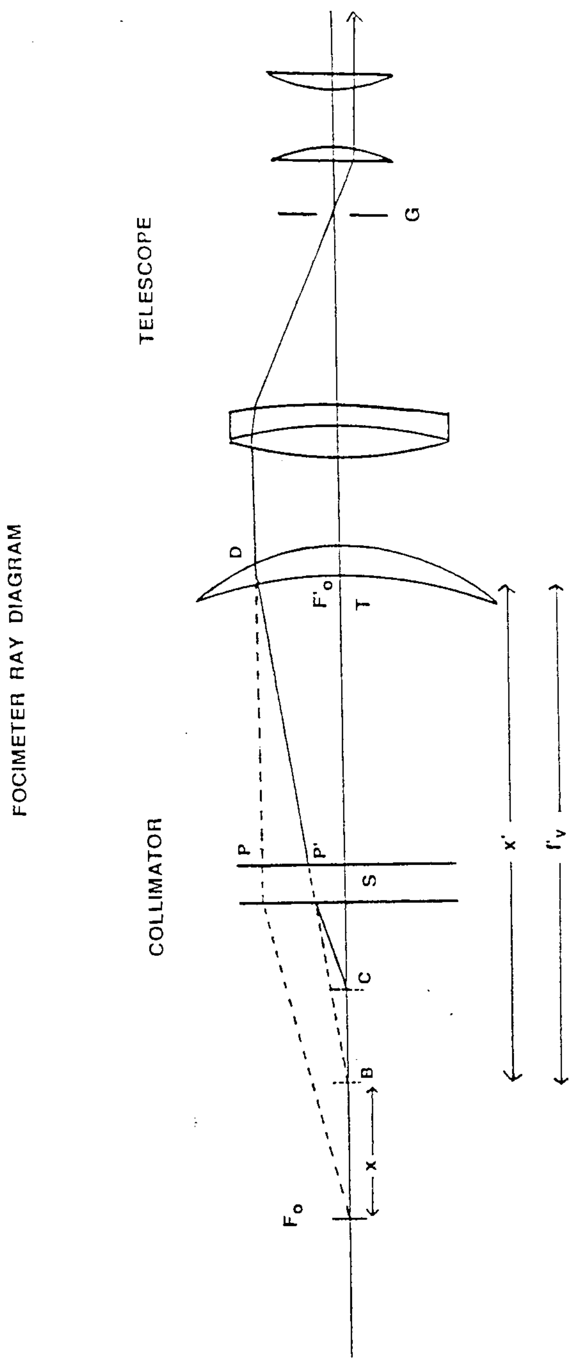


*Figure 7.1.* A ray diagram showing the principle of the focimeter. When the telescope is focused for parallel light a clear image of the target (C) is located at $F_o$, the focal point of the standard lens(S). When a lens(T) of unknown power is inserted at D the target must be moved in order to ensure the light leaving the collimator is parallel. When the image of C is moved from $F_o$ to B the ray PD is again parallel and C will again be sharply focused at G. The movement of the target is directly proportional to the back vertex power of the lens under test.

measured from the first principle focus($F_0$) of the standard lens, and if x' denotes the distance from the second principle focus ($F_0$' - situated at the lens rest) to the image, then it may be shown that x' is also equivalent to the back vertex focal length , $f'_v$ , of the lens being assessed.

This is done by taking Newton's relationship, $x\ x' = f\ f'$

however, as noted in the diagram, $x' = -f'_v$

therefore $x'\ f'_v = f'^{\,2}$

and thus $F'_v = x\ F^2$

Figure 7.2 shows a schematic diagram of a conventional focimeter design and this should be compared to the schematic diagram in Figure 7.3, of a focimeter designed to measure the power of a convex optical surface. The conventional focimeter used in this work was a Topcon LM 6. The focusing range of this focimeter is between -25D and +25D, with a variable prism device capable of deviation up to 15Δ in any orientation.

### 7.2B The Scanning Focimeter / Morgan(1961) Rotating Mount

The conventional focimeter when used for lateral positions of the lens does not account for the increased vertex distance and the eccentric nature of the light striking the lens surface. The scanning focimeter involved in this study, which is designed to overcome these difficulties(Morgan,1961), was constructed from the Topcon LM-6 conventional focimeter. To this instrument was placed a rotating mount construction, which is capable of lens rotation in both the horizontal and vertical directions. The distance of the lens under test from the lens stop could be altered in order to vary 'z', the distance from the rear surface of the test lens to the centre of rotation of the eye. The aperture size of the lens stop was 5mm. The lens holder was capable of rotating up to around 35° or 40°; further movement was restricted due to mechanical restrictions of the lens holder, the value of 'z' and the 'sag' of the rear surface of the lens under test. When the lens under test was tilted a prismatic effect was induced which shifted the image of the focimeter target. The variable prism device on the LM-6 allowed this movement to be corrected. A schematic diagram of a scanning focimeter in both (a)the on axis and (b)the off axis positions is shown in Chapter 5.

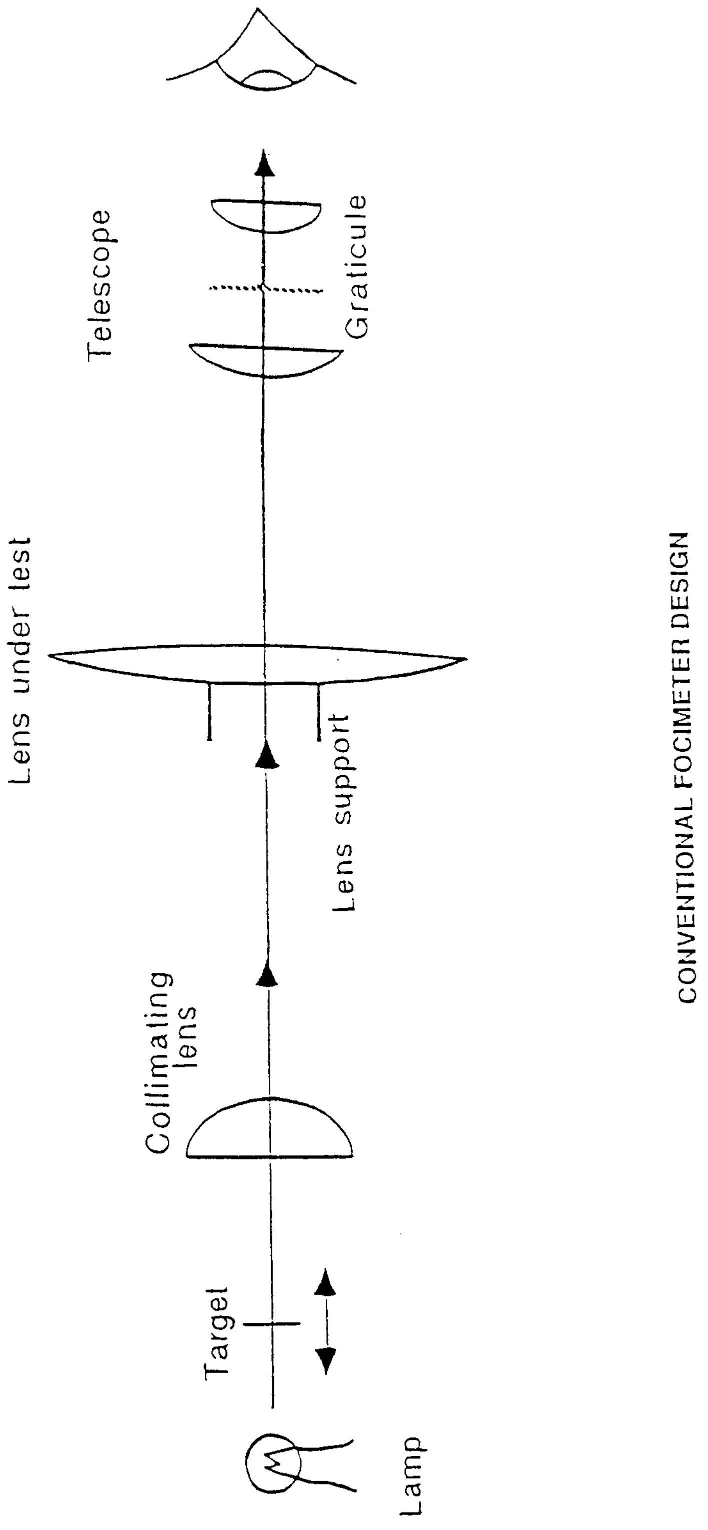


***Figure 7.2.*** A schematic diagram of the major components of a modern conventionally designed focimeter.

Ray Diagram of Surface Reflection Focimeter

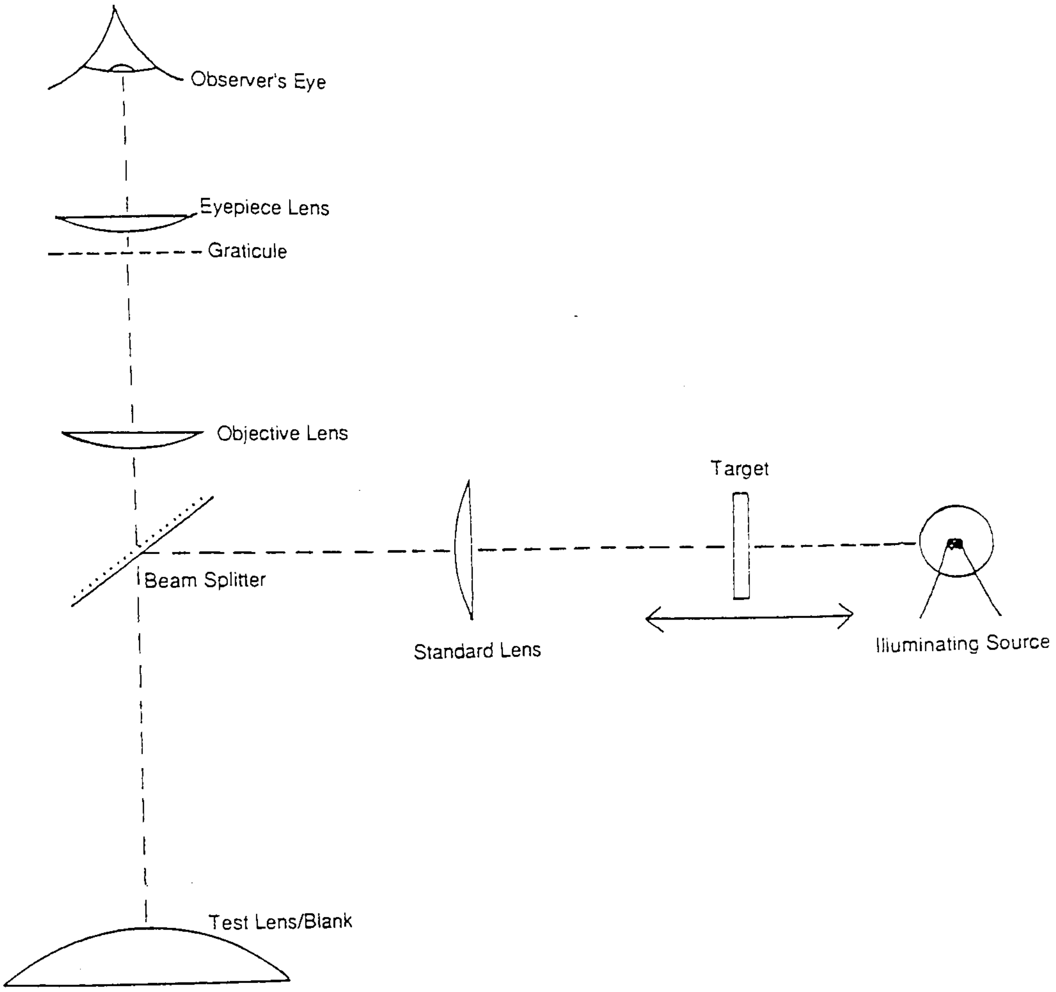


*Figure 7.3.* A schematic diagram of the Surface Reflection Focimeter shown measuring the convex surface of a finished spectacle lens or a semi-finished lens blank.

### 7.2C The Surface Reflection Focimeter

The technique, described here as the Surface Reflection Focimeter, is a new approach which has not previously been employed, although the possible use of some form of surface reflection has been noted by Fowler(1981). Figure 7.3 shows a schematic diagram of the instrument which was constructed from a conventional vertex power focimeter(Neitz). This diagram should be compared to Figure 7.2, a schematic diagram of a conventional focimeter. The adapted optical arrangement measures the surface power of a convex surface rather than the transmitted vertex power of a lens, and in so doing acts like an optical spherometer. Light from the target is reflected on to the convex surface under test by a collimating lens and beam splitter. The beam splitter comprised a thin sheet of optical glass. The surface reflection of the target is viewed through the beam splitter by the telescope, which was removed from the original instrument and repositioned at 90° to the target housing. A new lens mount was also constructed in line with the relocated telescope. The focusing system of a conventional focimeter alters the vergence of light incident on the rear surface of a lens under test, so that light passing through the lens under test leaves the front surface parallel and a sharp image of the focimeter target can be seen in the telescope.

The distance of the target from the lens under test was adjusted until the reflected image of the lens surface is seen in clear focus. This distance, between the location of the target housing and the newly constructed lens mount, was greater than before the instrument was altered. Subsequently, each dioptric division on the power drum corresponded to less than one dioptre of surface power and the instrument had to be recalibrated with the use of known spherical surfaces to arrive at a series of values of measured surface power against the readings marked on the power drum. These values were then plotted to produce a calibration curve(Figure 7.4) allowing the surface power readings to be deduced from the originally calibrated Neitz focimeter power drum.

Light loss was a problem due to the low level of reflection which occurs at the point of the convex surface under test and to a lesser extent at the beam splitter. To increase the amount of reflected light entering the telescope the original low power lamp(15W) of the focimeter was replaced by a 150W projection bulb, whilst a damp black felt cloth was held against the rear surface of the lens under test to avoid reflections from this surface confusing the image which appeared in the telescope eyepiece. The area of the lens surface measured by the instrument was approximately 8 mm in diameter. This figure is dependent upon the distance

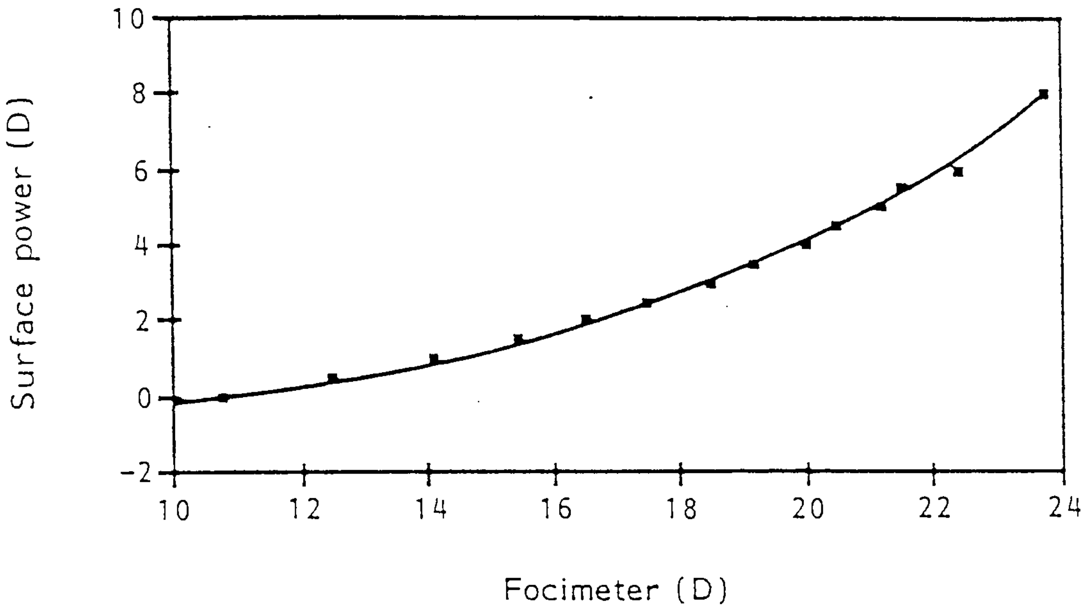


***Figure 7.4.*** Calibration curve for the SRF showing convex surface power readings( n = 1.523) against the focimeter power drum readings. The focimeter zero was taken at an arbitrary point on the power drum scale following mechanical changes to the adapted Neitz focimeter.

of the lens holder from the target housing; the diameter increases as the distance increases because the size of the target alters with the vergence of light incident upon the convex surface being tested. With a conventional focimeter design the image in the telescope will move as a spherical lens moves across the mount, due to an induced prismatic effect. This does not occur with the SRF as the mount always positions the area of the surface under examination with the normal parallel to the optical axis.

### 7.2D Automatic Focimeter Technique

The use of an automatic focimeter, in an adaptation of the scanning technique for the assessment of PALs, has been undertaken by Sheedy *et al* (1987) and Atchison(1987). These experiments, whilst being much more economical in terms of time spent, still involved the active participation of the experimenter to move the rotating mount device and to operate the automatic focimeter. A fully automated technique was constructed to allow detailed analysis of PALs. This work made use of a Nidek automatic focimeter which was programmed using a BBC Acorn B computer, to move a rotating mount using two stepper motors by a predetermined degree, and also to record the results of the power measurement triggered by the computer. This instrument was developed following the initial physical investigations discussed in sections 7.3, 7.4, and 7.5, and is described in section 7.7.

## 7.3 STUDY OF POWER DISTRIBUTION

A number of experiments were undertaken to investigate the power distribution(both iso-cylindrical and mean spherical) of the non-rotational symmetrical nature of PALs. The different types of focimeter measurement were investigated to establish whether any significant differences existed and a PAL design was also assessed to establish whether there were production variations between lenses of the same design. A pilot study of PAL surface topography was undertaken using the surface reflection focimeter(SRF) and this was followed up with a more detailed study using the automated device. This instrument was checked for measurement repeatability and then employed to undertake investigations concerning the possible change in PAL surface power distribution when the reading addition and nominal base curve powers change.

## 7.4 A STUDY OF INTER-TECHNIQUE MEASUREMENT VARIATION

A lateral movement technique, which is undertaken with the conventional use of a focimeter(lensmeter) is of use to the practising optometrist, whereas a rotating mount technique which simulates the rotation of the eye is a more accurate method and is of interest to the lens designer. A method of measurement which evaluates the progressive surface in isolation from the rest of the lens, allows for semi-finished lens assessment, and is of great value to the manufacturer.

### 7.4A Introduction

There may be a notable variation between the different types of optico-physical measurement. It is important to be aware of this variation before embarking upon a project which investigates the physical properties of progressive addition lenses. Torgersen (1987) notes that there is often a notable difference in the results obtained by different workers when measuring the same type of lens, due to the different approaches adopted.

### 7.4B Method

The three methods of physical assessment which were studied in this investigation were; Lateral Movement, Rotating Mount, and Surface Reflection. A comparative analysis of these three techniques was undertaken The test lens was a Varilux 2 Right Eye lens, 6.50 base, plano/+2.00 D Add, in crown glass. The study involved recording 81 surface measurements arranged in a 9 x 9 matrix at 5mm intervals. Therefore, this analysis covered a 4.5 cm square area of the test lens. The degree and orientation of the astigmatism recorded was presented in graphical form. A line represents the degree of astigmatism present at each test point. The length of this line is proportional to the amount of astigmatism and the orientation denotes the cylinder axis. Spherical areas of the lens surface are denoted with filled circles - but no attempt was made to grade the spherical power.

### 7.4C Results

The results are presented in Figures 7.5 and 7.6. These three techniques may be of use for different purposes. However, comparison of the results from the horizontal section shown in Figure 7.6 shows there to be no significant differences(Student 't' test analysis to the 5% level) between the measured values using the three different methods of astigmatic evaluation. Discrepancies between the methods would be accentuated with high positive lenses which exhibit a greater centre thickness.

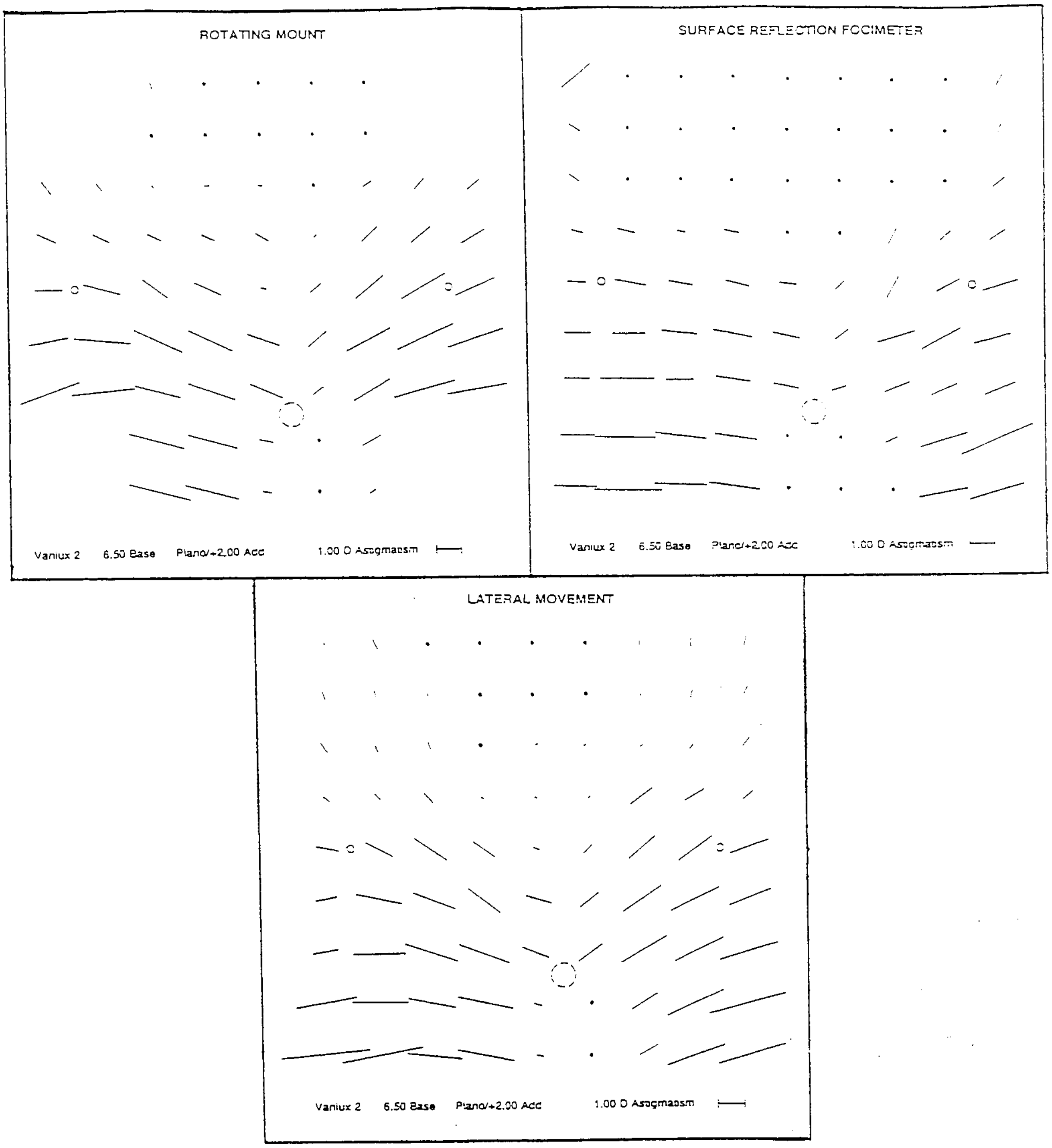


*Figure 7.5.* Diagrams showing the spread and orientation of astigmatism present with the three different techniques( Lateral Movement, Rotating Mount, and Surface Reflection) employed for the study. The surface points (81, except for mechanical restrictions in the case of the rotating mount) recorded were arranged in a 9 x 9 matrix with each point spaced 5mm apart. The astigmatism is denoted by lines; the lengths of which are proportional to the astigmatism present. The orientation of the line denotes the positive axis of the cylinder at a given point. Spherical areas of the lens are represented by filled circles. To keep the representation simple the spherical points are not graded according to surface power.

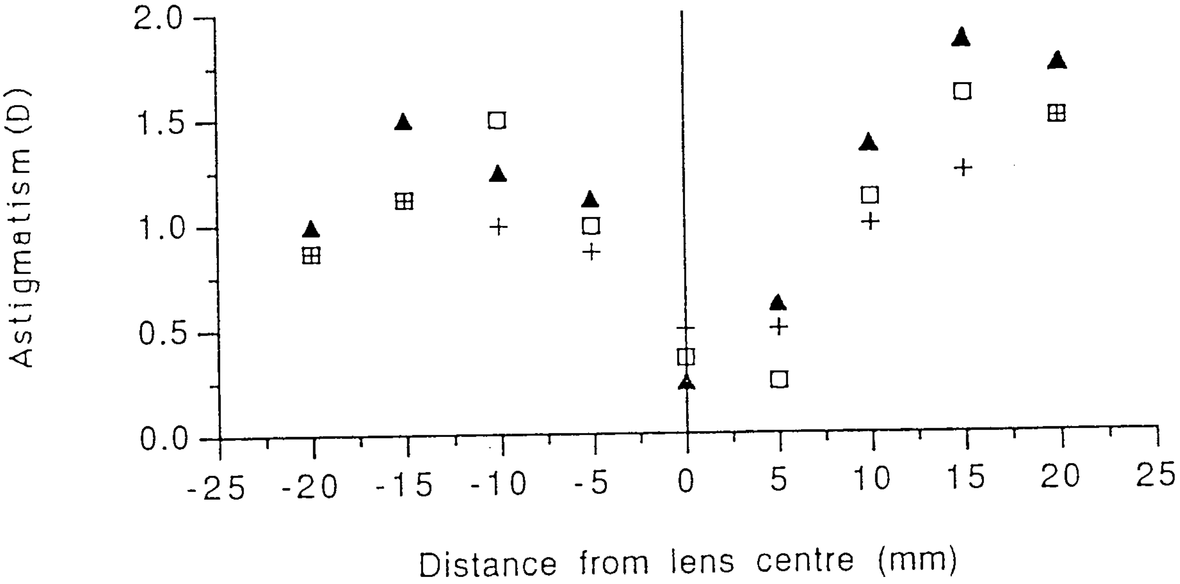


*Figure 7.6.* Graphical representation of the astigmatism found to be present, using the three different techniques. Measurements were taken of the Varilux V2 lens at 5mm intervals along a horizontal section through the engraved circles. ▲ = Rotating Mount, ☐ = Lateral Movement, + = Reflection Technique.

## 7.5 A STUDY OF THE PARAMETER VARIATION BETWEEN LENSES OF THE SAME DESIGN

### 7.5A Introduction

Is it possible for there to be significant variation between lenses of the same design? It is necessary to investigate this to gain an awareness of the standards of accuracy to which these lenses are produced. A study which investigated the variation between lenses of the same design was undertaken using the surface reflection focimeter.

### 7.5B Method

The instrument was employed to measure three different groups of lenses;
(a) Semi-finished glass lenses, taken from a prescription laboratory stock,
(b) Prescription glass lenses and finished lens samples acquired over a period of several years,
(c) Semi-finished CR39 plastic lenses, taken from a prescription laboratory stock.

All the lenses were of the same design, from one manufacturer, with the same nominal base curve. The reading addition of each lens was +2.00DS, and there were eight lenses in each group. Surface power measurements were taken at four points on each lens. These positions were, the distance and near checking points and the two permanently engraved reference circles which indicate the horizontal axis of the lens and are placed 34mm apart equidistant from the geometrical centre of the lens.

It was possible, due to the high level of illumination of the target, to locate a specific point on the lens surface to an estimated accuracy of 0.5mm. This margin of error could be further reduced by approximately 50% if a 'dotting lens', suggested by Davis(1979) were employed. Davis placed an annular lens over a focimeter telescope objective lens allowing the front surface of the PAL under examination to be inspected, at the same time as the focimeter target was viewed through the central hole. The centre of the lens could then be placed more accurately as a dot on the lens surface could be placed more accurately if the target image appearing on the lens surface could be aligned with the centre of the graticule of the focimeter telescope. A lens could also be placed more accurately if the target image appearing on the screen were smaller - this image in the case of the SRF being around 8mm wide with the lenses studied in this experiment. However, this cannot be completely controlled because the apparent

SURFACE REFLECTION FOCIMETER RESULTS

| | Group A | Group B | Group C | |
|---|---|---|---|---|
| | 1.523 | 1.523 | 1.498 | 1.523 |
| Distance | 6.4 ± 0.1 | 6.4 ± 0.2 | 6.0 ± 0.1 | 6.3 ± 0.1 |
| Near | 8.6 ± 0.1 | 8.5 ± 0.1* | 8.1 ± 0.2 | 8.5 ± 0.2 |
| Addition | 2.2 | 2.1 | 2.1 | 2.2 |
| Right circle (axis 120°) | 6.3 ± 0.1 | 6.2 ± 0.2 | 6.1 ± 0.2 | 6.4 ± 0.2 |
| Right circle (axis 30°) | 8.1 ± 0.1 | 8.0 ± 0.2 | 7.4 ± 0.2 | 7.7 ± 0.2 |
| Left circle (axis 170°) | 7.7 ± 0.1 | 7.8 ± 0.3 | 7.6 ± 0.3 | 8.0 ± 0.3 |
| Left circle (axis 80°) | 6.8 ± 0.1 | 6.4 ± 0.2 | 6.1 ± 0.2 | 6.5 ± 0.2 |

* Based on seven observations only. One lens with +7.75/+8.50 toroidal near surface not included in mean or standard deviation.

***Table 7.1.*** The mean surface power readings for the four points chosen from each progressive surface. Group A denotes the semi-finished glass lenses(n = 1.523), whilst group B comprises finished glass lenses and group C denotes the CR39 lenses(n = 1.498). Each figure and standard deviation refers to a mean value of 8 lenses, except where indicated.

image size not only depends upon the design of the apparatus but also upon the surface power of the lens under examination.

### 7.5C Results

All the lenses studied were nominally of the same base curve and reading addition power. With the exception of one lens, the surface topography at the distance and near checking points was shown to be spherical. Whereas, at the nasal and temporal fitting circles the anterior surface was recorded as astigmatic.

From Table 7.1 it may be noted that there was generally greater variation, with the exception of the distancechecking point, in the sample made up of CR39 lenses(Group C) compared to the glass lenses(Groups A and B). There was no significant difference( using a Student 't' test) between the surface radius measurements of the semi-finished glass and CR39 lenses, at the distance and near checking points. However, there is a notable difference in power due to different refractive indices of the two lens materials. A significant difference (at the 5% level) was shown to exist, in the surface toricity at the two fitting circles, between the CR39 and glass lenses.

There was no significant difference between semi-finished(Group A) and finished(Group B) glass lenses. However, one of Group B lenses displayed surface astigmatism at the near checking circle. Such a finding indicates the value of surface power quality control as such a lens if prescribed might be expected to lead to patient non-tolerance.

## 7.6 INITIAL STUDY OF THE SURFACE TOPOGRAPHY OF PAL's

### 7.6A Introduction

The value and consistency of the SRF has been demonstrated and it may now be used for the analysis of the anterior surface embodiments of different types of PALs. Use of the SRF was made in a study which evaluated the spread and orientation of astigmatism present in three types of PAL.

### 7.6B Method

Measurement of the three different designs was made in a similar fashion to that described above for the comparison of measurement techniques, with a 9 x 9 matrix of 81 surface points being recorded. The three lens designs chosen for examination were the Varilux V2, BBGR NZ, and the American Optical Truvision Omni. These designs were chosen because it was known they differed

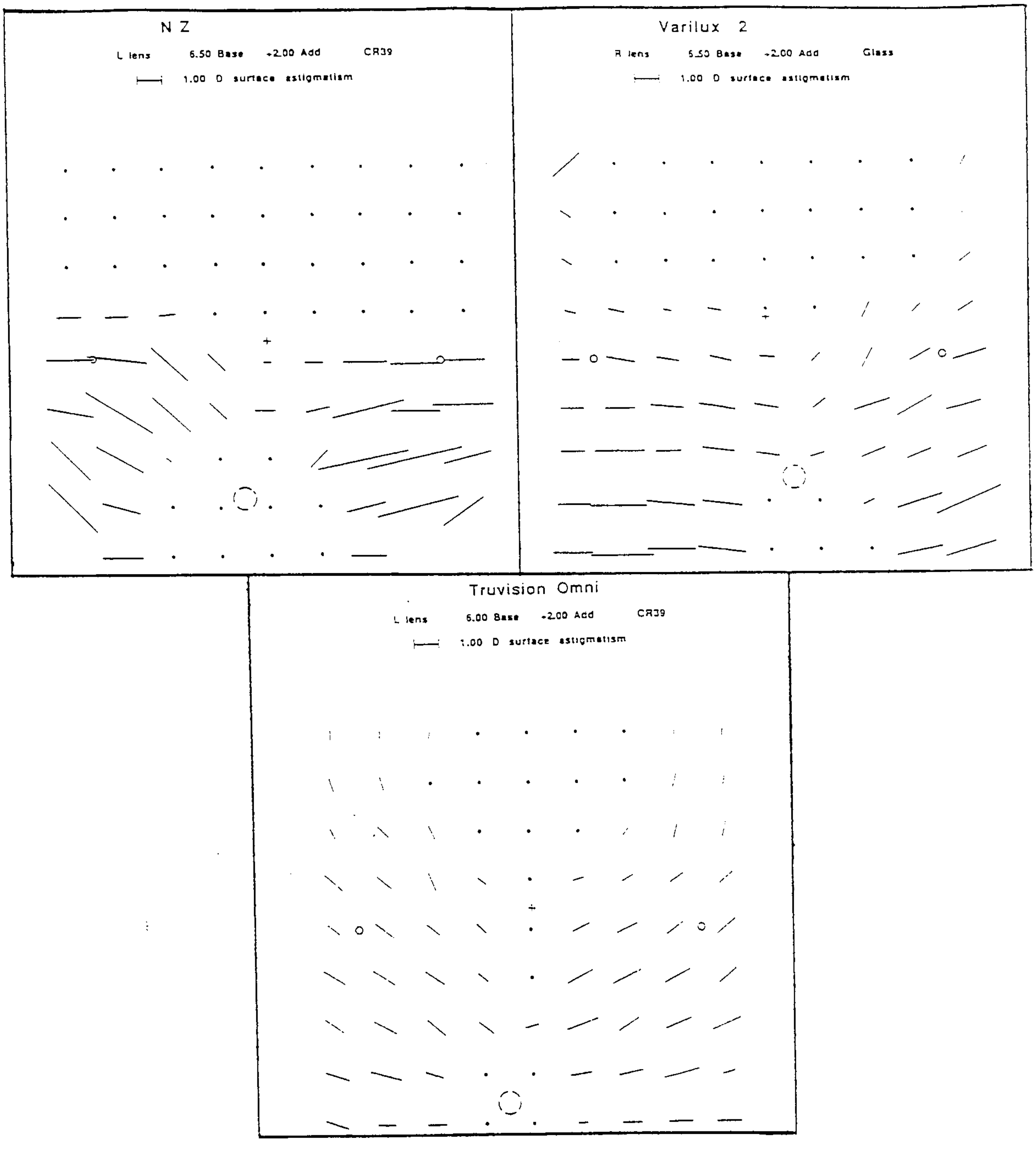


*Figure 7.7.* The distribution of aberrational astigmatism across the surfaces of the three lenses chosen for this study. As with Figure 7.5, the length and direction of each line is proportional to the size and orientation of astigmatism at each of the measured points. Spherical positions on the lens are illustrated by the filled circles.

significantly in terms of the hard/soft or static/dynamic design criterion. Each lens studied was in a plano/+2.00D addition form.

### 7.6C Results

The degree and orientation of the astigmatism present is shown diagrammatically (Figure 7.7). This technique clearly shows that the NZ lens is of a hard design with clearly defined limits to the distance and reading portions. To counter these large areas of spherical power, areas of relatively high degrees of oblique astigmatism may be noted. The Varilux V2 has been described (Maitenaz,1974) as being the first 'dynamically' designed PAL. The spherical areas are smaller, with the astigmatism encroaching into the periphery of the distance portion. However, the magnitude of the astigmatism is lower than that present in the NZ design.

The American Optical Truvision Omni is a relatively recent design and could be described as being extremely 'soft' or 'dynamic' in nature. The areas of purely spherical surface power are relatively small. Examination of the value of the astigmatism present reveals that the magnitude of astigmatism is at no point greater than 1.50D and that it is very uniformly distributed with no sharp power gradient changes located anywhere on the lens surface.

From this initial pilot study the value of surface topographical assessment as a method of revealing optico-physical characteristics was demonstrated, and a further more detailed project, using an automated technique, was proposed.

## 7.7. DETAILED STUDY OF THE SURFACE TOPOGRAPHY OF PALs.

### 7.7A Introduction

A detailed method of measurement involving a computer driven automatic focimeter was then constructed to allow a more comprehensive analysis of the lens power across the whole aperture of a PAL. The lens under examination was moved into position using two computer controlled stepper motors. The repeatability of the instrument was demonstrated and then this apparatus was employed for a detailed analysis of the effect that reading addition power and base curve have upon the spread of cylindrical and mean spherical power.

### 7.7B Apparatus

Figure 7.8 is a schematic diagram of the automatic focimeter equipment employed for the detailed study. A BBC model 'B' computer was connected to a

LENS PARAMETER RECORDING APPARATUS

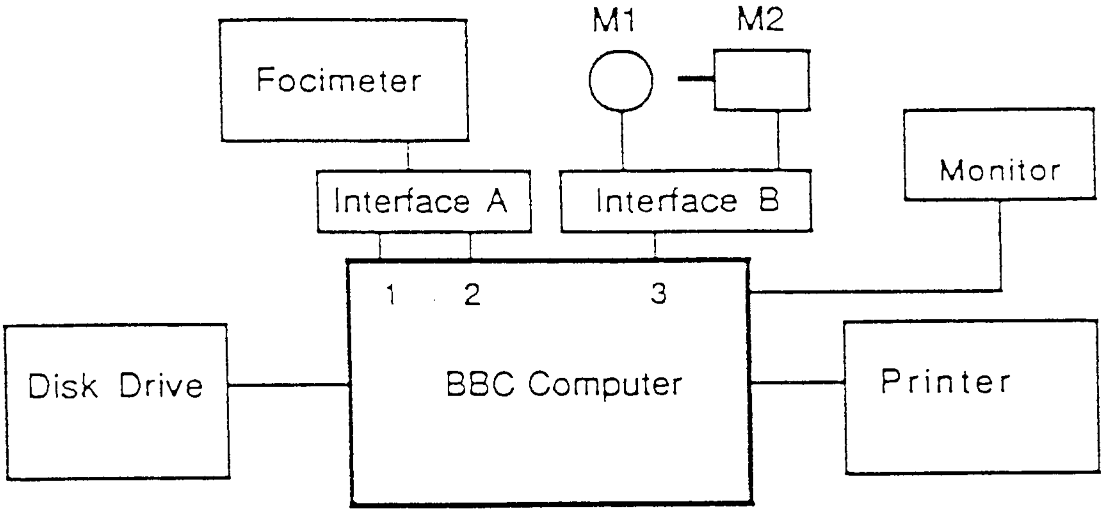


*Figure 7.8.* Schematic diagram of the automated focimeter device. The BBC model B computer is connected through an interface attached to the serial(1) and cassette(2) sockets to the RS232 port of the Nidek LM870 automatic focimeter electronic focimeter. The lens under examination is mounted on a holder which is positioned by two stepper motors motors(M1 and M2) operated through an interface connected to the user(3) port of the BBC.

## GEOMETRY OF LENS MOUNT

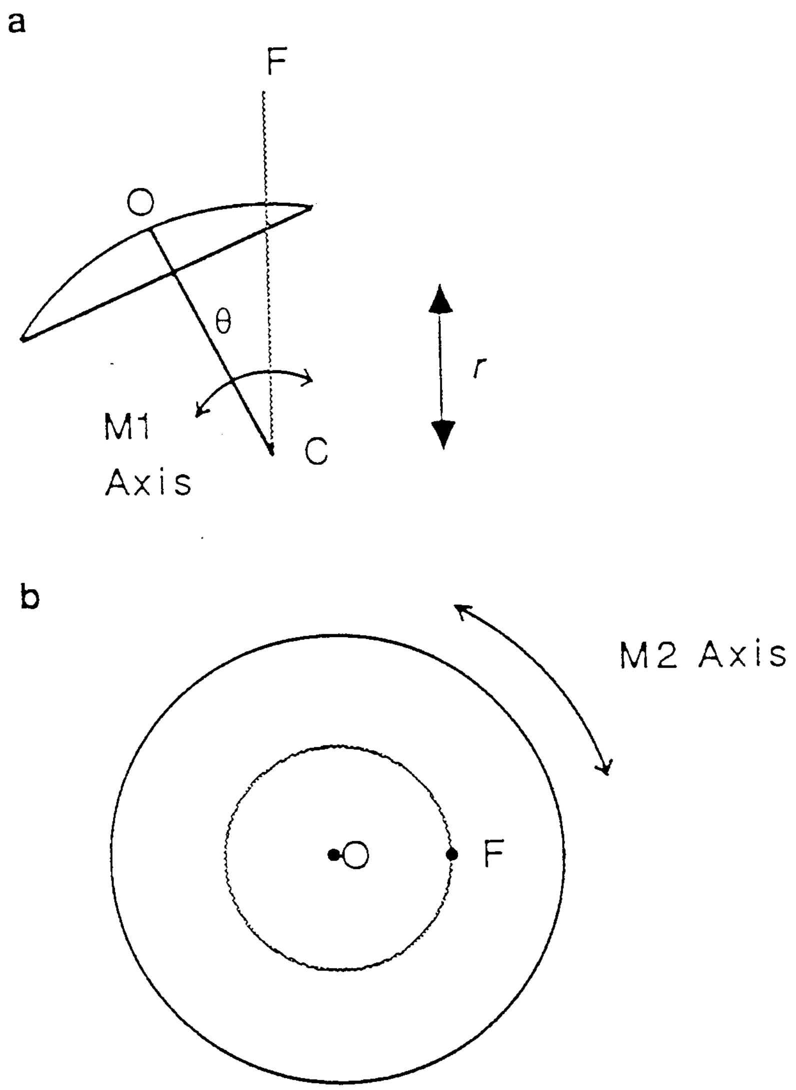


*Figure 7.9.* Schematic representation of the lens mounting, shown (a) from the side and (b) in plan view. The lens is tilted by M1 about a point C which is 83mm (r) below the plane of the focimeter lens support. The lens can also be turned to any angle θ, about point O, which is located at the centre of the lens holder, by means of a stepper motor M2. At each angle θ, the lens was turned through 360° about point O in a predetermined number of steps with a focimeter reading (along focimeter axis F) being taken at each step.

RS232 port of a Nidek LM870 automatic electronic focimeter via the serial(1) and cassette (2) sockets. Two stepper motors (M1 and M2) facilitated the movement of the lens holder, which were connected via the user(3) port of the BBC computer. The power readings from the focimeter could be stored on floppy disk and/or printed out. Details of lens holder movement are shown in Figure 7.9. The lensholder could be tilted( to a specified angle θ) by M1 about the point denoted C, which is 83mm (r) below the plane of the focimeter lens support. The lens could also be rotated about the central point O by means of the second stepper motor M2. If the apparatus were to be an automatic version of a scanning focimeter then the lens holder should have been rotated about a point which was closer to the back vertex of the lens; for example the value of 27mm is often chosen to simulate the position of the centre of rotation of the eye. This had been the intention when plans to construct an automatic device were first considered. Regretfully, the physical arrangement of the Nidek prevented adequate movement when the distance from the lens to point O was placed at 27mm. An alternative approach is to chose a value which is close to the average value of a 6 base plano powered single vision lens. This simulates the conventional use of a focimeter when a lens is slide across the lens aperture.

### 7.7C Method

The control program for the BBC 'B' Computer ran in the following sequence:

(1) Motor M1 moved the lens holder by the a predetermined value θ

(2) The lens was then rotated about point C by a predetermined number of steps.

(3) For each step the focimeter was activated to take a reading of sphere power, cylinder power, cylinder axis, and prism.

(4) These data were then relayed to the BBC computer by the serial link.

(5) Motor M2 then reset the lens by rotating it to the next step for automatic measurement as in (3) and (4).

(6) When motor M2 had moved through all the steps in one complete(360°) rotation, it returned the lens back to the zero position.

(7) Control then returned to step(1) and Motor M1 moved the lens holder to a new position θ. The sequence of events then continued through steps(2) to (6), until all the rotational measurements taken about the point O had been completed for the last specified angle θ.

(8) When all the programmed measurements were recorded, motors M1 and M2 returned to their original resting positions.

For the experiments undertaken in this thesis the program (see Appendix 2) was set up to record the following data:

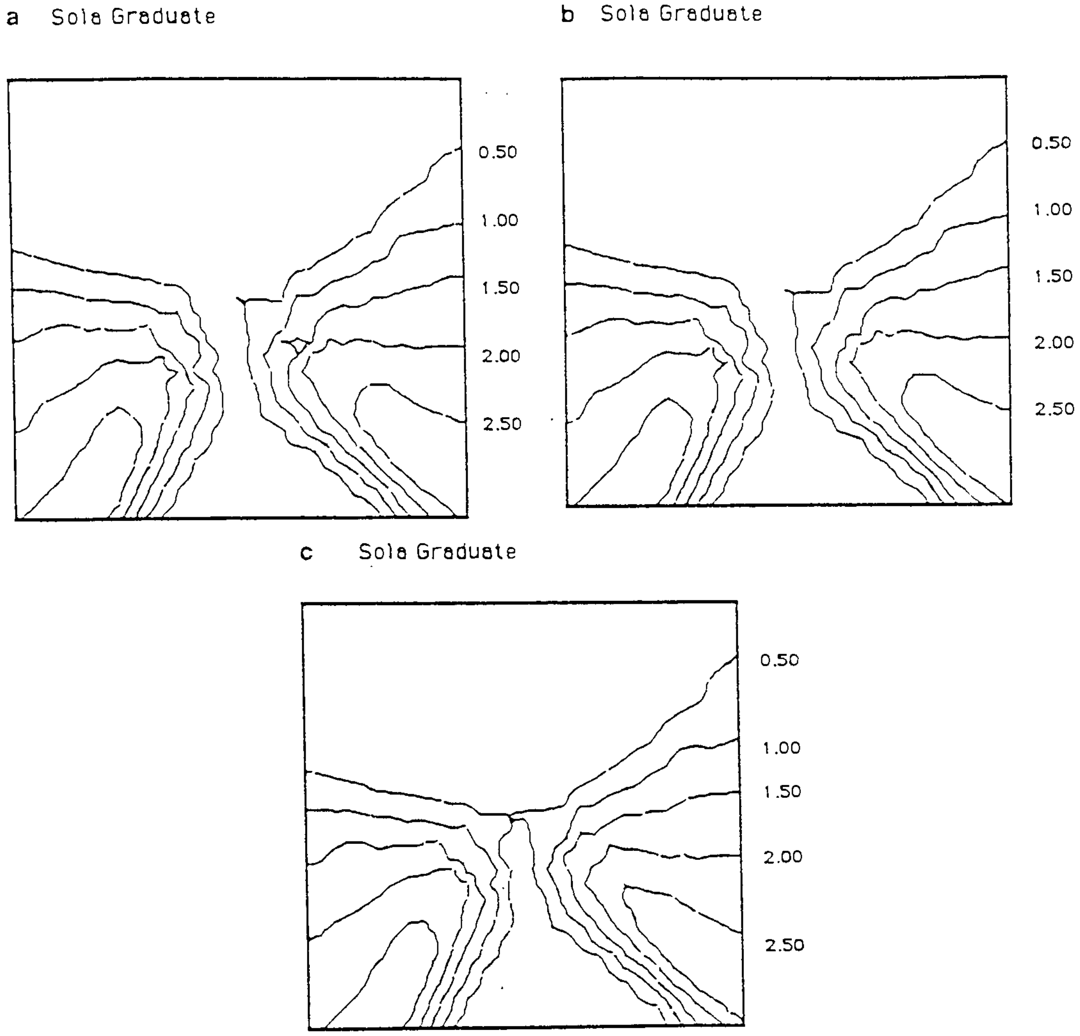
Motor M1 moved angle θ through seven equal steps of 2 degrees each, namely; 2°, 4°, 6°, 8°, 10°, 12°, and 14°. Motor M2 made one complete rotation of the lens about its centre point, C, in 114 equal step( 3.16 degrees/step). The total number of stepped movements per lens was therefore 114 x 7 = 798 and a focimeter reading (along focimeter axis F) was taken at each of these positions. Measurements of the spherical and cylindrical power were recorded to an indicated value of ±0.01 dioptres. Calibration of the focimeter was checked using trial case lenses which had been verified by the National Physical Laboratory(NPL). With these NPL lenses the focimeter was found to be accurate to ±0.04 dioptres for readings up to 4.00DS and to ±0.06 dioptres for readings between 4.00DS and 8.00DS.

