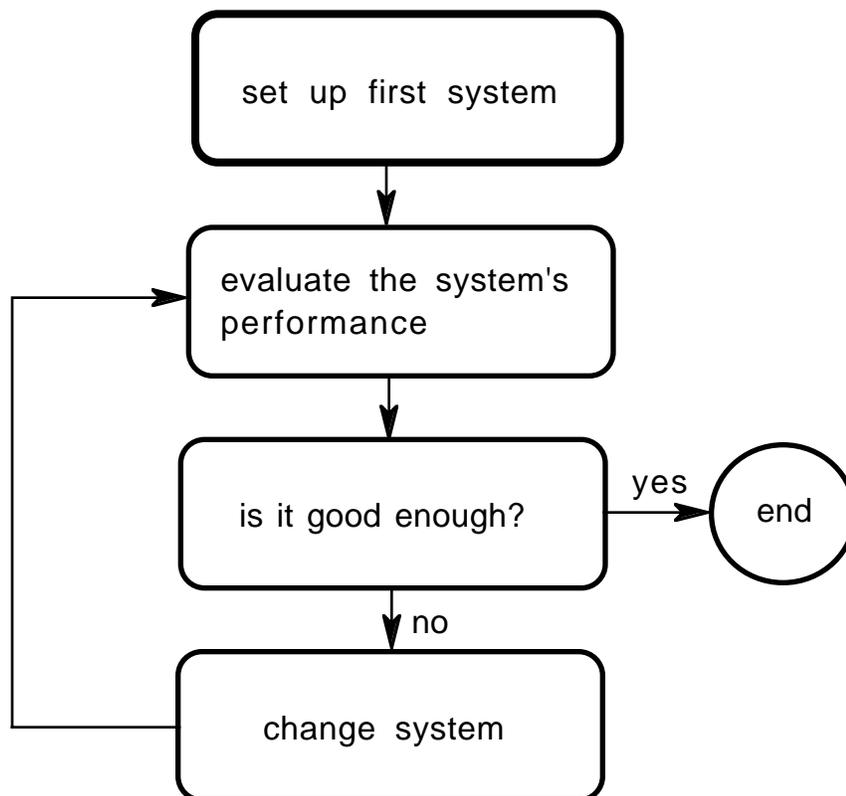


OPTICAL DESIGN of OPHTHALMIC LENSES

Introduction

We tend to prescribe ophthalmic lenses as though any lens with the right back vertex power will do. Lens curves are not, however, chosen haphazardly. Just like a telescope, photographic objective, or any other optical device, ophthalmic lenses are designed to maximize performance.

General Principles of Optical Design



The process of optical design follows the flow chart above.

Here are the parameters a lens designer may vary to improve performance:

-  surface curvatures
-  optical indices
-  number of elements
-  spacing of elements.

These are the "degrees of freedom". In addition to degrees of freedom there are constraints, for example,

-  focal lengths
-  magnification
-  physical constraints like weight, lens to screen distance, etc.

Here are the tools of the optical designer:

-  ray tracing
-  knowledge of aberrations
-  computation short cuts such as Seidel 3rd order formulas, the Abbe sine condition, Petzval sum
-  image evaluation including intercepts with the optic axis from meridional ray plots, and spot diagrams showing the intersection of rays with the image plane,
-  modulation transfer function
-  automatic improvement computer programs. A typical algorithm minimizes a "figure of merit", a function depending on a few traced rays.

A key step in lens design is trigonometric ray tracing. Traces were carried out with logarithms until 1925, desk calculators until 1950, and computers since then. At present microcomputers can solve most problems in real time.