After every 7 measurements the computer dumped the data on to a disk file. To record the 798 measurements from one lens the apparatus took approximately 80 minutes. At the end of the run the data was transferred from the BBC computer 5.25 inch disk to an Apple Macintosh 3.5 inch disk, through another serial link to the modem terminal of the Apple Macintosh computer, using 'MacTerminal' software. The numerical nature of the data was not easily interpreted and a means of graphical representation was therefore sought. The MacTerminal data for both the iso-cylindrical and mean sphere plots were fed into a BASIC program devised by Milne(1985) entitled 'MacContour' which processed the numerical data (over a period of 16-17 hours) and produced a $50mm^2$ view of each lens(actual size of each printed plot was $78mm^2$) when printed out using 'MacPaint' software. The contour plots shown in this thesis were spaced at 0.50 dioptre intervals, although MacContour software allows the contour intervals to be specified by the computer operator.

### 7.7D Repeatability Study

In order to demonstrate the degree of repeatability between measurements of the same lens using this technique a PAL was measured three times to establish if the plots produced were similar. The lens chosen was a CR39 version of a Sola Graduate Plano/+2.00D addition on a 4.00D nominal base curve. From Figure 7.10 it may be seen that the three plots(A, B, and C) are very similar. Only very slight variations occur and qualitatively there is no notable difference between the three iso-cylindrical plots. These 3 graphical representations may also be assessed quantitatively. The width and length of the progressive zone may

LENS REPEATABILITY


a Sola Graduate

b Sola Graduate

c Sola Graduate

***Figure 7.10.*** Iso-cylindrical plots from the repeatability study into successive lens measurements(A, B, and C) of the same lens. The lens studied was a plano / +2.00D addition CR39 version of a Sola Graduate with a 4.00D base curve.

be measured from a 78mm$^2$ printout of each lens plot. Alternatively, a random sample of 16 corresponding points from each plot (selected using random number tables) may be compared using paired Student t-tests. Assessing these values for plots A, B, and C produced no statistically significant differences in each case ( A with B, p= 0.153; B with C, p= 0.405; C with A, p= 0.803).

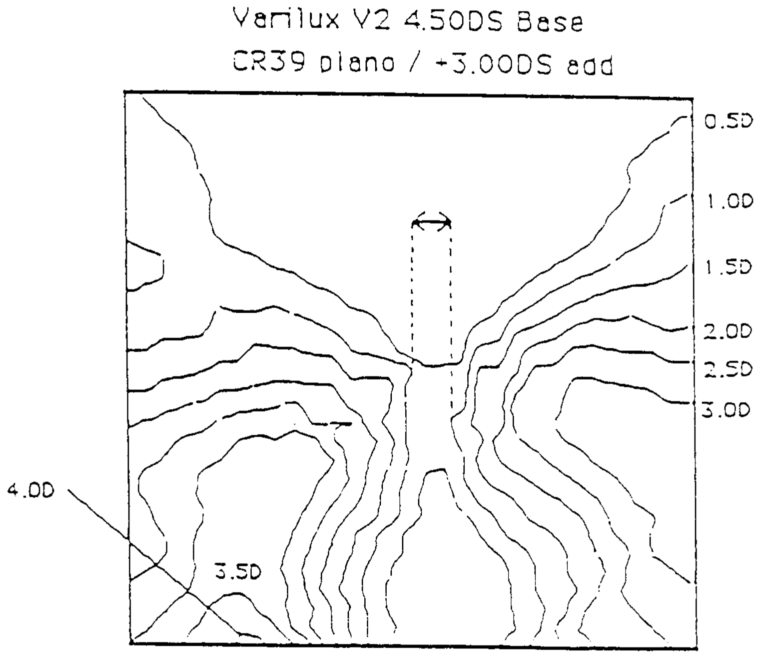
## 7.8 READING ADDITION STUDY

### 7.8A Introduction

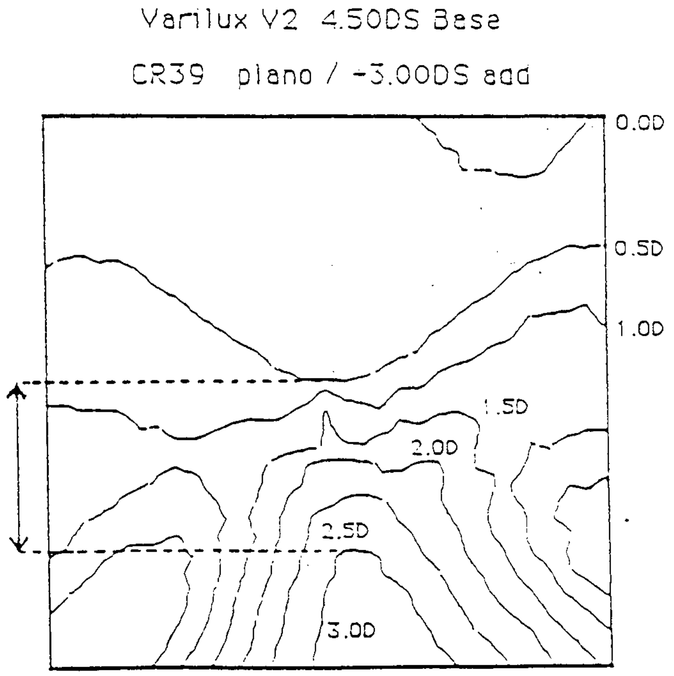
The iso-cylindrical and mean sphere plots represent considerable numerical information denoted in a pictorial manner. Analysis of these data must be undertaken in a manner which reduces the data to an easily assimilated amount. To obtain maximum information about a lens both the iso-cylindrical and the mean sphere plots must be considered. In Section 3.7 it was noted from the work of von Minkswitz(1963) that the surface astigmatism of a PAL surface may be described in terms of the reading addition, progression height and width. Evaluating the manner in which the progression height and width alter with the reading addition power may help to indicate how lens designs differ.

### 7.8B Method

From the spherical contour lines it is possible to measure the length of the lens progression. This is done by defining the progression length as the vertical distance from the plano power region (contour which denotes the beginning of the +0.50DS power zone) to the reading addition power region (contour which denotes the beginning of the nominal reading addition power). This was done for each of the 36 lenses studied. Data regarding the width of the progression channel may be taken from the iso-cylindrical plots to allow a comparative analysis of the spread of astigmatism across PAL surfaces. The width of an astigmatic channel was considered to be the minimum horizontal distance between two contours of the same power. In order to compare all the lenses in the study the only channels which could be considered were the 0.50DS and 1.00DS corridors, as higher values of astigmatism do not occur in some of the 1.00DS reading addition lenses. In many cases there was not an 0.50DS channel as the lens design assumed the wearer could tolerate this level of astigmatism along the umbilical line. Measurements of the 1.00DS corridor channel were therefore considered to be the most pertinent for a comparative analysis of PAL progression widths. Figure 7.11 shows how the progression length and 1.00D channel width were measured for one of the 36 lenses studied.



Cylindrical contour lines 0.5 to 4.00D



Spherical contour lines 0 to 3.00DS

***Figure 7.11.*** The iso-cylindrical and mean spherical power plots of one of the lenses assessed( plano / +3.00D CR 39 Varilux V2 4.50D Base). The progression length, the distance between the 0.50D contour and the reading addition power contour, and the minimum 1.00D corridor width are indicated.

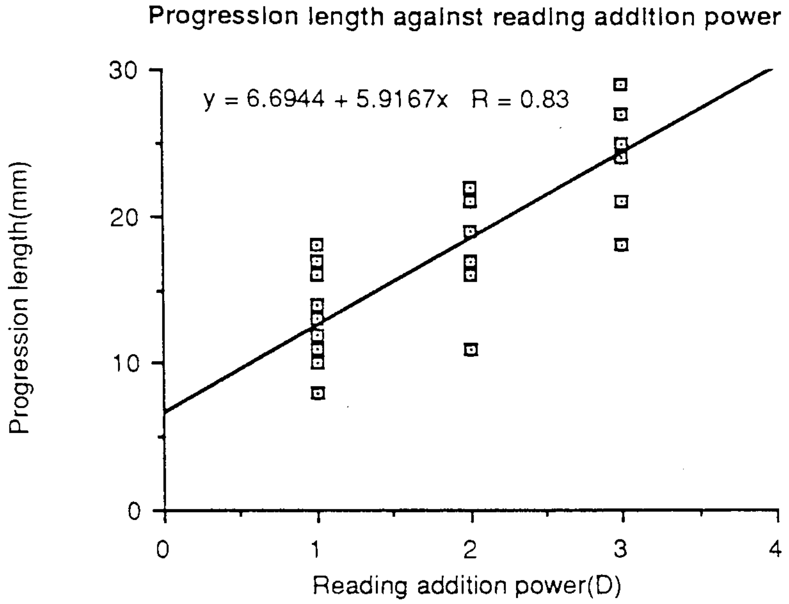


*Figure 7.12.* Graph showing the correlation(r=0.832, p<0.001)between the progression length(mm) and reading addition(D) for the four lens designs combined.

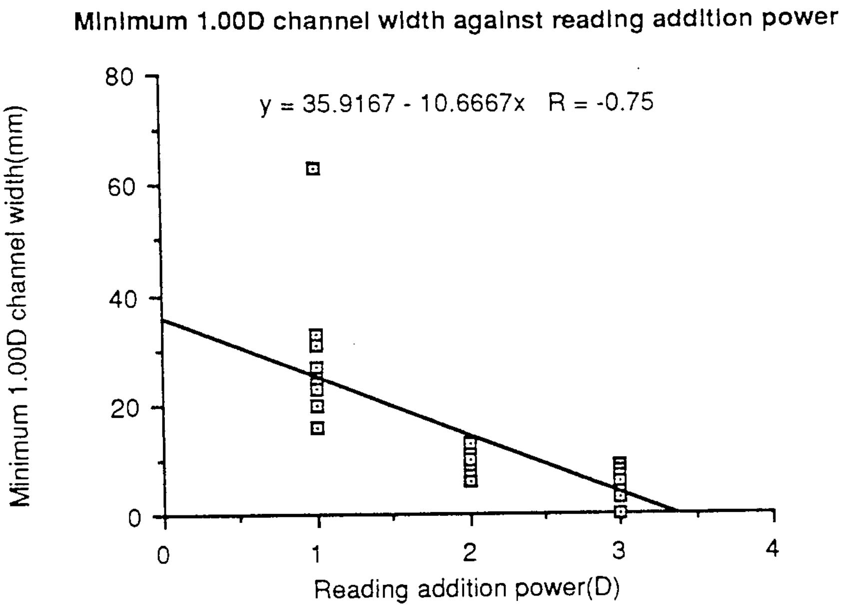


*Figure 7.13.* Graph showing the correlation($r=-0.748$, $p<0.001$)between the minimum 1.00D channel width(mm) and reading addition(D) for the four lens designs combined.

POWER MERIDIAN PROGRESSION LENGTH(mm)

| Lens Type | Base Curve(D)<br>2.00 | 2.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 | 7.25 | 8.00 |
|---|---|---|---|---|---|---|---|---|---|
| **VMD** | | | | | | | | | |
| +3.0D add | | | 25 | | | 27 | | | 24 |
| +2.0D add | | | 19 | | | 17 | | | 17 |
| +1.0D add | | | 11 | | | 8 | | | 10 |
| **Delta** | | | | | | | | | |
| +3.0D add | 29 | | | | 29 | | 24 | | |
| +2.0D add | 19 | | | | 11 | | 21 | | |
| +1.0D add | 11 | | | | 10 | | 12 | | |
| **Graduate** | | | | | | | | | |
| +3.0D add | | 18 | 27 | | | | | | 21 |
| +2.0D add | | 10.5 | 11 | | | | | | 21 |
| +1.0D add | | 13 | 11 | | | | | | 17 |
| **V2** | | | | | | | | | |
| +3.0D add | | 27 | | 18 | | | | 18 | |
| +2.0D add | | 22 | | 17 | | | | 16 | |
| +1.0D add | | 18 | | 16 | | | | 14 | |

***Table 7.2.*** The length(mm) of the each lens progression corridor, when measured from the mean spherical power plots, by the manner denoted in Figure 7.11. These values are presented in terms of the nominal base curve and the reading addition of each lens.

**MINIMUM 1.00D CORRIDOR WIDTH(mm)**

| | Base Curve(D) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.00 | 2.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 | 7.25 | 8.00 |
| **Lens Type** | | | | | | | | | |
| **VMD** | | | | | | | | | |
| +3.0D add | | | 8 | | | 8 | | | 7 |
| +2.0D add | | | 13 | | | 12 | | | 11 |
| +1.0D add | | | 33 | | | 26 | | | 26 |
| **Delta** | | | | | | | | | |
| +3.0D add | 3 | | | | 9 | | 0 | | |
| +2.0D add | 13 | | | | 6 | | 8 | | |
| +1.0D add | 16 | | | | 27 | | 16 | | |
| **Graduate** | | | | | | | | | |
| +3.0D add | | 8 | 7 | | | | | | 5 |
| +2.0D add | | 10 | 10 | | | | | | 10 |
| +1.0D add | | 25 | 24 | | | | | | 20 |
| **V2** | | | | | | | | | |
| +3.0D add | | 7 | | 6 | | | | 6 | |
| +2.0D add | | 9 | | 9 | | | | 10 | |
| +1.0D add | | 63 | | 31 | | | | 23 | |

***Table 7.3.*** The minimum corridor width(mm) between the 1.00DC contours found on either side of the umbilical line for each PAL studied. These values were taken from the iso-cylindrical plots in the manner depicted in Figure 7.11.

### 7.8C Results

The effect reading addition power had upon the lens parameters( Progression Length and Channel Width) was considered. Table 7.2 shows progression lengths for all of the 36 lenses( the 4 designs considered together) studied and Table 7.3 shows the corridor widths for the same lenses. When the four designs are considered together correlation analysis between the reading addition and progression lengths results in values of $r= 0.832$ and $p < 0.001$ (Figure 7.12). The correlation coefficient(r) and the probability(p) indicate that there is a significant relationship between these two factors, suggesting that the greater the reading addition - the longer the lens progression. When the corridor width(1.00D) is considered in a similar fashion( $r = -0.748$, $p < 0.001$) again a significant result is indicated suggesting that the width of the PAL progression corridor decreases with an increase in the reading addition power(Figure 7.13). The four lens designs should also be considered separately as each design differs in terms of the hard / soft design criterion. However, this appears to have little bearing upon the general effect that reading addition power has on the width and length of the lens progressions. The results( see Table 7.4) for the four designs indicate a similar overall picture. Namely, to increase the power of the reading addition the lens designer may either increase the length of the progression or increase the power gradient along the umbilical line.

Gradient(mm/D) was plotted against reading addition(D) to establish if there was a significant variation in the gradient as the reading addition increased(Table 7.5). The overall results and those of the four lens designs taken individually are presented in Table 7.6. The overall result ( $r = -0.646$, $p < 0.001$) showed that designers make a compromise and increase the power gradient whilst also increasing the length of the progression channel(Figure 7.14). However, whilst the overall trend is to increase the gradient with reading addition power, design differences are indicated between the four lens types. When the four lens designs are taken in isolation two lenses, the Varilux V2 and Sola Graduate(Figure 7.15), displayed a significant correlation between reading power and progression power gradient whereas, although a similar trend was noted with the Vision-Ease Delta(Figure 7.16) the correlation was not significant.

The Varilux VMD has a progression corridor divided into 3 portions(see section 2.6C), the longest of these is the central portion which is designed to have a constant length and a constant power law irrespective of the reading addition power(Dufour,1989). In this experiment the progression corridor of each lens

INFLUENCE OF READING ADDITION POWER UPON THE LENGTH AND WIDTH OF THE PAL PROGRESSION CHANNELS

| Lens Type | Correlation(r) | Probability(p) |
|---|---|---|
| VMD length v. Addition power | 0.989 | <0.001 |
| VMD width v. Addition power | 0.925 | <0.001 |
| Delta length v. Addition power | 0.909 | 0.001 |
| Delta width v. Addition power | 0.851 | 0.005 |
| Graduate length v. Addition power | 0.740 | 0.023 |
| Graduate width v. Addition power | 0.929 | <0.001 |
| V2 length v. Addition power | 0.707 | 0.033 |
| V2 width v. Addition power | 0.748 | 0.020 |
| 4 PALs (length) v. Addition power | 0.832 | <0.001 |
| 4 PALs (width) v. Addition power | 0.748 | <0.001 |

***Table 7.4.*** The simple correlation(r) and probability(p) values when reading addition power(D) is set against lens progression length and width(mm). Values from the four lens designs (Varilux VMD, Vision-Ease Delta, Sola Graduate, and Varilux V2) are treated separately and also collectively.

POWER MERIDIAN GRADIENTS(mm/D)

| | Base Curve(D) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.00 | 2.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 | 7.25 | 8.00 |
| **Lens Type** | | | | | | | | | |
| **VMD** | | | | | | | | | |
| +3.0D add | | | 8.33 | | | 9 | | | 8.0 |
| +2.0D add | | | 9.5 | | | 8.5 | | | 8.5 |
| +1.0D add | | | 11 | | | 8 | | | 10 |
| **Delta** | | | | | | | | | |
| +3.0D add | 9.66 | | | | 9.66 | | 8 | | |
| +2.0D add | 9.5 | | | | 5.5 | | 10.5 | | |
| +1.0D add | 11 | | | | 10 | | 12 | | |
| **Graduate** | | | | | | | | | |
| +3.0D add | | 6 | 9 | | | | | | 7 |
| +2.0D add | | 10.5 | 11 | | | | | | 10.5 |
| +1.0D add | | 13 | 11 | | | | | | 17 |
| **V2** | | | | | | | | | |
| +3.0D add | | 9 | | 6 | | | | 6 | |
| +2.0D add | | 11 | | 8.5 | | | | 8 | |
| +1.0D add | | 18 | | 16 | | | | 14 | |

*Table 7.5.* The rate of change( or gradient) of power(mm/D) along each lens progression considered in terms of the reading addition power(D) and the nominal base curve(D). The table shows that for most of the lens designs studied the power changes more abruptly with an increase in the reading addition power.

## INFLUENCE OF READING ADDITION POWER(D) UPON THE POWER GRADIENT(mm/D) OF THE LENS PROGRESSION

| Lens Type | Correlation(r) | Probability(p) |
|---|---|---|
| VMD | -0.523 | 0.139 |
| Delta | -0.437 | 0.201 |
| Graduate | -0.799 | 0.010 |
| V2 | -0.895 | 0.001 |
| 4 PALs combined | -0.646 | <0.001 |

***Table 7.6.*** The simple correlation(r) and probability(p) values when reading addition(D) power is plotted against the power gradient(mm/D). Each lens design is considered separately and the values of the four designs are also combined and considered collectively.

1.00D CORRIDOR WIDTH(mm) AT BOTTOM OF LENS PROGRESSION

| Lens Type | Base Curve(D) 2.00 | 2.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 | 7.25 | 8.00 |
|---|---|---|---|---|---|---|---|---|---|
| **VMD** | | | | | | | | | |
| +3.0D add | | | 12 | | | 11 | | | 13 |
| +2.0D add | | | 19 | | | 14 | | | 18 |
| +1.0D add | | | 34 | | | 27 | | | 27 |
| **Delta** | | | | | | | | | |
| +3.0D add | 21 | | | | 23 | | 19 | | |
| +2.0D add | 31 | | | | 12 | | 29 | | |
| +1.0D add | 21 | | | | 35 | | 23 | | |
| **Graduate** | | | | | | | | | |
| +3.0D add | | 21 | 25 | | | | | | 13 |
| +2.0D add | | 18 | 19 | | | | | | 20 |
| +1.0D add | | 32 | 28 | | | | | | 34 |
| **V2** | | | | | | | | | |
| +3.0D add | | 24 | | 16 | | | | 13 | |
| +2.0D add | | 12 | | 12 | | | | 15 | |
| +1.0D add | | 78+ | | 55 | | | | 37 | |

*Table 7.7.* The corridor width(mm) between the 1.00D contours found on either side of the umbilical line when measured across the bottom of the lens progression channel. These values were taken from the iso-cylindrical plots depicted in Appendix 1.

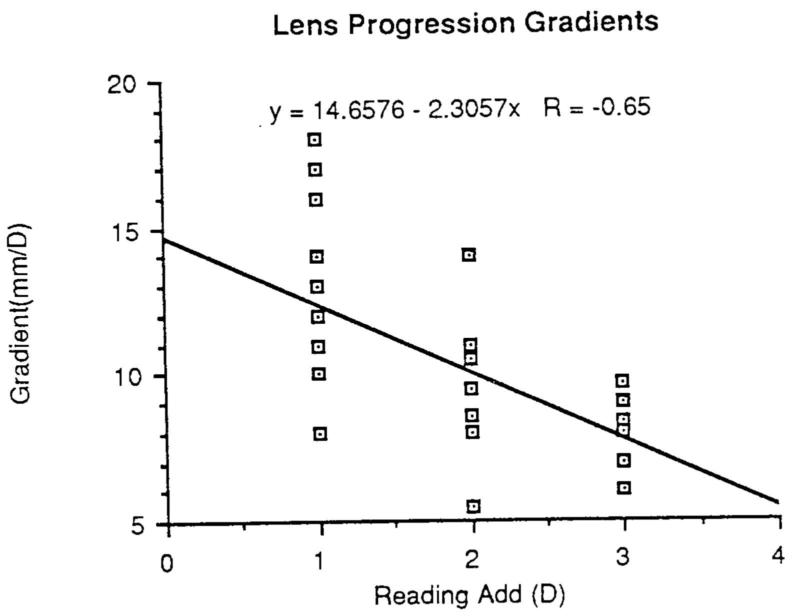
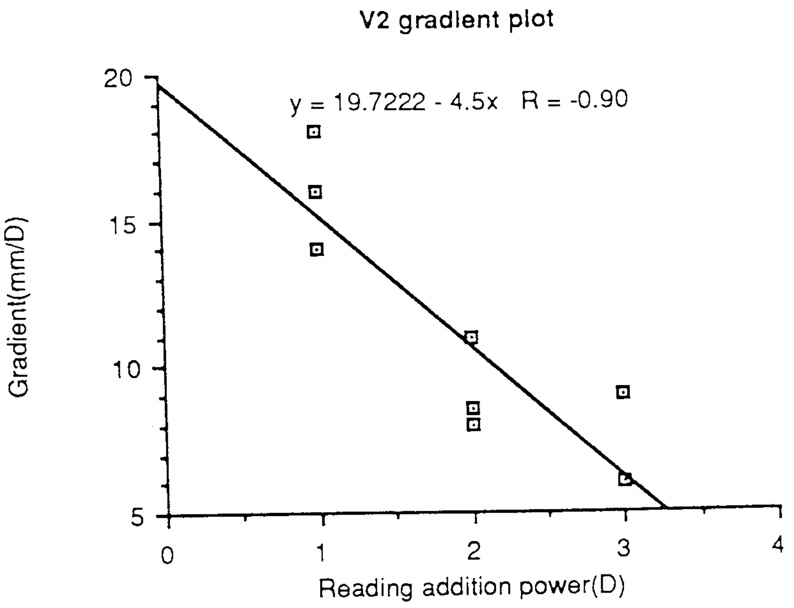


*Figure 7.14.* Graph showing the correlation(r=-0.646, p<0.001) between lens progression power gradient(mm/D) and reading addition(D) for the four lens designs combined.



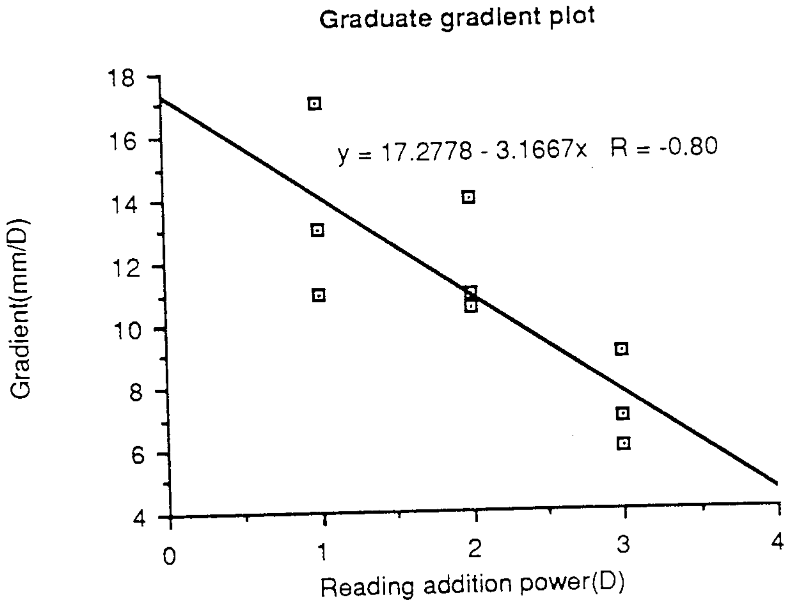
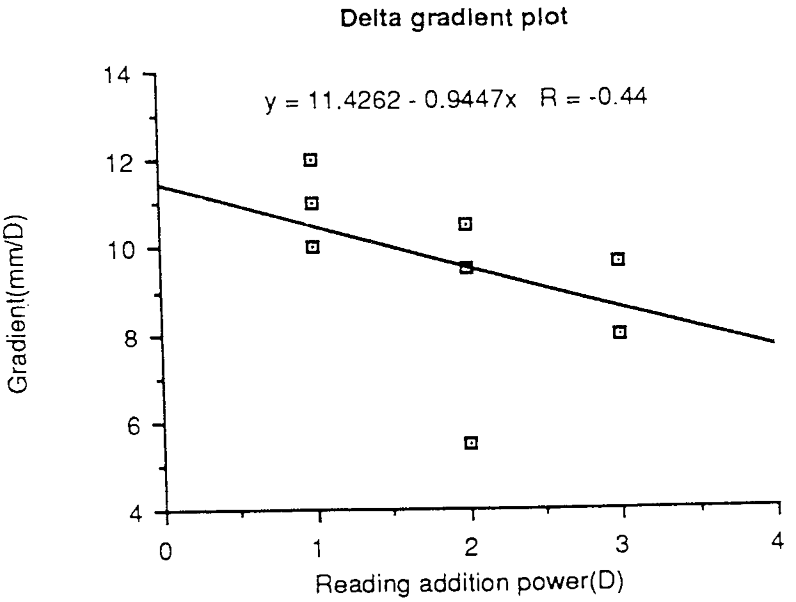


*Figure 7.15.* Correlation graphs of lens progression power gradient(mm/D) against reading addition(D) for (a) the Varilux V2 (r=-0.895, p=0.001) and (b) the Sola Graduate(r=-0.799, p=0.010) lens designs.



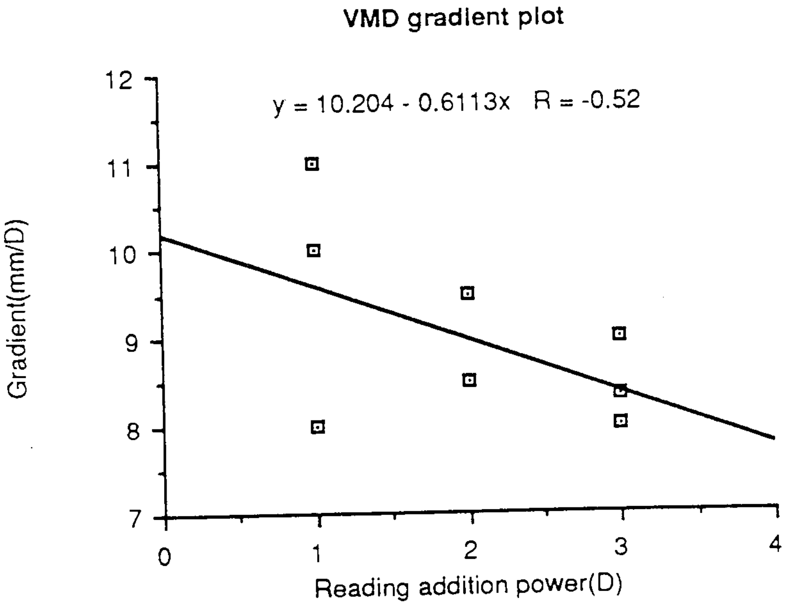


*Figure 7.16.* Correlation graphs of lens progression power gradient(mm/D) against reading addition(D) for (a) the Vision-Ease Delta(r=-0.437, p=0.201) and (b) the Varilux VMD(r=-0.523, p=0.139) lens designs.

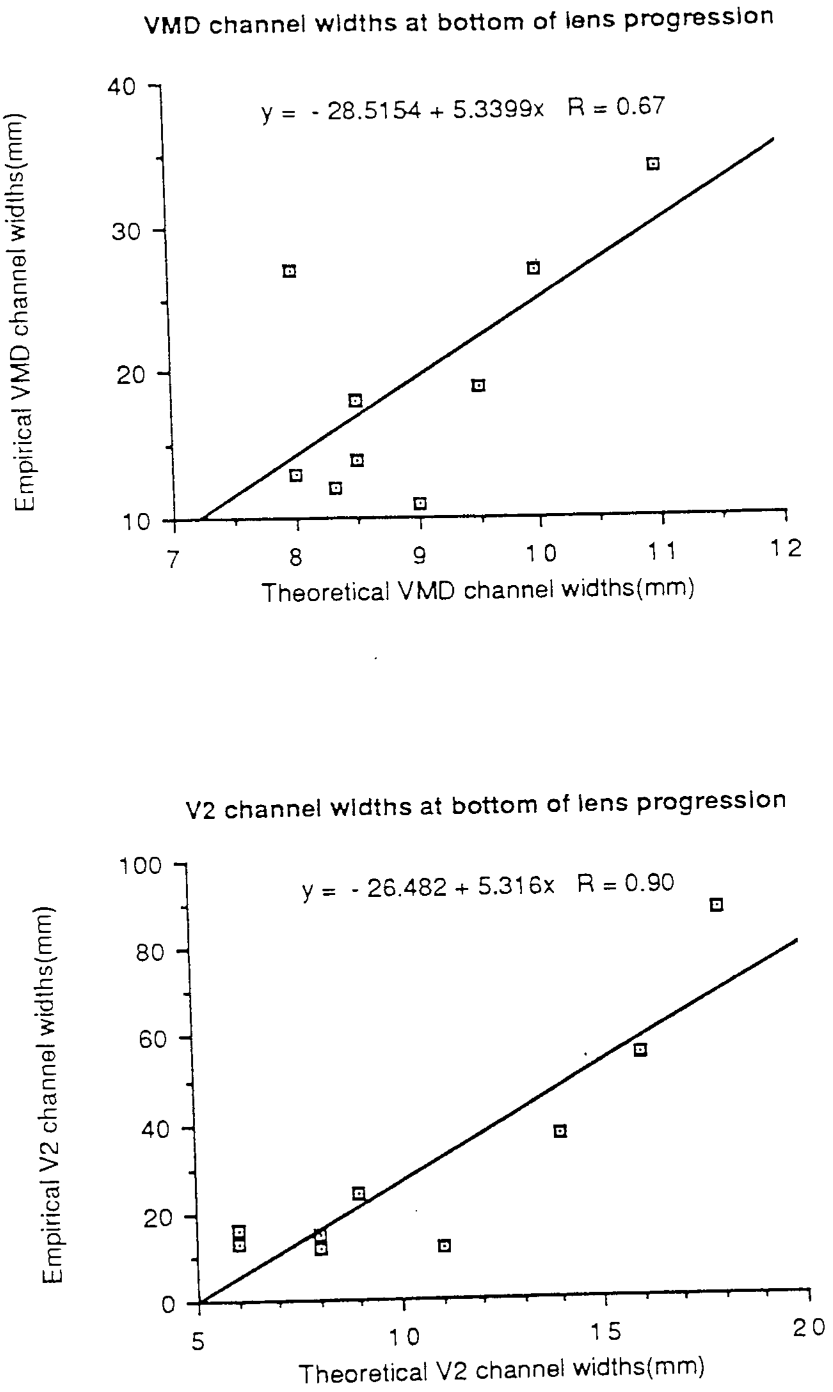
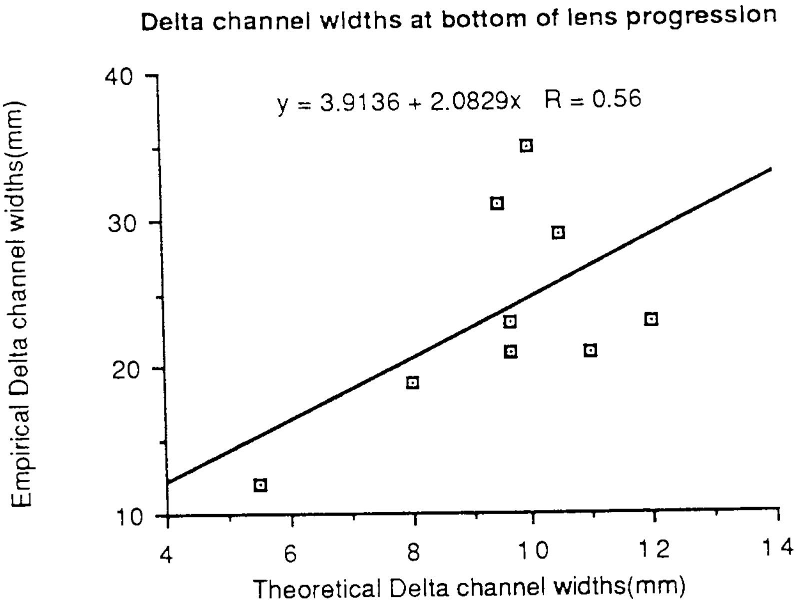


*Figure 7.17.* Graphs showing the empirical results of the 1.00D channel width taken at the bottom of each lens progression(mm) against the theoretical values predicted from von Minkwitz's(1963) formula, for (a) the Varilux VMD(r=0.666, p=0.050) and (b) the Varilux V2 (r=0.897, p=0.001) lens designs.



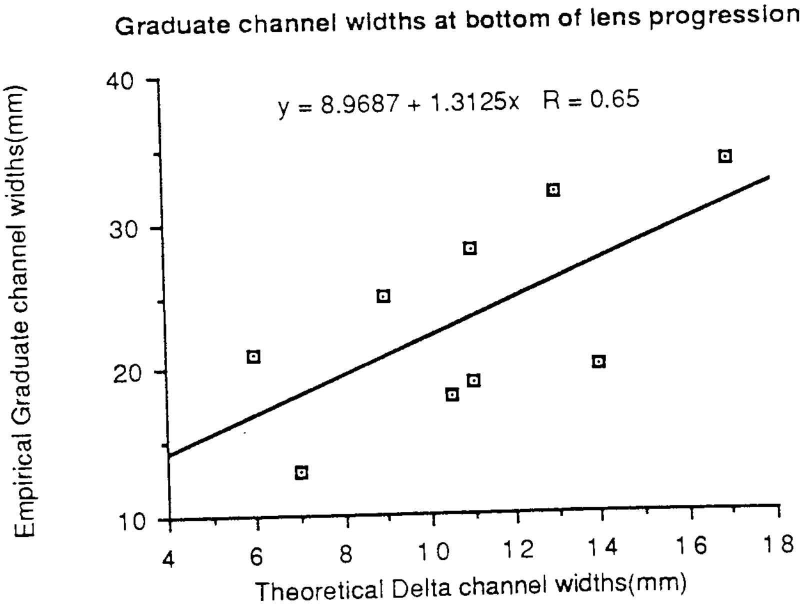


*Figure 7.18.* Graphs showing the empirical results of the 1.00D channel width taken at the bottom of each lens progression(mm) against the theoretical values predicted from von Minkwitz's(1963) formula, for (a) the Vision-Ease Delta(r=0.563, p=0.109) and (b) the Sola Graduate(r=0.650, p=0.058) lens designs.

was treated as a single constant gradient element and this may have masked the VMD results and account for a non significant result. However, the results for the variation in progression length with reading addition power( Tables 7.2 and 7.4) are of more interest as they show a significant increase in Varilux VMD progression length with reading addition power. Conversely, the patent claims(Dufour,1989) that there is a reduction in the progression corridor length with an increase in reading addition power(Figure 2.19).

Comparative analysis of PAL designs is an area of commercial interest. The promotional data of many different manufacturers has featured tables and diagrams which have sought to indicate the benefits of a particular lens over its rivals. PAL designers have to juggle a number of parameters to produce an acceptable compromise and for this reason there does not appear to be a single definitive method of physical analysis, by which all lenses may be judged.

One method of physical analysis might be to take the theoretical work of von Minkwitz(1963) and compare it to the empirical results in this experiment. Table 7.7 shows the results of the 1.00D channel widths(taken at the bottom of the progression) and these may be compared to the channel widths which would be produced from the von Minkwitz calculation(section 3.8). Figure 7.17 shows the empirical values of channel width at the bottom of the progression channel against the theoretical values calculated using von Minkwitz's equation for the VMD and V2 lenses. While Figure 7.18 shows the same comparison of empirical and theoretical values for the Delta and Graduate lenses. From each graph it may be noted that the channel widths that are measured are wider than those produced through calculation. This will be due to parameter manipulation eg., the introduction of several power discontinuities, undertaken by designers in order to produce wider reading and intermediate portions.

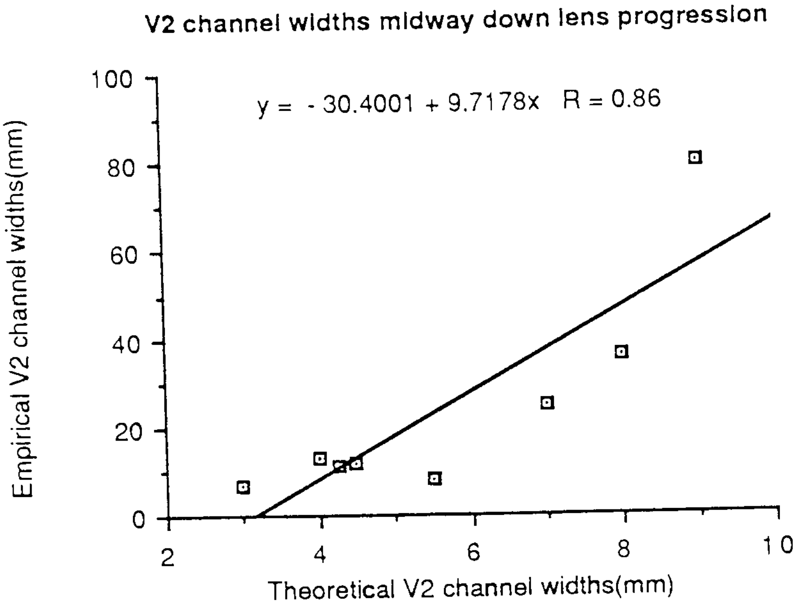
It is invalid to compare correlation(r) values however the gradient of each best fitting line may be compared to note how the empirical results depart from the theoretical values. Table 7.8 shows the theoretical values compared to the empirical results for the four lens designs studied. A gradient of 1 would occur when empirical and theoretical results match perfectly. When the gradient is greater than 1 then the empirical results show a wider corridor through the reading portion than that which would be expected from calculation using Minkwitz's calculation. This indicates that the PAL designers have altered the umbilical line power law from that of a continuously changing constant gradient to that of a variable gradient with a number of power discontinuities with the

*Table 7.8.* The values which result when the empirical readings and the theoretical deductions of von Minkwitz(1963) are compared. It is not statistically valid to compare correlations. These values are the gradients($m$ ) of the simple correlation lines($y = m x + b$ ) plotted between the empirical and theoretical figures for each lens design, where $b$ is a constant.

## 1.00D CORRIDOR WIDTH(mm) MIDWAY ALONG LENS PROGRESSION

| | Base Curve(D) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.00 | 2.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 | 7.25 | 8.00 |
| **Lens Type** | | | | | | | | | |
| **VMD** | | | | | | | | | |
| +3.0D add | | | 10 | | | 11 | | | 13 |
| +2.0D add | | | 14 | | | 13 | | | 13 |
| +1.0D add | | | 39 | | | 30 | | | 27 |
| **Delta** | | | | | | | | | |
| +3.0D add | 10 | | | | 12 | | 9 | | |
| +2.0D add | 15 | | | | 12 | | 13 | | |
| +1.0D add | 17 | | | | 45 | | 19 | | |
| **Graduate** | | | | | | | | | |
| +3.0D add | | 80 | 10 | | | | | | 10 |
| +2.0D add | | 12 | 16 | | | | | | 12 |
| +1.0D add | | 28 | 76 | | | | | | 26 |
| **V2** | | | | | | | | | |
| +3.0D add | | 12 | | 13 | | | | 7 | |
| +2.0D add | | 8 | | 11 | | | | 13 | |
| +1.0D add | | 78+ | | 36 | | | | 25 | |

*Table 7.9.* The corridor width(mm) between the 1.00D contours found on either side of the umbilical line when measured across the midpoint of each lens progression channel. These values were taken from the iso-cylindrical plots depicted in Appendix 1.



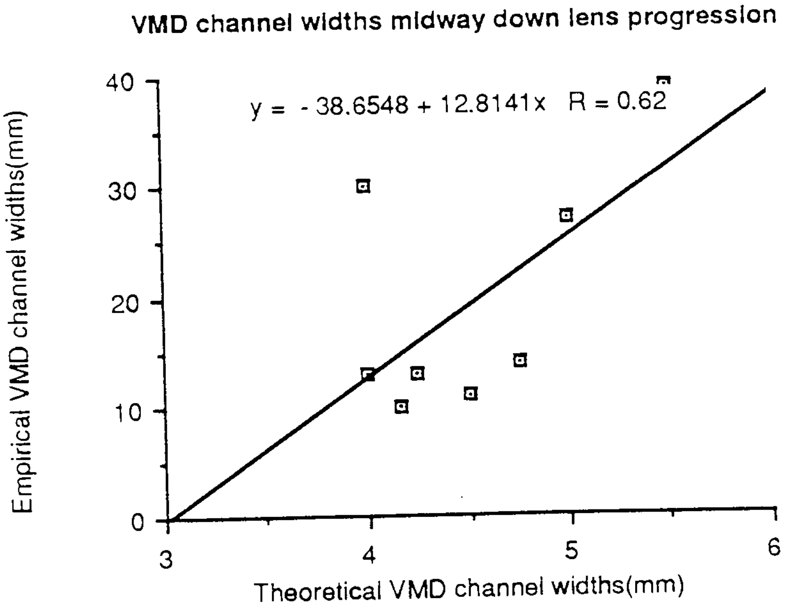


*Figure 7.19.* Graphs showing the empirical results of the 1.00D channel width taken midway along each lens progression(mm) against the theoretical values predicted from von Minkwitz's(1963) formula, for (a) the Varilux V2(r=0.858, p=0.003) and (b) the Varilux VMD(r=0.624, p=0.073) lens designs.

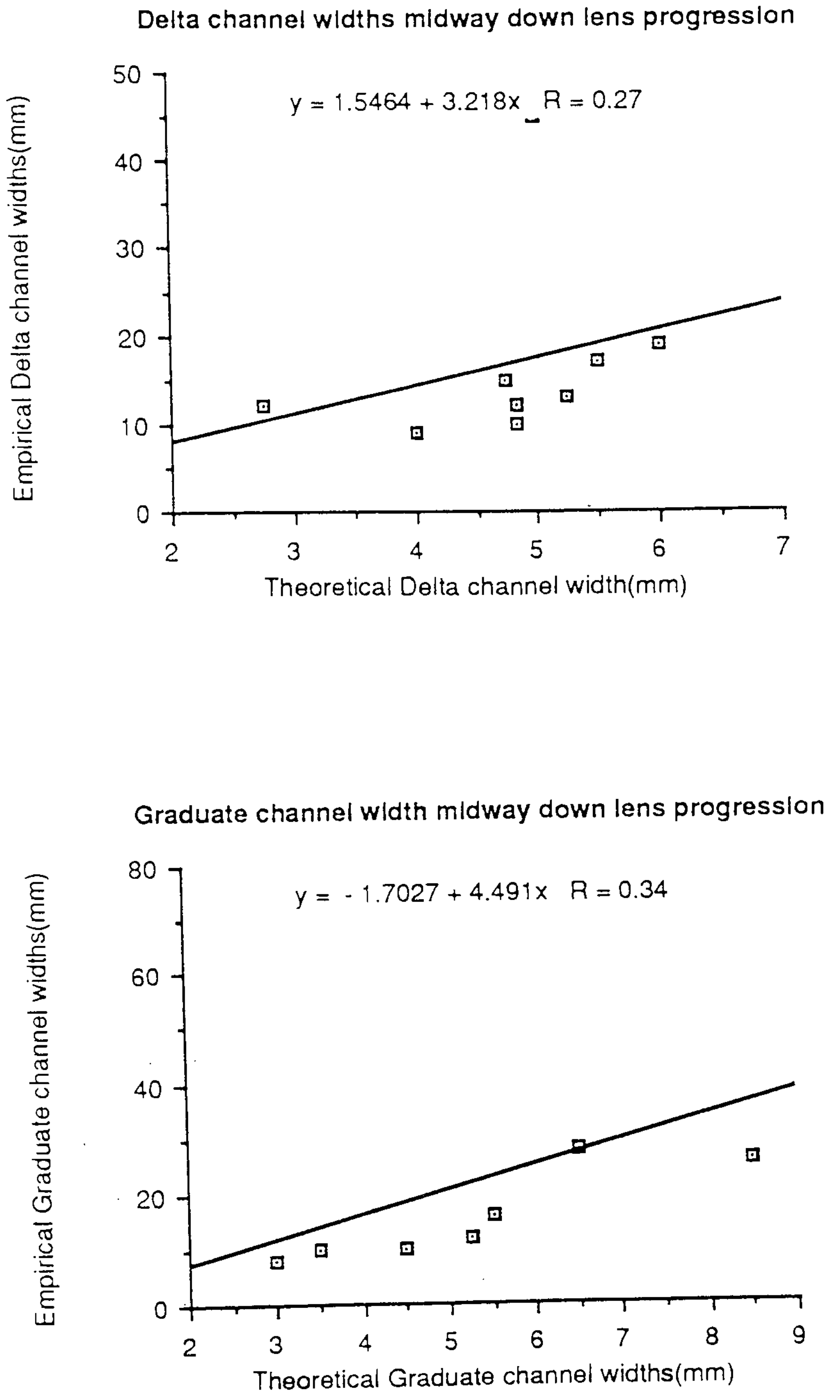


*Figure 7.20.* Graphs showing the empirical results of the 1.00D channel width taken midway along each lens progression(mm) against the theoretical values predicted from Minkwitz's(1963) formula, for (a) the Vision-Ease Delta(r=0.273, p=0.477) and (b) the Sola Graduate(r=0.338, p=0.373) lens designs.

necessary peripheral power blending, to avoid ridges in the anterior surface topography.

To compare the theoretical(1.00D) channel widths for the measured progression lengths against the empirical(1.00D) channel widths at only one location may give a very selective view. Channel widths were therefore also calculated at the umbilical line mid-point( half way down the progression length, in terms of distance and not dioptric power). The measured values of channel width(mm) halfway along each lens progression channel are shown in Table 7.9. Figures 7.19 and 7.20 show the graphical analysis for the VMD and V2, and the Delta and Graduate lenses respectively. The results of both the analysis taken at the full length of the lens progression and that taken midway along the lens channel would suggest that the two Varilux lenses - the VMD and the V2 departed most noticeably from the theoretical single power law model of von Minkwitz and subsequently have wider progression channels.

## 7.9 BASE CURVE ANALYSIS

### 7.9A Introduction

The nominal base curve upon which a lens design is manufactured may, like the reading addition powers, also have a significant bearing upon the optical qualities of the resulting PAL surface topography.

### 7.9B Method

This was investigated using the same parameters employed for the reading addition study, namely the progression length and corridor width. The measurements presented in Tables 7.2 and 7.3 may be graphically represented with the progression lengths(Figure 7.21) and channel widths(Figure 7.22) plotted against the base curve power.

### 7.9.C Results

Correlation analysis was undertaken to establish whether a relationship existed between the base curve of PALs and (a)the progression length and (b)the channel width. Table 7.10 shows there to be no significant correlation between the base curve of a lens and the progression length($r = -0.128$, $p = 0.456$). A non significant correlation( $r = -0.153$, $p = 0.373$) was also revealed between the base curve of a lens and the channel width.

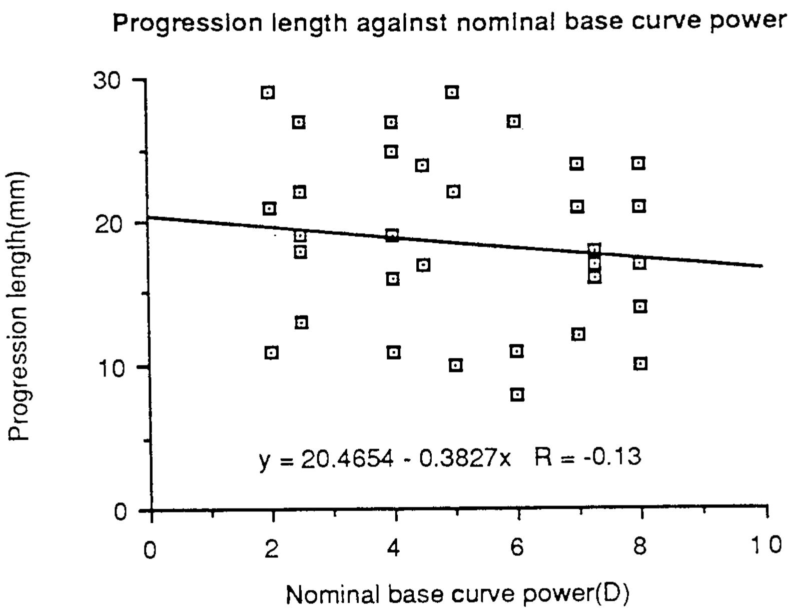


*Figure 7.21.* Graphs showing the correlation(r=-0.128, p=0.456) between the progression length(mm) and nominal base curve power(D) for the four lens designs combined.

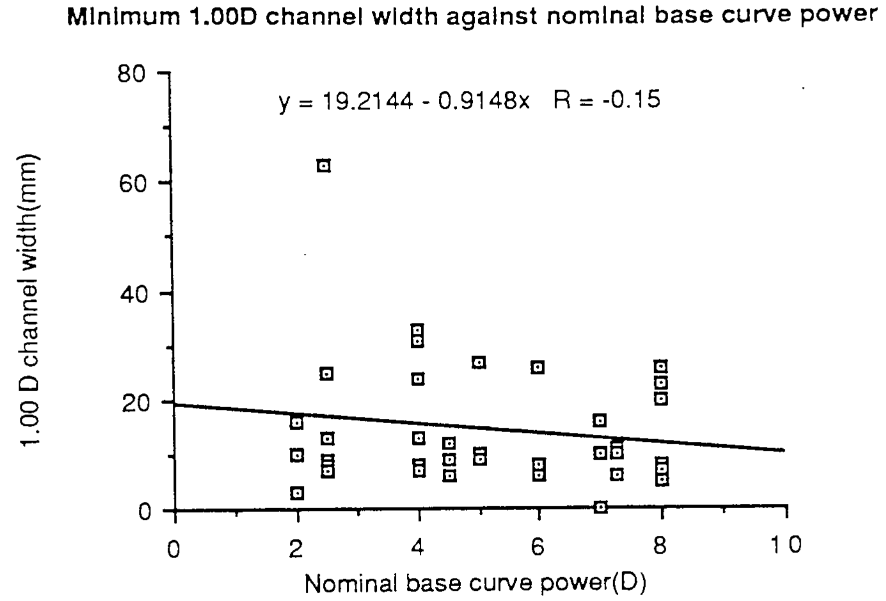


*Figure 7.22.* Graphs showing the correlation(r=-0.153, p=0.373) between the minimum 1.00D channel width(mm) and nominal base curve power(D) for the four lens designs combined.

## INFLUENCE OF NOMINAL BASE CURVE POWER UPON THE LENGTH AND WIDTH OF THE PAL PROGRESSION CHANNELS

| Lens Type | Correlation(r) | Probability(p) |
|---|---|---|
| VMD length v. Base curve power | -0.084 | 0.830 |
| VMD width v. Base curve power | -0.149 | 0.701 |
| Delta length v. Base curve power | -0.057 | 0.885 |
| Delta width v. Base curve power | -0.108 | 0.783 |
| Graduate length v. Base curve power | -0.161 | 0.678 |
| Graduate width v. Base curve power | -0.157 | 0.686 |
| V2 length v. Base curve power | -0.636 | 0.066 |
| V2 width v. Base curve power | -0.294 | 0.443 |
| 4 lens designs combined v. Base curve power | -0.128 | 0.456 |
| 4 lens designs combined v. Base curve power | -0.153 | 0.373 |

***Table 7.10.*** The simple correlation(r) and probability(p) values when the nominal base curve power(D) is set against lens progression length(mm). Values from the four lens designs (Varilux VMD, Vision-Ease Delta, Sola Graduate, and Varilux V2) are treated separately and also collectively.

## 1.00D CORRIDOR WIDTH(mm) AT TOP OF LENS PROGRESSION

| | Base Curve(D) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.00 | 2.50 | 4.00 | 4.50 | 5.00 | 6.00 | 7.00 | 7.25 | 8.00 |
| **Lens Type** | | | | | | | | | |
| **VMD** | | | | | | | | | |
| +3.0D add | | | 23 | | | 24 | | | 17 |
| +2.0D add | | | 20 | | | 23 | | | 20 |
| +1.0D add | | | 49 | | | 35 | | | 28 |
| **Delta** | | | | | | | | | |
| +3.0D add | 10 | | | | 8 | | 3 | | |
| +2.0D add | 18 | | | | 17 | | 7 | | |
| +1.0D add | 25 | | | | 68 | | 45 | | |
| **Graduate** | | | | | | | | | |
| +3.0D add | | 20 | 17 | | | | | | 35 |
| +2.0D add | | 17 | 27 | | | | | | 23 |
| +1.0D add | | 29 | 78+ | | | | | | 52 |
| **V2** | | | | | | | | | |
| +3.0D add | | 17 | | 14 | | | | 6 | |
| +2.0D add | | 57 | | 19 | | | | 19 | |
| +1.0D add | | 68 | | 62 | | | | 73 | |

***Table 7.11.*** The corridor width(mm) between the 1.00D contours found on either side of the umbilical line when measured at the top of each lens progression channel. These values were taken from the iso-cylindrical plots depicted in Appendix 1.

1.00D CHANNEL AS A FRACTION OF LENS PLOT WIDTH

|  | Channel Location |  |  |
|---|---|---|---|
| **Lens Type** | Top | Middle | Bottom |
| VMD | 0.34 | 0.24 | 0.25 |
| Delta | 0.34 | 0.21 | 0.30 |
| Graduate | 0.50 | 0.28 | 0.30 |
| V2 | 0.47 | 0.29 | 0.32 |

***Table 7.12.*** The mean results for each lens design when the minimum width of the 1.00D channel is considered as a decimal fraction of the total width of the iso -cylindrical lens plot. Values for the top, midpoint, and bottom of the lens progression corridor are presented.

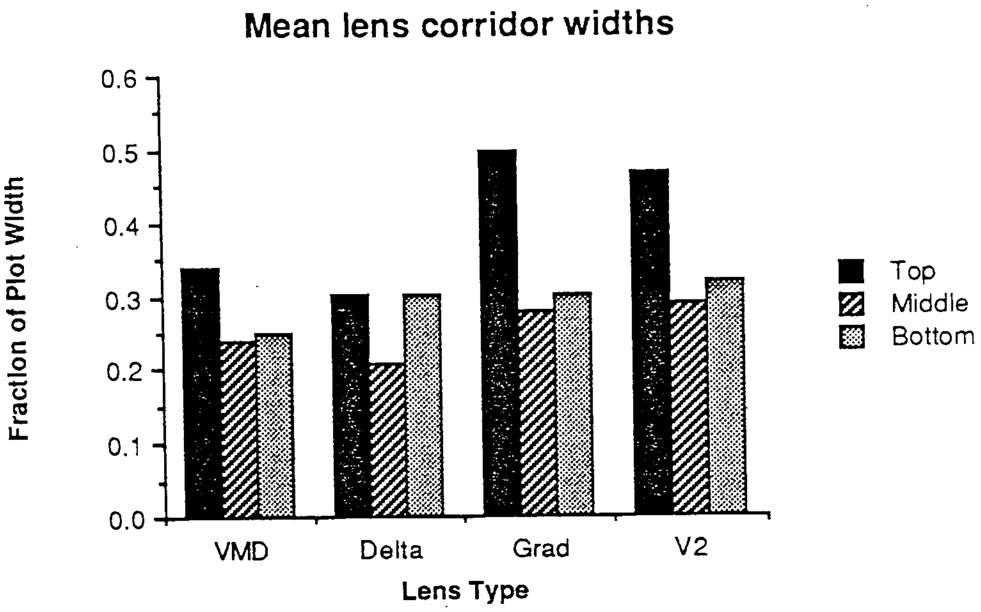


*Figure 7.23.* Histogram showing the mean values of 1.00D corridor width(mm) for each lens as a fraction of the total lens plot width taken at the top, bottom, and midway along the progression channel.

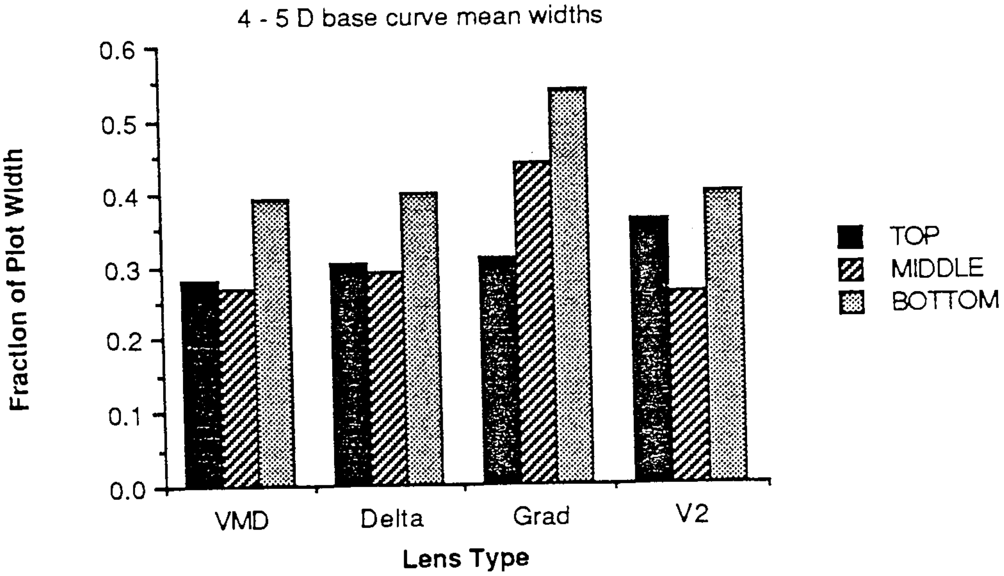


*Figure 7.24.* Histogram showing the mean values of 1.00D corridor width(mm), for 4 D to 5 D base curve lenses of each design, as a fraction of the total lens plot width taken at the top, bottom, and midway along the progression channel.

When the lens designs are considered separately, then a similar pattern emerges. These results(Table 7.10) suggest that despite the differences in the four designs studied, base curve has little effect upon the parameters of a PAL. From Table 7.11 it would appear that the most marked effects of base curve power design appear when low powered adds are present upon low power base curves. The effect is for the astigmatism to be spread very widely across the surface, with a large 1.00D channel width. for example, with the 1.00D addition version of the 2.50D base curve Varilux V2 lens.

The von Minkwitz approach (section 7.8)may not be the best optico-physical method of PAL analysis. An alternative technique is to compare the 1.00D progression widths as a fraction of the lens plot width. This may be done at the top, mid-point, and bottom of each lens progression. Tables 7.11, 7.9, and 7.7 show the channel widths at the top, midway along, and at the bottom of the lens progression. The lens plot width of each diagram is 78mm and Table 7.12 shows the mean values for the nine lenses(3 base curves and 3 reading additions) of each PAL design studied. The mean results (graphically represented in Figure 7.23) are expressed as a fraction of 1, which would indicate that the width of the 1.00D corridor was equivalent to the total aperture width of the PAL plot. These results would suggest that the Sola Graduate lens, which scored lower than the VMD in the von Minkwitz approach, does much better when considered in these terms.

Comparing lenses with different base curves introduces an inconsistent variable (as the four lens designs are made up on different base curves) which should be avoided. A lens of each design with base curves as near as possible was taken. Three lenses(1.00D, 2.00D, and 3.00D adds.) of the 4.00D Base VMD, 4.00D Base Graduate, 4.50D Base V2, and 5.00D Base Delta were used. This plot(Figure 7.24) further accentuates the differences between the VMD and the Graduate, both of which have the same base curve in this instance. Therefore, if this technique were adopted the Graduate would appear to be a 'better' lens in terms of the channel width, however, in the previous section the VMD appeared to depart more successfully than the Graduate, from the von Minkwitz equation. Hence the advantages of a soft( VMD) and a hard (Graduate) lens may be made apparent depending upon the technique of analysis and these two different approaches highlight the difficulties associated with physical analysis of PALs.

## 7.10 DISCUSSION

This chapter covered a variety of optico-physical techniques for the evaluation of PALs. The optico-physical properties of PALs and the efficacy of different evaluation techniques were considered. It was shown from section 7.4 that for low powered lenses there was not a significant difference as to whether PALs were measured using a focimeter in a conventional, scanning, or reflective manner. This validated the use of the SRF for analysing semi-finished lens blanks. Repeatability for the lens design studied was demonstrated - although it is also worth noting that one of the lenses departed from the accepted design - which proved the need for pertinent quality control procedures to be adopted by PAL manufacturers. The SRF was also used for an initial study of PAL surface astigmatism and although such a technique is time consuming and subsequently not as comprehensive as would be desired it was nevertheless possible by taking a relatively small number of measurements(81) to demonstrate the differences in PAL design which exist. This technique would be of greater value were it to be automated.

A more comprehensive method of assessment is that described in section 7.8, using the computer controlled automated focimeter. This allowed a very detailed analysis of PAL surface topography. With this instrument it was possible to demonstrate the importance of reading addition power to the width and length of the lens progression zone. Furthermore, it was shown that the four lens designs involved in the reading addition study, which are very different in terms of the dynamic/static design criterion, all exhibited the same properties of having a wider, longer progression zone for higher reading additions. The four lens designs studied were shown to rely primarily upon alterations in the progression length rather than an increase in the progression power gradient in order to provide higher reading addition powers. This is presumably because a lens design which depended solely upon increasing the progression power gradient might subject a patient to intolerably high levels of astigmatism within the central corridor of the progression channel.

The Nidek automatic focimeter was used in a similar fashion to investigate the importance of base curve upon PAL surface topography. Unlike the reading addition power, the nominal base curve power appears to be of little consequence in determining the width or length of a progression channel. The exception being with low reading addition, low base curve power lenses, when the astigmatism is spread more extensively across the PAL with a wider progression corridor resulting.

The difficulties of interpreting optico-physical analysis were also considered. This was done by comparing the results of two different methods of interpreting the detailed plots produced. One approach, to compare the empirical results with theoretical values( von Minkwitz,1963) showed the Varilux VMD to have the optimum physical qualities. However, another technique of comparing the progression channel widths as a fraction of the lens plot width showed the Sola Graduate to be the most successful. The results of relative comparisons clearly depend upon which criterion, of which there are several, is employed. Indeed, commercial interests rather than valid statistical criteria have often determined the preferred technique of optico-physical measurement and data presentation. Herein lies one of the disadvantages of assessing PALs with exclusively optico-physical techniques. Physical techniques may be more objective than psychophysical methods, however an evaluation of PALs which does not involve patients cannot be a comprehensive analysis.

# Chapter 8

## THE PSYCHOPHYSICAL ASSESSMENT OF PROGRESSIVE ADDITION LENS WEARERS

### 8.1 PREAMBLE

Psychophysical assessment involves the study of relationships between the physical entity - the PAL, and the responses of patients. Physical assessment is important for analysing the design characteristics of different lenses in terms of the spread and orientation of astigmatism, the influence of reading addition and base curve, for a comparative analysis of PAL design, for verification of PALs i.e., quality control purposes and for regarding PAL standards. However, these features must be viewed in terms of the way they influence the patient's ability to adapt to and successfully wear PALs. Köppen(1987) suggests that physical methods of PAL assessment have been more commonly employed as they are more objective than psychophysical methods and do not require the co-operation of patients. Nevertheless, Diepes and Tameling(1988) note that psychophysical techniques should be undertaken as the ultimate test of a PAL's success is judged in terms of a patient's ability to wear it successfully.

As noted previously(Chapter 3), Seidel aberrations affect the quality of the image obtained through spectacle lenses. Lens designers take particular notice of radial astigmatism and distortion as these two aberrations are more troublesome than the others. As with other spectacle lenses, astigmatism and distortion are present in PALs but to an additional degree due to the aspheric anterior surface of a PAL. Astigmatism affects the clarity on an image, and this may be assessed using visual acuity(VA) and contrast sensitivity(CS) measures whereas distortion affects the shape of the image and this must be assessed by considering the effect upon the optical distortion of form.

### 8.2 IMAGE CLARITY

The effect astigmatism has upon image clarity was considered with two experiments. Firstly, as a pilot study the effect of peripheral PAL astigmatism upon grating VA was considered. Then in a more extensive study of PAL visual performance, two groups of subjects - those who had successfully adapted to PALs and those who had failed to adapt, were compared using a measure of CS.

## 8.3 GRATING VISUAL ACUITY TESTING AS A PSYCHOPHYSICAL MEANS OF PROGRESSIVE ADDITION LENS ASSESSMENT

### 8.3A Introduction

One of the important factors which affects the quality and hence the suitability of a progressive addition spectacle lens is the presence of astigmatism. Indeed, the presence of oblique astigmatism and surface astigmatism are arguably the most significant factors when considering the loss of image definition. The quantity of astigmatism present probably has a direct bearing upon the visual acuity obtainable through the periphery of a PAL. If this premise is correct, then an appropriate psychophysical test might involve study of foveal visual performance through the lens periphery.

Emsley(1956) notes that vision is subnormal in the presence of astigmatism and that this depends to an extent on its degree and to a smaller extent on its orientation. If the principal meridians of a patient's astigmatism are obliquely orientated that person will not see as well as a person with an equal degree of astigmatism when the principal meridian orientations are vertical and horizontal. Campbell, Kulikowski and Levinson(1966) also noted that acuity was better for vertical and horizontal targets than for oblique ones, when they used gratings. Campbell explained this in terms of the neural structure and organisation of the visual system rather than in terms of the optics of the eye. Geddes *et al* (1966) found that when they measured VA at differing distances - the best VA was found between 1.5 and 3.5m. This suggests that accommodation may have an influence upon the VA and it is therefore important to stabilise the accommodation when measuring VA. It would appear that VA depends upon many factors and Borish(1970) has compiled a very comprehensive study of these.

A number of workers have attempted to relate the refractive error, either naturally occurring or induced by fogging lenses, to visual acuity. Borish(1970) notes that there is no conclusive correlation between them. Sloan(1951) listed average refractive states against visual acuity and she concluded that an increase of 0.18 D of spherical myopia will cause a reduction in VA by one line of Snellen acuity. In a similar study Giles(1960) placed the steps of the chart at 0.16 D. Humphriss(1968) found considerable variation in the degree of acuity reduction produced by a fogging lens. With 42 subjects he recorded acuities between 6/9 and 6/60 with a +1.50 DS fogging lens - a subject's pupil size will have some bearing upon the VA attained. Garcia and Loshin(1988) considered the visual performance of PALs by testing the contrast sensitivity function(CSF) when viewing gratings through six different portions of the lens. They noted that the CSF was reduced in the lens periphery but that along the umbilical line it was similar to a single vision spherical lens.

Whilst it is clear that astigmatism reduces the VA - a certain amount of astigmatic error must be tolerated by the patient when wearing PALs because all progressive addition lenses display astigmatism at some point in the field of view. It is likely there is considerable variation in the astigmatic thresholds observed by patients. Indeed, one suggestion is that a patient's ability to adapt/adjust to astigmatism may be an indication of their suitability as a PAL wearing candidate. A lens designer must therefore produce a lens which is acceptable to the majority of observers. As noted previously, Maitenaz(1974) assumed 0.3 D to be the limit of spectacle lens induced astigmatism tolerated by the human eye. Whereas Guilino and Barth(1980) put the figure at 0.5 D and Shinohara and Okazaki(1985) arrived at the figure of 1.00 D. Unfortunately, none of these three patents indicate how their results were derived, although Shinohara and Okazaki state they carried out psychophysical tests on linear progressive portions of varying length. It should be further noted that Maitenaz, and Shinohara and Okazaki consider the rate of change of surface power at a given location to be a more significant factor than the magnitude of astigmatism at that point.

The resulting visual acuity may depend upon the type of target employed. This study employed high contrast gratings, which may indicate better acuity than Snellen letters, because the threshold relates to detection of the grating while with Snellen letters the thresholds relate to recognition of the optotype.

### 8.3B Method

Visual acuity assessment was undertaken using an adaptation of a technique first proposed by Reiner(1966) for studying contact lenses; and later used for the assessment of aspheric spectacle lenses by Köppen and Barth(1982). Guilino and Köppen(1982) also employed this technique for the assessment of distance vision, in an article of commercial literature, through the Rodenstock Progressiv R lens using Snellen letter test charts. With an adapted version of Reiner's apparatus, grating VA measurements were recorded through the aspheric intermediate corridor of several different designs of PAL. The apparatus(Figure 8.1) consisted of an astronomical telescope with unit magnification which was attached to an optical bench. In front of the telescope, which was focused for infinity, was a lens holder into which the PAL under test

Measurement of Grating Acuity

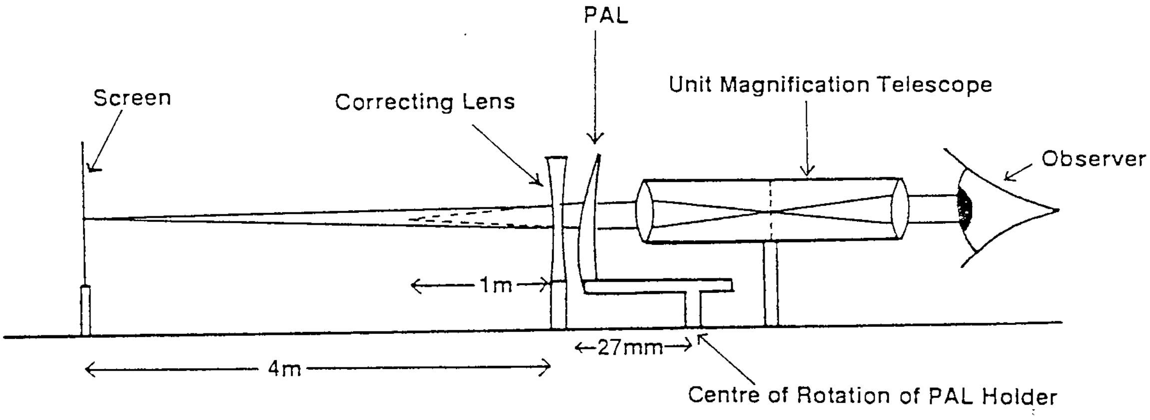


*Figure 8.1.* A schematic diagram of the apparatus used to measure grating acuity through PALs.

was placed. This PAL lens holder could be rotated, to allow the monitor to be viewed through portions of the lens lateral to the umbilical line, about a centre of rotation 27mm behind the rear surface of the lens under test. The objective of the telescope was placed at 12mm behind the rear surface of the test lens.

Keeping the graticule in focus helped to stabilize subject accommodation. Nevertheless, small microfluctations would still occur. The magnitude of these oscillations are affected by such factors as the target luminance, the target vergence, and pupil size(Charman and Heron, 1988). However, Miege and Denieul(1988) have shown, using natural pupils, that for a 4m target (luminance = 20cd/m$^2$) the amplitude of such fluctuations would be very small($\sim$0.05D).

The study was undertaken to investigate the validity of measuring grating VA as a means of assessing the relative change in VA along a horizontal section through various PALs. A single subject(caucasian male 26 yrs) was tested for threshold VA through three PALs and a single vision glass lens. A number of physical measurements of astigmatism and power at values of increasing eccentricity from the umbilical line of the PAL were made. The acuities achieved, when a small circular portion of a monitor screen(0.716° target) displaying gratings was viewed by the subject through the same portions of each lens, were recorded and then assessed. The PALs employed for the study were plano versions of the Varilux V2(6.50D Base Curve), the Super No-Line NZ(6.25D Base Curve), and the Orcolite Line Free(LF) - 8.00D Base Curve, and each had a +2.00 D near addition. A +1.00D single vision glass lens with a 6 D base curve was also tested for comparative purposes. The portion of each PAL assessed was a horizontal section taken through the dioptric midpoint, which is located at that point on the umbilical line where the vertex power, or mean spherical power, is equivalent to +1.00DS. This area of the lens was chosen to facilitate an evaluation of the intermediate portion of a PAL, which is the portion unique to a PAL due to the non rotationally symmetrical nature of the lens. As the vertex power was nominally +1.00DS at the point where the section cut the umbilical line, therefore, the focal length of this portion of the lens is 1m. However, in order to facilitate a range of smaller grating sizes the monitor was located 4m from the lens under test, this meant that a correcting lens(-0.75D) was required to place the target at optical infinity.

The lens holder was rotated up to 35° in either direction from the central point located on the umbilical line of the progressive lens, although with large

## PHYSICAL AND PSYCHOPHYSICAL MEAN RESULTS

| | -35. | -30. | -25. | -20. | -15. | -10. | -5. | 0. | 5. | 10. | 15. | 20. | 25. | 30. | 35. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V2 Astig. | 1.6 | 1.83 | 1.77 | 1.69 | 1.62 | 1.41 | 1.18 | 0.65 | 0.44 | 1.18 | 1.8 | 2.07 | 2.25 | 2.27 | 2.19 |
| NZ Astig. | | 2.46 | 2.75 | 2.80 | 2.53 | 1.48 | 1.23 | 0.43 | 0.8 | 1.8 | 2.62 | 3.33 | 3.5 | 4.1 | |
| LF Astig. | | 2.09 | 2.12 | 1.94 | 1.79 | 1.23 | 0.63 | 0.25 | 1.15 | 1.76 | 2.25 | 2.47 | | | |
| Sph Astig. | 0.34 | 0.27 | 0.13 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.1 | 0.16 | 0.25 | 0.37 | |
| V2 MSP | 0.63 | 0.74 | 0.94 | 0.96 | 0.95 | 0.92 | 0.88 | 0.97 | 1.05 | 1.15 | 1.15 | 1.03 | 0.83 | 0.70 | 0.51 |
| NZ MSP | | 1.12 | 1.09 | 0.84 | 0.77 | 0.92 | 0.96 | 0.96 | 0.8 | 1.8 | 2.62 | 3.33 | 3.5 | 4.1 | |
| LF MSP | | 0.64 | 0.56 | 0.57 | 0.66 | 0.76 | 0.93 | 1.02 | 0.79 | 0.63 | 0.56 | 0.48 | | | |
| Sph MSP | | 1.3 | 1.26 | 1.17 | 1.10 | 1.03 | 1.03 | 1.03 | 1.04 | 1.06 | 1.13 | 1.16 | 1.25 | 1.33 | |
| V2 VA | 0.78 | 0.79 | 0.76 | 0.86 | 0.89 | 1.05 | 1.18 | 1.33 | 1.20 | 1.04 | 0.91 | 0.83 | 0.77 | 0.76 | 0.76 |
| NZ VA | | 0.78 | 0.91 | 0.94 | 0.95 | 1.06 | 1.21 | 1.30 | 1.24 | 1.03 | 0.92 | 0.77 | 0.67 | 0.59 | |
| LF VA | | 0.87 | 0.91 | 0.94 | 0.97 | 1.02 | 1.09 | 1.11 | 1.09 | 1.02 | 0.97 | 0.95 | 0.90 | 0.86 | |
| Sph VA | | 1.22 | 1.26 | 1.30 | 1.32 | 1.34 | 1.37 | 1.38 | 1.35 | 1.32 | 1.30 | 1.30 | 1.30 | 1.27 | 1.23 |

***Table 8.1.*** The means of three readings for each angle of eccentricity are presented for Astigmatism and the Mean Spherical Power in dioptres. The table also gives the mean grating acuity achieved (of six readings) through the four lenses tested. Values in the nasal sector were considered positive and those in the temporal sector negative.

decentred lens blanks mechanical considerations prevented movement as far as 35° in the case of the NZ and LF lenses. Grating acuities were recorded at 5° intervals. Each acuity recorded is the mean of six readings, taken using an adjustment method(Table 8.1). The measure of visual acuity chosen is that described by Borish(1970) as the 'routine visual acuity', and is defined as the reciprocal of the angular subtense(w) of a target, in minutes of arc, which is just detectable;

$$\text{Visual Acuity (VA)} = 1 / w$$

An SC Electronics IOL Sine/Square Wave Grating Generator was employed to produce vertical and horizontal square wave gratings, the spatial frequency of which could be altered by the subject using a dial gauge. Contrast was set at a high value(94.2%); this value was recorded using a digital telescope photometer. The percentage value of contrast is derived from the equation;

$$\text{Contrast (M)} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \times 100$$

where L represents the luminance. The average luminance may also be calculated using the equation;

$$\text{Average Luminance (A)} = \frac{L_{max} + L_{min}}{2}$$

where again L represents the luminance. In this case the average luminance was calculated to be 138.5 cd/m$^2$.

The optico-physical measurements(Table 8.1) were also recorded at 5° intervals along the same horizontal section through the umbilical line; namely, the point on that line where the mean spherical power was nearest to +1.00D. The most eccentric points recorded were 35° in either direction from the meridian line. Mechanical considerations due to lens blank size were also a factor with these focimeter measurements as they had been with the measurements of grating acuity. The power of the three PALs in this study were recorded at the same points as those chosen for the grating acuity experiments, using a Nidek Automatic Focimeter and a rotating mount device which simulates the movement of an eye behind a fixed lens(Morgan,1961). The lenses were rotated about a point 27mm from the back surface of the lens under test.

As noted above, both Maitenaz(1974) and Shinohara and Okazaki(1985) consider the rate of change of surface power over the surface of a PAL to be a more significant factor, when judging patient tolerance than a given numerical value of astigmatism. To investigate this the astigmatic power change over the lens surface was plotted and a polynomial regression line fitted to these data. The gradient of this line was then deduced by differentiation.

### 8.3C Results

*Grating Acuity*

Grating acuities were recorded in the manner described above. Figure 8.2 shows the distribution of mean grating acuities achieved when plotted against the angle of eccentricity, where temporal is denoted as negative(-ve) and nasal as positive(+ve). The scatter graph shows that the grating acuity drops, with each of the three PALs and the +1.00D spherical lens, as the eye rotates in either the nasal or temporal direction away from the umbilical line. In each case the observer obtained the maximum acuity when looking through the central "progressive" channel of the intermediate portion of the PAL. The grating VA obtained through the spherical lens was better than in the case of the three PALs, although it also decreased with the increase in eccentricity.

*Power Measurements*

With these results it is possible to compare the changes which occur in the grating acuity, the mean spherical power(MSP), and the astigmatism with increasing eccentricity from the umbilical line of the PAL. Figure 8.3 shows a graph of the three PALs and the spherical lens tested in this study in which eccentricity from the umbilical line is plotted against the mean spherical power. The graph shows that the mean spherical power is greatest with the LF lens at the umbilical line and that the power decreases in either direction from this point. The distribution of the mean spherical power is quite different with the V2 lens in which the maximum power is found 20° nasally from the umbilical line. From this point the power drops to a minimum at 5° temporally and then increases before again reducing in the periphery. The graph shows that the maximum power of the NZ lens also occurs at 20° nasally, however unlike the V2 lens it is difficult to notice a discernible pattern in the results of the NZ mean spherical power assessment. The spherical comparison showed a slight symmetrical increase in the MSP with eccentricity.

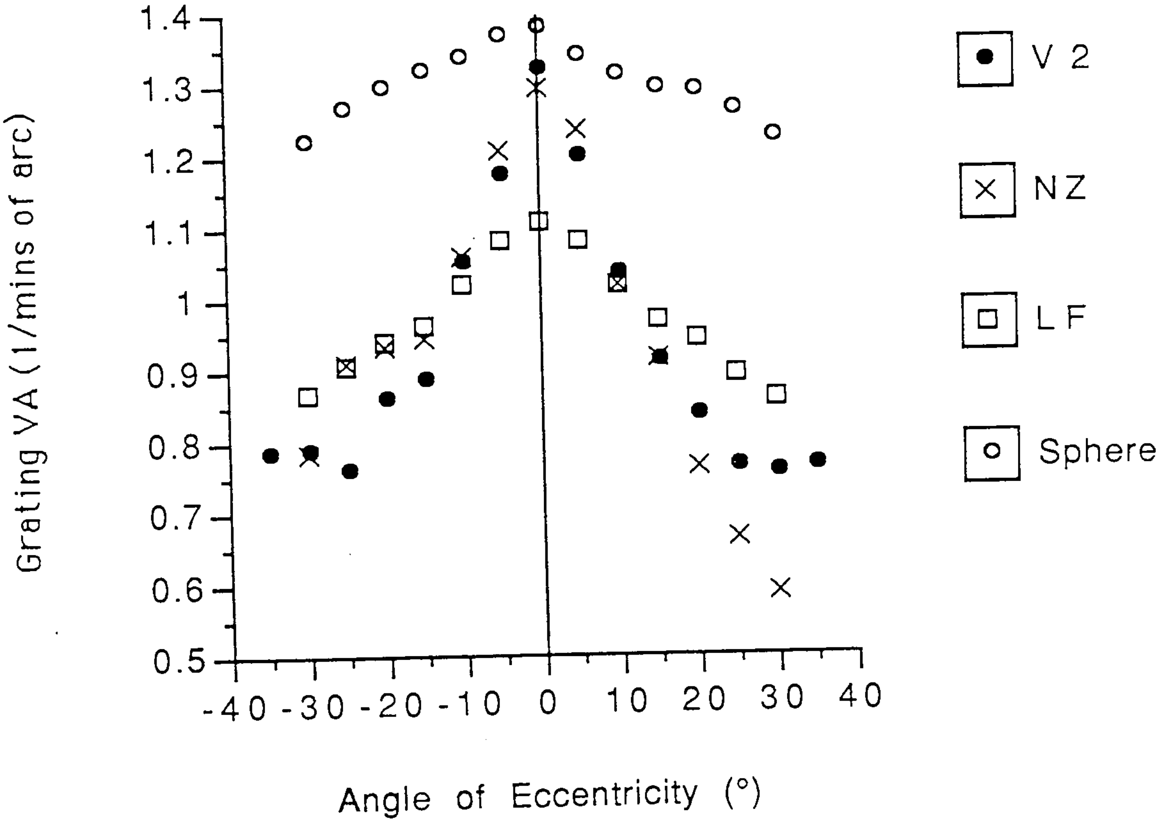


***Figure 8.2.*** A scatter graph which depicts the grating acuity, when measured through the PALs involved in this study, plotted against the angle of eccentricity from the meridian line. Nasal values are shown as positive and temporal values as negative.

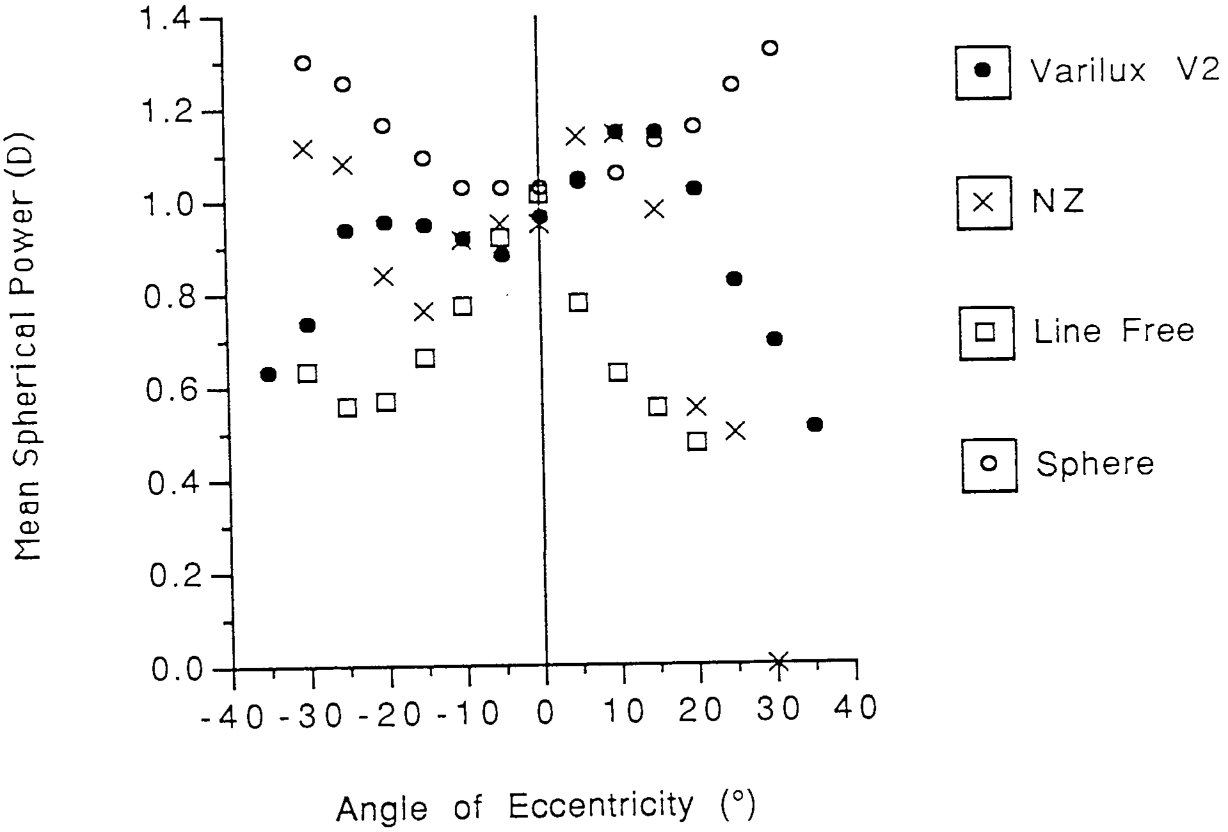


*Figure 8.3.* A scatter graph which shows the mean spherical power(MSP) of the three PALs and the spherical control lens plotted against the angle of eccentricity from the meridian line. Nasal values are shown as positive and temporal values as negative.

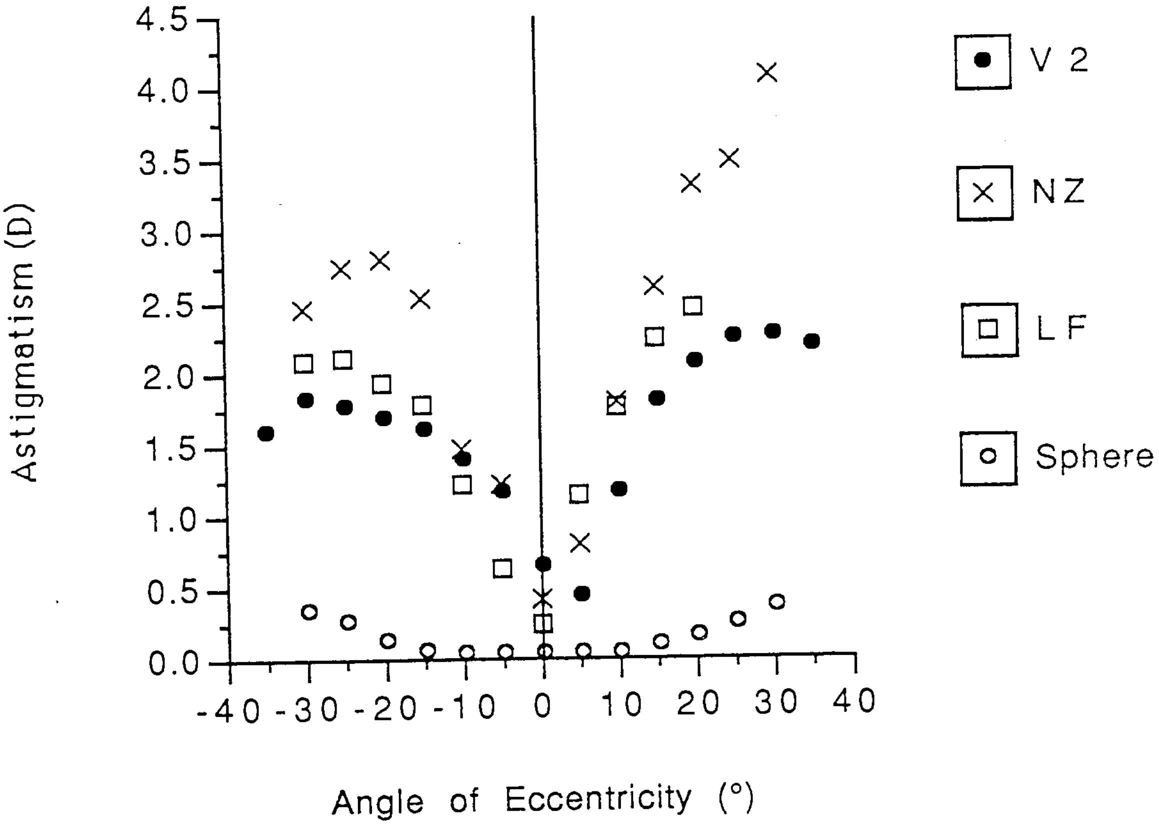


*Figure 8.4.* A scatter graph denoting the astigmatism present with each of the three PALs measured and the spherical control lens plotted against the angle of eccentricity from the meridian line. Nasal values are shown as positive and temporal values as negative.

In Figure 8.4 eccentricity from the umbilical line is plotted against astigmatism. This graph shows that astigmatism increases with eccentricity for each of the three PALs and to a lesser extent the spherical lens. Nevertheless, it is possible to note from the graph that the distribution of astigmatism is much more uniform with the V2 and the LF lens than in the case of the NZ lens. A polynomial regression line ($y = a + bx + cx^2 + dx^3 + ex^4$) may be fitted to the scatter plot for each lens shown in Figure 8.4. Differentiation of each polynomial equation will produce an expression ($dy/dx = b + 2cx + 3dx^2 + 4ex^3$) which is an indication of the gradient or rate-of-change of surface power for each lens and these may then be plotted against the angle of eccentricity(Figure 8.5).

Evaluation of the rate of change of PAL astigmatism along each horizontal section shows a clear division between the "hard" NZ lens and the two "soft" lenses assessed. In each case the astigmatic gradient is smallest within the central portion of the intermediate channel. In the case of the NZ and the LF the gradient is least along the umbilical line, whereas with the V2 lens it is least at 5° nasally from the umbilical line. From Figure 8.5 it would appear that in the case of the LF and V2 lenses, the astigmatic gradient is almost constant along the horizontal section assessed. However, with the hard NZ lens the astigmatic gradient is not constant, being least along the umbilical line and greater in the lens periphery. The gradient of astigmatic power change is, as might be expected, negligible in the case of the spherical lens.