Spectacle Lens Design

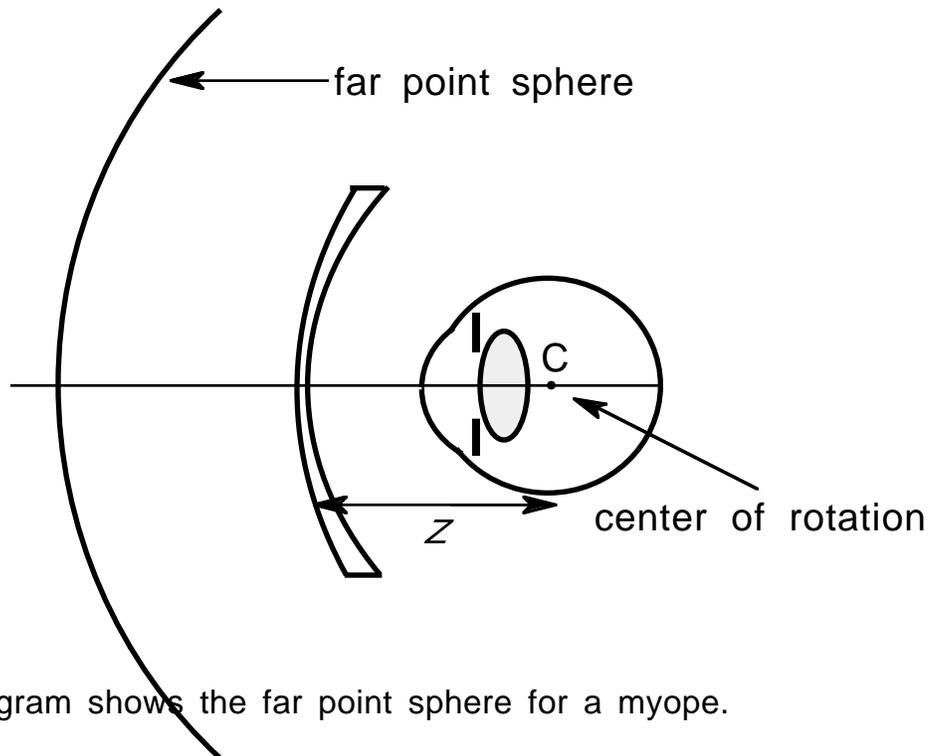
The goal of the spectacle lens designer is to give the patient clear vision at all distances through any portion of the spectacle lens. He has a very limited number of degrees of freedom. Practical conditions specify lens materials, safety considerations fix lens thickness, fashion dictates lens position before the face, weight and cosmesis mean only two lens surfaces may be used.

With so few degrees of freedom, few aberrations may be corrected. Fortunately, few are needed. The wide angle aberrations, spherical aberration and coma are of no importance since the entrance pupil of the eye is so small. The visual system adapts quickly to distortion, so distortion may be neglected. Likewise, the eye already has chromatic aberration and the additional aberration of spectacle materials may be ignored.

The spectacle lens designer is left only with the job of correcting to within tolerable limits astigmatism and curvature of field so as to produce maximum dynamic field of view for the patient.

Layout of the Spectacle Design Problem

As the eye rotates about its center of rotation, C, the image will be in focus for the ametropic eye if it is in focus on the far point sphere of the eye. The far point sphere is a sphere with its center at C, and the far point of the ametropic eye on its surface.



The diagram shows the far point sphere for a myope.

If the image is not in sharp focus on the far point sphere, it may be good enough if the line foci from the lens (line foci because of marginal astigmatism) lie close to the far point sphere or bracket it.

Design calculations are done by tracing rays trigonometrically through the lens and calculating the positions of the two line foci according to formulas which are not too difficult to derive. (We won't derive them, however.) Ideally, the two line foci coincide on the far point sphere. If, as usual, they don't, other criteria may be used, i.e. the line foci coinciding with each other somewhere off the far point sphere, line foci bracketing the far point sphere and being close to each other, etc. If a criterion is not satisfied for a given base curve, a new one is tried, etc.

Incidentally, the layout above shows why patients with high prescriptions may notice some blurring if the optical center of the spectacle lens is below their eye's optical axis.