Is grating VA more dependent upon the astigmatism or the rate of change of astigmatism with eccentricity from the umbilical line? To study this the three sets of data ( grating VA, astigmatism, and the astigmatic gradient) for each lens are plotted against the angle of eccentricity on a ratio basis which awards a value of unity (R=1) to the point on each lens through the umbilical line. The other data points are plotted relative to the value for the umbilical line as a ratio of the reading taken at the umbilical line. The ratio may be presented as shown below;

$$\text{Ratio(R)} = \frac{\text{Value at angle } \Theta}{\text{Value through the umbilical line(0°)}}$$

where $\Theta$ is any angle of eccentricity. The results of this study are plotted in Figure 8.6, which does not deal with absolute values, but rather the results of Ratio(R) are plotted to provide a relative comparison of the way the grating VA,

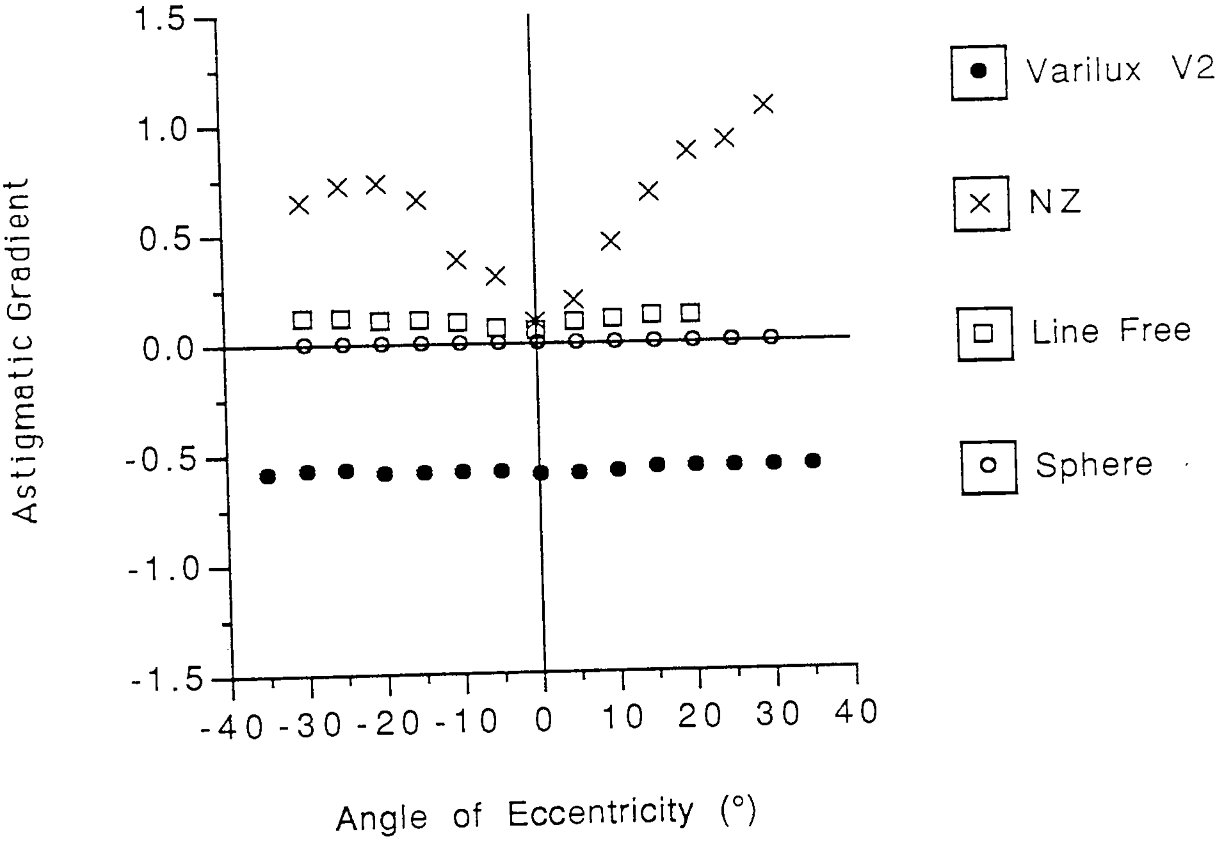


*Figure 8.5.* A scatter graph with the angle of eccentricity plotted against the rate of change(or gradient) of the PAL surface power for the three PALs and spherical control lens tested in this study. Nasal values are shown as positive and temporal values as negative.

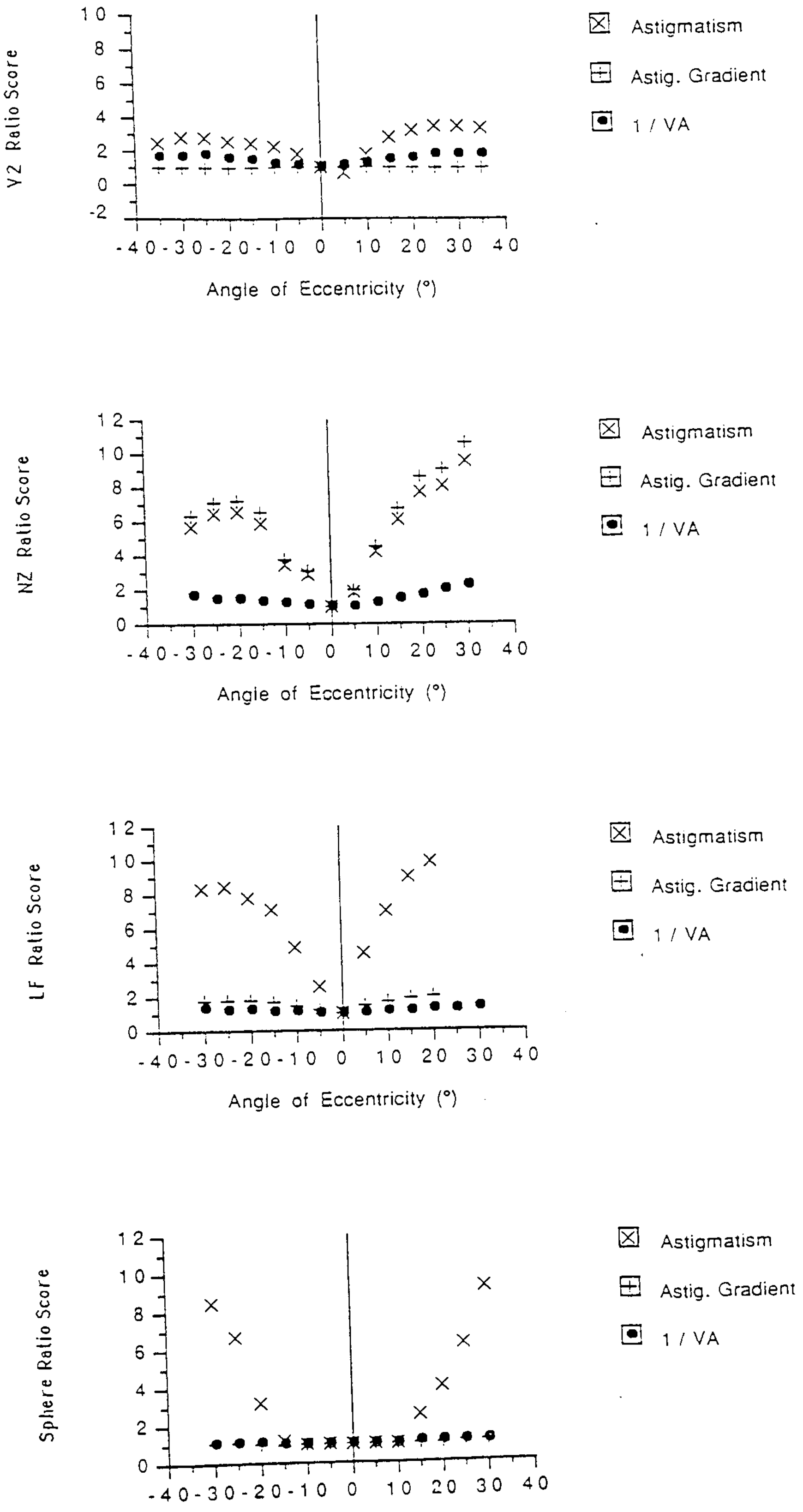


***Figure 8.6.*** Four scatter plots showing the relative change in (a)astigmatism, (b)the rate of change of astigmatism, and (c)1/VA for the three PALs and the spherical control lens. Nasal values are shown as positive and temporal values as negative.

the astigmatism and the astigmatic gradient of each lens vary along the horizontal section chosen. Therefore, while Figure 8.6 may at first give the impression that the NZ lens is more astigmatic than the V2 it should be noted that the cylindrical value at each umbilical line is 0.65 D for the V2, 0.43 D for the NZ, 0.25 D for the LF and only 0.04 D for the spherical lens. Figure 8.6 should be compared to Figure 8.4 to note the difference between the relative and absolute change in astigmatism across a PAL.

The relative change in MSP compared to VA along the horizontal section of each lens may also be studied using a ratio. These results are shown in Figure 8.7. The rate of change of MSP was also considered in a similar fashion to the rate of change of astigmatism. In this case there was no discernible pattern compared to the pattern which appeared in Figure 8.6.

### 8.3D Discussion

The use of a presbyopic patient might have been desirable for this experiment. Using the unit magnification telescope technique the accommodation should be controlled, however patients who are presbyopic often have smaller pupils than pre-presbyopic subjects. Indeed the size of a patient's pupil may be one of the factors which governs successful wear. If this technique were to be used as a means of assessing the psychophysical properties of a subject population it would be advisable to use presbyopic subjects. In a comparative analysis of patients who successfully wear PALs and those who cannot adapt to wearing them all the patients would have already worn PALs and therefore would be by definition presbyopic.

The ascending method of measurement which is thought to be better than a descending method was adopted for this study. Theoretically, a forced choice approach would be a better psychophysical technique. However, it is inappropriate to split the field of view when viewing through an aspheric surface, as the vergence of light from the two halves of the field is different. A more comprehensive study should also involve testing the grating acuity with gratings of oblique orientation to take account of the fact that the orientation of the astigmatism along the horizontal section under examination may have an effect upon the resolution of the grating. Study of the orientation of the astigmatism present with each of the three PALs showed astigmatism in with-the-rule, against-the-rule, and oblique orientations(Figure 8.8).

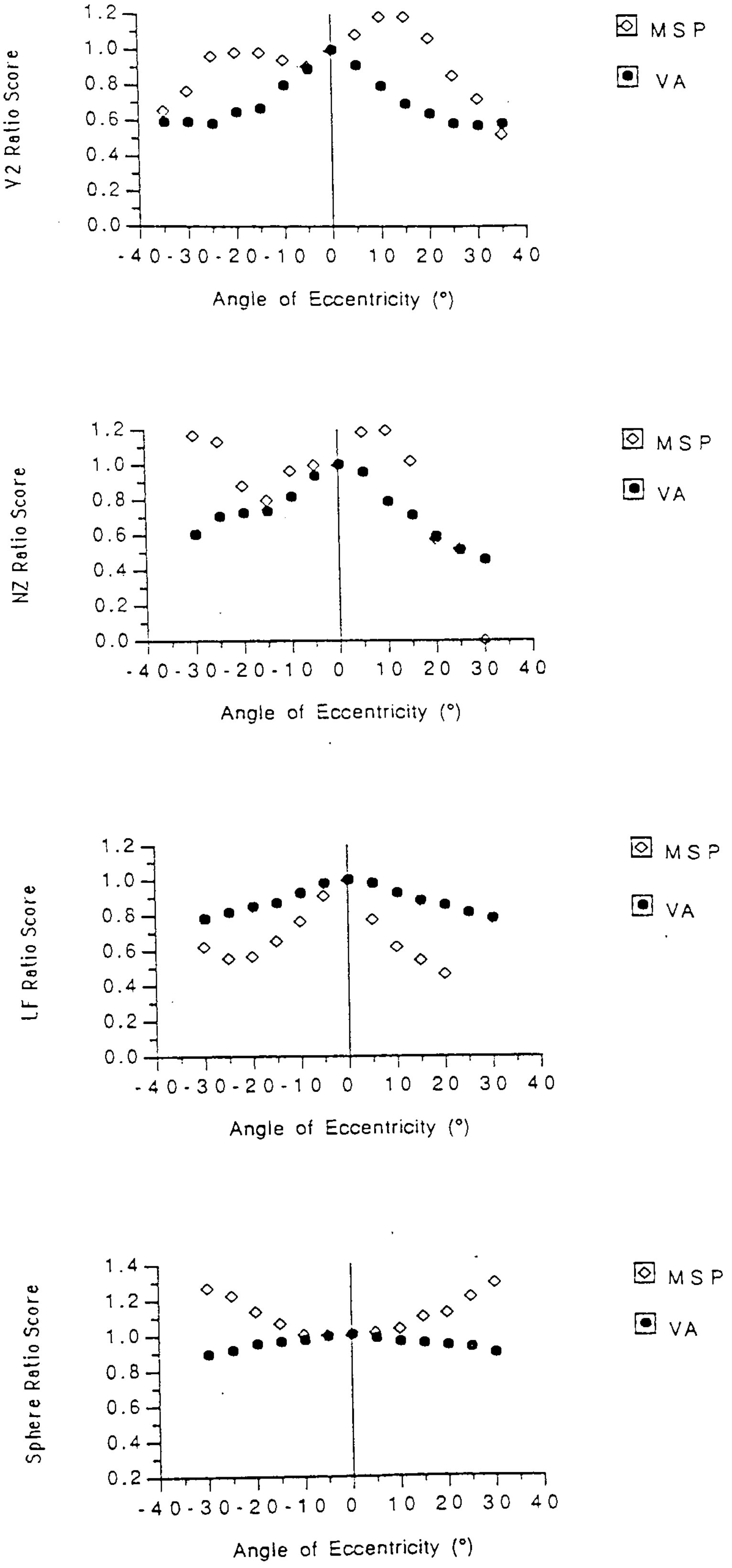


***Figure 8.7.*** Four scatter plots showing the manner in which (a) VA and (b) Mean Spherical Power alters for the three PALs and the spherical control lens. Nasal values are shown as positive and temporal values as negative.

The results show that astigmatism is reduced at the point where the horizontal section cuts the umbilical line. The V2 and LF lenses demonstrate their soft designation with less astigmatism, which is also more smoothly spread, compared to the hard style of the NZ lens(Figure 8.4). In addition, the results show that the least astigmatism for the V2 is not located at the umbilical line but rather at a point 5° nasally. The spherical lens chosen for comparative purposes also demonstrated peripheral astigmatism but this was of a lesser magnitude than that recorded from the PALs.

Another interesting aspect is the reduction in astigmatism that occurs in the lens periphery of some PALs. In the case of the V2 lens astigmatism appears to reduce beyond 30°. This may also be true with the LF lens. Unfortunately, it was not possible to measure each lens as far as 35° in either direction due to the mechanical restrictions imposed by the large blank size. This problem is exacerbated when a lens is decentred within the blank. The spread of astigmatism with the NZ lens is less uniform than with the other two lenses. However, it would appear that astigmatism reduces in the temporal periphery of the lens but not in the nasal periphery. The results pertaining to the spread of astigmatism are largely consistent with an earlier study(section 7.6) which compared the spread of surface astigmatism over a 45 mm$^2$ area of three different PALs, two of which were the V2 (soft) and the NZ (hard). We further considered the mean spherical power along the same horizontal section. From the results it appears that the mean spherical power is a less useful way of gauging the aspheric nature of a PAL surface than considering the astigmatism in insolation from the spherical element of the optical power.

When considering the orientation of a cylinder axis one interesting pattern emerged. The orientation of astigmatism may be divided into three categories, namely, with-the-rule, which has an axis orientation between 0° and 30° and 150° - 180°, oblique astigmatism which falls between 31° and 59° and 121° and 149° and against-the-rule when the axis of the cylinder is between 60° and 120°. When the three PALs under test in this study are considered an interesting pattern emerged regarding the orientation of the cylinder axis. Figure 8.8 shows that the orientation of cylinder axis is with-the-rule in the temporal side of each lens, and largely oblique on the nasal side. There are a few with-the-rule orientations on the nasal side of the umbilical line but these are in the periphery of the lens.

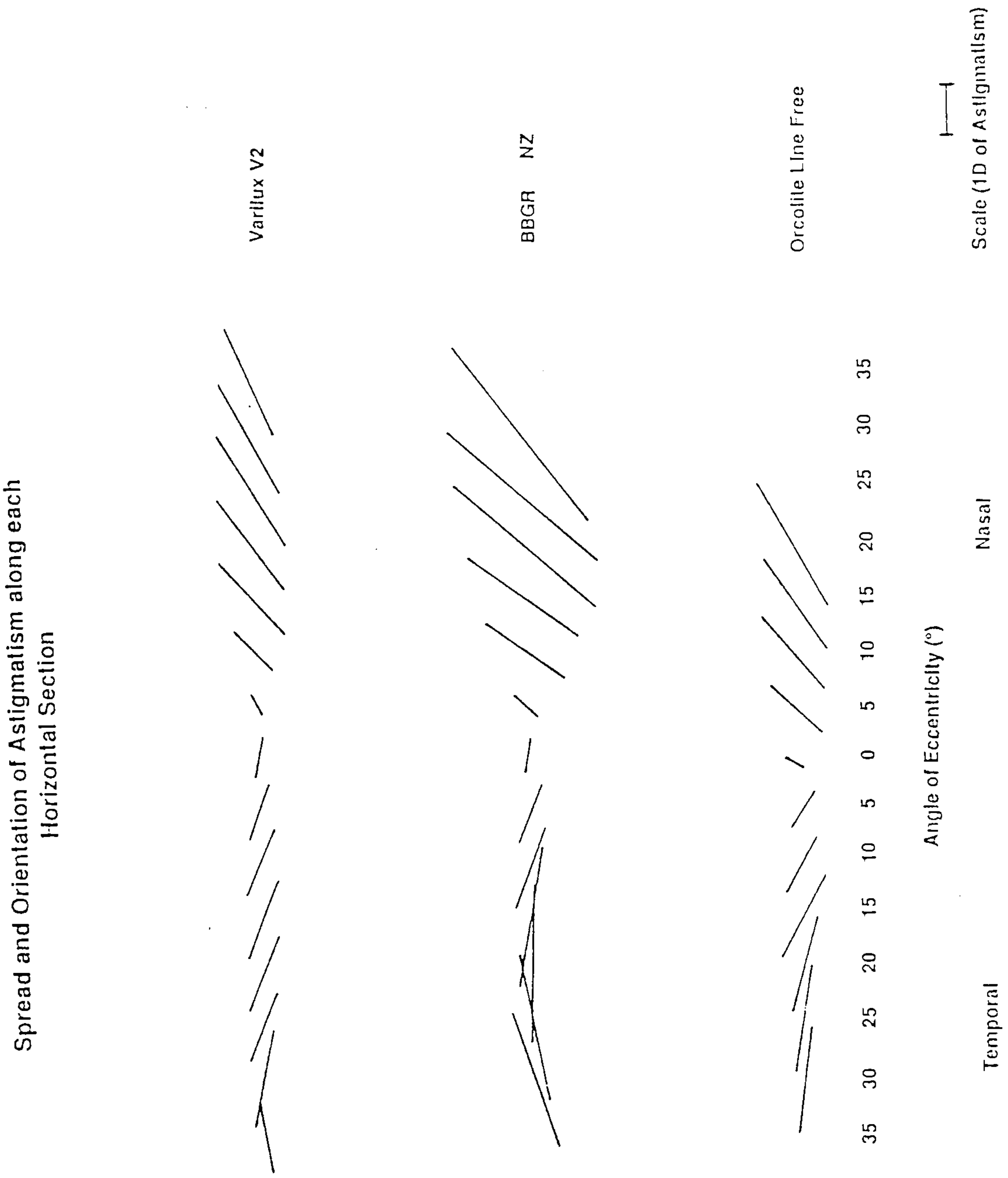


***Figure 8.8.*** This scale diagram depicts the extent and orientation of astigmatism along each of the three PAL horizontal sections studied. Astigmatism appears to be generally greater in the nasal sector compared to the temporal portion. The orientation of astigmatism is with-the-rule in the temporal portion and mostly oblique in the nasal portion.

The question; how significant is the orientation of the axis of the cylinder upon grating VA obtained? - may be considered by comparing similar magnitudes of astigmatism with different orientations. It is difficult to make a direct comparison because points on a lens with similar amounts of astigmatism may have a different mean spherical power. With the V2 the point 5° temporal has the same magnitude of astigmatism(1.18 DC) as the 10° nasal point. The astigmatism at the temporal point is orientated with-the-rule and at the nasal point it is oblique, the mean spherical power is 0.85 D temporally and 1.18 D nasally and the resulting acuities obtained are 1.18 and 1.04 respectively. With the LF lens, the 15° temporal point (1.79 DC) may be compared to the 10° nasal (1.76 DC) point, where the mean spherical powers are 2.45D and 2.39D respectively and the grating acuities obtained were 0.97 and 1.02. Equating points of similar magnitude astigmatism is more difficult with the NZ lens, however, if the 25° temporal (2.75DC with-the-rule) and 15° nasal (2.62 DC oblique) points are compared then the mean spherical powers are shown to be 1.96 D and 1.80 D with resulting acuities 0.91 and 0.92. It is difficult to make direct comparisons but the result of different orientations of astigmatism in relation to the vertical test grating appears to have a minimal effect, and does not mask the underlying trend relating the drop in VA to the increase in astigmatism.

Some workers(Maitenaz,1974; Shinohara and Okazaki,1985) have attributed the drop in VA across a progressive addition lens to be more closely related to the rate of change in astigmatism across the lens(astigmatic gradient) than the magnitude of astigmatism itself. Fig 8.6 shows that the astigmatic gradient closely matched the drop in 1/VA in the case of the LF lens, however there is no discernible difference between astigmatism and the astigmatic gradient in the case of the NZ lens. The relative drop in 1/VA falls somewhere between the change in astigmatism and the change in the astigmatic gradient in the case of the V2 lens. A study of the MSP along the horizontal section, showed that power tended to decrease from the umbilical line towards the periphery. In the case of the V2 and the NZ, there was a slight increase in the power relative to the MSP at the umbilical line in the nasal sector with a reduction in power towards the periphery. The decrease in PAL power largely matched the decrease in the VA, however, in the case of the spherical lens there was an increase in MSP with eccentricity whilst the VA reduced(Figure 8.7). The rate of change of MSP was also considered in a similar fashion to the rate of change of astigmatism, however, in this case there was no discernible pattern compared to the pattern which appeared in Figure 8.6.

The apparatus was shown to be a useful instrument suitable for the psychophysical assessment of PALs. In this study the drop in VA appeared to be more closely related to the spread and orientation of the astigmatism along the horizontal section than the mean spherical power along the same horizontal section. This visual performance experiment was inconclusive when considering whether astigmatism or the astigmatic gradient is more closely related to the drop in VA.

## 8.4 CONTRAST SENSITIVITY MEASUREMENT OF PROGRESSIVE ADDITION LENS PATIENTS. DOES VISUAL PERFORMANCE GOVERN PATIENT TOLERANCE ?

In section 8.3 visual performance was shown to be affected by the physical parameters of a PAL. Whether these parameters are responsible for lens non-tolerance is unclear and was therefore investigated. The unit magnification telescope apparatus was again employed for this more detailed study comparing the psychophysical responses of two subject populations - those who successfully adapt to PALs and those who fail to adapt.

### 8.4A Introduction

Adaptation to PALs may be dependent upon a number of physiological features such as refractive error, pupil size, and/or accommodative state, and these factors may determine the visual performance attained whilst wearing PAL spectacles.

When a patient presents complaining about being unable to accept the prescribed spectacles the practitioner will check the physical properties of the lenses such as the power, base curve, lens material, and lens decentration to ensure the spectacles have been correctly manufactured and dispensed. The clinician will also assess the visual performance attained by investigating the patient's visual acuity through the lenses. Visual performance may also be evaluated by using some measure of contrast sensitivity(CS) although it is unusual for this technique to be employed in a refractive examination. Ward and Davis(1972) have shown the value of CS as a means of assessing spectacle lenses and Woo and Otto(1988) have also employed CS in addition to VA measures for the study of an aspheric spectacle lens. Garcia and Loshin(1988) have considered the visual performance obtained through Progressive Addition Lenses(PALs). They tested the contrast sensitivity function(CSF) by viewing gratings through six different portions of a lens and noted that the CSF was reduced in the lens periphery but that along the umbilical line it was similar to a single vision spherical lens.

The degree of disruption may affect the length of time required for adaptation and therefore with an aspheric spectacle lens adaptation may be delayed further due to the additional Seidel aberrations(von Seidel,1854) present on the anterior front surface of the lens. The image may be degraded by distortion, which alters the perceived image shape, and astigmatism, which affects the image clarity. Lens designers must take particular notice of radial astigmatism, distortion and curvature as these aberrations are more troublesome than the others. Astigmatism may be assessed using measures of visual performance, including visual acuity and contrast sensitivity, whilst, distortion and curvature must be assessed by considering the effect of the optical distortion of form. The visual performance through spectacle lenses may be undertaken using a number of different techniques. It has been noted previously(Emsley,1956) that a given degree of astigmatism may affect the vision of one observer more than another. It may be that those whose visual performance is more adversely affected by astigmatism may find adaptation to PALs more difficult. Freeman and Thibos(1975) have shown that when astigmatism is present there is a reduced CSF due to the defocus. The results of their empirical work agreed with the theoretical diffraction limited predictions of Hopkins(1955).

This experiment considers the relationship between the physical measurement of astigmatism and the psychophysical CS response of patients. The study asks whether measuring contrast is a useful tool for identifying patients who are likely to have adaptational problems with PALs. This is done by comparing the CS result produced with two patient population samples; one group who failed to wear PALs successfully and one group who managed successfully. Statistically, the null hypothesis suggests there to be no difference between the CS of those who adapt successfully and those who do not.

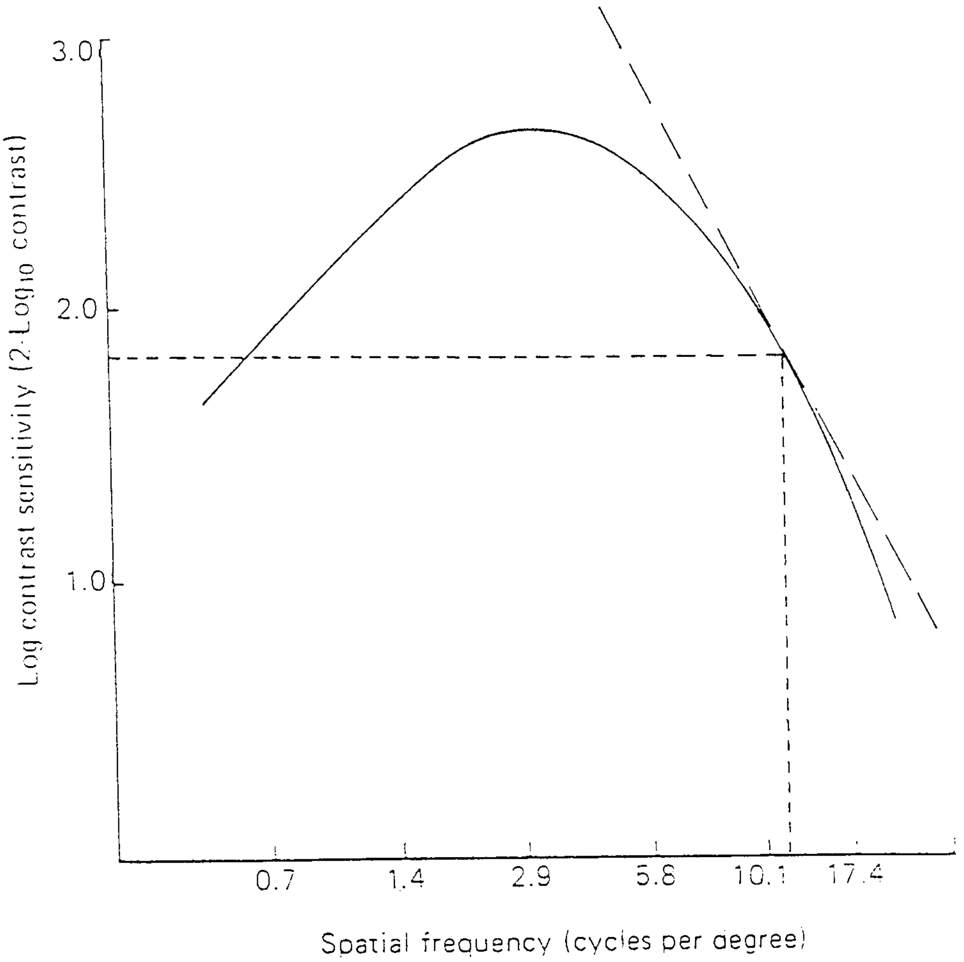
### 8.4B Method

This study involved 40 presbyopic subjects, 20 of whom were PAL wearers who adapted readily to wearing these lenses and the other 20 subjects were presbyopes who failed to adapt to wearing PALs. Patients for this study had been selected from the questionnaire analysis (Chapter 6) and there was no pre-selection of subjects in terms of the reasons why they found adaptation difficult. The CS values were recorded through the same PAL for each subject. This was a glass version of a Varilux V2 plano/+2.00D add, 6.50D Base Curve lens. A Varilux V2 was chosen because each patient had been previously corrected with Varilux V2 lenses from the Aston University Optometric Clinic.

CS measurements were recorded at five different locations along a horizontal section taken at the dioptric mid-point of the umbilical line which links the distance and near viewing portions. Only the right eye of each subject was assessed. Subject ametropia was corrected using trial case lenses and the left eye was occluded. Patients observed a monitor screen (a circular target which subtended 1.91°) through the unit magnification telescopic apparatus used for the grating visual acuity experiment. The test monitor was located 3m from the PAL under test and a -0.66D correcting lens was introduced in order to render the target at optical infinity. Only one value of spatial frequency was selected due to the time consuming nature of the experiment. The luminance of the Nicolet monitor was 101.3 cd/m$^2$.

The ascending method of adjustment was the technique by which contrast thresholds were established, as it is inappropriate to use the forced choice technique when dealing with a varifocal lens. The ascending method of adjustment is not so repeatable as the forced choice approach. However, Higgins *et al* (1984) note that there is a similarity between the confidence levels which may be attached to these two techniques at high spatial frequencies. Figure 8.9, which comprises normative data for presbyopes in the 51 - 60 year age range, shows the relationship between contrast sensitivity and spatial frequency. From the graph it may be noted that the value of 11.4 cpd, which was the value of spatial frequency chosen for this study, is towards the higher end of the spatial frequency range.

Patients indicated when they could detect the sine wave gratings image by pressing a push button control. CS thresholds were measured at 40°nasally, 20°nasally, 0°, 20°temporally, 40°temporally and with a +1.00DS single vision trial case lens used as a control. The six different views ( 5 with the PAL and one with the single vision lens control) were undertaken with both horizontal and vertical orientations of the CS gratings. A number of trial runs, to help to explain the test procedure and to put the patient at ease, were undertaken before recording began. The CS sine wave gratings were produced using a Nicolet CS 2000 which is an instrument designed for testing CS in clinical situations; most patients found it straightforward and easy to use. The result for each angle of eccentricity was the mean value of 6 readings and the test routine lasted around 30 minutes.



CONTRAST SENSITIVITY FUNCTION

51 - 60 year old normative data after Reeves, Hill and Ross(1988)

*Figure 8.9.* A diagram(after Hill, Reeves, and Ross; 1988)showing the normative contrast sensitivity function for 51 - 60 year old subjects. Spatial frequency is plotted against threshold contrast sensitivity. From the graph it may be noted that the spatial frequency value chosen for this experiment(11.4 cpd) occurs where the relationship between log. contrast sensitivity and log. spatial frequency is approximately linear.

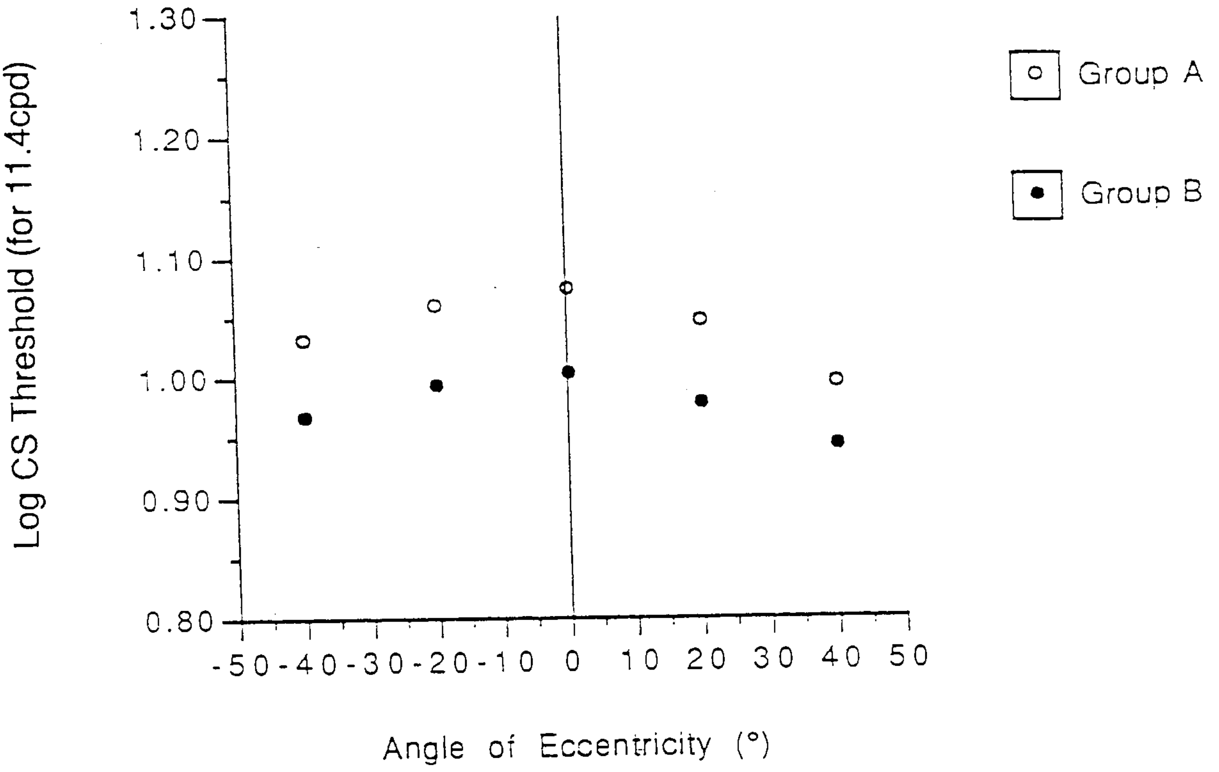


*Figure 8.10.* The mean contrast sensitivity results for Group A and Group B subjects plotted against eccentricity from the PAL umbilical line.

MEAN CONTRAST SENSITIVITY THRESHOLDS (Log. units)

| | 40°N | 20°N | 0° | 20°T | 40°T | Control |
|---|---|---|---|---|---|---|
| **Group A** | 1.032 | 1.061 | 1.076 | 1.049 | 0.995 | 1.132 |
| **Group B** | 0.965 | 0.995 | 1.005 | 0.978 | 0.945 | 1.002 |

*Table 8.2.* The mean results of the contrast measurements taken along the horizontal sections for the two subject populations.

### 8.4C Results

The mean result for each angle of eccentricity and the single vision control lens comprised 6 readings. The values presented in Figure 8.10 are the mean results for the two groups of 20 subjects(Table 8.2). The CS recorded for each group is plotted against the angle of eccentricity from the central umbilical line. The visual performance(CS) of Groups A and B may be compared to note whether there is a significant difference between the two groups. The CS values for each angle of eccentricity may be individually compared between Groups A and B. No significant differences was established using a Mann-Whitney (Wilcoxon two sample) non-parametric U test.

However, as each value of Group B is below the corresponding value of group A an effect may be present. Therefore analysis of the five mean values for the two groups should be undertaken together. This may be done using the non-parametric Wilcoxon signed rank test. When N = 5 values are only quoted for one tailed analysis. However, a one tailed analysis may be appropriate when the results in Figure 8.10 are considered as each empirical value of Group B is below that of Group A. When this test was undertaken a significant difference was shown to exist at the 5% level. Theoretically, the results of Group B subjects could have been either larger or smaller than those of Group A, which would make a two tailed test more appropriate. Another non-parametric analysis(Walsh test) which allows analysis of the results of these two groups produced significant results for two tailed analysis at 6.2% and for one tailed analysis at 3.1%.

The CS recordings may be compared to the spread of astigmatism(BVP) along the horizontal section through which foveal visual performance was tested(Figure 8.11). As in the case of grating VA(section8.3C), the reduction in visual performance(Groups A and B) matches the rate of change of astigmatism along the section better than the change in the magnitude of surface astigmatism.

The VA of the subjects tested may also be compared for the two groups. VA measurements of the right eye of each subject involved in the study were recorded for distance vision. The mean right eye VA for the adapting group was found to be 1.08 and for the non-adapting group it was 1.18(Table 8.3). Although the VA for the non-adapting group is greater a Mann-Whitney U test showed there to be no significant difference between the two groups($p > 0.05$). The CS measurements recorded through the +1.00DS control lens may also be treated in a similar fashion. This examination revealed there to be no statistical

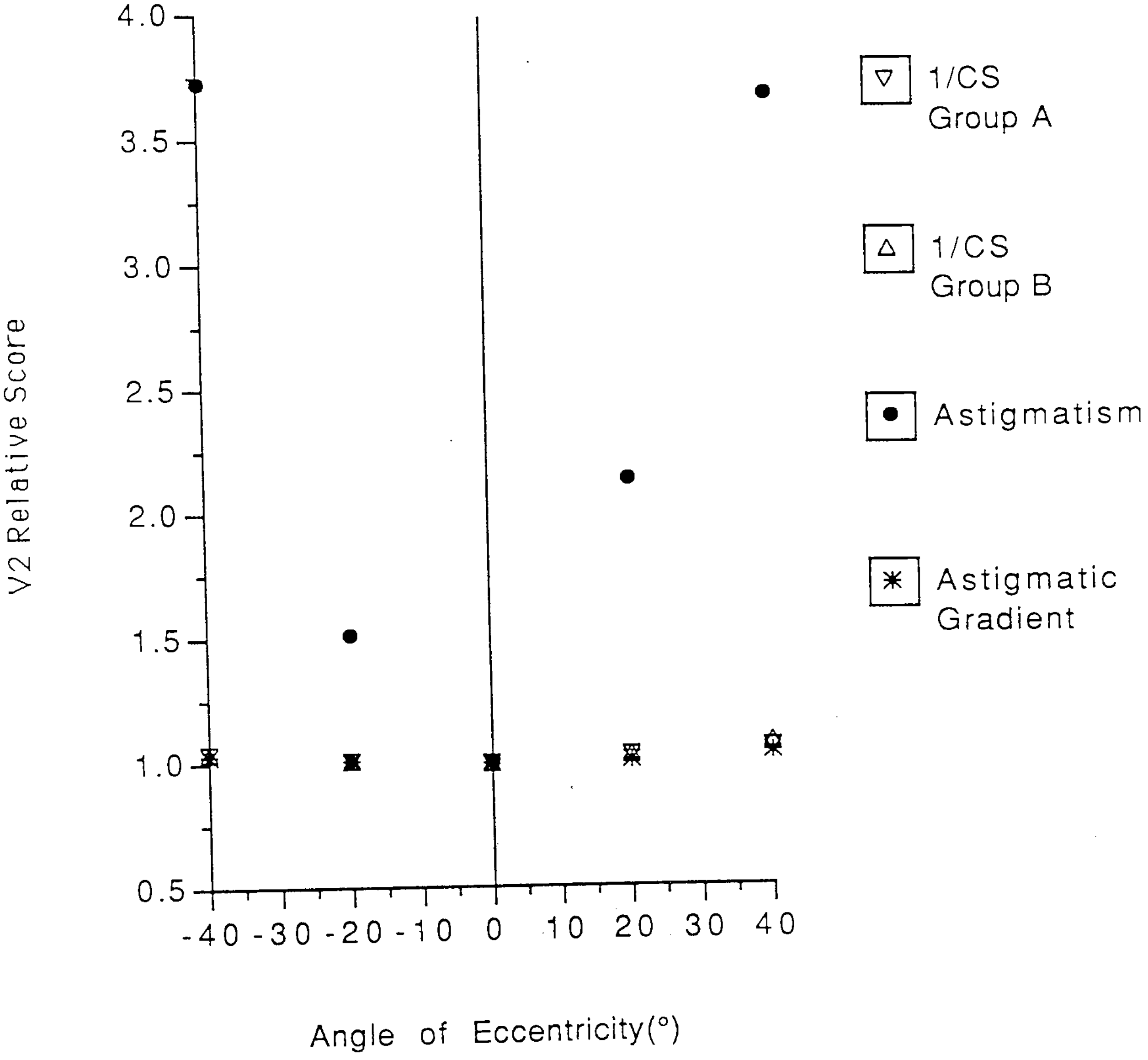


*Figure 8.11.* A graph showing on a relative scale the comparative change along the horizontal section in: astigmatism, the astigmatic gradient, and 1/CS for both the successful wearers(Group A) and the unsuccessful wearers(Group B). Nasal angles of eccentricity are shown as positive and temporal angles as negative. This graph is compiled in a similar manner to Figures 8.6 and 8.7, which are described in Section8.3C. It will be noted that the values for the astigmatic gradient and for 1/CS for both Groups A and B are largely coincident.

Right Eye

Visual Performance

| | Group A | Group B |
|---|---|---|
| CS at the Meridian Line(+1.00D) | 1.076 | 1.005 |
| CS through +1.00D Spherical Lens | 1.132 | 1.002 |
| Visual Acuity | 1.08 | 1.18 |

Contrast measured in Log. units

Visual Acuity : 1 = 20/20 or 6/6

*Table 8.3.* The mean results for the contrast sensitivity through the umbilical line, the contrast sensitivity through the control lens, and patient VA for the test eye(right) of Group A and Group B subjects.

difference in the CS for the two groups when viewing the target through the single vision control lens(p > 0.05).

### 8.4D Discussion

The above experiment showed that the visual performance(using VA) of successful and unsuccessful patients is similar. However, when foveal visual performance is assessed using a measure of CS a significant difference was noted between successful and unsuccessful wearers. Further investigation would be required to confirm the results of this study as only one value of spatial frequency was employed and it might be argued that the results presented in this study are a function of the value of spatial frequency which was used. To have assessed more subjects would therefore have been desirable. Indeed, this study was handicapped by the difficulty of getting patients who had failed to adapt to PALs.

It is often difficult to obtain willing subjects from a group of patients who have not managed to adapt to the lenses prescribed - many subjects declined the invitation to participate. Eventually enough patients were found and the study undertaken. The Chapter 6 study analysed the characteristics of a population of PAL wearers. One of those investigations ascertained how long it had taken patients to adapt to these complex aspherically designed lenses. Some patients had managed to adapt within a very short period whilst others took over three months to adapt and a number failed to adapt at all. It was shown that the population spread of wearers against adaptation time was normally distributed, which confirms the work of Young(1984).

It would have been more satisfactory if angles of eccentricity at 10° or even 5° intervals could have been recorded as this would have allowed a more comprehensive analysis. However, this would have been more time consuming- the testing procedure described in the method took around 30 minutes to complete and it was thought this was the limit to a patient's concentration. One criticism might relate to the use of a single spatial frequency, 11.4 cpd. This was done due to the limitations of time and the need to undertake an adequate number of readings for each patient. Taking the mean value of six recordings for each angle of eccentricity increased confidence in the ascending method of adjustment. It was not possible to employ a forced choice technique as this approach involves splitting the field, and the two halves would not be similar when viewed through a varifocal lens. Higgins *et al* (1984) have shown that repeatability of the ascending method of adjustment can approach that of the forced choice technique with medium to high values of spatial frequency. It was for this reason that the value of 11.4 cpd, which is within the medium to high range, was chosen.

Another factor which may have influenced the results, and restricted the number of subjects involved in the study, is that most patients were aged 60 years and over. A more even distribution of ages between 40 and 80 years would have involved more young presbyopes. However, many of the younger presbyopic patients are in full-time employment and were unwilling or unable to commit time to this project.

Pupil size is another factor known to affect contrast sensitivity and because there was no preselection of subjects it may be argued that the pupil size of a Group B subject was greater than that of a Group A subject. If this were so it might account for the poorer contrast thresholds for the Group B subjects. Indeed, further investigation might reveal that pupil size was a factor which accounts for better tolerance of some subjects to the peripheral lens aberrations.

The value of the Reiner(1966) unit magnification telescope was again demonstrated for the psychophysical analysis of PALs. From this study, and the grating VA investigation, it would appear that whilst visual performance is affected by peripheral astigmatism, further investigation is required to ascertain the nature of the influence of visual performance upon patient tolerance to PALs.

## 8.5 SHAPE OF IMAGE

The effects of distortion and curvature upon the resulting image may be the cause of why some PAL wearers fail to adapt to their lenses. Adaptation to optically altered transformations of the retinal image has been widely studied since the pioneering work of Stratton(1897). Rock(1966) lists the different kinds of image transformation which have been studied(see Chapter 4). This area of investigation warranted further study and the effect of curvature distortion upon PAL tolerance was therefore investigated.

## 8.6 VISUAL DETECTION AND ADAPTATION TO OPTICALLY INDUCED CURVATURE DISTORTION. DOES CURVATURE DISTORTION GOVERN PAL TOLERANCE ?

### 8.6A Introduction

When considering the distorting effects of PAL's a number of these optical transformations may be present simultaneously. The psychophysical curvature distortion experiments in this chapter consider if there is a difference in the detection and adaptation to shape anomalies of two groups of subjects - those who adapted and those who failed to adapt. Whether successful PAL adaptation can be predicted by adopting a screening procedure is unknown. If the prediction of PAL adaptation is to have any merit there must be a notable difference between the adaptation of those who previously have been successful and those who have not.

Workers dispute whether adaptation to optically induced curvature distortion may be attributed to the visual, proprioceptive, or motor systems(Howard and Templeton, 1966). Whatever the cause, Gibson(1933), in a 'classic' article, was the first to show adaptation due to prismatically induced curvature. Bales and Follansbee(1935) who repeated this experiment reported that this effect did not occur equally with all subjects and indeed some experienced no adaptation to optical distortion. In a follow up study, Gibson(1937) again demonstrated adaptation to prismatically induced curvature distortion and in addition noted there was a negative after effect resulting for a time following prism removal.