Third Order Theory

In third order optical theory we use the expansions of the sine and cosine up through third order instead of to first order as in paraxial optics. These expansions are

$$\sin\theta = \theta - \theta^3/3!$$

$$\cos\theta = 1 - \theta^2/2!$$

By using these third order approximations, we can solve analytically for the base curve F_2 as a function of the back vertex power of the lens, F_V' , n the index of the lens, and z , the distance from the back vertex of the lens to the center of rotation of the eye, assuming the lens is a thin lens. The results are valid if the eye rotates no more than 15° from the primary line of sight. The result is an equation of the form

$$aF_2^2 + bF_2 + c = 0$$

where a , b , and c depend on lens power F , n , and z .

Ostwald and Wollaston Solutions

If our design criterion is that the two line foci coincide, though not necessarily on the far point sphere, astigmatism is wholly compensated though a sphere error remains. In 3rd order this leads to the equation above where

$$a = n + 2$$

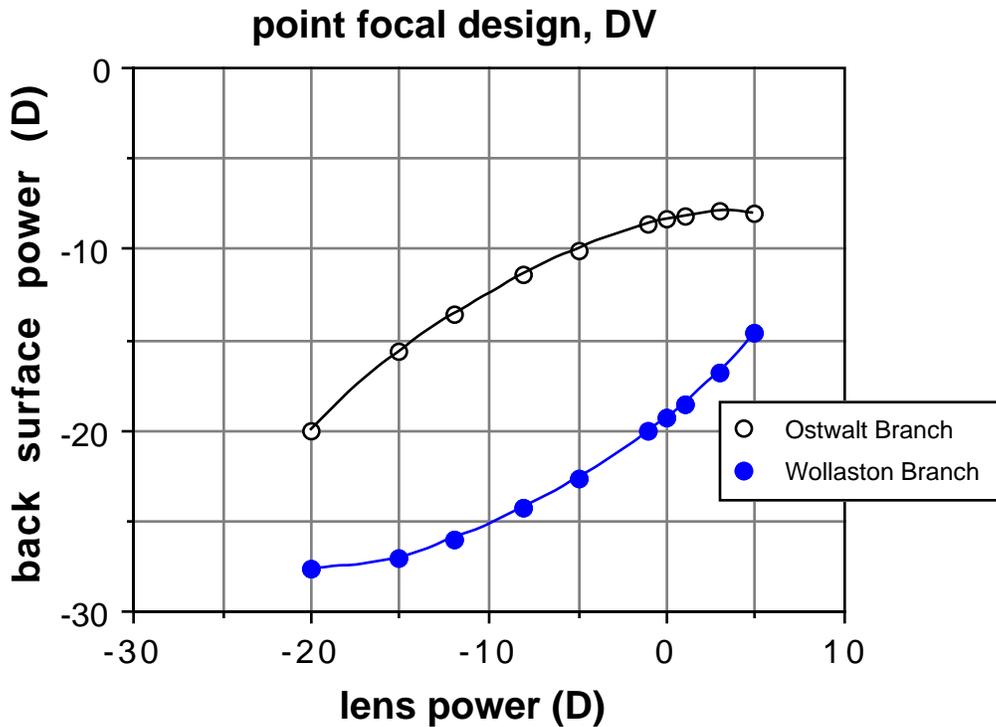
$$b = 2(n^2 - 1)/z - (n + 2)F$$

$$c = nF^2 - 2(n - 1)F/z + n(n - 1)^2/z$$

If this is plotted as F_2 vs. F , we get the famous Tscherning ellipses. The graph below shows the Tscherning ellipse for a working distance 33cm with $z=25$ mm. The ellipse is plotted for remote objects.

The upper division is labelled the Ostwald branch and the lower the Wollaston branch, after their designers. The Wollaston branch lenses have

the advantage of having the same form at distance and near, but the curves are steep and hard to make as well as uncosmetic. The Ostwalt branches are more practical, but ideally require about a three diopter flatter base curve when used for near objects.