The distorting element may vary in the degree of distortion induced depending upon the angle of gaze(Köhler,1964). This is a further complication for the eye to adapt to, and may help to account for the greater adaptation problems present with PALs than with single vision lenses. With a PAL the human visual system must learn to accept unequal optical distortion of form depending upon the angle of gaze, in addition to undergoing oculomotor adaptation. Adaptation to prism displacement resulting in oculomotor adjustment has been well documented by North and Henson(1985), who have considered oculomotor adaptation to both lens and prism induced heterophorias(section 4.1). The nature of the variation of the adaptation of a PAL population i.e., whether it is normally or bimodally distributed etc., is uncertain. Young(1984) considers the adaptation response of patients to be normally distributed. These experiments consider the nature of adaptation to the optical distortion of form using the Gibson(1933) curved strip technique and compares the adaptation resulting from three different groups;

(A) 20 Presbyopes who failed to adapt to PALs
(B) 20 Presbyopic PAL wearers who readily adapted to their lenses
(C) 20 Prepresbyopic emmetropic subjects

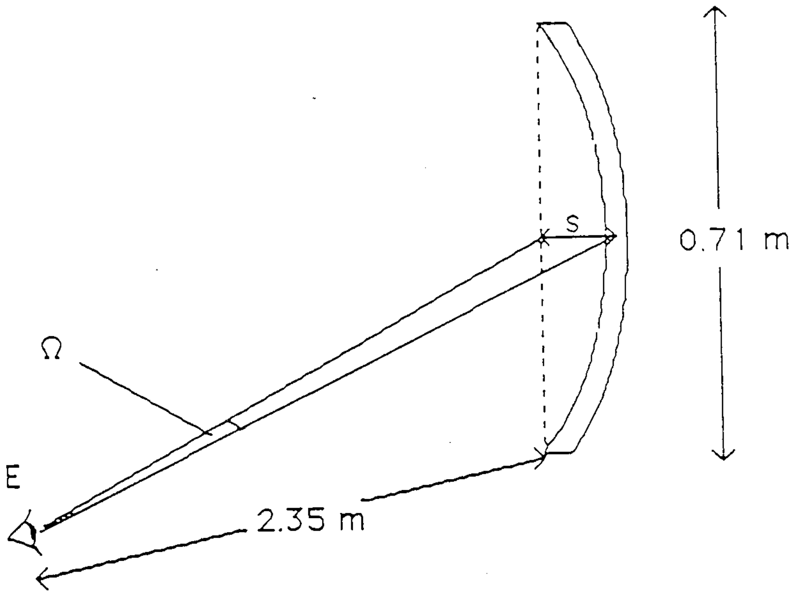
### 8.6B Method

*Experimental Technique*

Rock(1966) notes that Stratton's(1897) experiments(section4.1) consisted of introspective reports and therefore take no account of the fact that the subject may become accustomed to the new images, forgetting how the object appears to the normal observer. Rock draws the distinction between 'growing accustomed to' an image and genuine adaptation to it. Proper measurement of adaptation requires a before-after comparison of how the object of regard 'appears' to the subject and there are two ways to undertake such an evaluation. The simplest method is to ask the observer to make a perceptual judgment when the optical device is fitted initially and then to make another similar judgment following a period of exposure. This approach assumes that when the wedge prism is first worn that the reported displacement would be equal to the angular displacement induced by the prism and that subsequent judgments would show a smaller displacement dependent upon the degree of adaptation.

One criticism of this approach is that during the exposure period, while the subject is wearing the prism spectacles they are likely to become aware of the nature in which the image is distorted. Subsequently, they may try to negate the effect of the distorting image to give the 'correct answer'. The alternative approach, which avoids these problems is to undertake the pre- and post-exposure tests without the optical device. Welch(1971) has shown that these two approaches, namely, whether adaptation is best judged whilst the patient is wearing the prism or by considering the negative after effect when the prism is removed, will produce different results.

Nevertheless, in a study which considers the relative difference in adaptation between three different subject groups, the absolute value is not as important as noting whether a significant difference exists between the three subject groups. For the first 10 minute period the patient is being assessed by asking them to perform the task, and make curvature judgments, whilst wearing the prism. When the subject removes the prism from before the right eye it is possible to measure the degree of adaptation in terms of the negative after effect, by comparing these readings to the pre-exposure period.



Schematic diagram of curvature detection apparatus

*Figure 8.12.* A schematic diagram of the apparatus used for testing the ability of a patient to detect curvature and to note the effects of optically induced curvature distortion. The patient's eye is located at E, with the angle of displacement and the apparent sag denoted as Ω and s respectively. The curvature of the vertical strip could be altered using a pulley system operated by the subject whilst viewing the strip from the head rest. A scale hidden from the subject's view indicated the displacement present when the subject had adjusted the strip to make it appear straight.

When a straight line is viewed through a plano prism the image will appear to be curved. It will also be deviated away from the base towards the prism apex. The line appears curved because the effective prism power increases with oblique incidence. It is possible to calculate the induced prismatic effect and therefore the curvature. For this experiment the curvature was measured in terms of the sag of the adjustable strip.

*Apparatus*

The apparatus was constructed with a vertical strip device(Figure 8.12) clamped to a long workbench in front of a large screen devoid of major orientational clues. A head rest was positioned at the other end of the workbench. A pulley system allowed the subject to adjust the curvature of the vertical strip whilst sitting with their head placed in the head rest. The vertical strip was 0.71m long and it was situated 2.35m from the subject head rest. The subject was asked to set the curved line so that it appeared straight.

*Subjects*

Forty presbyopic subjects were involved in this study; aged between 46 and 80 years of age, with 28 males and 12 females. The 20 pre-presbyopic subjects were undergraduate students aged between 18 and 30, with 11 males and 9 females. The mean age of adapting presbyopes was 61.05, it was 63.23 for the non-adapters and 21.15 for the pre-presbyopic group. None of the subjects involved in this study were trained observers. Obtaining subjects was very difficult and hence it proved impossible to have equal numbers of male and female patients. Discrete variables for patient sex may not have been ensured but this may not be essential as the results analysis of PAL wearers(Chapter 6) suggested there is no statistical difference in the extent of male and female PAL adaptation.

### 8.6C (Expt. 1) Detection of curvature distortion

*Procedure*

An evaluation of each patient's ability to detect shift changes in curvature may be a way of predicting ability to adapt to PALs. It may be that those patients with a very acute ability to detect slight changes in skewness and curvature notice the peripheral distortions present with PALs more readily. This may be studied by analysing the variation (ANOVA) which exists between the measurements taken when obtaining the preadaptation "straight" position. This variation, which was assessed for the three groups of 20 subjects involved in this experiment, is an indication of the patients ability to tolerate a slightly curved line as straight.

CURVATURE DETECTION RESULTS

| | A | B | C |
|---|---|---|---|
| Mean (cm) | 0.063 | - 0.103 | - 0.129 |
| SE of Mean | 0.030 | 0.035 | 0.021 |
| Standard Deviation(SD) | 0.113 | 0.155 | 0.095 |

*Table 8.4.* The results of the curvature distortion detection investigation showing the mean, standard error(SE) of the mean, and the standard deviation(SD) of the values recorded for the three groups assessed. Analysis of variance(ANOVA) revealed there to be no significant differences in the manner and accuracy with which subjects from the three groups could detect small curvature shifts.

PALs were not employed for this investigation into the ability of a patient to discriminate curvature. This experiment was undertaken whilst the presbyopic patients were corrected, using trial case lenses, for their distance prescription; Group C subjects were emmetropic.

*Results*

Three readings were recorded for each subject so as to find a mean value for the zero sag position. Some showed considerable variation, whilst with others the three readings were similar. The mean curvature shift(mean position of strip in relation to the zero sag position) and standard error of the mean for each group is shown in Table 8.4. Analysis of variance was used to establish whether there were any significant differences between the treatments(Groups A, B and C), between the subjects, and between the replicates( the number of responses derived from each subject). For degrees of freedom of 2 and 57 the value of the f distribution which shows a significant difference ($p=0.05$) is 3.13 or greater. The difference between the three groups A, B and C(treatments) was 1.53 and the intersubject variability within a group was 0.65. The variation between the groups was therefore greater than the variation between subjects within a group but with both these values being below 3.13, the null hypothesis that there is no difference in curvature detection between successful PAL wearers(Group A), unsuccessful PAL wearers(Group B), and a prepresbyopic control(Group C) was confirmed.

### 8.6D (Expt. 2) Adaptation to curvature distortion

*Procedure*

The horizontal prism (15Δ) was then positioned before the subjects right eye, with the left eye being occluded. Measurements of the 'apparently' straight position of the strip were taken at intervals of two minutes for a period of 10 mins. The prism was then removed and the measurements were continued for a further period of 10 mins. It is not important whether the prism is placed base in or base out, but for ease and consistency it was always placed base out in this experiment. The subject looked away between recordings to a blank screen devoid of major orientational clues where the vertical strip could not be seen.

Adaptation to prism induced curvature was investigated monocularly. Each patient wore a 15Δ wedge prism for 10 minutes. A 15 dioptre prism was chosen in order to accentuate the optically induced distortion and reduce the significance of measurement error. During this period the subject altered the strip from an exaggerated curved position, either positively or negatively, to the location

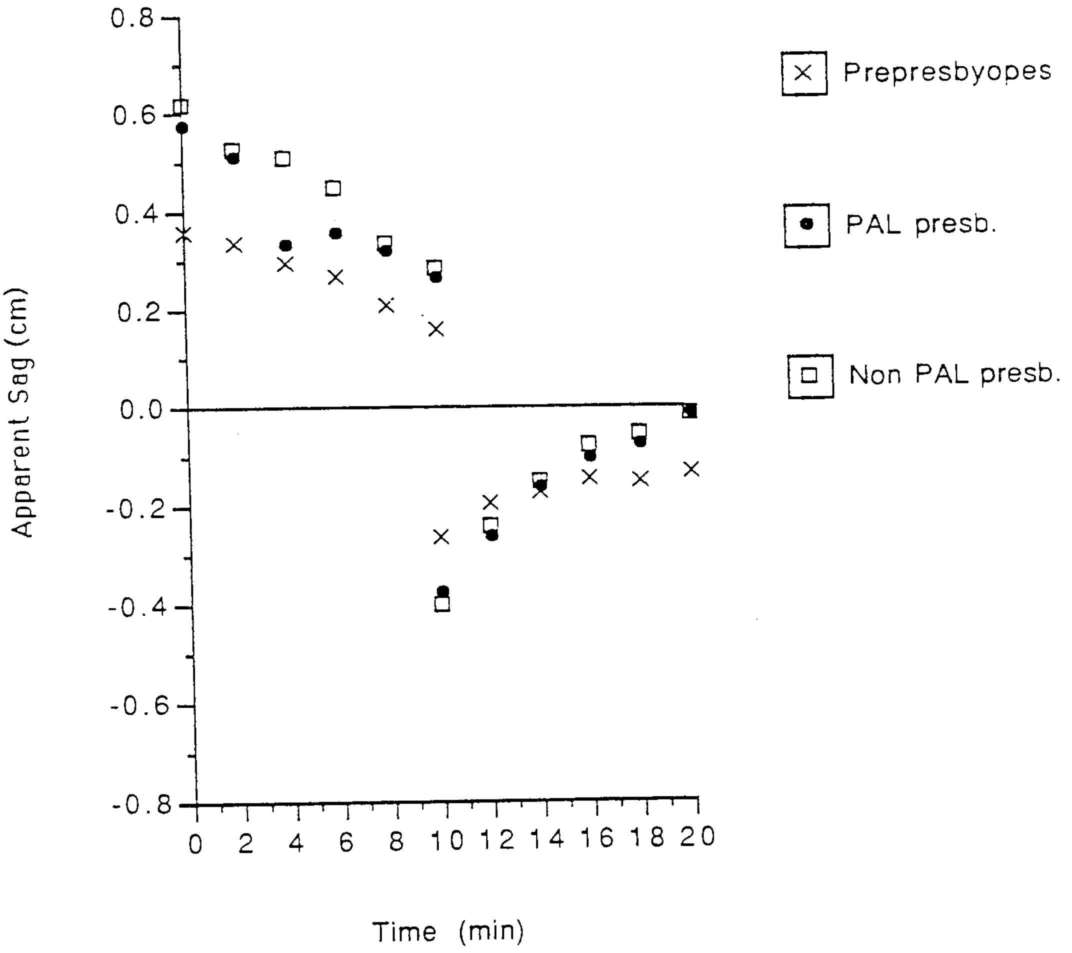


*Figure 8.13.* Three graphical plots showing the mean sag of the apparatus for each group against time. Subjects wore the 15Δ prism for the time period 0 - 10 mins in order to study adaptation and the prism was absent during the 10 - 20 minute period in order to study the negative after effect during the recovery phase. These plots clearly show that apparent curvature reduces with time for both the adaptation and recovery phases.

perceived as straight. A measure of perceived curvature was made every 2 minutes. Following the 10 minute period of adaptation to the prism, the prism was removed and perceived curvature monitored every 2 minutes for a further 10 minutes to investigate the nature of the negative after effect.

*Results*

The variation in the sag of the apparatus can be evaluated against time for each subject and the rate of adaptation may also be considered. Figure 8.13 shows; the mean values for the three groups of 20 subjects. The degree of adaptation which occurred during the wearing of the prism may be noted by comparing the readings before and after removal of the prism.

Each group showed an adaptation to apparent curvature with time. When the prism was removed a negative after effect which decayed with time was also noted for each group. The rate of change(gradient) of the adaptation process and the decay of the negative after effect may be considered. It is possible to place the best fitting line, or curve through each set of figures and to then consider whether the null hypothesis, that these three sets of data points are from the same population, is correct.

Comparisons of the three 'adaptation' slopes and the three 'recovery' slopes were made by estimating the standard error(S.E.) of each slope from the scatter of points around the best fitting line. This approach is similar to estimating the standard error of the mean of a set of numbers from their spread. If the slope of one line is denoted as $\beta_1$ and the standard error as $SE(\beta_1)$ and similarly for a second line the slope will be $\beta_2$ and the standard error will be $SE(\beta_2)$. The null hypothesis will then be confirmed if $\beta_1 = \beta_2$, i.e., $\beta_1 - \beta_2 = 0$. The difference between these slopes will be significant($p = 0.05$) when,

$$\frac{\beta_1 - \beta_2}{SE(\beta_1 - \beta_2)} > 1.96$$

This assumes that the distribution is normal, however, because the number of points(in this case 6) is small normality may not be assumed and significance should be judged against the t-distribution. Use of a t-distribution is only valid if the scatter of points, around the two lines being compared, is the same. This we can assume for the three subject groups in this study as the previous

## CURVATURE ADAPTATION RESULTS

### Fitted Equations

*Straight Line*

| | Adaptation Phase | | Recovery Phase |
|---|---|---|---|
| A | $y = -0.033x + 0.617$ | A | $y = 0.037x - 0.704$ |
| B | $y = -0.030x + 0.542$ | B | $y = 0.035x - 0.689$ |
| C | $y = -0.020x + 0.371$ | C | $y = 0.012x - 0.355$ |

*Second Order Polynomial Curve*

| | Adaptation Phase | | Recovery Phase |
|---|---|---|---|
| A | $y = 0.003x^2 - 0.059x + 0.373$ | A | $y = -0.037x^2 - 0.152x - 1.526$ |
| B | $y = 0.003x^2 - 0.058x + 0.580$ | B | $y = -0.035x^2 - 0.107x - 1.199$ |
| C | $y = -0.001x^2 - 0.010x + 0.358$ | C | $y = -0.012x^2 - 0.057x - 0.675$ |

### Significance Testing

*Straight Line Assessment*

| Adaptation Phase | | |
|---|---|---|
| A compared to B | | NS |
| B compared to C | | NS |
| C compared to A | $t_m = 3.47$ | Significant |

| Recovery Phase | | |
|---|---|---|
| A compared to B | | NS |
| B compared to C | | NS |
| C compared to A | | NS |

*Second Order Polynomial Curve Assessment*

| Adaptation Phase | | |
|---|---|---|
| A compared to B | | NS |
| B compared to C | | NS |
| C compared to A | $t_a = 4.46$, $t_b = 6.06$ | Significant |

| Recovery Phase | | |
|---|---|---|
| A compared to B | | NS |
| B compared to C | $t_a = 4.53$, $t_b = 3.20$ | Significant |
| C compared to A | $t_a = 6.91$, $t_b = 3.74$ | Significant |

***Table 8.5.*** The results of the rate of change(gradient) of adaptation to the optically induced prism and the recovery of the negative after-effect study. The gradient of each slope ( considered both as a straight line, m, and a second order polynomial curve, $2ax + b$ ) was compared with those from the other two groups. NS denotes a non significant difference($p > 0.05$) between two slopes, when the value of the t distribution is less than 2.3. Some significant gradient differences occurred($t \geq 2.3$), in the adaptation and recovery phases, between the presbyopic groups(A and B) and the prepresbyopic group(C).

experiment showed there to be difference in the placing of the curved strip for each group. If this is done to assess differences between the slopes a value of 2.3 or greater must be recorded from the t-distribution for significance at the 5% level.

Either second order polynomial curves or straight lines may be fitted to the adaptation and recovery plots shown in Figure 8.13. This was done and from the coefficients derived from curve fitting the slopes were compared to establish if there were any significant differences in the rate and nature of adaptation and recovery for the three groups. The results of this analysis are recorded in Table 8.5. The straight line assessment involved comparing the values of 'm' , which is the gradient of the standard straight line equation, $y = mx + c$. Whereas the second order polynomial differential is given by the expression, $ax + b$, from the general expression $y = ax^2 + bx + c$. This means that the gradient of a polynomial is dependent upon a given value of x, however, this should not affect the validity of such an assessment when the comparison between three slopes is relative and not absolute.

A straight line was a better match for the three adaptation slopes, although the polynomial assessment gave the same results, suggesting a significant difference existed between Groups A and C, but not between Groups A and B, or B and C. Assessment of the recovery slopes showed some differences between the straight line fit and the polynomial curve fit, however the three recovery plots were much more obviously curved than the adaptation slopes. It is therefore not surprising that while the straight line evaluation revealed no significant difference between the three groups, that the better fitting polynomial analysis showed a difference between Groups B and C, and A and C; but not between Groups A and B.

### 8.6E Discussion

Each of the three groups showed the trend noted by Gibson(1933), with an apparent curvature decrease as the prism wear time increased. When the prism was removed the apparent curvature altered and the strip now appeared to be bowed in the opposite direction, due to a negative after effect. As the time without the prism increased the after-effect decreased. Polynomial curves fitted the adaptation and recovery plots better than straight lines and this is to be expected because the rate of adaptation and recovery to the prism slows with time(Henson and North,1980). From Experiment 2 prism adaptation does not appear to be a significant factor when considering patient tolerance to PALs.

Those groups of patients who showed a significant difference were separated by their age and not by tolerance to PALs. This may be seen when the gradients of the regression lines with and without the prism are compared it may be noted that the two presbyopic groups have very similar values while the younger prepresbyopic group has a shallower gradient. This suggests the vision of the younger group is disrupted less than the older presbyopic subjects.

Experiment 1 shows that the ability to discriminate curves is not significantly different for the three groups studied. This suggests that ability to detect small shifts in curvature is not a valid indication of a subject being unsuitable for PAL wear. Binocular effects have not been considered as interpretation difficulties may arise. However, Gibson(1937) showed that the adaptation effect of one eye will be translated to the other such that the occluded eye will demonstrate a negative after effect, following an adaptation phase. The 'sympathetic' adaptation of the other eye has not been considered in this work but may have a significant bearing upon PAL wearer success.

# Chapter 9

## ALTERNATIVE FACTORS GOVERNING PATIENT TOLERANCE

### 9.1 PREAMBLE

Numerous reasons have been cited(Schultz,1983) for patient non-tolerance to Progressive Addition Lenses(PALs). This chapter considers the surface quality of those lenses worn by unsuccessful patients and the dispensing accuracy of the PALs worn by both successful and unsuccessful patients, to establish whether these factors account for non-tolerance to PALs.

When a practitioner is faced with a non-tolerant PAL wearer, the cause of the patient's difficulties might be attributed to one or more of the following;

(a) An incorrect prescription
(b) A non-tolerant prescription
(c) Incorrect dispensing
(d) Incorrectly manufactured PALs
(e) Adaptational difficulties.

Problems may arise when the lenses dispensed are a poor reproduction of the manufacturers lens design. The surface power characteristics of the lenses worn by the unsuccessful group therefore need to be investigated using the surface reflection focimeter(section 7.2C). This chapter also investigates the essentials of PAL dispensing and notes whether there are any significant differences in the dispensing accuracy of two groups - one of successful PAL wearers and the other of unsuccessful patients.

### 9.2 SURFACE POWER INVESTIGATION

#### 9.2.A Introduction

The lenses of the patients who failed to adapt (section 8.4 and 8.6) were evaluated with the surface reflection focimeter(SRF), which may be used as a diagnostic tool to establish if a patient's non-tolerance is related to inferiorly manufactured spectacle lenses. This technique was chosen because it allows an assessment of the progressive surface in isolation from the rest of the lens. Patients may fail to wear PALs because their lenses were not manufactured to an acceptable standard. In addition, the base curves of the two lenses dispensed together in one frame may be markedly different for similar degrees of ametropia, which may lead to asthenopic symptoms.

### 9.2.B Method

The unsuccessful group of 18 patients(Group B from section 8.6 less two subjects who no longer had their PALs) participated in this study. The aspheric anterior surfaces of their lenses were assessed with the use of the SRF. PALs had to be removed from the patient's spectacle frame to avoid mechanical restrictions before readings could be taken. Each lens was then marked up using the two fitting circles, which are located 34mm apart, 17mm equidistant from the original geometrical centre of the lens blank.

Four points were chosen for the surface power study. These were the same positions employed for the study of Varilux V2 repeatability(section 7.5): the distance and near checking points and the nasal and temporal fitting circles. The calibration curve used in the previous study(Figure 7.4) had to be extended to include the range of power measurements taken in this investigation. The extended calibration curve for this assessment(Figure 9.1) was a second order polynomial fitting the equation; $y = -0.99x + 0.045x^2 + 5.76$. Surface power readings could be taken to ±0.25D from the SRF power drum and with the above polynomial expression the possible surface power error may be calculated. For a power drum reading of 10D, the error limits are ±0.023D, and for a power drum reading of 27D, the error limits are ±0.360D.

### 9.2.C Results

The results of the SRF analysis of unsuccessful patients is given in Table 9.1. The glass and CR39 surface power measurements were calculated from the polynomial expression given in Figure 9.2. Each lens demonstrated spherical surface power at the distance and near areas. All nasal and temporal measurements, taken at the fitting circles, were toroidal. Table 9.1 shows the measured values of the distance and near surface powers. The difference between these values being the measured addition(MA), which may be compared to the values of nominal reading addition(NA). A paired 't' test produced a significant difference($p=0.015$) between these values. The correlation($r=0.735$, $p<0.001$) between the measured reading addition(MA) and the nominal reading addition(NA) is shown in Figure 9.3. This diagram allows a prediction of the nominal addition(NA) from measured addition values (MA).

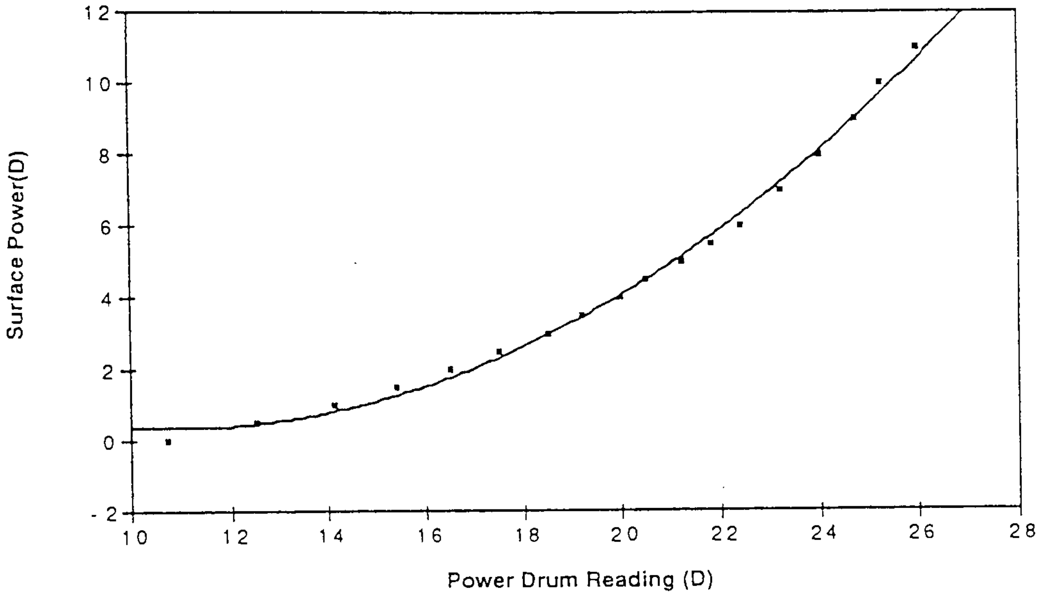


***Figure 9.1.*** An extended calibration curve(compared with Figure 7.4.) for the surface reflection focimeter with convex power surface reading (in dioptres, n = 1.523) plotted against the power drum scale of the converted focimeter. Due to an increase in the distance between the focimeter target and test lens holder the focimeter zero is at an arbitrary point on the power scale.

Surface Reflection Focimeter Measurements

| Subject | Lens | n | Base | NA | Dist. | Near | MA | N Ast | T Ast |
|---|---|---|---|---|---|---|---|---|---|
| RM | R | 1.498 | 6.50 | 2.50 | 6.39 | 8.91 | 2.52 | 1.63 | 1.89 |
| | L | 1.498 | 6.50 | 2.50 | 6.65 | 8.61 | 1.96 | 1.08 | 0.54 |
| BY | R | 1.498 | 4.00 | 1.00 | 4.10 | 5.18 | 1.08 | 0.43 | 0.65 |
| | L | 1.498 | 6.25 | 1.00 | 6.65 | 7.45 | 0.80 | 0.79 | 0.80 |
| JB | R | 1.498 | 6.50 | 2.75 | 7.18 | 9.53 | 2.35 | 1.70 | 0.84 |
| | L | 1.498 | 6.50 | 2.75 | 6.65 | 8.91 | 2.26 | 1.66 | 1.08 |
| BM | R | | | | | | | | |
| | L | | | | | | | | |
| ED | R | 1.498 | 9.00 | 2.25 | 8.31 | 10.17 | 1.86 | 1.54 | 0.92 |
| | L | 1.498 | 7.00 | 2.25 | 6.91 | 9.22 | 2.31 | 1.43 | 2.08 |
| HS | R | 1.498 | 8.50 | 3.25 | 8.61 | 10.50 | 1.89 | 1.86 | 1.22 |
| | L | 1.498 | 8.50 | 3.25 | 8.61 | 10.83 | 2.22 | 1.80 | 1.54 |
| GB | R | | | | | | | | |
| | L | | | | | | | | |
| BBu | R | 1.498 | 4.50 | 2.00 | 4.51 | 6.39 | 1.88 | 1.88 | 0.91 |
| | L | 1.498 | 4.50 | 2.00 | 4.95 | 6.91 | 1.96 | 0.90 | 1.54 |
| AJ | R | 1.523 | 7.00 | 1.75 | 7.54 | 9.04 | 1.50 | 1.19 | 1.19 |
| | L | 1.523 | 7.00 | 1.75 | 7.54 | 9.04 | 1.50 | 1.19 | 1.19 |
| VM | R | 1.498 | 6.00 | 2.25 | 6.65 | 8.31 | 1.66 | 1.63 | 0.26 |
| | L | 1.498 | 6.50 | 2.25 | 7.18 | 8.91 | 1.73 | 1.73 | 0.55 |
| MS | R | 1.523 | 7.00 | 2.50 | 7.83 | 9.68 | 1.85 | 1.19 | 1.21 |
| | L | 1.523 | 7.00 | 2.50 | 7.83 | 9.68 | 1.85 | 1.19 | 1.21 |
| SA | R | 1.498 | 6.50 | 1.25 | 4.73 | 5.89 | 1.16 | 1.13 | 0.67 |
| | L | 1.498 | 4.50 | 1.25 | 6.39 | 7.45 | 1.06 | 1.08 | 0.53 |
| VH | R | 1.498 | 4.50 | 2.50 | 4.73 | 7.18 | 2.45 | 1.74 | 1.69 |
| | L | 1.498 | 4.50 | 2.50 | 4.73 | 7.18 | 2.45 | 1.74 | 1.69 |
| JS | R | 1.523 | 5.00 | 2.25 | 5.20 | 7.54 | 2.34 | 2.01 | 1.00 |
| | L | 1.523 | 5.00 | 2.25 | 5.20 | 7.54 | 2.34 | 2.01 | 1.00 |
| ID | R | 1.498 | 6.00 | 2.50 | 6.13 | 8.91 | 2.78 | 2.21 | 1.08 |
| | L | 1.498 | 7.00 | 2.50 | 7.18 | 10.17 | 2.99 | 1.23 | 1.18 |
| BB | R | 1.498 | 7.00 | 2.50 | 6.13 | 9.36 | 3.23 | 1.08 | 0.55 |
| | L | 1.498 | 7.00 | 2.50 | 6.13 | 9.36 | 3.23 | 1.08 | 0.55 |
| RB | R | 1.523 | 6.25 | 1.75 | 6.71 | 8.12 | 1.41 | 1.39 | 1.12 |
| | L | 1.523 | 6.25 | 1.75 | 6.71 | 8.12 | 1.41 | 1.41 | 1.21 |
| GBu | R | 1.498 | 4.00 | 1.50 | 4.30 | 5.89 | 1.69 | 1.74 | 1.11 |
| | L | 1.498 | 4.00 | 1.50 | 4.30 | 5.89 | 1.69 | 1.38 | 1.34 |
| DL | R | 1.498 | 6.00 | 2.50 | 6.39 | 8.31 | 1.92 | 1.63 | 1.08 |
| | L | 1.498 | 6.00 | 2.50 | 6.65 | 8.61 | 1.96 | 1.92 | 1.11 |
| MRu | R | 1.498 | 8.00 | 1.25 | 8.31 | 9.53 | 1.22 | 1.05 | 1.05 |
| | L | 1.498 | 8.00 | 1.25 | 8.31 | 9.53 | 1.22 | 1.05 | 1.05 |

***Table 9.1.*** Surface Reflection Focimeter analysis of the lenses worn by Group B - the unsuccessful wearer group. Two patients, BM and GB no longer wore PALs when they presented for examination. The table shows the refractive index(n), base curve(Base), nominal reading addition(NA), distance surface power(Dist.), near surface power(Near), and the astigmatism at the nasal(N Ast) and temporal(T Ast) fitting circles for each lens. The difference between the distance and near surface powers is given as the measured reading addition(MA). The nominal reading addition was noted from the engraved markings on the anterior PAL surface and the base curve values were derived with a lens measure.

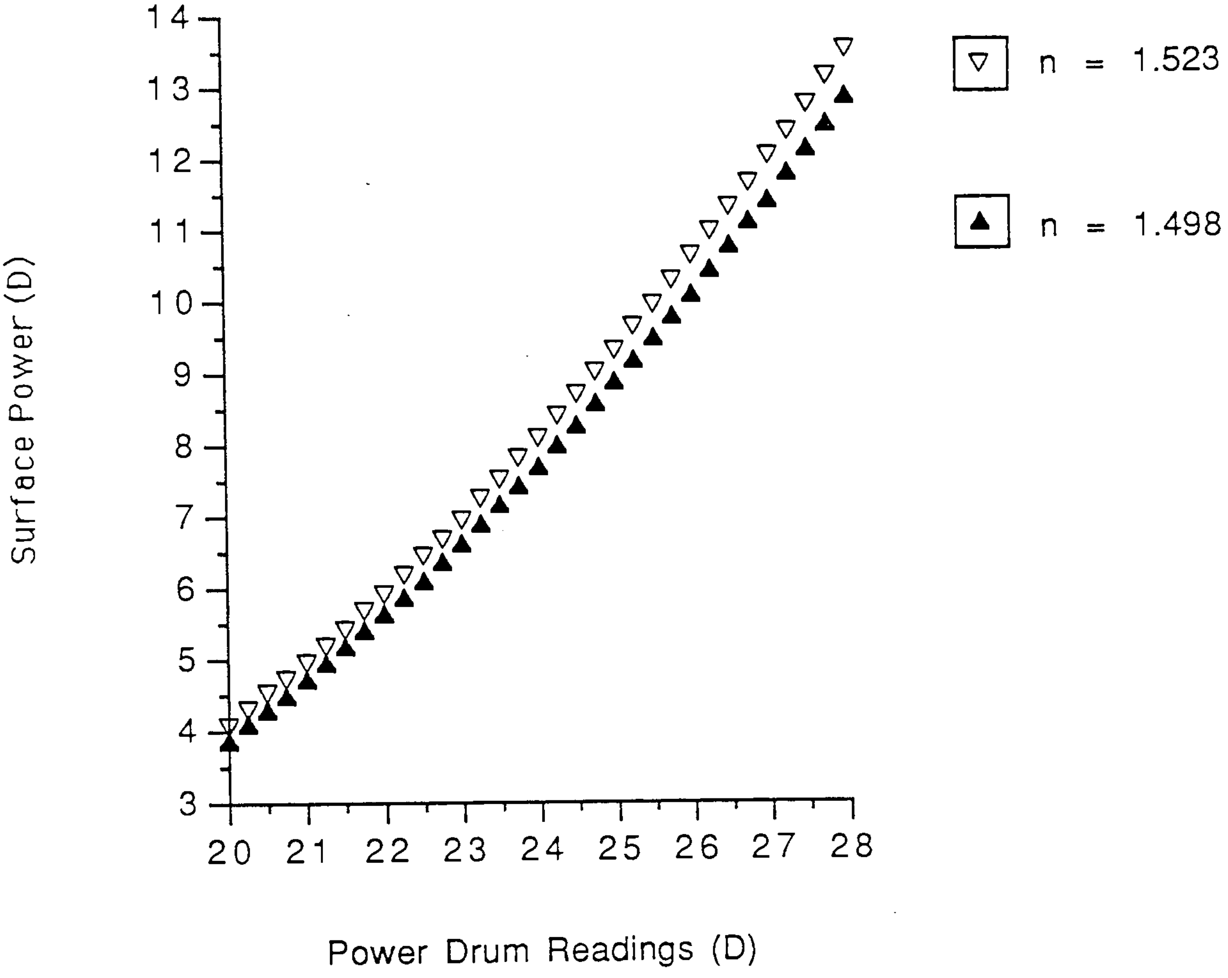


*Figure 9.2.* The calibration curve from Figure 9.1. was found to be a second order polynomial with the equation $y = -0.99x + 0.045x^2 + 5.76$. Surface power figures may then be produced for both glass( n = 1.523) and CR 39( n = 1.498) lenses. These plots are shown graphically. The 'glass' curve should be similar to the plot in Figure 9.1., but the surface power values for the 'CR 39' curve will be reduced as similar degrees of surface curvature are less powerful in the lower refractive index material.

The nasal astigmatism(N Ast) was shown to be significantly greater than the temporal astigmatism(T Ast) for the lenses in Group B($p<0.001$), using a paired 't' test. This is to be expected from the design of a PAL as the umbilical line is deflected towards the nasal fitting circle due to the convergence of a patient's eyes when viewing a near object.

## 9.3 DISPENSING ACCURACY INVESTIGATION

### 9.3.A Introduction

The necessary criteria cited by the major manufacturers for successful dispensing of PALs relate to measurement of: (a) Monocular PDs, (b) Pupils Heights, (c) Angle of Side and / or Pantoscopic Tilt, and (d) Back Vertex Distance. In the case of the Varilux V2 lens(Daley,1979; Brookes and Borish,1979) which was used for this study, it is recommended that the monocular PDs and pupil heights be measured to within 0.5mm; the pupil height should be at least 21mm from the bottom edge of the frame. The pantoscopic tilt of the spectacle frame should be around 5°- 10°, which is a compromise between the optimum positioning for distance and near vision, and the back vertex distance(BVD) should be between 12 and 14 mm.

### 9.3.B Method

This investigation comprised 38 presbyopic subjects, aged between 43 and 80 years, Group A is a population of successful wearers(N =20) with the mean age of 61.05 and Group B, a population of unsuccessful wearers(N=18) with the mean age of 63.22. The Group A and Group B subjects were the same patients who participated in the psychophysical experiments in Chapter 8 and comprised 26 females and 12 males. Equal numbers of males and females would be desirable but unsuccessful patients were relatively difficult to obtain. It was shown(section 6.3) that the success of males and females to PAL wear is not significantly different. Originally there were 20 subjects in each group, however, two Group B subjects stopped wearing PALs in preference to another type of optical correction whilst the study was being undertaken.

The four recommended dispensing criteria were measured for both eyes from each of the 38 PAL wearing subjects. Pupil heights and monocular PDs were measured and compared with the figures recorded from the spectacles worn by the patient. The misalignment from the 'true' pupil centres was measured both horizontally (for monocular PDs) and vertically (for pupil heights) for each eye.

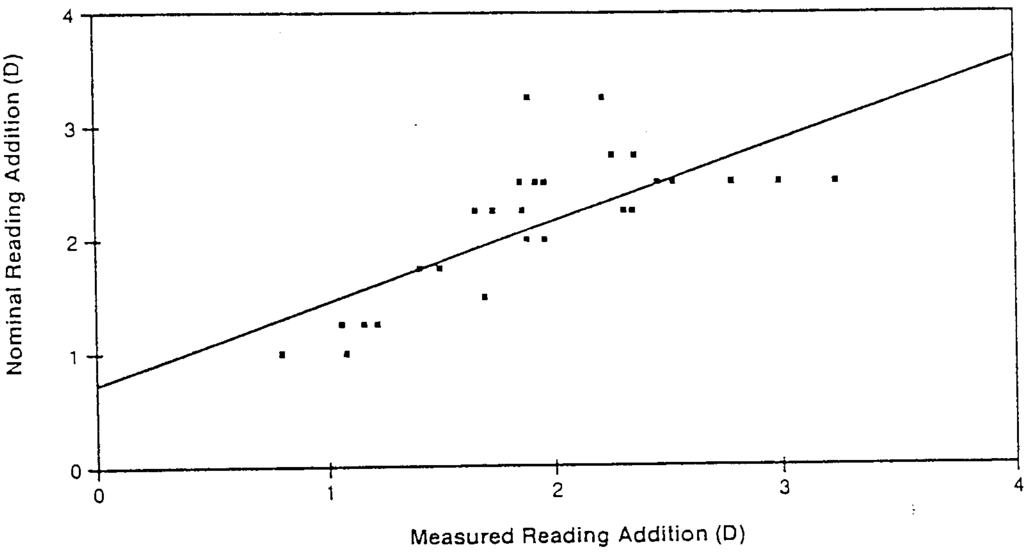


***Figure 9.3.*** Graph showing the values of the nominal reading addition(NA) plotted against the difference between measurements taken for the distance and near anterior surface powers(MA). The best fitting simple correlation ($r=0.735$, $p<0.001$) has the straight line equation, $y = 0.72x + 0.73$.

The total misalignment was calculated for each patient in both the horizontal and vertical directions. These were then converted to values of induced prism with the use of Prentice's Formula:

$$P = Fc$$

where P is the resulting induced prism in prism dioptres; F is the calculated distance power of the PAL, when split into either the horizontal or vertical planes, in dioptres; and c is the decentration of the PAL relative to the location of the pupil centre in centimetres. These results were then analysed to establish whether a significant difference existed between the two subject groups. BVD and Angle of Side measurements were also taken for each eye and assessed in a similar fashion. No noteworthy asymmetry of BVD or Angle of Side measurements, between the two eyes of a patient, were recorded.

### 9.3.C Results

The results of the induced prism due to decentred Monocular PD(horizontal prism) and Pupil Height(vertical prism) measurements are presented in Table 9.2. Analysis of the spread of induced prism showed it to be non normally(non Gaussian) distributed in both directions. The mean induced prism for the two subject populations was 0.01Δ down and 0.01Δ out for Group A, and 0.02Δ up and 0.01Δ in for Group B. The Mann-Whitney U test, a non-parametric method for comparing two populations, was employed to establish whether a statistical difference existed between Groups A and B. The U test revealed a non significant difference, at the 5% level, in the degree of induced prism present in either the vertical or horizontal directions.

Where the misalignment was equally displaced in both eyes e.g., pupil heights 1mm up right and left, this cancelled out as the patient would be able to make a positional change to overcome this dispensing anomaly. Displacing both lenses equally by the same degree may cause problems, however, asymmetrical displacement is likely to be considerably more troublesome. When those subjects whose lenses were symmetrically displaced are excluded, subjects with asymmetrically induced prism may be considered in isolation. Again, statistical analysis using the Mann-Whitney distribution-free technique showed there to be no noteworthy difference($p > 5\%$) between the two groups in either the vertical or horizontal components.

Induced Prism due to dispensing misalignment (Δ)

| Subject | Horizontal Prism |  | Vertical Prism |  |
|---|---|---|---|---|
|  | RE | LE | RE | LE |
| Group A |  |  |  |  |
| BBr | .0 | .02 in | .0 | .01 up |
| MN | .04 in | .04 out | .08 up | .08 up |
| MR | .0 | .05 out | .0 | .0 |
| MEv | .01 in | .02 out | .02 up | .02 up |
| MW | .06 in | .03 out | .01 up | .01 down |
| MD | .01 out | .03 out | .06 up | .05 up |
| JM | .01 in | .0 | .01 up | .0 |
| JD | .01 out | .0 | .02 up | .0 |
| HY | .0 | .01 in | .0 | .0 |
| BS | .01 in | .0 | .03 down | .0 |
| MP | .01 out | .01 in | .02 down | .0 |
| ID | .0 | .05 in | .0 | .02 down |
| TL | .0 | .0 | .0 | .0 |
| JW | .04 in | .05 out | .08 down | .12 down |
| FW | .0 | .0 | .04 up | .05 up |
| VC | .0 | .01 in | .0 | .0 |
| JWi | .0 | .0 | .01 up | .0 |
| MEI | .03 out | .02 in | .03 up | .03 down |
| BBe | .01 out | .0 | .01 up | .01 down |
| LR | .0 | .0 | .0 | .01 down |
| Group B |  |  |  |  |
| RL | .01 in | .01 in | .02 up | .03 up |
| BY | .0 | .02 in | .02 up | .01 up |
| JB | .0 | .02 in | .01 down | .02 up |
| BM |  |  |  |  |
| ED | .0 | .0 | .0 | .04 down |
| HS | .04 in | .05 in | .0 | .0 |
| GB |  |  |  |  |
| BBu | .0 | .09 out | .03 down | .07 down |
| AJ | .0 | .03 out | .0 | .04 down |
| VM | .0 | .01 in | .01 up | .02 up |
| MS | .0 | .04 in | .0 | .03 down |
| SA | .03 in | .0 | .0 | .02 down |
| VH | .0 | .01 in | .01 up | .01 up |
| JS | .0 | .01 out | .01 down | .02 down |
| ID | .0 | .03 in | .0 | .0 |
| BB | .01 in | .0 | .0 | .0 |
| RB | .0 | .0 | .0 | .0 |
| GBu | .02 in | .0 | .0 | .0 |
| DL | .01 out | .02 in | .08 up | .09 down |
| MRu | .0 | .02 in | .0 | .06 down |

***Table 9.2.*** The calculated horizontal and vertical induced prism results which arise from the differences in the anatomical pupil positions and the pupil locations measured from the PALs.

Table 9.3 denotes the results of the BVD and the Angle of Side measurements. The distributions of these measurements were also tested for normality. Both distributions were shown to be non normal for the two subject populations. Groups A and B were analysed to establish whether the lenses of one group had been dispensed more closely to the eye than the other. Non parametric analysis(U test) revealed there to be no significant difference between the vertex distance of the two subject populations. A similar null result was obtained at the 5% level for the Angle of Side measurements comparison.

The scaled measures used for this experiment allowed the monocular PDs, pupil centre heights, and BVD results to be measured to ±1mm, and the Angle of Side results to ±1°. The significance of the Mann-Whitney U tests employed in this experiment would not be altered by measurement error within these limits.

## 9.4 DISCUSSION

Collectively analysing the results from a subject population may be a little confusing. In clinical situations some patients who are correctly dispensed cannot manage with their glasses whilst others who do not have their glasses so accurately dispensed can manage perfectly well. Comparing the dispensing accuracy of the two subject populations establishes whether the problems of unsuccessful wearers arose due to a particular factor of faulty dispensing.

The induced prism evaluation showed the prism resulting from decentration of a few millimetres to be negligible and within the limits which North and Henson(1985) have shown to be tolerable in most cases of lens induced heterophoria. It is unlikely that small degrees of prismatic power which are not subjectively significant would account for differences between the two groups. This suggests that when patient tolerance is affected by decentration the non-tolerance arises because the eyes do not pass along the progressive corridor correctly rather than due to the distance prism induced by minor degrees of lens misalignment.

As with the PD and pupil height analysis, there were notable individual variations, with the BVD and Angle of Side measurements. Although, when the two groups were studied no significant difference was established for either measurement. That no significant differences were found for the four criteria studied does not imply these measures are unimportant. However, had one factor shown a statistical difference between these two groups then this measure could have been attributed as being a significant contribution to group B's inability to

## Back Vertex Distance(BVD) and Angle of Side measurements

| Subject | BVD(mm) | Angle of Side(°) |
|---|---|---|
| **Group A** | | |
| BBr | 14.0 | 5. |
| MN | 15.0 | 5. |
| MR | 14.0 | 5. |
| MEv | 15.0 | 10. |
| MW | 10.0 | 5. |
| MD | 12.0 | 5. |
| JM | 13.0 | 15. |
| JD | 14.0 | 7. |
| HY | 14.0 | 5. |
| BS | 12.0 | 10. |
| MP | 10.0 | 5. |
| ID | 15.0 | 5. |
| TL | 12.0 | 10. |
| JW | 10.0 | 15. |
| FW | 10.0 | 5. |
| VC | 12.0 | 0. |
| JWi | 12.0 | 10. |
| MEl | 12.0 | 0. |
| BBe | 10.0 | 10. |
| LR | 10.5 | 5. |
| **Group B** | | |
| RL | 11.0 | 0. |
| BY | 16.0 | 10. |
| JB | 15.0 | 5. |
| BM | | |
| ED | 15.0 | 5. |
| HS | 13.0 | 5. |
| GB | | |
| BBu | 10.5 | 5. |
| AJ | 12.0 | 5. |
| VM | 12.0 | 3. |
| MS | 14.5 | 10. |
| SA | 11.5 | 10. |
| VH | 14.0 | 0. |
| JS | 13.0 | 5. |
| ID | 12.0 | 5. |
| BB | 12.0 | 10. |
| RB | 12.0 | 5. |
| GBu | 12.0 | 5. |
| DL | 13.0 | 10. |
| MRu | 15.0 | 10. |

*Table 9.3.* The back vertex distance(BVD) and angle of side measurements recorded from the spectacles of the 38 subjects assessed.

wear PALs. The results of this chapter suggest that other causes apart from poor lens reproducibility and poor dispensing must also be considered when studying PAL non-tolerance.

The SRF is a very useful instrument for measuring surface power, especially the degree and orientation of astigmatism. One difficulty with this device is that to build up a comprehensive pattern of the surface topography of the PAL is very time consuming and the approach adopted for this study allowed only a general overview of PAL surface integrity. Considering four areas of evaluation does not constitute a comprehensive assessment. No lens manufacturer can claim 100% repeatability for their lens design and occasionally even the most exacting methods of quality control will admit inferior lenses to the patient. Surface power differences between lenses that were classed as being similar were noted in the first experiment. The correlation line plotted in Figure 9.3, shows that for a given lens the nominal reading addition value(NA) can be notably different from the measured surface power(MA) addition. However, it must be remembered that the measured surface power(MA) does not take account of lens thickness, which will contribute to the total dioptric power of a lens.

There is a need for the practitioner to isolate lens integrity from the numerous other possible causes of patient non-tolerance. However, it could be argued that for this technique to be of practical assistance to the clinician - the measurements must either be delegated or automated, and hence not so time consuming. The SRF is of use for individual cases, for example, it was useful in noting that subject BY was unable to cope with his PALs because despite having fairly similar prescriptions in both eyes the lenses were made up from different base curves. This patient was changed to an alternative type of PAL(Varilux VMD) with similar bases curves and is now wearing these lenses successfully. To note whether the lenses of the sample in Group B are significantly inferior to the whole population of this PAL design is something this study cannot address - a more detailed and extensive investigation would be required.

It would be interesting to measure the lenses worn by Group A using the SRF and establish whether there was a significant difference between the PAL surface integrity of Groups A and B. Measurement of the lenses of Group B subjects was not difficult as their lenses were removed from the spectacle frames following the dispensing accuracy experiment, in preparation for an alternative optical correction. This allowed SRF analysis when Group B subjects were absent, which would not have been possible for many Group A subjects who wished to wear their lenses continuously.

This chapter, therefore, reiterates that there are many disparate factors which may govern the success of PAL wear(Schultz,1983). It is noted by a number of workers that the psychological make up of a patient's character may be important. Young(1984) considers the psychological disposition of the population to be normally distributed, with very demanding patients on one side and easily satisfied patients on the other. He points out that demanding subjects do not make as successful PAL wearers as those who are more placid due to their inability to accept the peripheral aberrations present with these lenses. Psychological testing might help the optometrist predict successful wearers but one drawback of quantifiable character analysis is the time involved.

# Chapter 10

## GENERAL DISCUSSION AND CONCLUSIONS

### 10.1 INTRODUCTION

The aims of this study into the physical and psychophysical embodiments related to PALs have been outlined in Chapter 1. Each aspect of these aims is discussed below in view of the preceding empirical and statistical analysis.

### 10.2. LITERATURE AND PATENT REVIEW

From the literature and patent review it is apparent that whilst there have been a number of different designs suggested, it has been the work of Maitenaz(1966,1974) which has had the most impact upon current PAL design. Over the past two decades the majority of progressive addition lenses patented have taken one of two forms. They have been based upon either a lens with a relatively large distance viewing zone and sharp boundaries, or a relatively smaller distance viewing zone with more diffuse boundaries. These two designs are structured upon the concepts of static and dynamic vision. However, it is perhaps a little artificial to consider a specific lens design to fit either one model or the other. Many manufacturers aim for a compromise design which is suitable, under most circumstances, for the majority of wearers.

In the past few years attempts have been made to produce a "multiple design" lens in which the surface characteristics of a particular lens blank alter with reading addition power and are not rigidly controlled by a single design. It is uncertain whether the Dufour(1989) patent will become a design 'trendsetter' in a similar manner to the Maitenaz(1966 and 1974) patents.

All currently available commercially manufactured lenses within this field are based upon the use of surface curves to produce a change in focal length. Fowler (1986) notes that new variations in this approach may have reached the point of diminishing returns and that new lens patents of this type are unlikely to offer major advantages over the existing designs. Methods employing liquid cells and gradient index optics have not to date been a commercial success. Perhaps the most promising alternative technique is that pertaining to Freeman's (1984b) design, which incorporates negative diffractive power into a spectacle lens. This design has been produced commercially in a contact lens but not as a progressive addition spectacle lens.

## 10.3 ANALYSIS OF PAL POPULATION SAMPLE

This work preceded any of the psychophysical analysis of patients and proved a useful method of recruiting some of the unsuccessful PAL patients. This was an important consideration as it proved difficult to obtain a group of 20 unsuccessful patients willing to assist these experiments.

The patient survey using mailed questionnaire and clinical records assessed various aspects of a sample of the total PAL subject population. The study showed the success rate of the undergraduate clinic to be either 85.7% or 80.6% depending upon how the criterion for successful wear is judged. The success rate is lower than most other surveys completed in this area of research. The Augsburger *et al* (1984) study reported a 93% success rate by judging patients to be successful if they still wore PALs when reassessed. The reasons why the analysis described in Chapter 6 should have given a lower success rate in unclear. However, a number of factors which may affect the results should be considered. Firstly, in the Aston survey the patients were not under the same financial pressure because the lenses were provided at a reduced cost. This may have encouraged patients who were unsuitable to consider PAL correction. Furthermore, those who were unsuccessful were not penalised financially, because an alternative correction was provided at no extra cost. A third consideration is that patients were not screened in any way and any patient with a suitable prescription was considered.

It may be argued that the sample chosen (patients seen in an undergraduate clinic) is not truly representative of the whole PAL population. This may be a valid criticism and could be investigated by comparing a similar analysis with patients from general optometric practice. One advantage with the Aston University clinic was that the Kalamazoo computer search facility enabled the immediate recall of PAL patients and if a parallel study were to be undertaken in private practice a similar arrangement of computer based dispensing records would be desirable. It should also be remembered, the Aston clinic only dispensed one type of PAL - the Varilux V2 lens, which is a unique situation as other practices would dispense a range of PAL designs. Another consideration is that private practice patients are unlikely to have been as loyal as those seen in the undergraduate clinic and the return rate of mailed questionnaires might not then be so great. The value of comparing two survey samples with notably different return rates must be questioned.

The results, which were assessed using chi squared analysis, showed the factors of age and sex to have no bearing upon a patient's ability to adapt successfully to PAL wear. When considering the prescription details one interesting factor emerged. Adaptation did not appear to be dependent upon the reading addition power or the mean spherical power of the lenses. However, chi squared analysis showed that patients with high astigmatic corrections adapted more quickly and successfully than those with low cylindrical or spherical corrections. Two possible explanations were proposed to explain this result in Chapter 6. Namely, astigmatic patients may have a poorer standard of vision and not notice the aberrations or alternatively being astigmatic they may adapt more readily to a nonrotationally aspheric correction. Whatever, the reason for this finding the fact that Wittenberg(1978) produced similar results would suggest that astigmatism is one of the factors which affects PAL tolerance and adaptation. The results of one of the experiments(CS analysis) in the psychophysical assessment (Chapter 8) would also suggest that astigmatism may to some degree affect the tolerance of and adaptation to PAL wear. This an area of study which requires further investigation.

The questionnaire also considered patient preference of the various portions of a PAL. The V2 wearers in the undergraduate clinic gave a score to each portion and collectively found the reading portion to give the poorest subjective result. It would be interesting to note whether a similar pattern would emerge with different PAL designs. This method of assessment might be an interesting way of subjectively evaluating the worth of various alterations quoted in PAL patents.

## 10.4 PHYSICAL ASSESSMENT OF PALs

### 10.4A The different techniques of optico-physical evaluation

For PALs with a low powered distance prescription, the three methods gave essentially similar readings of aberrational astigmatism. Whilst the conventional use of a focimeter is the most commonly adopted approach, the rotating mount focimeter is theoretically the best, as it simulates a moving eye behind a pair of spectacles. Surface reflection is useful for allowing an assessment of a PAL surface whilst still in the semi-finished form. Indeed, an automated SRF somewhat like the automated rotating mount Nidek used in Chapter 7 would be an instrument useful to both designers and manufacturers. The important point to note from this analysis is that the three methods of assessment give very similar results, thus validating the use of the rotating mount and the surface reflection methods as alternative, and theoretically better, means of PAL evaluation.

### 10.4B The relative variation in lenses of the same design

The SRF proved to be a useful instrument for assessing the integrity of convex aspheric surfaces, such as those present in PALs. Differences were shown to occur between lenses of the same design and similar parameters. Sheedy *et al* (1987) demonstrated differences between lenses of the same design which were made in different materials.

### 10.4C Reading Addition Analysis

Reading addition power is known to have a bearing upon the surface characteristics of PALs. From the results it was interesting to note that irrespective of the type of PAL, i.e., whether it confirms to the hard/static(eg. Sola Graduate), soft/dynamic(e.g, Vision-Ease Delta), or claims to be a multiple design lens(e.g, Varilux VMD); the reading addition power had a similar effect upon PAL surface topography. Namely, an increase in reading addition power results in a contraction of the progressive channel width and an increase in the progressive zone length. A study of the rate of change of power along the progression channel indicated that the power law gradient tends to increase with most lenses as the reading addition increases. However, increasing the progression channel length appears to play a more significant part when designers wish to increase the reading addition power.

### 10.4D Base Curve Analysis

Manufacturers produce lenses in different base curves to facilitate a series of best form lenses for the range of possible distance prescriptions. Although base curve is not a parameter noted by von Minkwitz(1963) to have a bearing upon the astigmatism of PAL surfaces, it is nevertheless a variable in lens design which ought to be investigated. The study was undertaken using the plots produced with the Nidek automatically driven focimeter. This base curve analysis considered three base curves from each of the four lens designs studied. Unfortunately, the range of base curves chosen for a particular PAL design will vary between manufacturers and comparison of different designs with identical base curves is not often possible. Nevertheless, a clear picture emerged suggesting that the progression channel length and width are largely independent of base curve.

Where base curve does not have a notable bearing upon the progressive zone is in the case of low powered reading additions worked on low powered base curves. The result is to widen the progression channel and push the astigmatism into the lens periphery. Whether this effect has a significant bearing upon lens tolerance is unclear. The results from Chapter 6 would suggest that a patient's mean spherical prescription has no bearing upon PAL tolerance, when lenses are made up in the most appropriate base curves. It is unlikely that prescribing a young presbyope(low reading addition) in a flatter base curve (e.g., 2.00D base) when their distance prescription requires a higher base curve(e.g., 6.00D) would have a significant effect. Indeed, prescribing in an inappropriate base curve might only add to a patient's problems of lens tolerance.

### 10.4E Validity of Optico-Physical Assessment

Whilst completing the Reading Addition and Base Curve studies(see sections 7.8 and 7.9), the validity of attaching importance to a single physical measure was also considered. This is a practise often undertaken by PAL manufacturers to gain professional recognition for their product. Two techniques of physical assessment were contrasted. One method compared the expected progression corridor widths( after von Minkwitz's 1963 equation, $A = 2Bh/y$, see section 7.8C for details) to the empirical results, whereas the other method of assessment considered the corridor widths as a fraction of the lens plot widths. Using the first technique the Varilux VMD was shown to depart most successfully from the expected values for progression corridor width, whereas with the second technique the Sola Graduate was shown to have wider progression corridors.

The results of each assessment are numerically correct although they appear to contradict when considering which lens is best. The discrepancies arise because although each method of evaluation involves 'corridor width' the parameters being evaluated are different. These results highlight that taking a single physical measure can be most misleading. Thus, it is possible to understand why manufacturers are reluctant to agree to officially recognisable standards for these lenses, because by choosing a limited number of parameters the apparent characteristics of a PAL can be greatly misrepresented.

## 10.5 PSYCHOPHYSICAL ASSESSMENT OF PALs

Whilst official standards do not involve patient responses, the limitations of physical assessment show the need for greater knowledge regarding psychophysical evaluation of PALs.

### 10.5A Grating Visual Acuity through PALs

The use of a presbyopic patient might have been desirable for this work, which acted as a pilot study for the more comprehensive assessment of PAL visual performance using a measure of contrast sensitivity. Using the unit magnification telescope technique the accommodation should be controlled irrespective of the patient's amplitude of accommodation; however, a presbyopic patient might have smaller pupils than a prepresbyope. This would give the presbyope a larger depth of field. In a comparative analysis of grating VA through different lens designs this should not be a relevant consideration.

There were a number of interesting factors which emerged from this study. The apparatus was shown to be a valuable instrument suitable for the psychophysical assessment of PAL properties. The VA was shown to drop with increasing eccentricity from the central umbilical line. This appeared to be more closely related to the spread and orientation of the astigmatism along the horizontal section than the mean spherical power along the same horizontal section. This would suggest that a lens designer should be more concerned about the spread of surface astigmatism than the spread of mean spherical power when considering the effect a lens patent may have upon visual performance. A number of lens designers(Maitenaz,1974; Shinohara and Okazaki,1985) have suggested that one factor which affects patient tolerance is the rate of change of astigmatism over a surface rather than the numerical value of astigmatism itself. This study showed that with two lenses(Line Free and Varilux V2) the drop in grating VA was more closely related to the astigmatic gradient. However, the overall results were inconclusive when considering whether astigmatism or the astigmatic gradient is more closely related to the drop in grating VA.

### 10.5B Contrast sensitivity measurement of PAL visual performance

This study showed that contrast sensitivity reduced as the angle of eccentricity from the PAL umbilical line increased, in a similar manner to the way grating VA reduced. This drop in CS may be attributed to an increase in defocus caused by lens aberrations and in particular surface astigmatism. The drop in CS was also considered in terms of the astigmatic gradient across the the horizontal section studied. The CS investigation was undertaken with the same Varilux V2 lens as that used for the Grating VA experiment. The relative variation in CS along the horizontal section, for both the successful and the unsuccessful wearer groups, was much more closely matched to the relative change in the astigmatic gradient than in astigmatism itself(Figure 8.11). In the previous experiment the astigmatic gradient was a closer match to the relative change in visual acuity (1/VA) than the astigmatism(Figure 8.6). Therefore, the V2 lens was shown to have a similar effect upon the contrast sensitivity as the visual acuity. The NZ and LF lenses used in the previous experiment were not assessed for CS, due to the time consuming nature of this experiment. Further study in this area might produce interesting results.

Contrast sensitivity was greater for the successful wearer group than the unsuccessful wearer group. A significant difference was shown to exist between the two groups using a non-parametric analysis. This would suggest that visual performance testing may be a useful indicator of patient tolerance to PALs. However, further study would be necessary as no difference in foveal visual performance was detected when visual performance was assessed in terms of visual acuity and with the contrast sensitivity measurement only one value of spatial frequency was employed.

### 10.5C Adaptation and detection of curvature distortion

Study of the adaptation and detection of curvature distortion was considered as an appropriate way to consider whether the resulting image shape was a discriminatory factor.

This analysis described in section 8.6 confirmed the work of Gibson(1933), showing visual adaptation to curvature and the work of Gibson(1937) which indicated a negative after effect. The rate of adaptation to the prismatically induced distortion and the rate of recovery from the negative after effect may be considered. This study suggests that no significant rate differences occur between the successful and unsuccessful PAL wearers. An age related difference between the two presbyopic PAL groups and the prepresbyopic group was detected. The younger group of prepresbyopes appeared to have their vision disrupted less by optically induced distortion of form compared to the presbyopic subjects. No significant difference was noted in the manner and ability of subjects to detect curvature irrespective of whether they were successful PAL presbyopes, unsuccessful PAL presbyopes or prepresbyopic. This suggests that a subject's ability to detect or adapt to optically induced curvature do not appear to be factors which govern patient tolerance to complex aspherically designed spectacle lenses.

## 10.6. ALTERNATIVE FACTORS GOVERNING PATIENT TOLERANCE

Relating the physical factors of importance to the psychophysical results is not a straightforward procedure - when, for example, it is unclear which physical measure affects visual performance(astigmatism or astigmatic gradient). Of the psychophysical factors studied only the measure of CS showed a significant difference between the two groups. This thesis, and other work which has gone before, would suggest that no single physical factor can be directly related to the psychophysical responses to account for all the reported non tolerances. There are, of course, many aspects of the physical entity which were not studied and other psychophysical considerations not investigated which might reveal a significant relationship.

The physical assessment undertaken would suggest that astigmatism and the reading addition power are the physical properties likely to have the most significant impact upon a patient's tolerance. Other factors outside the confines of physical and psychophysical assessment might also be considered. Personality has often been attributed to the success of PAL wear. Physiological factors such as a subject being prone to travel sickness may have some part to play. If this is true it may be that a patient's ability to wear PALs is related to their vestibular rather than their ophthalmic attributes. This would account for the reason why visual performance testing revealed no significant differences between the two groups under examination. A patient's lifestyle(occupation and hobbies) may also affect PAL tolerance.

### 10.6A SRF analysis of the PALs worn by unsuccessful wearers

The SRF study showed the variation in nasal and temporal astigmatism between different reading additions of the same lens design. Astigmatism at the nasal and temporal fitting circles generally increases with the increase in reading addition. The value of astigmatism is greater at the nasal fitting circle than the temporal fitting circle. The study also emphasised the importance of dispensing a patient, when possible, with two lenses of similar base curve.

No notably aberrant lenses were detected using this means of analysis. A comparison between the lenses worn by the Group A and Group B subjects might have been of interest, but it is unlikely that a significant result would have been obtained as the reproducibility of the Group B subjects was not considered to be abnormal.

### 10.6B Dispensing Anomalies

PALs worn by the subjects of the two groups in the psychophysical analysis may not have been dispensed properly. This was investigated because an individual's non-tolerance may be attributed to poor dispensing or inferiorly manufactured lenses. However, this study suggests that small dispensing errors are insufficient to explain non-tolerances to PALs, and other reasons must therefore be considered. The differences between the two subject populations might also be attributed to poor repeatability of the PAL design. This was considered by assessing the lenses of unsuccessful patients with the SRF.

## 10.7 CONCLUSIONS

Progressive addition spectacle lenses are making an increasingly valuable contribution to the correction of presbyopia and as a result design efforts are still trying to improve their characteristics and make them more acceptable to a greater proportion of presbyopes. Many reasons have been cited for non-tolerance and a number of these have been considered in this study. The results show that age, sex and many of the prescription details appear to have no bearing on patient tolerance. However, those patients with high cylindrical corrections were shown to adapt more readily than patients with low cylindrical or spherical corrections. Reading addition power did not appear to play a significant part in patient tolerance.

A comprehensive physical analysis of the surface topographical properties of PALs was undertaken. Three methods of power measurement were employed and the similarity of the results for low powered lenses was demonstrated. A computer driven automatic focimeter allowed a detailed analysis of the spread of cylindrical power and mean spherical power for four different PAL designs. The cylindrical power plots proved to be the most informative and revealed that the reading addition has much more bearing upon a PAL's surface characteristics than the base curve. A surface reflection focimeter was employed to study the repeatability of a PAL design and to test that the lenses worn by unsuccessful patients were within the normal manufactured limits. The PALs worn by the unsuccessful patients were shown to be dispensed correctly nor did faulty manufacture account for patient non-tolerance.

The image of an object seen through a PAL can be affected by clarity and shape anomalies. Psychophysical investigations were carried out to establish whether PAL tolerance was affected by these factors. Clarity was assessed using the visual performance measures of contrast sensitivity and visual acuity, and the shape anomalies by testing detection and adaptation to optically induced curvature distortion. Statistical analysis suggested that visual performance, when measured in terms of CS may be a method of predicting patient tolerance to PALs. However, no significant difference was detected for visual performance between successful and unsuccessful wearers when assessed using visual acuity measurements. The method chosen to study optically induced curvature distortion confirmed the null hypothesis, namely, that a patient's ability to detect or adapt to image shape anomalies does not account for PAL non-tolerance.

## 10.8 FUTURE STUDY

The thesis did not and could not consider every factor of the physical and psychophysical embodiments of PALs. The physical analysis would suggest that the reading addition power, astigmatism and, in some PAL designs, the astigmatic gradient are important considerations and these require further investigation. The psychophysical analysis of PALs is an area of study which few workers have previously considered. Indeed, it might be suggested that this thesis has largely pioneered the psychophysical assessment of PAL wearers. Further work should be undertaken to establish indicators of PAL tolerance and to show how these may be applied clinically.

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# Appendices

**Appendix 1**

Iso-cylindrical power and mean spherical power plots, for the 36 lenses studied in Chapter 7.

**Appendix 2**

BBC BASIC programs for controlling and accessing data from the automatically driven focimeter employed for detailed PAL analysis.

**Appendix 3**

Supporting publications.

# Appendix 1

## Iso-Cylindrical Power and Mean Spherical Power PAL Plots

### Lens Designs

**Varilux V2**

2.00D, 4.50D, and 7.25D base curve versions of plano powered distance prescription lenses with +1.00D, +2.00D, and +3.00D reading additions.

**Varilux VMD**

4.00D, 6.00D, and 8.00D base curve versions of plano powered distance prescription lenses with +1.00D, +2.00D, and +3.00D reading additions.

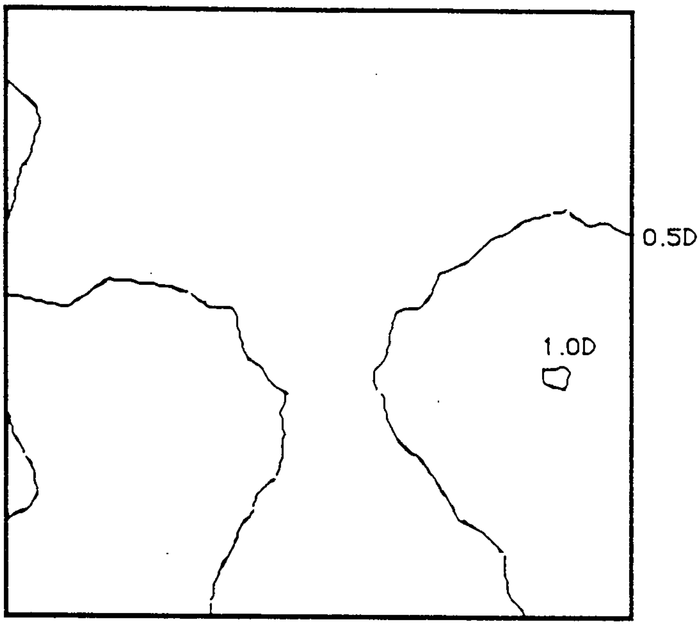
**Sola Graduate**

2.00D, 5.00D, and 8.00D base curve versions of plano powered distance prescription lenses with +1.00D, +2.00D, and +3.00D reading additions.

**Vision-Ease Delta**

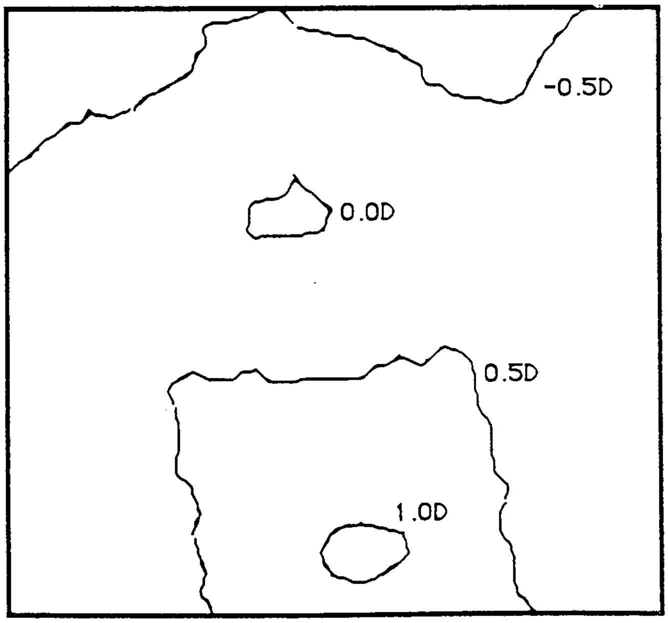
2.00D, 5.00D, and 7.00D base curve versions of plano powered distance prescription lenses with +1.00D, +2.00D, and +3.00D reading additions.

Varilux V2 2.50DS Base
CR39 plano / +1.00DS add



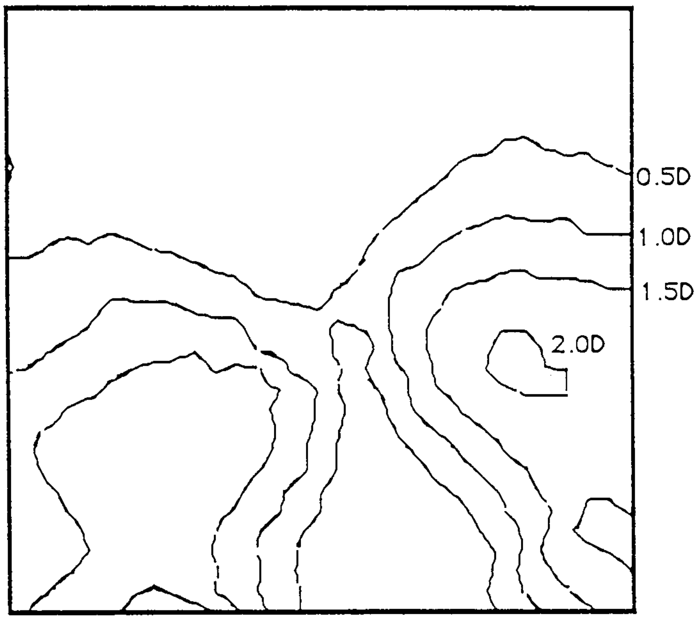
Cylindrical contour lines 0.5 to 1.00D

Varilux V2 2.50DS Base
CR39 plano / +1.00D add



Spherical contour lines -0.5 to 1.00DS

Varilux V2 2.50DS Base
CR39 plano / +2.00DS add



Cylindrical contour lines 0.5 to 2.00D

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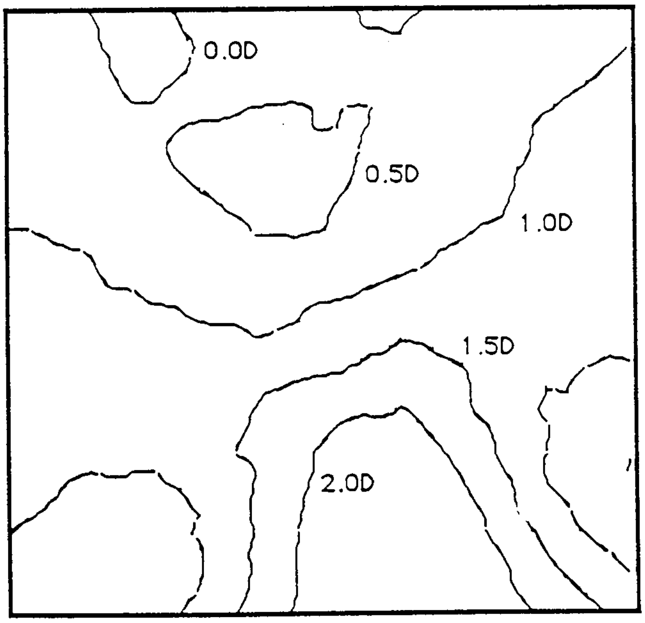
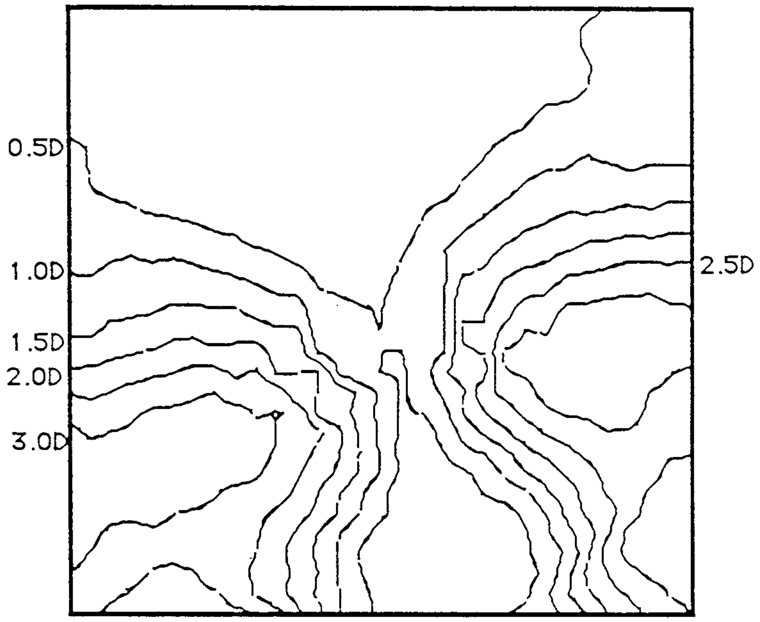
CR39 plano / +2.00DS add



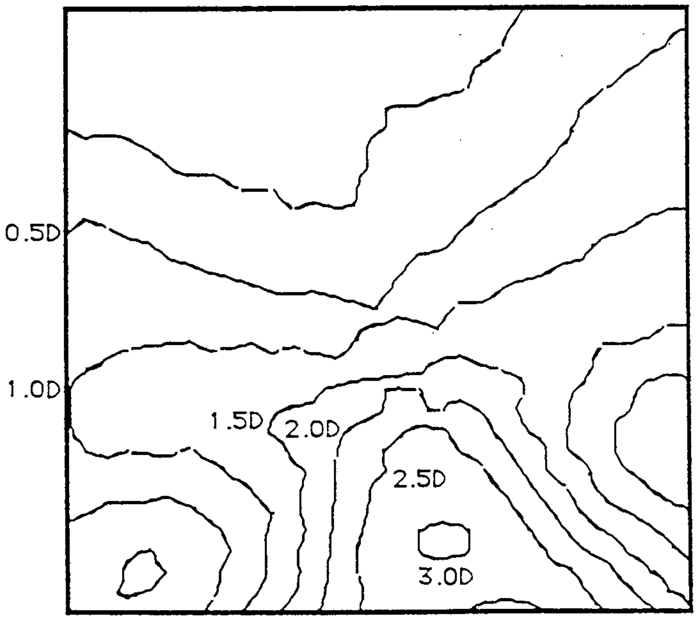
Spherical contour lines 0 to 2.00DS

Varilux V2 2.50DS Base
CR39 plano / +3.00DS add



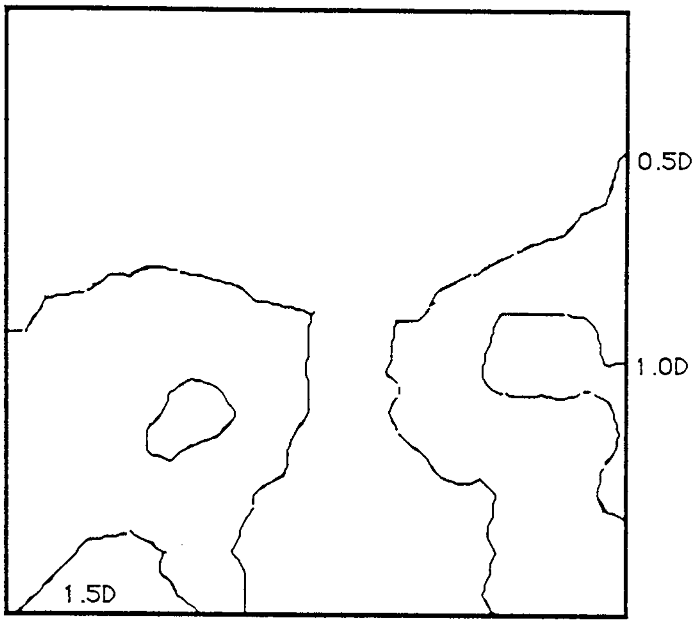
Cylindrical contour lines 0.5 to 3.00D

Varilux V2 2.50DS Base
CR39 plano / +3.00DS add



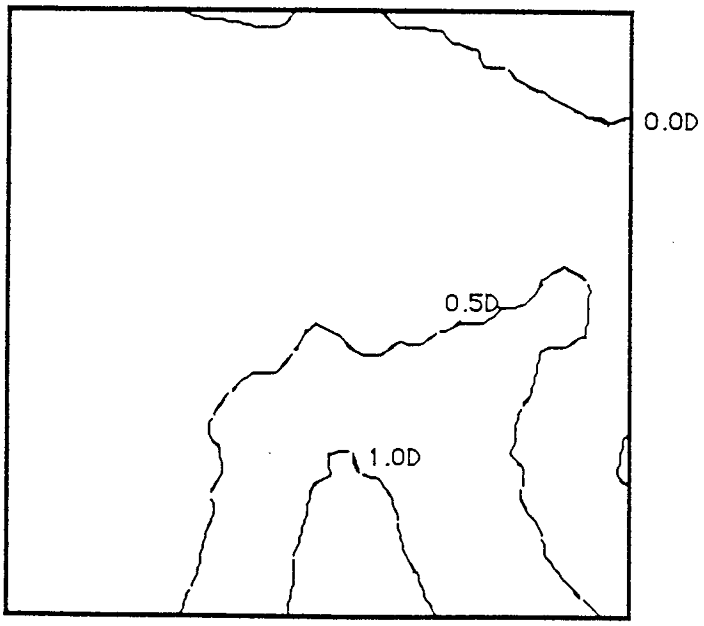
Spherical contour lines 0 to 3.00DS

Varilux V2 4.50 DS Base
CR39 plano / +1.00DS add



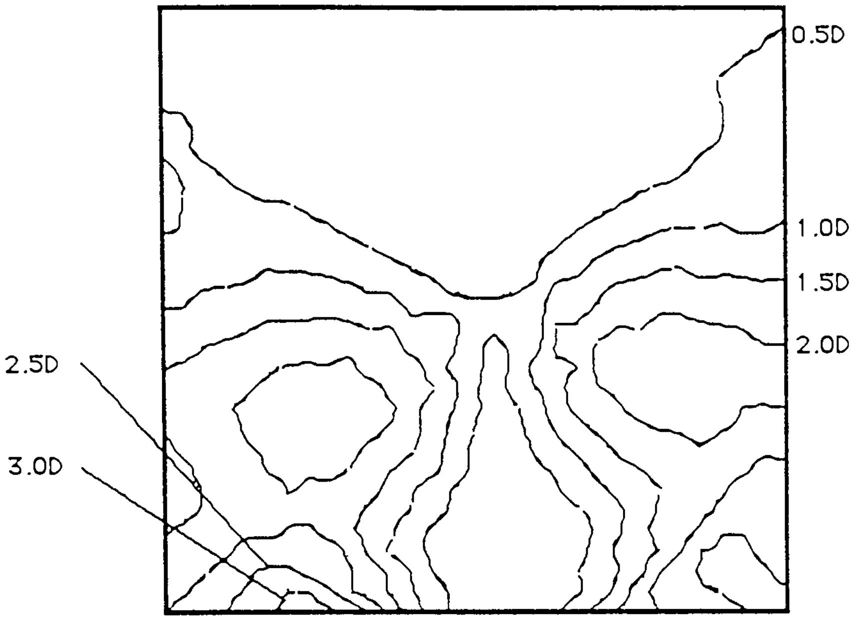
Cylindrical contour lines 0.5 to 1.50D

Varilux V2 4.50 DS Base
CR39 plano / +1.00DS add



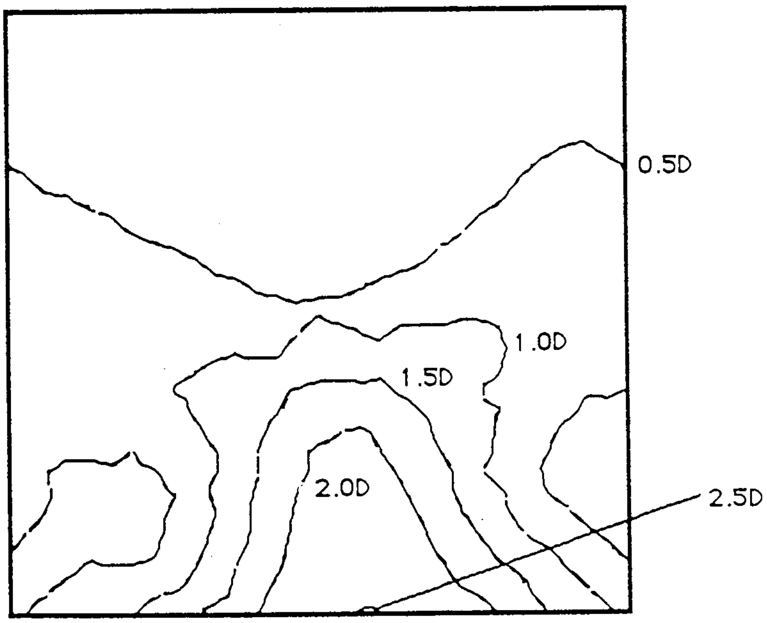
Spherical contour lines 0 to 1.00DS

Varilux V2 4.50D Base
CR39 plano / +2.00DS add



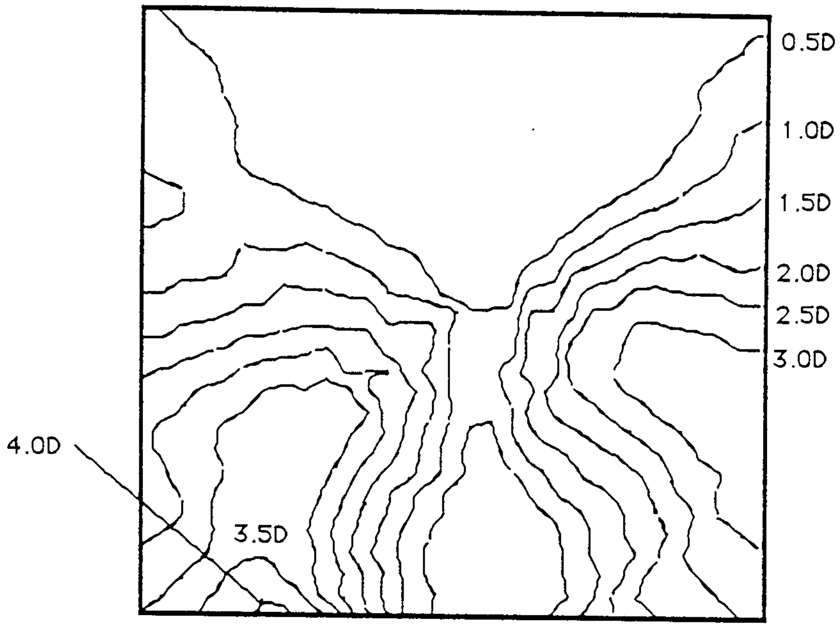
Cylindrical contour lines 0.5 to 3.00D

Varilux V2 4.50D Base
CR39 plano / +2.00DS add



Spherical contour lines 0.5 to 2.50D

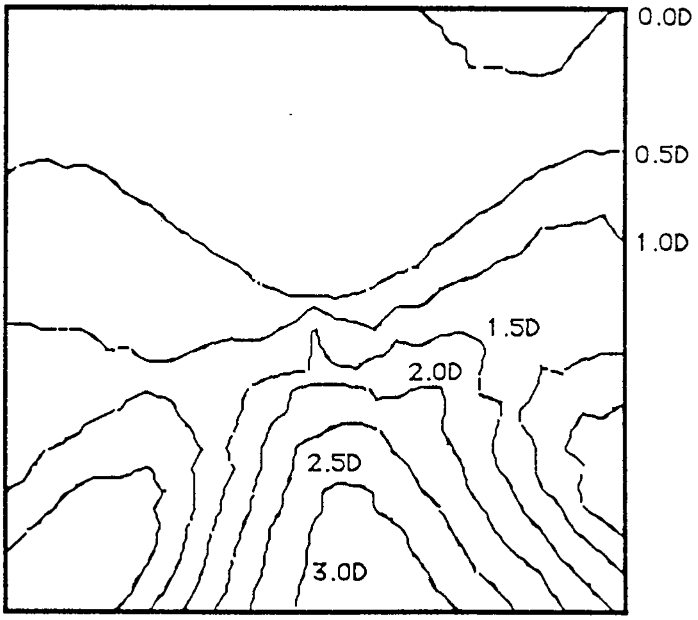
Varilux V2 4.50DS Base
CR39 plano / +3.00DS add



Cylindrical contour lines 0.5 to 4.00D

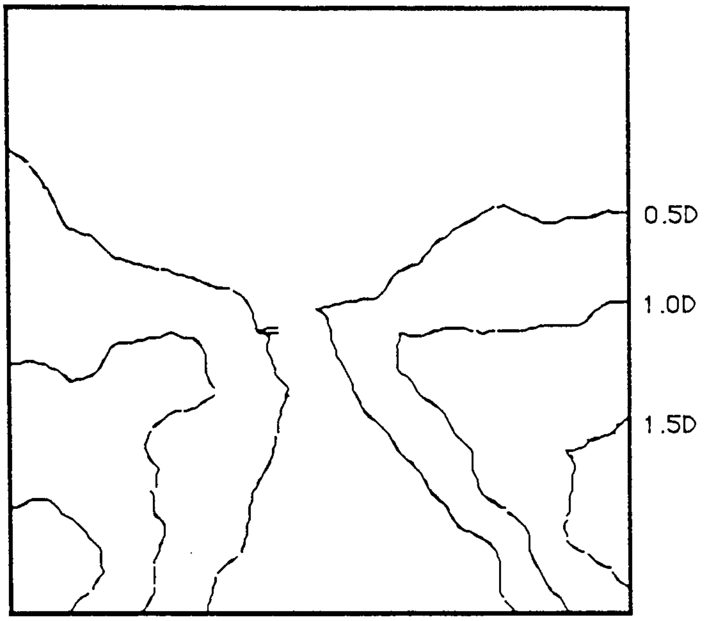
Varilux V2 4.50DS Base

CR39 plano / +3.00DS add



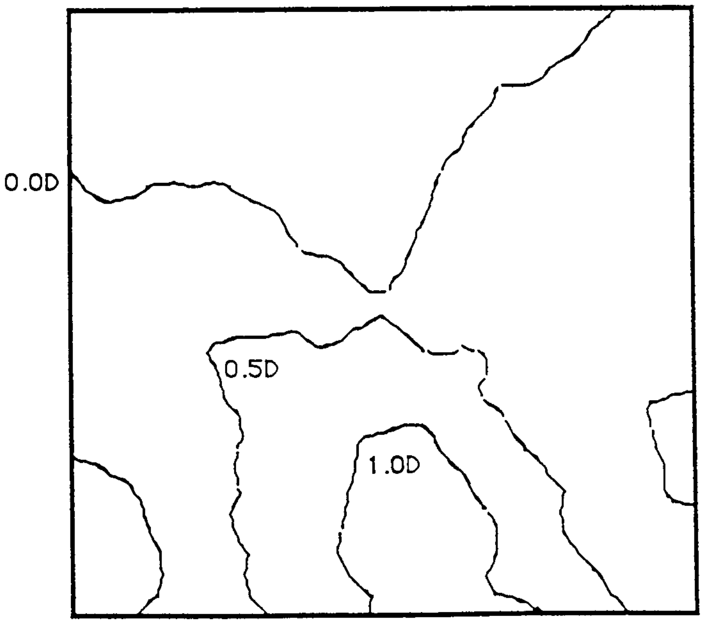
Spherical contour lines 0 to 3.00DS

Varilux V2 7.25DS Base
CR39 plano / +1.00DS add



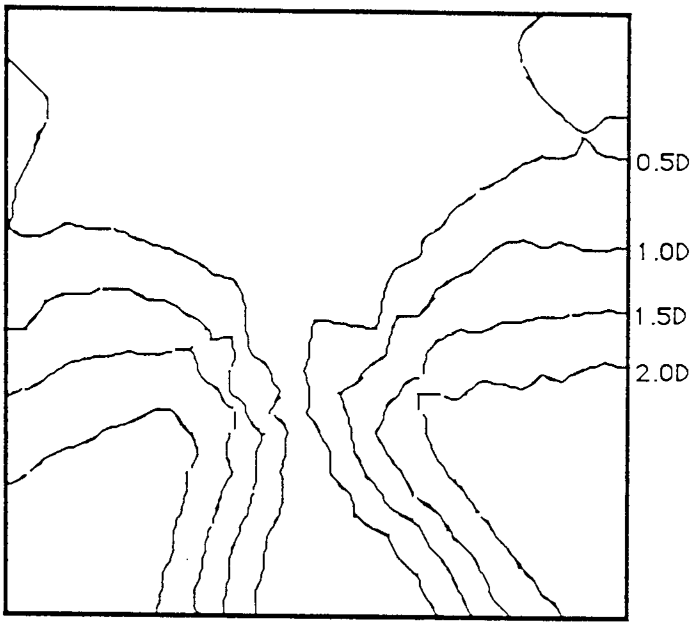
Cylindrical contour lines 0.5 to 1.50D

Varilux V2 7.25DS Base
CR39 plano / +1.00DS add



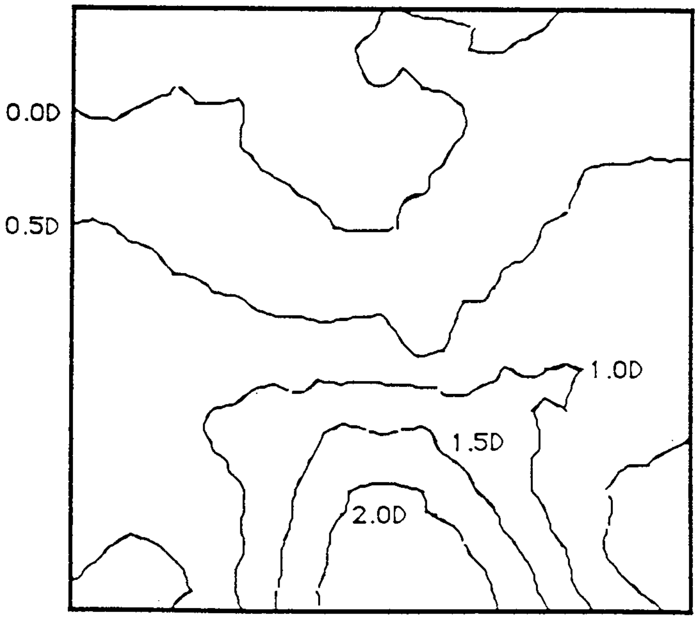
Spherical contour lines 0 to 1.00 DS

Varilux V2 7.25D Base
CR39 plano / +2.00DS add



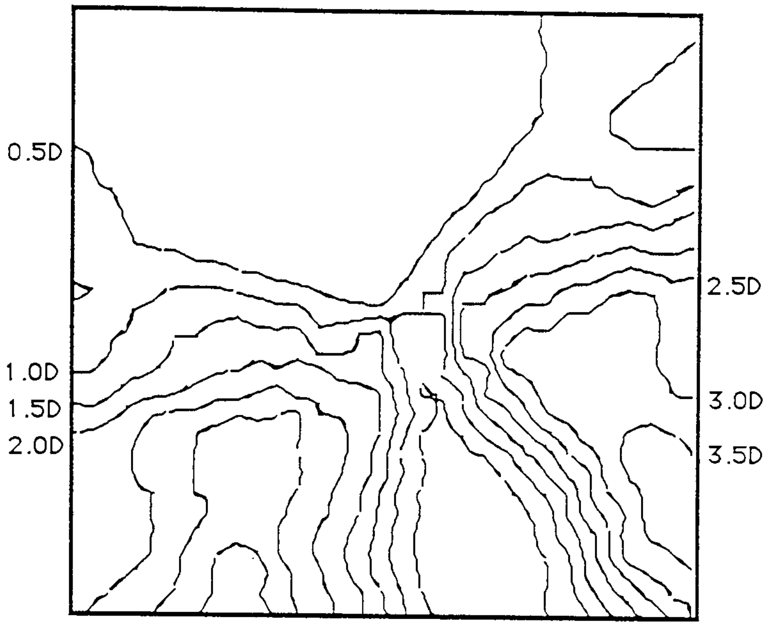
Cylindrical contour lines 0.5 to 2.00D

Varilux V2 7.25DS Base
CR39 plano / +2.00D add



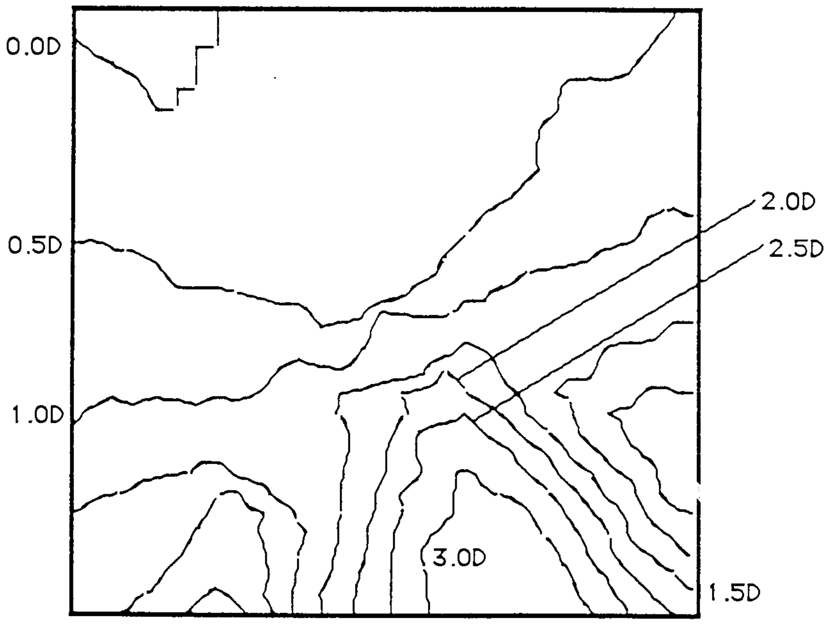
Spherical contour lines 0 to 2.00 DS

Varilux V2 7.25DS Base
CR39 plano / +3.00DS add

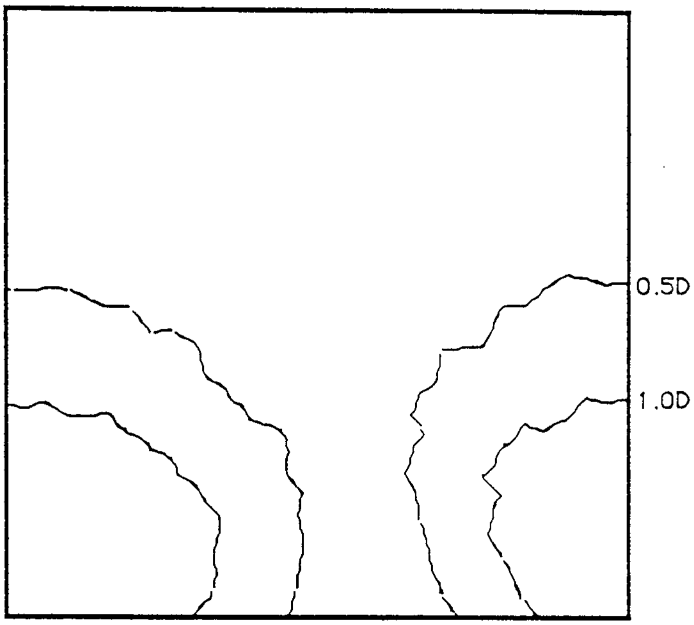


Cylindrical contour lines 0.5 to 3.50D

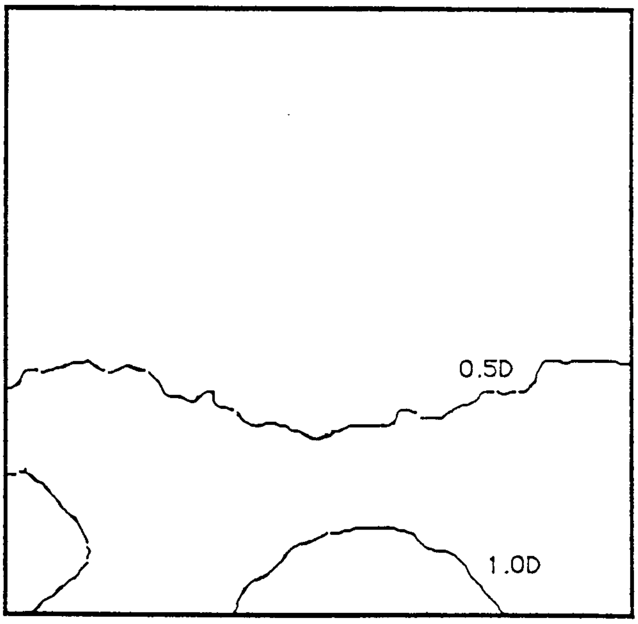
Varilux V2 7.25DS Base
CR39 plano / +3.00DS add