Percival Solution

In Percival's design philosophy, we allow astigmatism but require the mean error to be correct, that is the far point foci straddle the far point sphere. In third order theory this gives

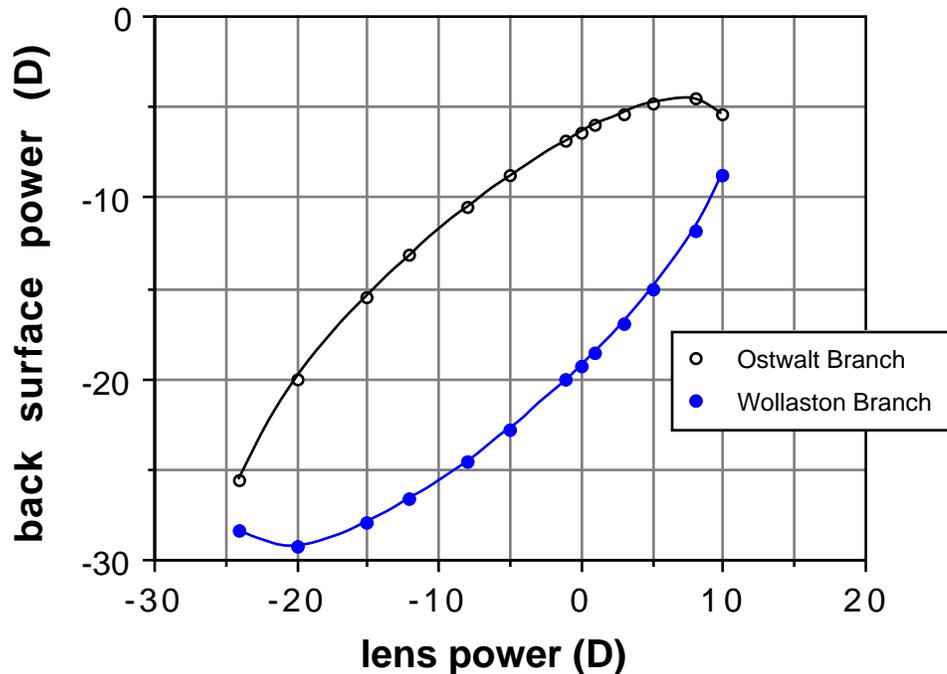
$$a=3$$

$$b=4(n-1)/z-(n+2)F$$

$$c=nF^2-2(n-1)F/z+(n-1)^2/z^2$$

These parameters lead to ellipses similar to the point-focal philosophy lens ellipses. Design for near and distant viewing distances is essentially identical. The Percival philosophy is similar to that used in modern spectacle lens design.

Percival design, DV



Design of Sphero-Cylinder Lenses

Sphero-cyl lenses have two far point spheres and appropriate line foci must approximate each sphere. Line foci are a combination of radial and non-radial astigmatism. Ray tracing becomes much more difficult.

Modern Corrected Curve Lens Series

Modern corrected curve lens series are calculated using trigonometric ray tracing so as to consider angles of rotation of -30° about the line of sight. Slightly different philosophies have been employed. Most use a Percival type philosophy to minimize importance of astigmatism.

Punktal (Zeiss). Rotation of 35° for $F > 0$, 30° for $F < 0$, $z = 25\text{mm}$.

Tillyer (A. O.). Rotation of 30° , $z = 27\text{mm}$. Allows some astigmatism to reduce curvature.

Other series include Tillyer Masterpiece (A. O.), Orthogon (B & L), Normal Site (Titmus)

Optometric Specification of Curves

Various authors, most notably Fry, have advocated optometric specification of base curves in Rx. Here follows an example of what is involved.

Some influential Ontario O.D.'s advocated flattening of standard base curves when prescribing near lenses. The degree of flattening would depend on the lens form. On the basis of the Ostwalt solutions of the point focus lenses, the base curve for a +5.00DS reading glasses Rx would be -2.50D flatter than that of a +5.00DS distance lens.