Spherical contour lines 0 to 3.00DS

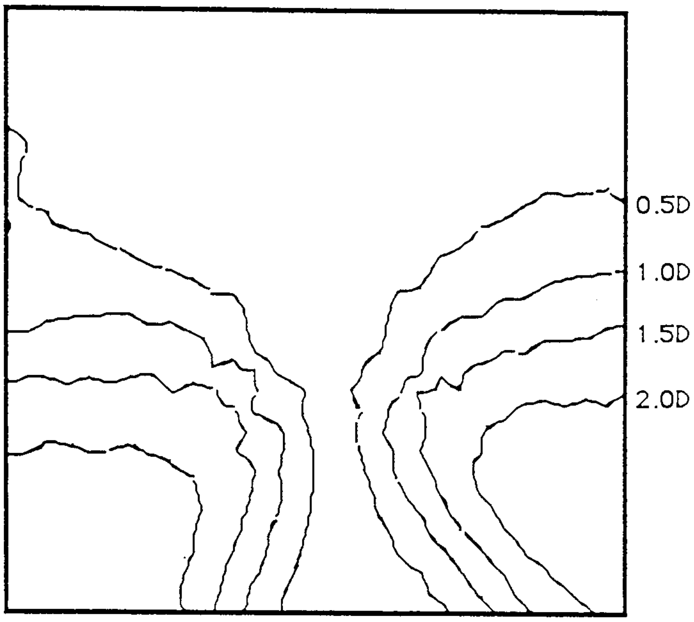

Varilux VMD 4.00DS Base
CR39 plano / +1.00DS add

Cylindrical contour lines 0.5 to 1.00D


Varilux VMD 4.00DS Base
CR39 plano / +1.00DS add

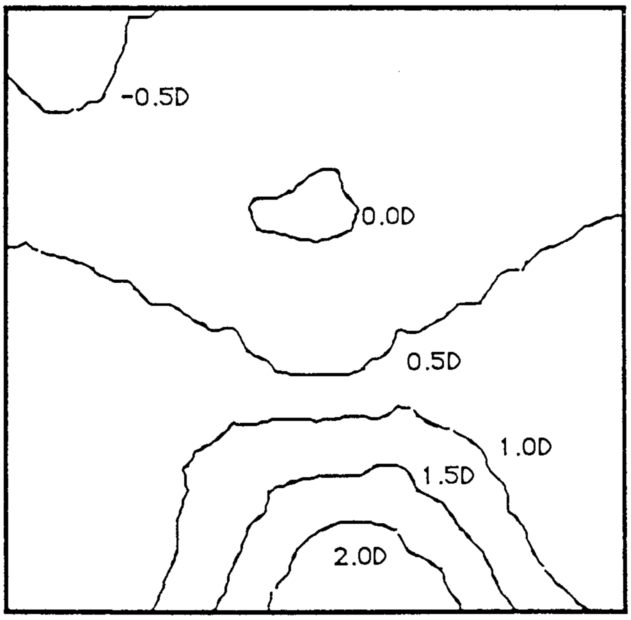
Spherical contour lines 0.5 to 1.00DS

Varilux VMD 4.00DS Base
CR39 plano / +2.00DS add



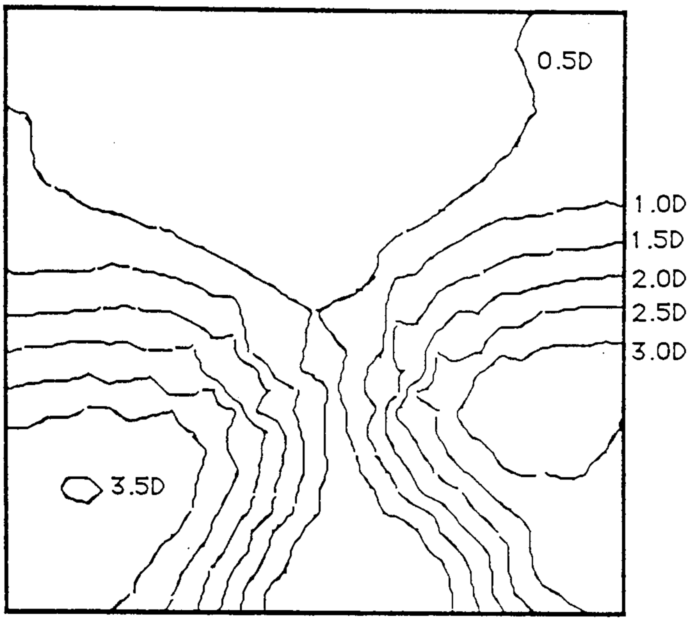
Cylindrical contour lines 0.5 to 2.00D

Varilux VMD 4.00DS Base
CR39 plano/ +2.00DS add



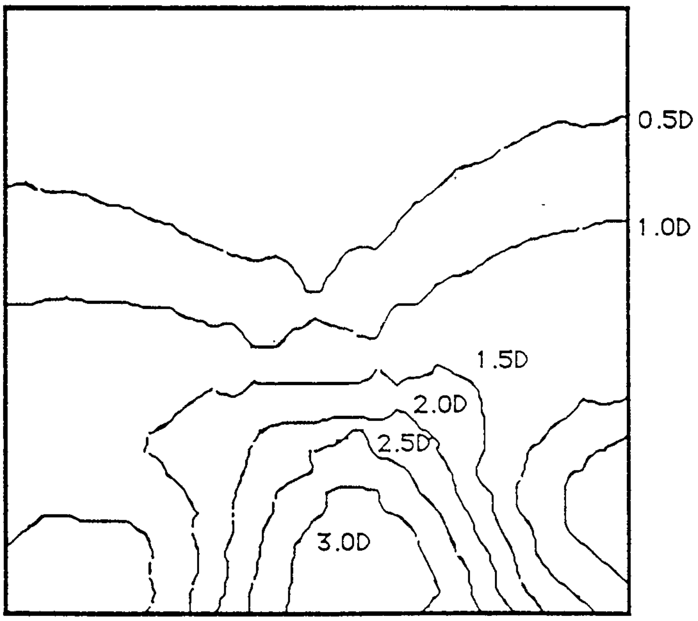
Spherical contour lines -0.5 to 2.00D

Varilux VMD 4.00DS Base
CR39 plano / +3.00DS add



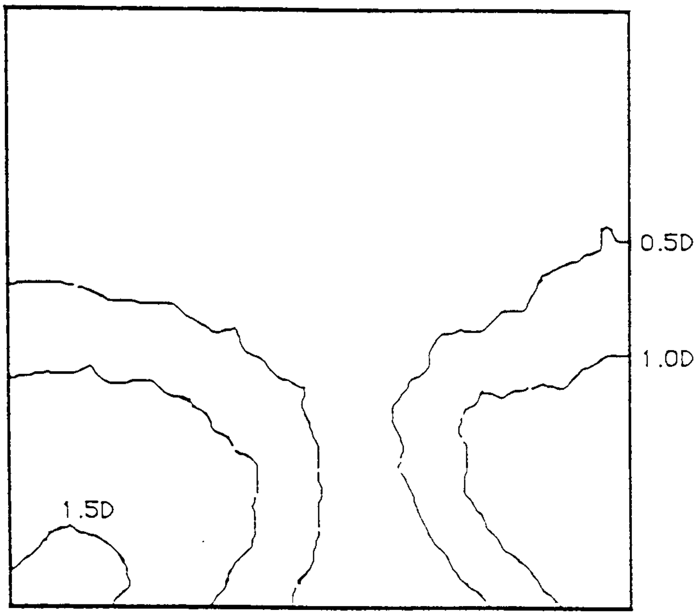
Cylindrical contour lines 0.5 to 3.50D

Varilux VMD 4.00DS Base
CR39 plano / +3.00DS add



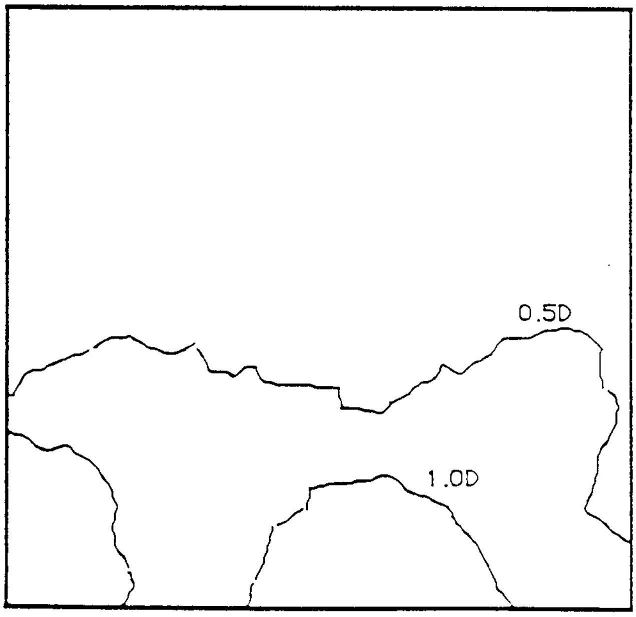
Spherical contour lines 0.5 to 3.00DS

Varilux VMD 6.00DS Base
CR39 plano / +1.00DS add



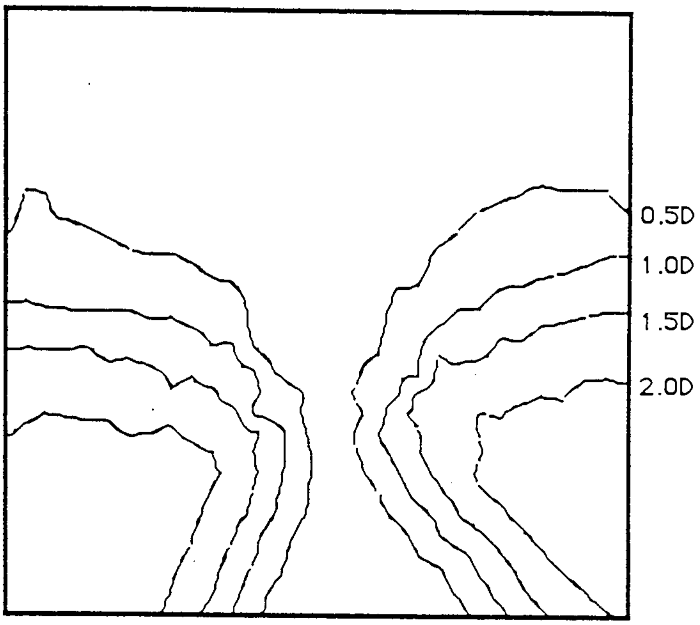
Cylindrical contour lines 0.5 to 1.50D

Varilux VMD 6.00DS Base
CR39 plano /+1.00DS add



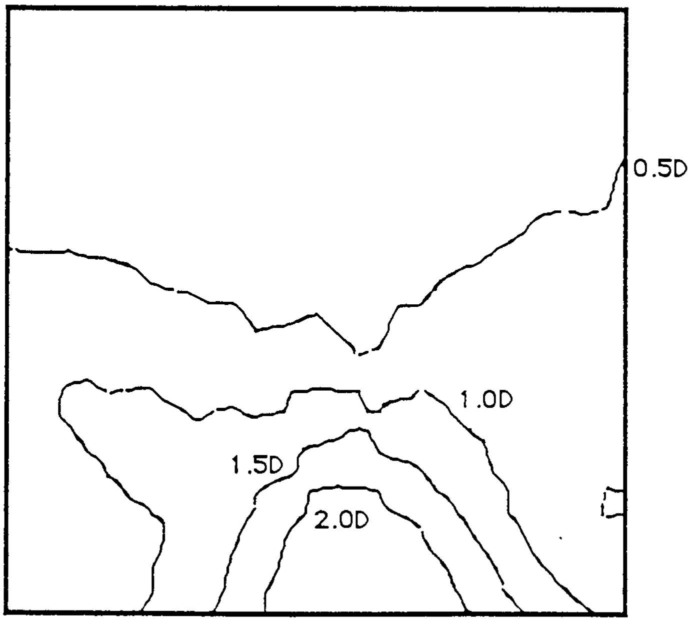
Spherical contour lines 0.5 to 1.00D

Varilux VMD 6.00DS Base
CR39 plano / +2.00DS add



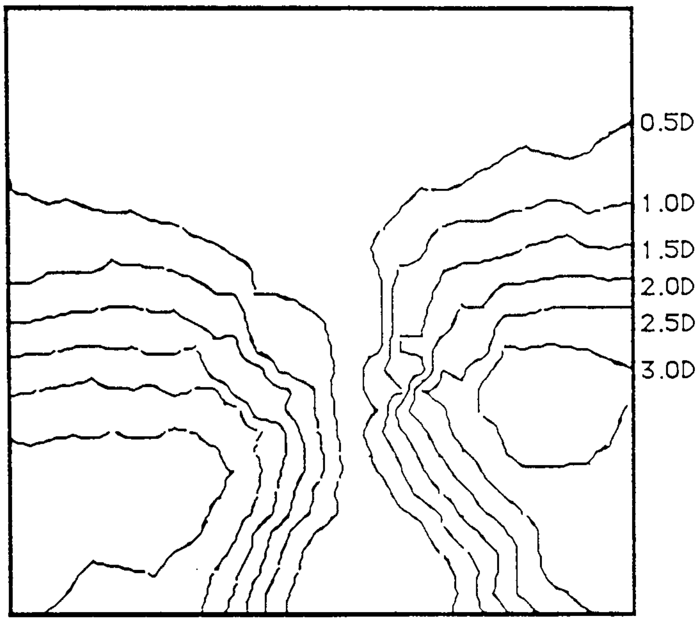
Cylindrical contour lines 0.5 to 2.00D

Varilux VMD 6.00DS Base
CR39 plano /+2.00DS add



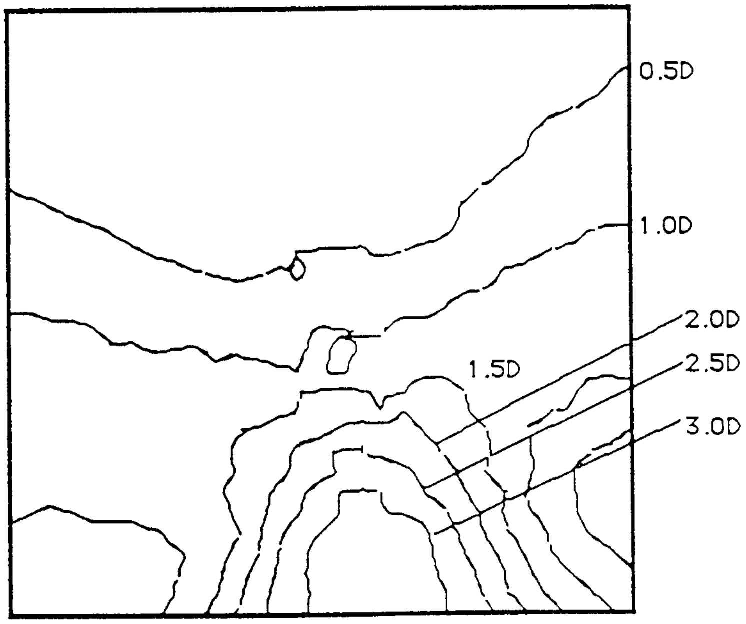
Spherical contour lines 0.5 to 2.00D

Varilux VMD 6.00DS Base
CR39 plano / +3.00DS add



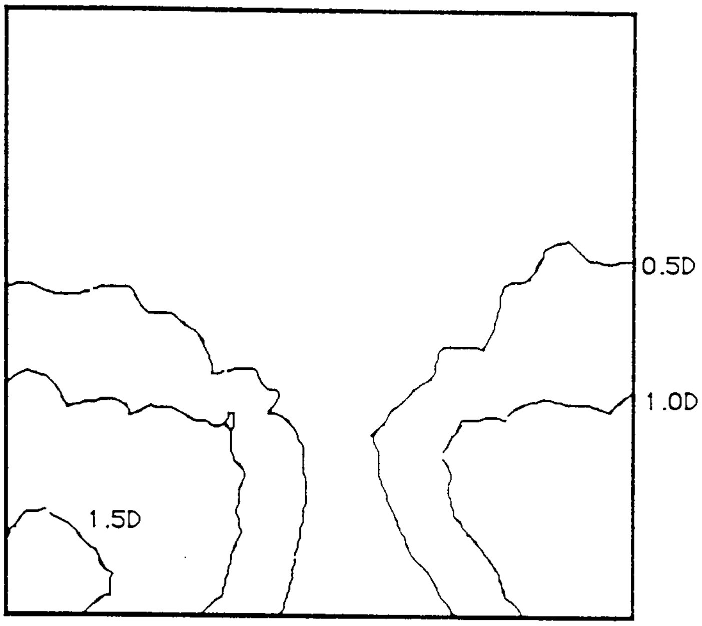
Cylindrical contour lines 0.5 to 3.00D

Varilux VMD 6.00DS Base
CR39 plano / +3.00DS add



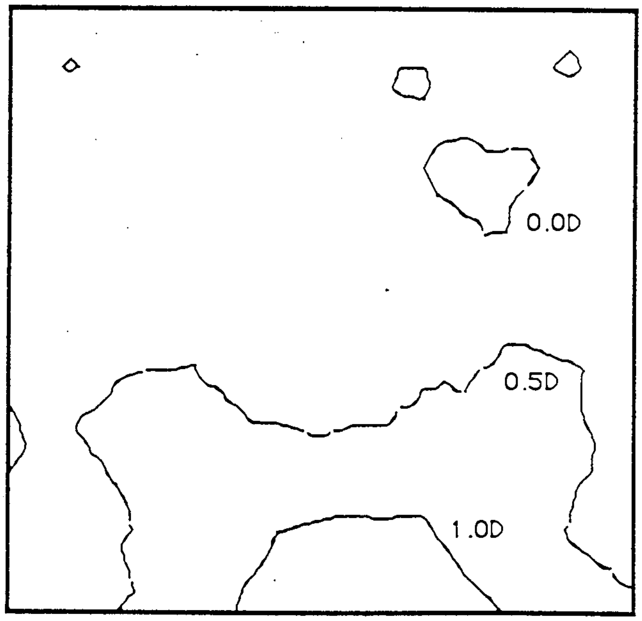
Spherical contour lines 0.5 to 3.00D

Varilux VMD 8.00DS Base
CR39 plano / +1.00DS add



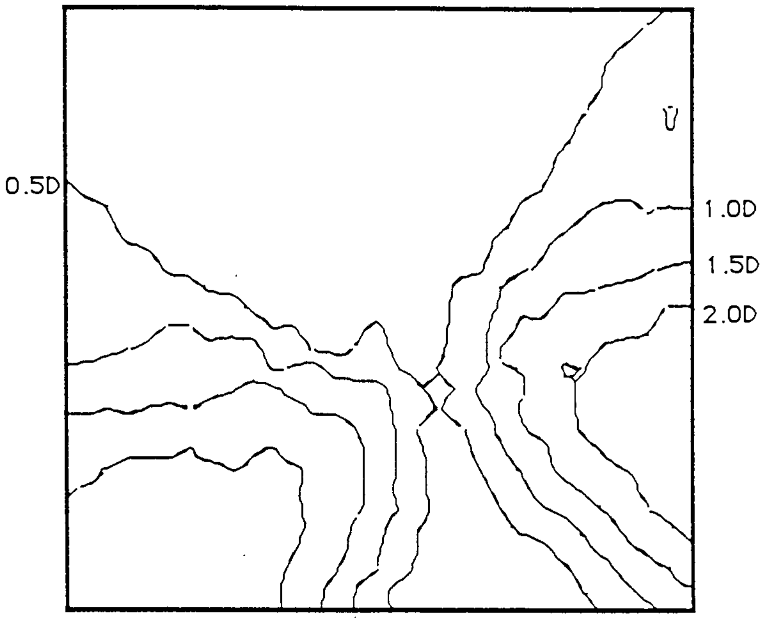
Cylindrical contour lines 0.5 to 1.50D

Varilux VMD 8.00DS Base
CR39 plano / +1.00DS add



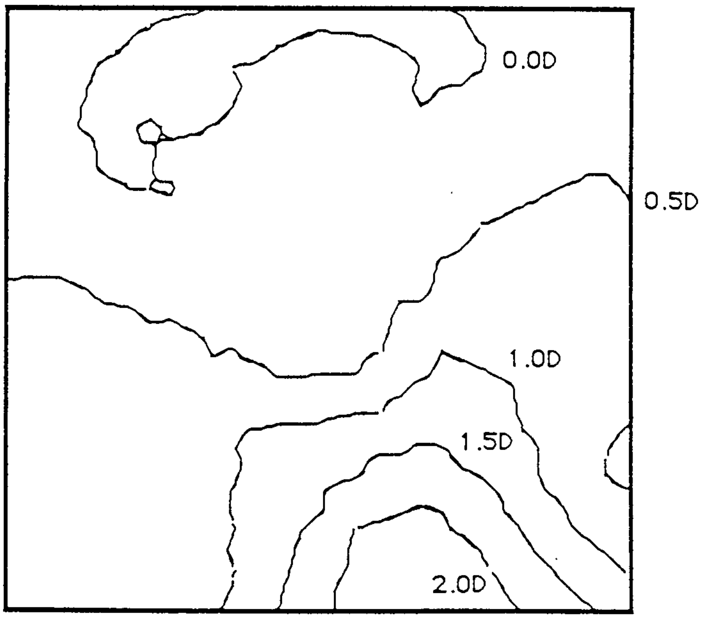
Spherical contour lines 0 to 1.00DS

Varilux VMD 8.00DS Base
CR39 plano / +2.00DS add



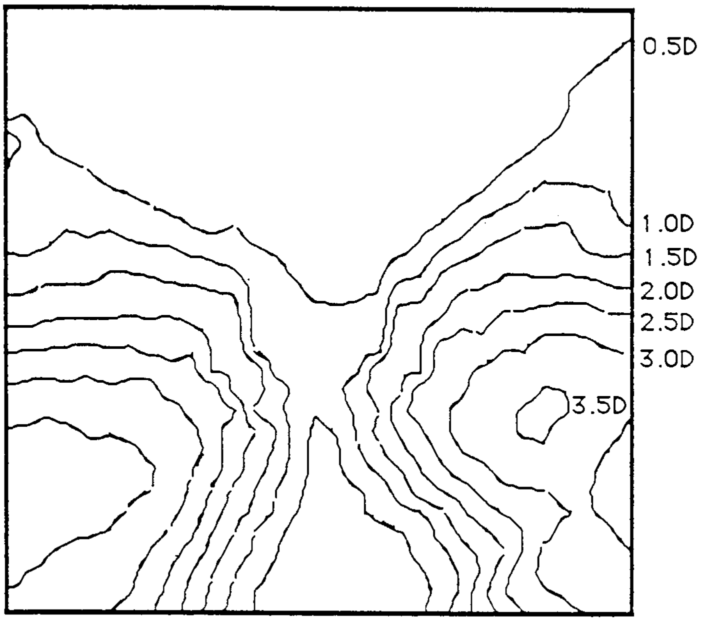
Cylindrical contour lines 0.5 to 2.00D

Varilux VMD 8.00DS Base
CR39 plano / +2.00DS add



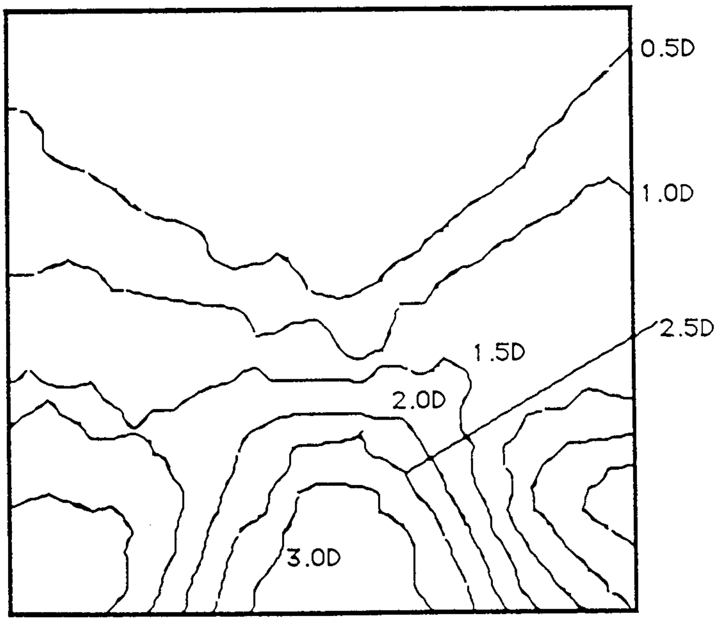
Spherical contour lines 0 to 2.00DS

Varilux VMD 8.00DS Base
CR39 plano / +3.00DS add



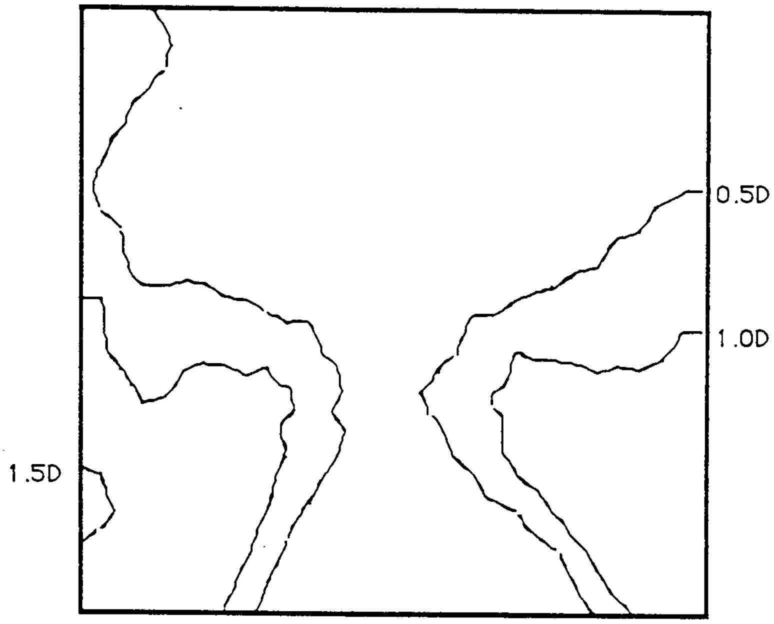
Cylindrical contour lines 0.5 to 3.50D

Varilux VMD 8.00DS Base
CR39 plano / +3.00DS add



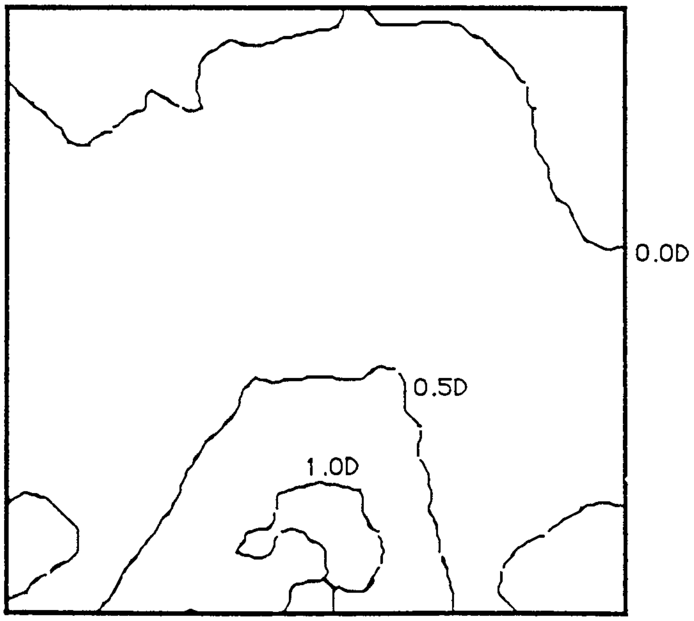
Spherical contour lines 0.5 to 3.00DS

Sola Graduate 2.50DS Base
CR39 plano / +1.00DS add



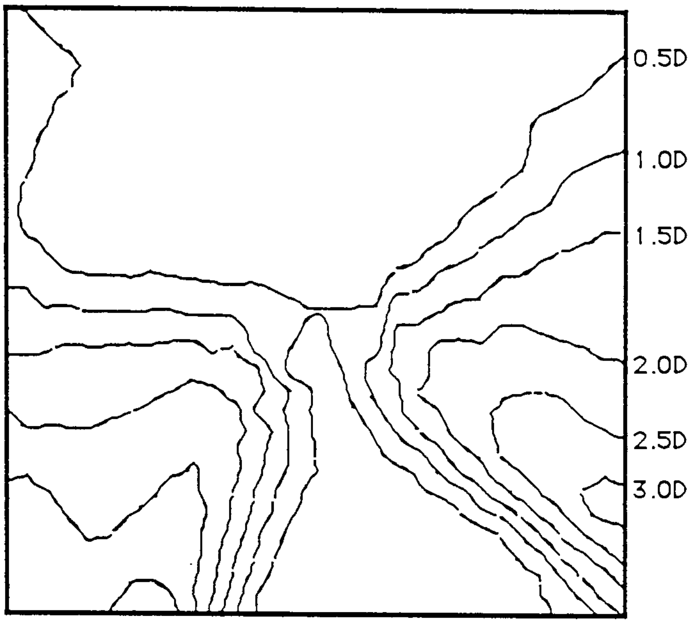
Cylindrical contour lines 0.5 to 1.50D

Sola Graduate 2.50DS Base
CR39 plano / +1.00DS add



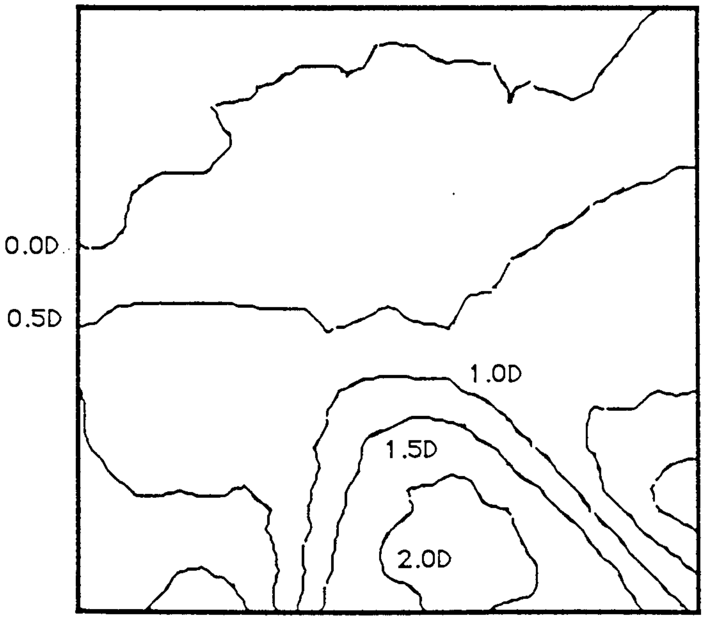
Spherical contour lines 0 to 1.00DS

Sola Graduate 2.50DS Base
CR39 plano / +2.00DS add

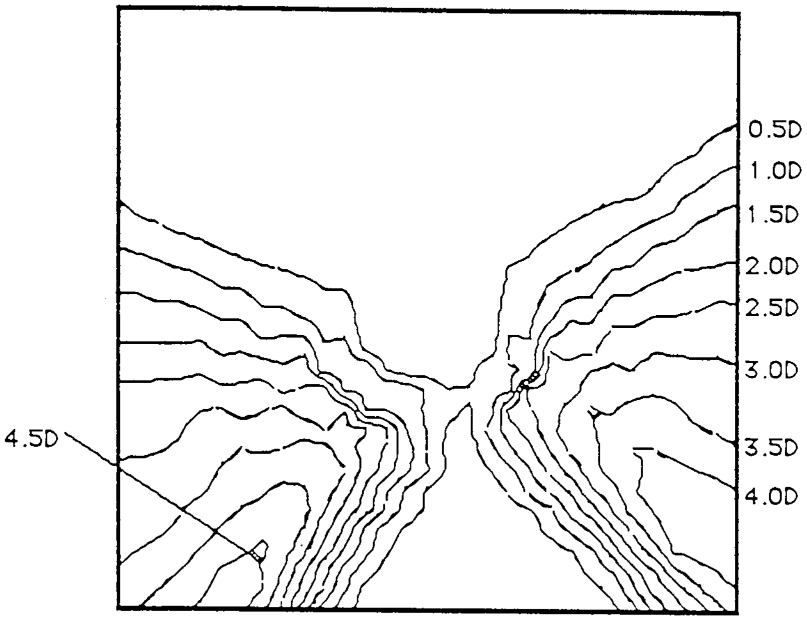


Cylindrical contour lines 0.5 to 3.00D

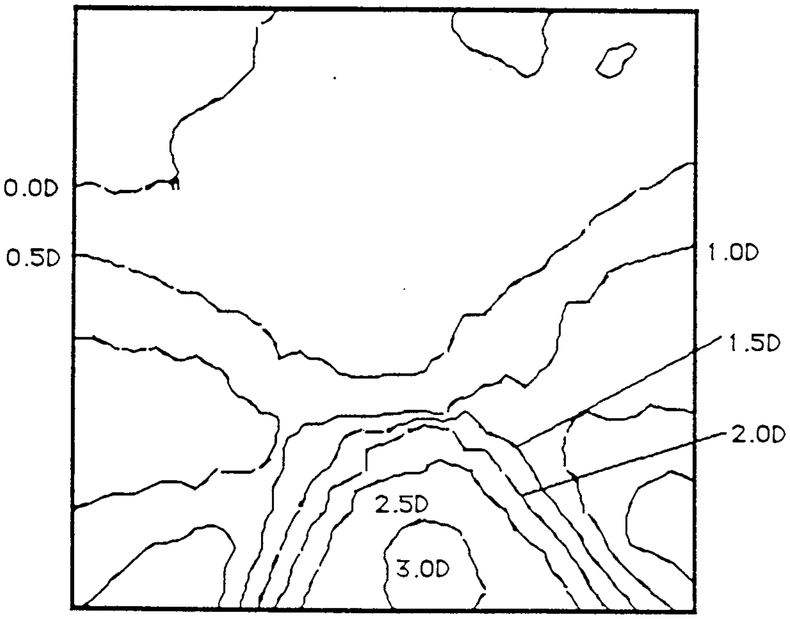
Sola Graduate 2.50DS Base
CR39 plano / +2.00DS add



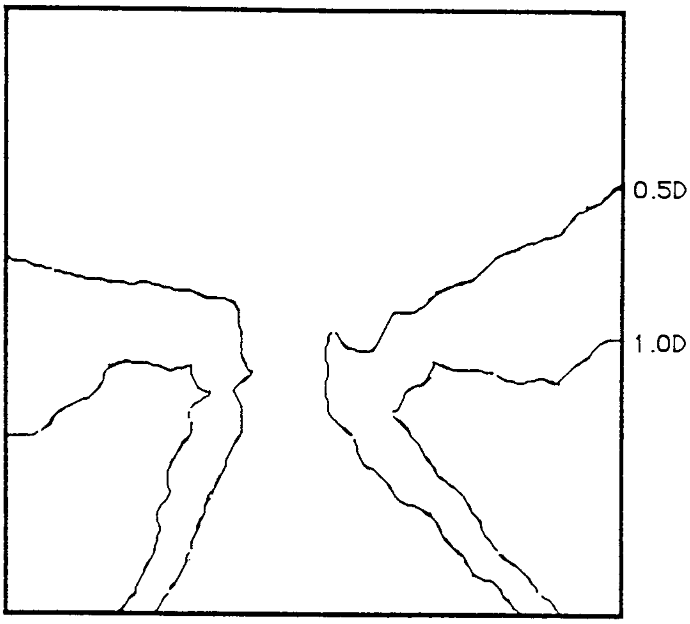
Spherical contour lines 0 to 2.00DS


Sola Graduate 2.50DS Base
CR39 plano / +3.00DS add

Cylindrical contour lines 0.5 to 4.50D

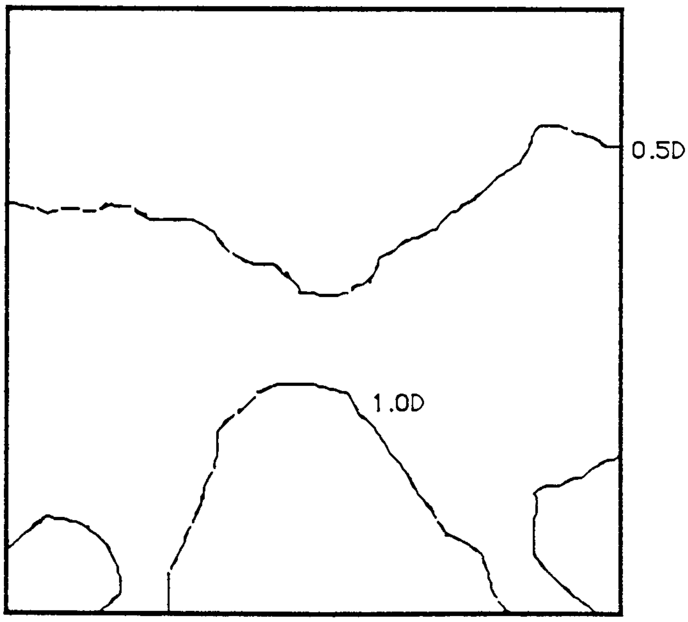

Sola Graduate 2.50DS Base
CR39 plano / +3.00DS add

Spherical contour lines 0 to 3.00 DS



Sola Graduate 4.00DS Base
CR39 plano / +1.00DS add

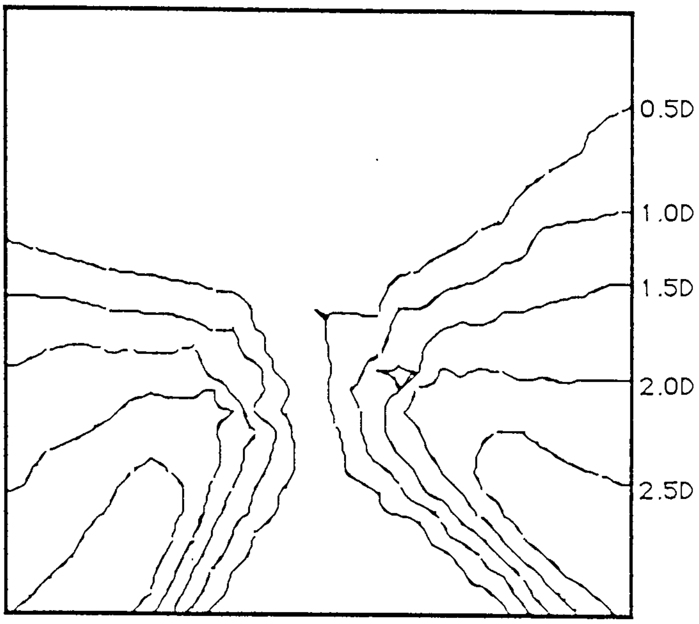
Cylindrical contour lines 0.5 to 1.00D



Sola Graduate 4.00DS Base
CR39 plano / +1.00DS add

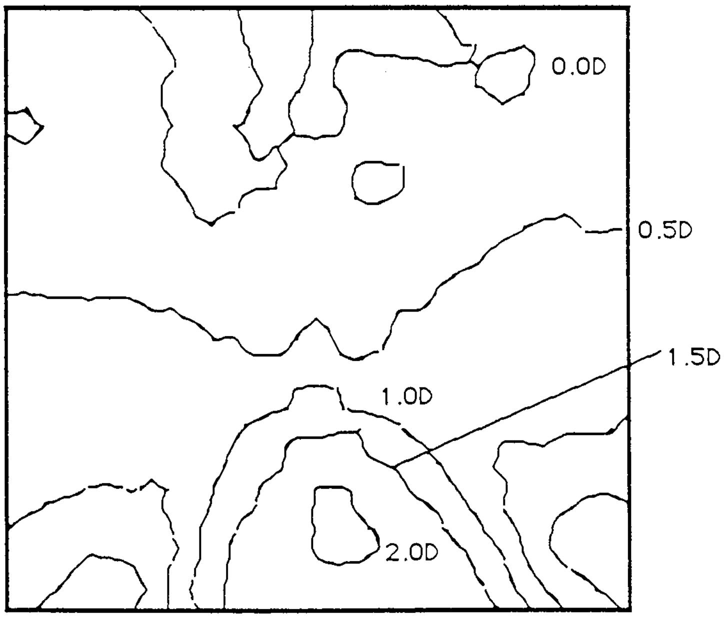
Spherical contour lines 0.5 to 1.00D

Sola Graduate 4.00DS Base
CR39 plano / +2.00DS add



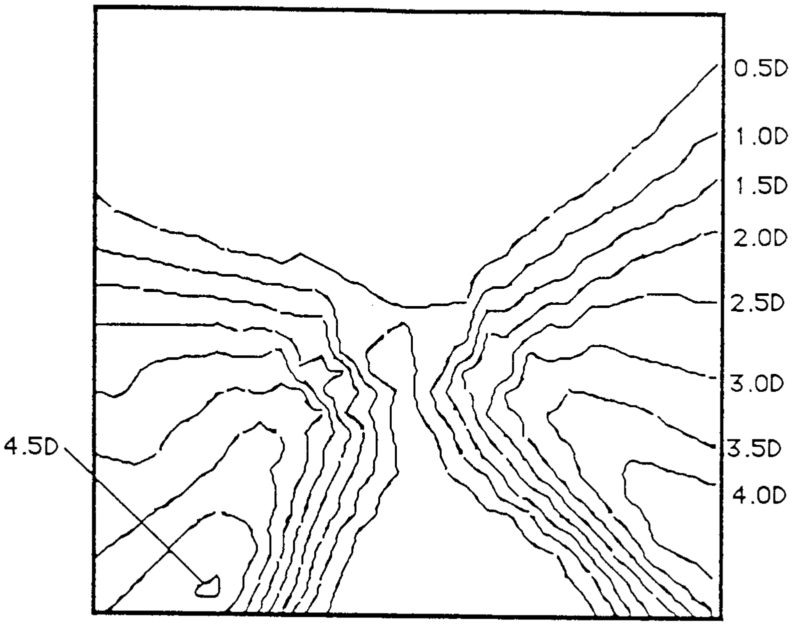
Cylindrical contour lines 0.5 to 2.50D

Sola Graduate 4.00DS Base
CR39 plano / +2.00DS add



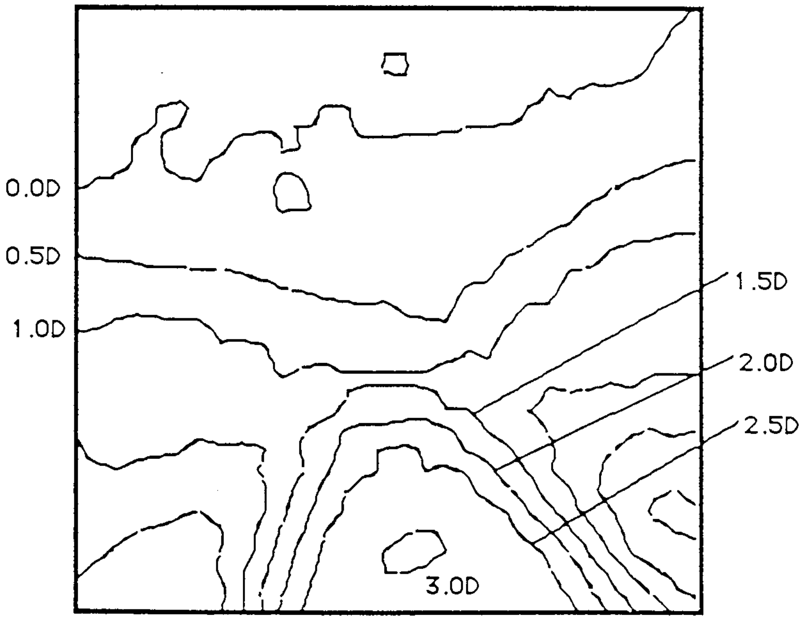
Spherical contour lines 0 to 2.00DS

Sola Graduate 4.00DS Base
CR39 plano / +3.00DS add



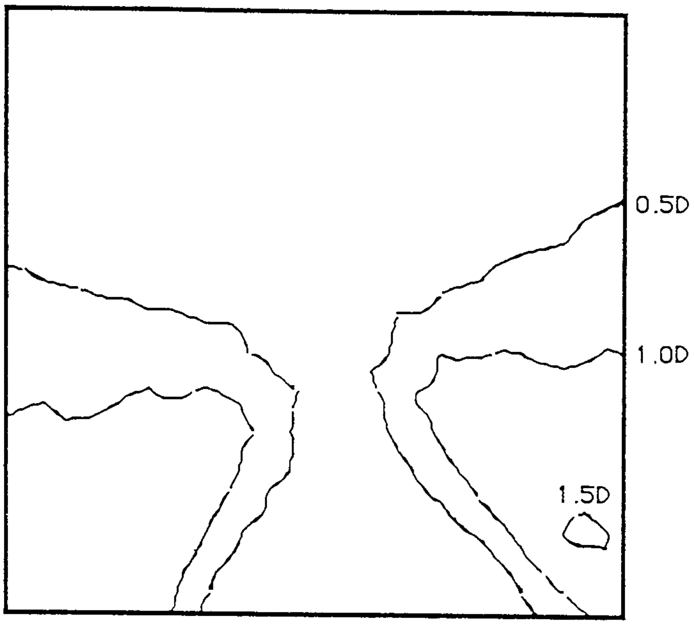
Cylindrical contour lines 0.5 to 4.50D

Sola Graduate 4.00DS Base
CR39 plano /+3.00DS add



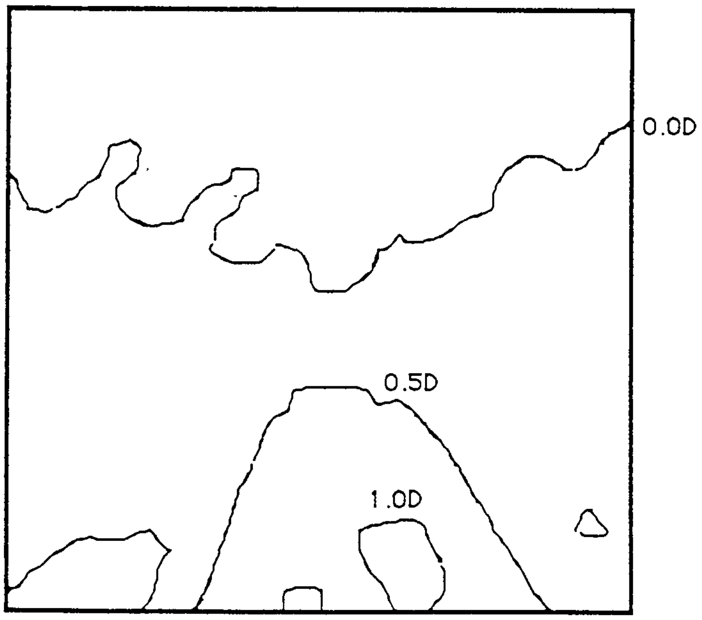
Spherical contour lines 0 to 3.00 DS

Sola Graduate 8.00DS Base
CR39 plano / +1.00DS add



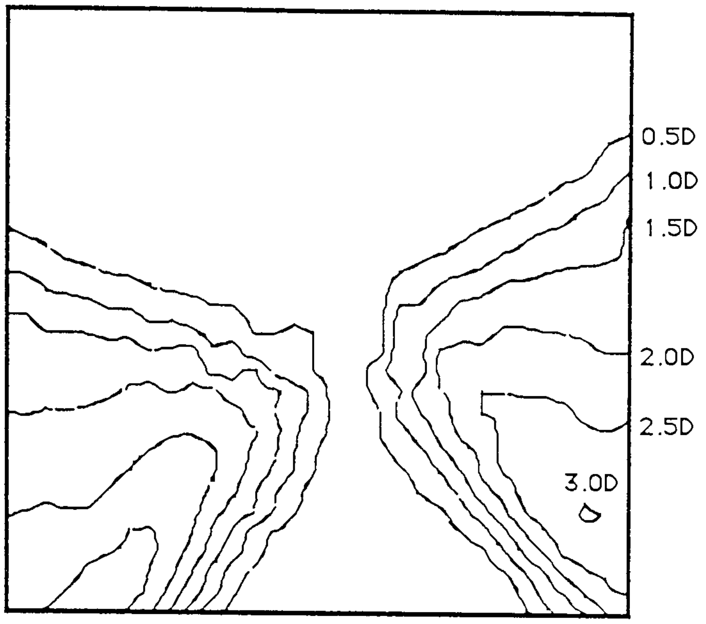
Cylindrical contour lines 0.5to 1.50D

Sola Graduate 8.00DS Base
CR39 plano / +1.00DS add



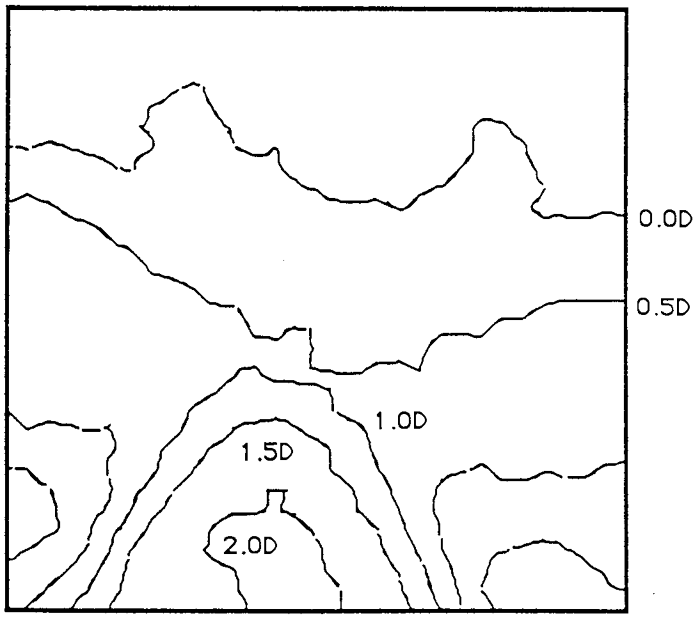
Spherical contour lines 0 to 1.00DS

Sola Graduate 8.00DS Base
CR39 plano /+2.00DS add



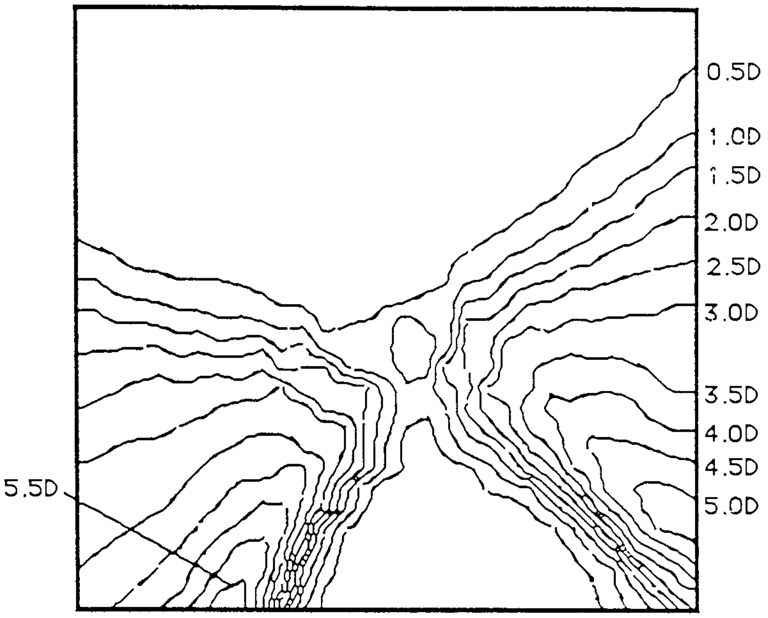
Cylindrical contour lines 0.5 to 3.00D

Sola Graduate 8.00DS Base
CR39 plano / +2.00DS add



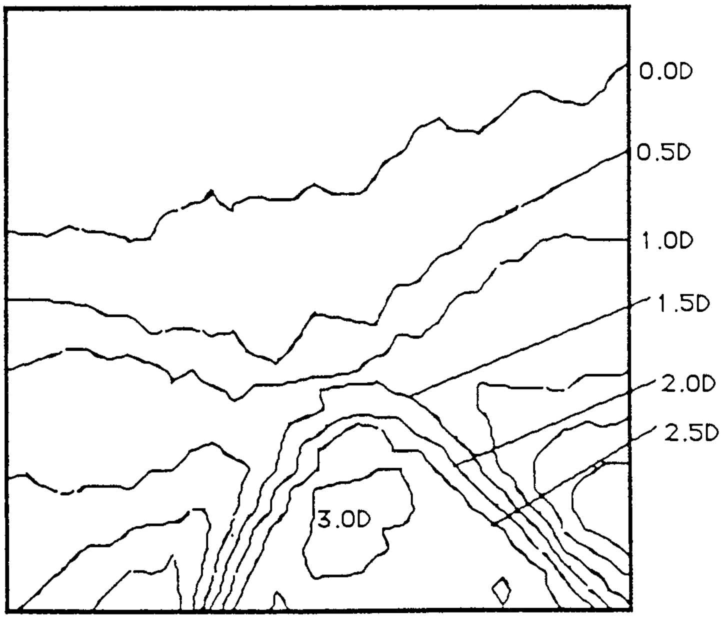
Spherical contour lines 0 to 2.00DS

Sola Graduate 8.00DS Base
CR39 plano / +3.00DS add



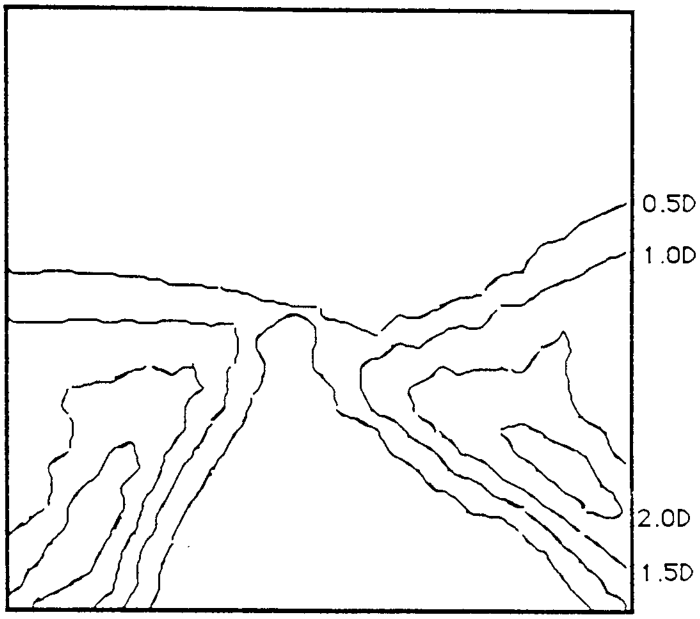
Cylindrical contour lines 0.5 to 5.50D

Sola Graduate 8.00 DS Base
CR39 plano / +3.00DS add



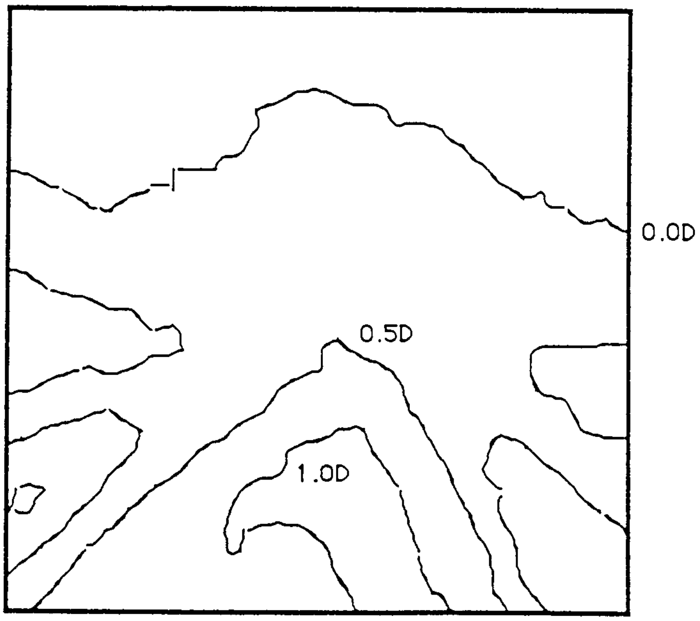
Spherical contour lines 0 to 3.00DS

Vision-Ease Delta 2.00DS Base
CR39 plano / +1.00DS add



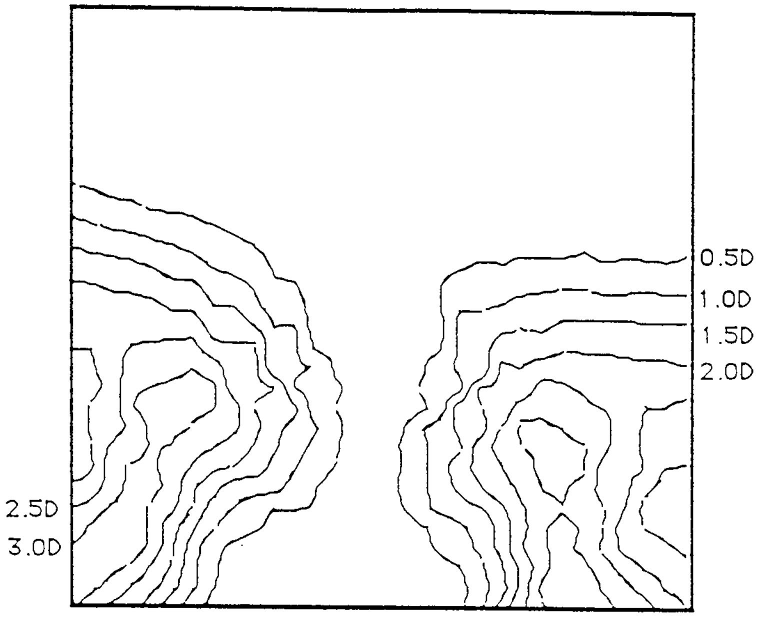
Cylindrical contour lines 0.5 to 2.00D

Vision-Ease Delta 2.00DS Base
CR39 plano / +1.00DS add



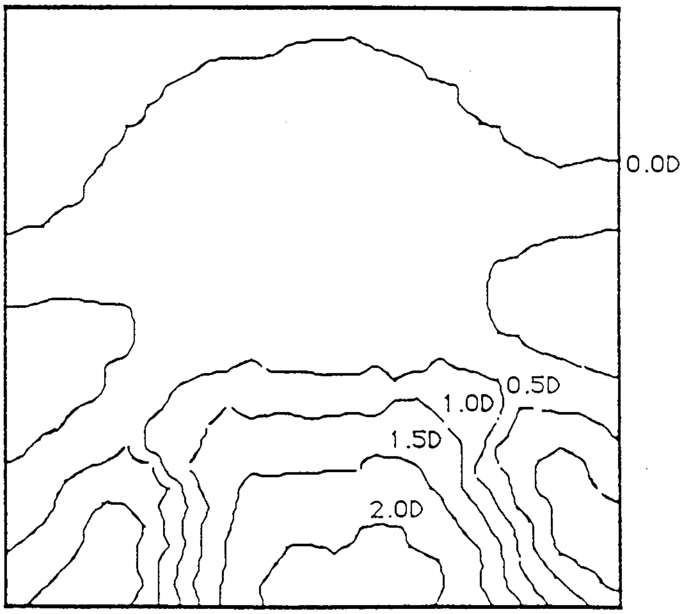
Spherical contour lines 0 to 1.00 D

Vision-Ease Delta 2.00DS Base
CR39 plano / +2.00DS add



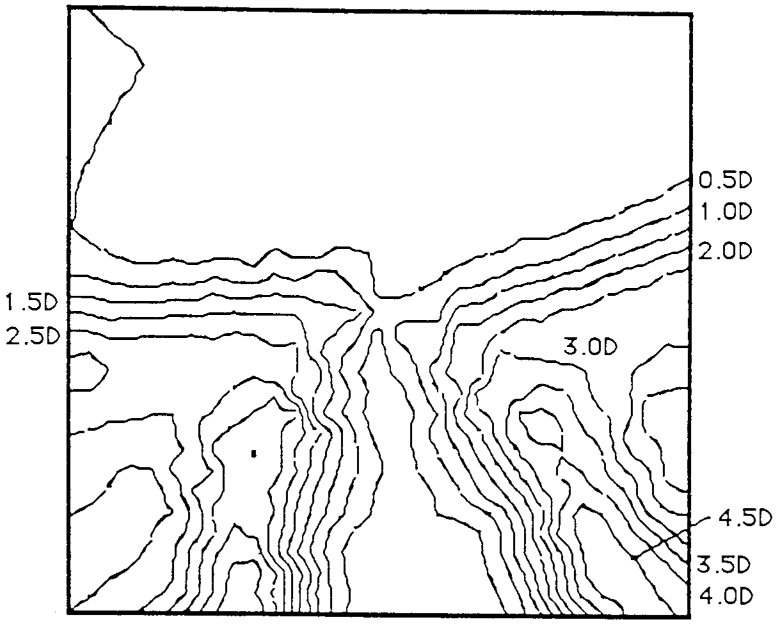
Cylindrical contour lines 0.5 to 3.00 D

Vision-Ease Delta 2.00DS Base
CR39 plano / +2.00DS add



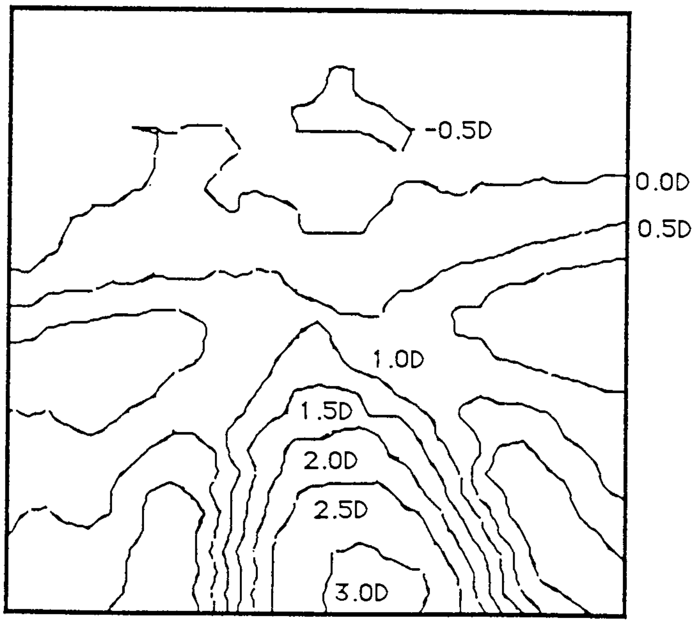
Spherical contour lines 0 to 2.00DS

Vision-Ease Delta 2.00DS Base
CR39 plano / +3.00DS add

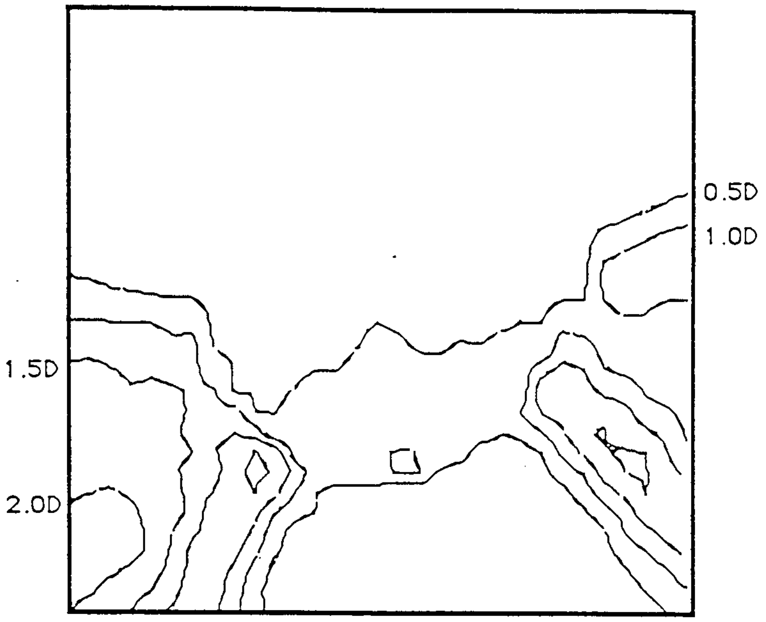


Cylindrical contour lines 0.5 to 4.50D

Vision-Ease Delta 2.00DS Base
CR39 plano / +3.00DS add

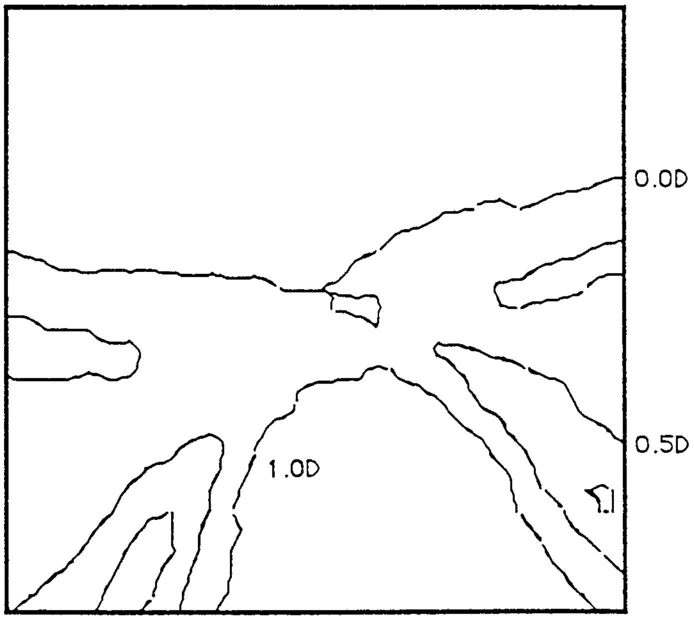


Spherical contour lines -0.5 to 3.00D



Vision-Ease Delta 5.00DS Base
CR39 plano / +1.00DS add

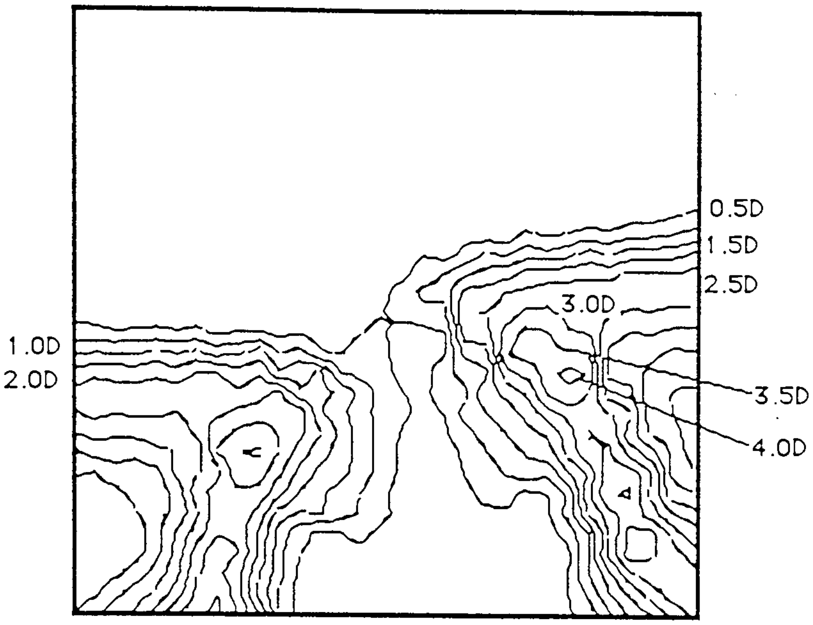
Cylindrical contour lines 0.5 to 2.00D



Vision-Ease Delta 5.00DS Base
CR39 plano/+1.00DS add

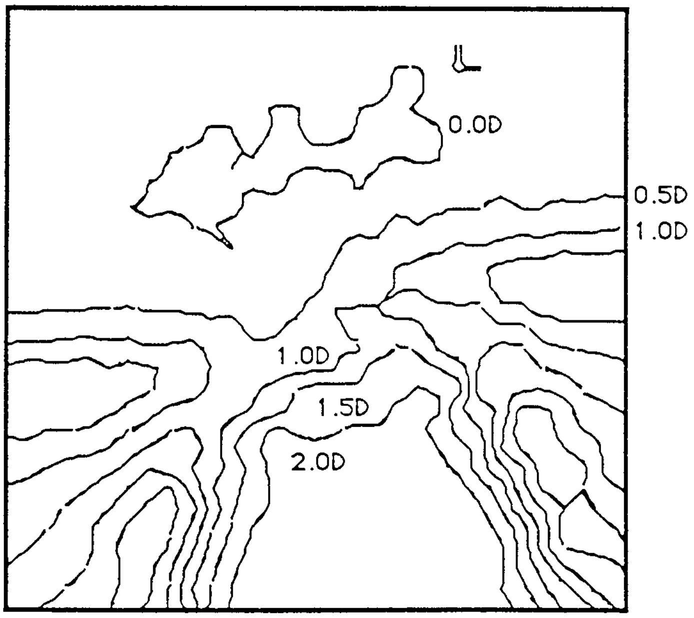
Spherical contour lines 0 to 1.00DS

Vision-Ease Delta 5.00DS Base
CR39 plano / +2.00DS add



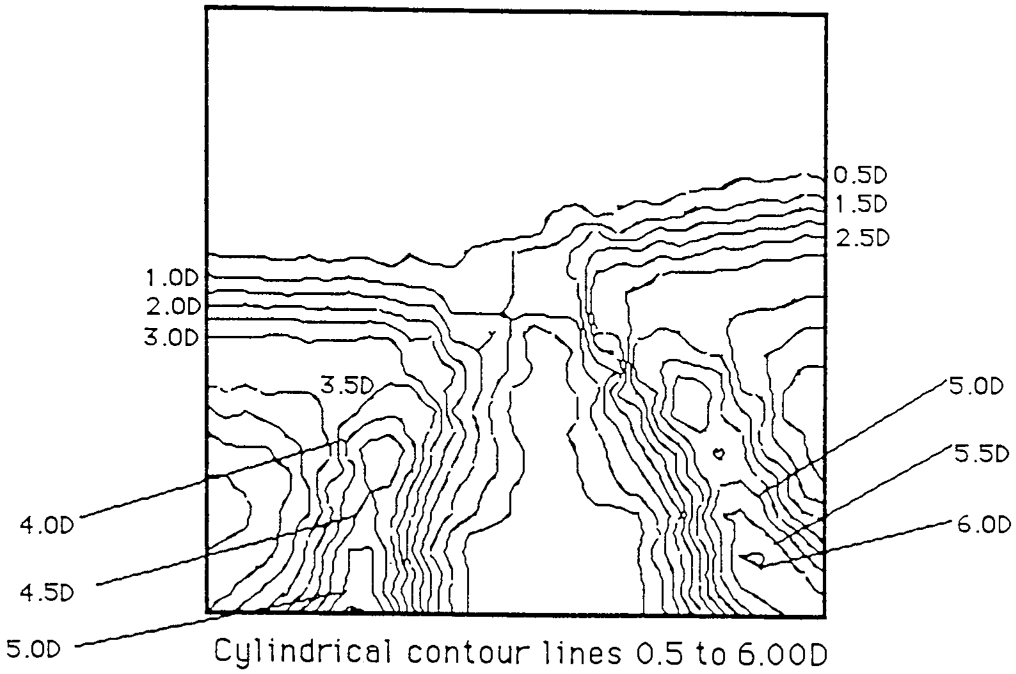
Cylindrical contour lines 0.5 to 4.00D

Vision-Ease Delta 5.00DS Base
CR39 plano / +2.00DS add



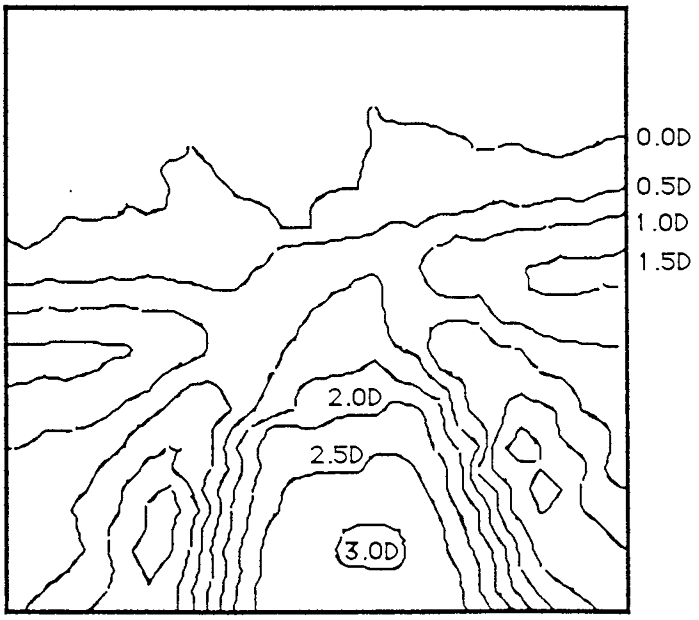
Spherical contour lines 0 to 2.00DS

Vision-Ease Delta 5.00DS Base
CR39 plano /+3.00DS add



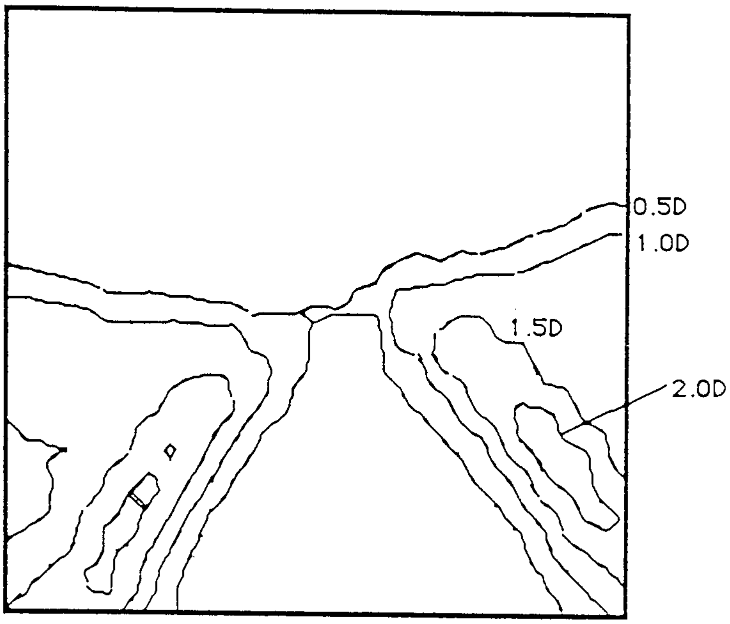
Cylindrical contour lines 0.5 to 6.00D

Vision-Ease Delta 5.00DS Base
CR39 plano / +3.00DS add



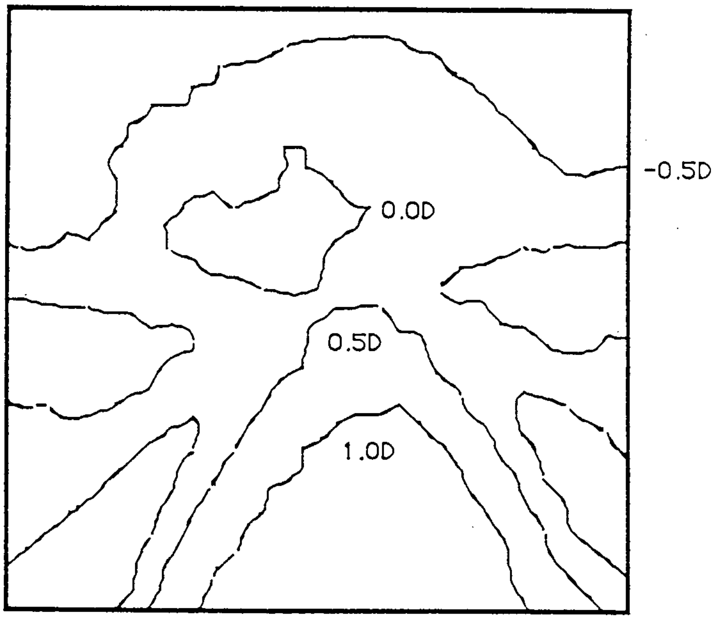
Spherical contour lines 0 to 3.00DS

Vision-Ease Delta 7.00D Base
CR39 plano / +1.00DS add



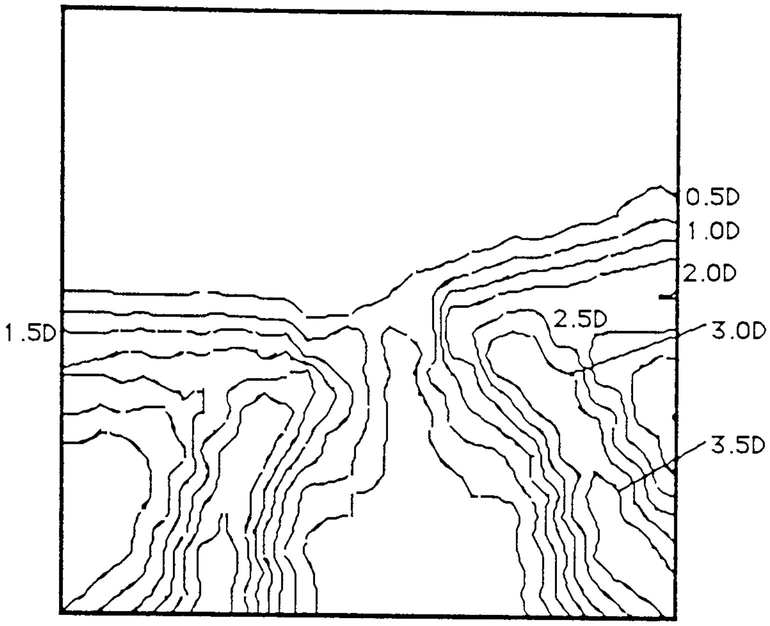
Cylindrical contour lines 0.5 to 2.00D

Vision-Ease Delta 7.00DS Base
CR39 plano / +1.00DS add



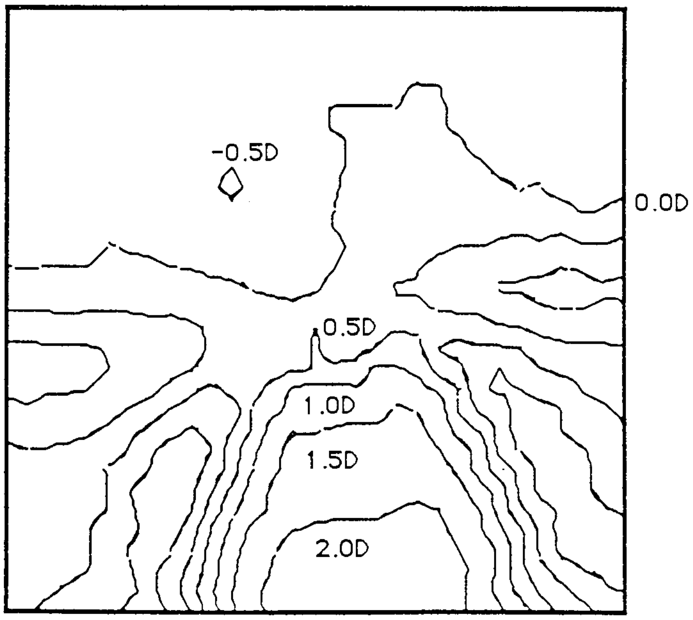
Spherical contour lines-0.5 to 1.00DS

Vision-Ease Delta 7.00DS Base
CR39 plano / +2.00DS add



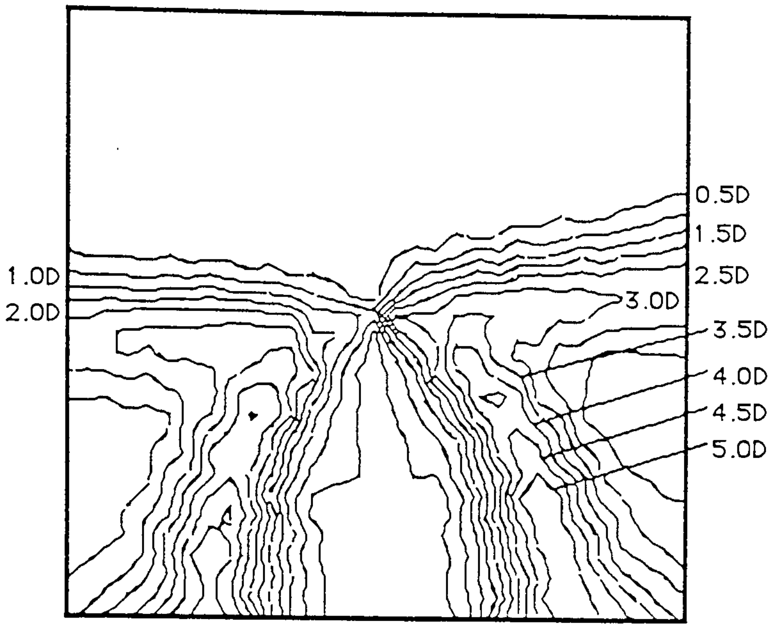
Cylindrical contour lines 0.5 to 3.50D

Vision-Ease Delta 7.00D Base
CR39 plano /+2.00DS add



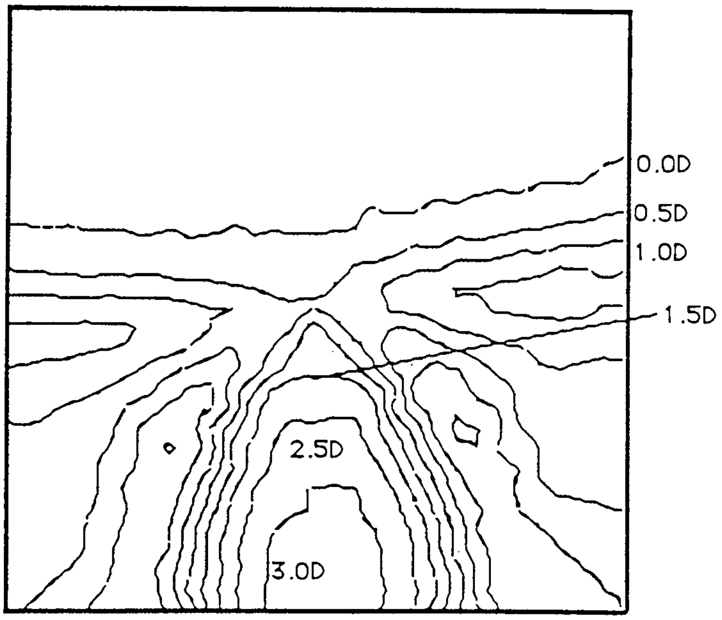
Spherical contour lines -0.5 to 2.00D

Vision-Ease Delta 7.00D Base
CR39 plano /+3.00DS add



Cylindrical contour lines 0.5 to 5.00 D

Vision-Ease Delta 7.00D Base
CR39 plano / +3.00DS add



Spherical contour lines 0 to 3.00DS

# Appendix 2

## BBC BASIC Programs

(A) BBC BASIC program for transferring numerical data in iso-cylindrical form to the Macintosh computer from the BBC Acorn 'B' computer.

(B) BBC BASIC program for transferring numerical data in mean spherical form to the Macintosh computer from the BBC Acorn 'B' computer.

(C) BBC BASIC program for driving the Nidek automatic focimeter and the automatic recording of numerical data.

(A) BBC basic program for transferring numerical data in iso-cylindrical form to the Macintosh computer from the BBC Acorn 'B' computer.

```
 1*CAT
 2 *FX8.3
 3 REM ABOVE LINE IS 300 BAUD TRANSMIT
 5 INPUT "OPEN FILE NAMED",F$
10 V=OPENIN F$
11 *FX5.2
12 VDU2
20 FOR Z=1 TO 798
25 INPUT£V,A,B,A$,X,Y,CYL.AX,SPH
30 PRINT A;" ";A$;" ";B;", ";X;",";Y;",":CYL
35 VDU 1,10
40 NEXT
45 VDU3
50 CLOSE£ V
```

(B) BBC basic program for transferring numerical data in mean spherical form to the Macintosh computer from the BBC Acorn 'B' computer.

```
 1*CAT
 2 *FX8,3
 3 REM ABOVE LINE IS 300 BAUD TRANSMIT
 5 INPUT "OPEN FILE NAMED",F$
10 V=OPENIN F$
11 *FX5,2
12 VDU2
20 FOR Z=1 TO 798
25 INPUT£V,A,B,A$,X,Y,CYL,AX,SPH
30 PRINT A;" ";A$;" ";B;", ";X;",";Y;",";SPH+CYL/2
35 VDU 1,10
40 NEXT
45 VDU3
50 CLOSE£ V
```

(C) BBC basic program for driving the Nidek automatic focimeter and the automatic recording of numerical data.

```
 10CLS
 15 REM L VARIABLE IS THE INITIAL LINE NUMBER ADDITIVE
 20 L=0
 30 REM TWO AXIS STEPPER MOTOR CONTROL
 32 REM AND NIDEK OPERATING PROGRAM
 35 CON=25 :REM OFFSET OF COORDINATE SYSTEM
 36 *CAT
 40 INPUT "DATA FILE NAME".F$
 50 U=OPENOUT F$
 60 *KEY 0 RUN |M
 70 *KEY 1 *RES |M
 80 *KEY 2 *M2F0001 |M
 90 *KEY 3 *M2R0001 |M
100 *KEY 4 *M1F0001  |M
110 *KEY 5 *M1R0001  |M
120 PRINT"ADJUST POSITION OF LENS USING F3 AND F2 (MOTOR 2)"
125 PRINT"AND F5 AND F4 (MOTOR 1) THEN CONTINUE"
126 PRINT"BY TYPING GOTO 135"
130 STOP
135 *ZER
140 *FX 5.1
150 DIM D(100)
160 INPUT "NUMBER OF STEPS".K
170 FOR Y=1 TO K
175 HY=Y*SIN(RAD(2.176))*63.5
180 VDU2
190 PRINT "ANGLE ":Y*2:" DEGREES"
200 *M1F0034
210 FOR I=1 TO 2000:NEXT I
220 FOR Q=1 TO 114
225 TH=RAD(Q*10*0.3158)
230 VDU2
240 PRINT "RADIAL":Q
250 VDU3
260 SPH$=""
270 CYL$=""
280 AX$=""
290 FOR I=1 TO 2000:NEXT I
300 *M2F0010
310 FOR I=1 TO 5000:NEXT
320*FX 2,1
330*FX 5,2
340*FX 7,7
350*FX 8,7
360*MOTOR 1
370 VDU 2
380 VDU1,1
390 VDU1.67
400 VDU1,76
410 VDU1.77
420 VDU1,2
430 VDU1,82
440 VDU1,68
450 VDU1.23
```

```
460 VDU1.4
470 VDU3
480 FOR X=1 TO 200:NEXT
490 *MOTOR 0
500 FOR I=1 TO 500:NEXT
510 *FX21.1
520 *MOTOR 1
530 FOR X=1 TO 105:NEXT X
540 VDU 2
550 VDU1.1
560 VDU1.67
570 VDU1.76
580 VDU1.77
590 VDU1.2
600 VDU1.83
610 VDU1.68
620 VDU1.23
630 VDU1.4
640 VDU3
650 FOR C=1 TO 42: D(C)=GET:NEXT
660 *MOTOR 0
670 *FX2.2
680 PRINT
690 *FX5.1
700 VDU2
710 FOR C=1 TO 42
720 IF D(C)>127 THEN LET D(C)=D(C)-128
730 IF D(C)>31 THEN PRINT CHR$( D(C)):
740 IF D(C)=23 THEN PRINT " ":
750 NEXT
760 FOR X=8 TO 13
770 SPH$=SPH$+CHR$(D(X))
780 NEXT
790 SPH=VAL(SPH$)
800 FOR X=14 TO 19
810 CYL$=CYL$+CHR$(D(X))
820 NEXT
830 CYL=VAL(CYL$)
840 FOR X=20 TO 22
850 AX$=AX$+CHR$(D(X))
855 NEXT
860 AX=VAL(AX$)
880 L=L+1
885 XC=HY*COS(TH)+CON
886 YC=HY*SIN(TH)+CON
890 PRINT£U.5039+L.L,"  DATA".XC,YC.CYL.AX.SPH
900 PRINT
910 VDU3
920 NEXT Q
930 *M2R1140
940 NEXT Y
950 *ORG
960 *RES
970 CLOSE£ U
```

# Appendix 3

## Supporting Publications

Sullivan C M and Fowler C W (1988) Progressive addition and variable focus lenses: a review. *Ophthal.Physiol.Opt.* **8**, 402 - 414.

Sullivan C M and Fowler C W (1989) Evaluation of the spread and orientation of astigmatism present in three types of progressive addition lens. *Ophthal.Physiol.Opt.* **9**, 100 (Abstract).

Sullivan C M and Fowler C W (1989) Analysis of a progressive addition lens population. *Ophthal.Physiol.Opt.* **9**, 163 - 170.

Sullivan C M and Fowler C W (1989) Grating visual acuity testing as a means of psychophysical assessment of progressive addition lenses. *Optom. Vis. Sci.* **77**, 567 - 572.

Sullivan C M and Fowler C W (1989) Contrast sensitivity measurement of progressive addition lens patients: does visual performance govern tolerance? *Optom. Vis. Sci.* **77**, 137 (Abstract)

Sullivan C M and Fowler C W (1990) Investigation of progressive addition lens dispensing anomalies. *Ophthal.Physiol.Opt.* **10**, 16 - 20.

Sullivan C M and Fowler C W (1990) Base curve analysis of progressive addition lenses. *Ophthal.Physiol.Opt.* **10**, 112 (Abstract)

Fowler C W and Sullivan C M (1988) Varifocal spectacle lens surface power measurement. *Ophthal.Physiol.Opt.* **8**, 231 - 233.

Fowler C W and Sullivan C M (1988) Comparison of three techniques of progressive addition lens measurement. *Ophthal.Physiol.Opt.* **9**, 81 - 85.

Fowler C W and Sullivan C M (1990) Automatic measurement of varifocal spectacle lenses. *Ophthal.Physiol.Opt.* **10**, 86 - 89.