But the reasoning here becomes somewhat fuzzy. The Percival solutions which are much more like modern corrected curve series would be flattened only about 1.00D. Worse yet, the Percival-Ostwalt distance Rx in low plus is nearly the same as the point focal Ostwalt near Rx.

And recall that the Tscherning ellipses are for 33cm working distance, good only up to 15° rotation. In a typical calculation for a +4.00D lens used at 40cm, the only effects of not flattening base curves was to require an additional +0.25D accommodation at a 30° rotation.

The bottom line is that the situation is rather complicated and only marginal benefit is achieved by the flattening.

Various authors have advocated having the optometrist take a more active role in base curve specification. To that end Fry provided the following table in which he gives base curves acceptable for crown glass spectacle lenses within certain power ranges. That table is reproduced below.

BASE CURVE	<u>RANGE OF SPHERICAL EQUIVALENT POWERS</u>	
	LOWER LIMIT	UPPER LIMIT
+12.50	+6.399	---.---
+10.50	+4.387	+6.399
+8.50	+1.446	+4.387
+6.50	-2.106	+1.446
+4.50	-5.880	-2.106
+2.50	-10.503	-5.880
+0.50	---.---	-10.503

Such a table is of some use if, for example, base curves must be changed for some mechanical reason, say long eyelashes. About the only other cases in which it is worthwhile to specify base curves is when a patient appears to have discomfort stemming from current choice of curves. Usually going back to his last base curve will solve his problem.

Pantoscopic Tilt and Induced Astigmatism

If a patient looks obliquely through a spherical lens he will encounter some astigmatism due to the marginal astigmatism aberration. The formula for the sphere S and cylinder C induced by tilting a spherical lens of power F through an angle θ is

$$S = [1 + \sin^2\theta / (2n)] F,$$
$$C = S \tan^2\theta.$$

where the cylinder axis is the same as the axis of rotation.

Example: A -5.00DS crown glass lens is tilted 7° about the horizontal. What is its effective Rx?

Solution: $S = [1 + \sin^2 7^\circ / (2 \times 1.523)](-5D) = -5.024D.$
 $C = (-5.024D) \tan^2 7^\circ = -0.076, \text{ axis } 180^\circ.$

As in the above example, the effect in any reasonable case is negligible.

It has been suggested that this formula can be applied in principal meridians of spherocylinder lenses. It can't.

Cataract Lenses

Aphakic spectacle corrections require powers of +8.00 to +15.00 diopters. Such high powered corrections produce a number of difficulties. Among them

-  Spectacle magnification of about 35%
-  Decreased field of view with ring scotoma
-  Aberrations and swimming of objects in field of view
-  "Popeye" appearance of patients
-  Sensitivity to exact position of the lens
-  Lens weight and thickness

Various design approaches have been taken to cataract lenses, some paralleling the philosophies used in developing corrected curve series, some not. There are two main approaches the "foveal philosophy" and the "peripheral philosophy". Both, as we'll see, make use of aspheric curves, but each with a different reason.

Foveal Philosophy

This philosophy parallels the standard lens design philosophy, namely trying to give the patient the largest possible dynamic field of view. As indicated by Tscherning ellipses, this cannot be done for high plus lenses with spherical curves. Instead aspheric curves are used. In order to cut down on weight, lenticular designs are often employed.

Peripheral Philosophy

This assumes aphakics are head--not eye--turners. It uses front surface curves of diminishing power away from center as in the Welsh Four Drop or Signet Hyperaspheric. These diminish the lens thickness and lower its weight.

When these came out they were accompanied by much fitting information and, especially useful, nice looking frames.

Aphakic Summary

For better or worse, cataract spectacles aren't much used any more. Implants are almost universal, and they allow use of ordinary corrections. A minority of patients are in cataract contact lenses. They need glasses for part-time wear. A few still have true aphakia, mostly those who've had surgery over ten years ago or who've had trouble.

