86th birthday series

The Refractor/Phoropter—
An Important Tool in Vision Correction

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ABSTRACT

In the field of vision care, *refractor* refers to an instrument (sometimes called a *phoropter*; Phoroptor is a trademark) used to examine a patient to determine the optimum properties of corrective lenses used to overcome various deficiencies in his vision.

In this article we describe the traditional "manual" form of this instrument, its organization and operation, and the basic way in which it is used.

Considerable background is given in the basics of corrective lenses and the way their "prescriptions" are developed using a refractor

1 DISCLAIMER

I am not an eye care professional, nor do I have any formal training in the practice in that field nor in its own unique branch of optical science. The information in this article is my own interpretation of the results of extensive research into the available literature, through the prism of my own scientific and engineering background and outlook.

2 INTRODUCTION

A *manual refractor* is the scary "mask-like" instrument used by ophthalmologists and optometrists to test the refractive behavior of eyes and determine the optimal parameters of corrective lenses.

The instrument is often called a *phoropter*, a "genericization" of "Phoropter" (note the spelling difference), a name given the instrument at one stage of its evolution by its inventor, and registered as a trademark, and to this day a trademark of one manufacturer for their line of manual refractors[1].

In figure 1 we see a typical contemporary manual refractor, a Topcon VT-10 Vision Tester. We see it from the refractionist's side.

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[1] Reichert Technologies, who acquired the trademark from American Optical, who acquired it from the firm of Henry L. deZeng, generally recognized as the inventor of the instrument, who coined the term "Phoroptor" and registered it as a trademark.

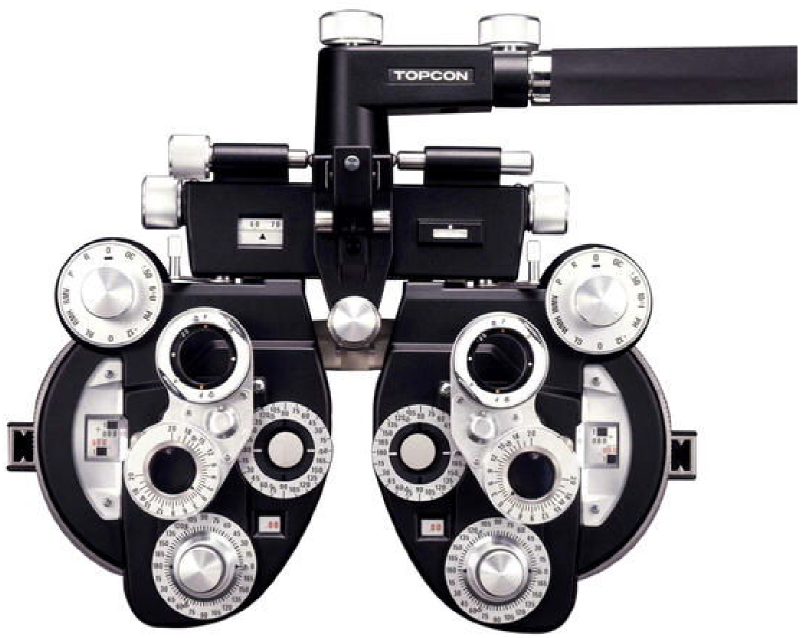


Figure 1. Topcon VT-10 Vision Tester

A refractor is essentially an corrective lens simulator. It allows the refractionist (the term used here for the “operator” of the instrument for best generality) to establish the same optical properties as would a pair of eyeglass lenses or contact lenses, changing them in order to determine what parameters produce the best vision result to the subject.

3 LENSES

3.1 Lens refractive power

The *refractive power* (“power”) of a lens is the degree to which it will converge (or diverge) rays of light emanating from the same point on an object and entering the lens at different points on its face.

Quantitatively, in normal optical technical work, the power of a lens is defined as the reciprocal of its *focal length*. The traditional unit of power is the *inverse meter* (m^{-1}), alternately called *diopter* (symbol D)[2]. A lens with a power of one diopter has a focal length of one meter.

In connection with ophthalmic (vision correction) lenses, a different definition of power is used from the one most often found in general optical work. It is called the *vertex power*. It is the reciprocal of the

[2] The unit diopter is the one always used in optometric and ophthalmic practice.

back focal distance. The unit *diopter* is universally used for this quantity.

3.2 Lens terminology

In what follows, I will speak of what are called in most optical work *spherical* and *cylindrical* lenses. In the fields of optometry and ophthalmology, these are spoken of as "sphere" and "cylinder" lenses, respectively, and I will use that notation from here on.

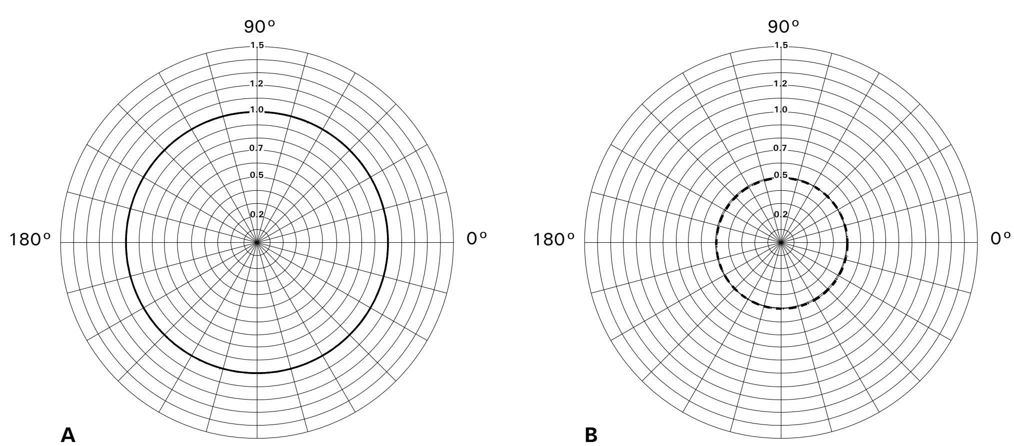
The power of a lens is a signed quantity. In the fields of optometry and ophthalmology, the *positive* and *negative* signs of powers are spoken of as "plus" and "minus", respectively, and I will use that notation from here on.

3.3 Sphere lenses

In ophthalmic work, a *sphere lens* is any lens that is a figure of revolution, whether or not its surface is actually a portion of a sphere. Thus we can (and often do) have aspherical "sphere lenses"!

A converging lens (which has a plus focal length) has a plus power. A diverging lens (which has a minus focal length) has a minus power. A sphere lens exhibits the same power along any direction.

We can present the variation (if any) in the refractive power of a lens with direction on a polar chart. In figure 2, panel A, we see a plot of a sphere lens with refractive power +1.0 D (a converging lens).



Spherical lens
(refractive power +1.00 diopter)

Spherical lens
(refractive power -0.50 diopter)

Figure 2. Sphere lens—power plot

This is a trivial case, and hardly requires a chart to explain. But I show the plot here to establish the format and notation.

The radius to the curve in a certain direction indicates the refractive power (in diopters) for that direction. Recall that a "direction" here means both ways: either way along the line at a certain angle. Because of that symmetry, we only need to plot half the curve. But I show the curve for a full 360° for aesthetic completeness.

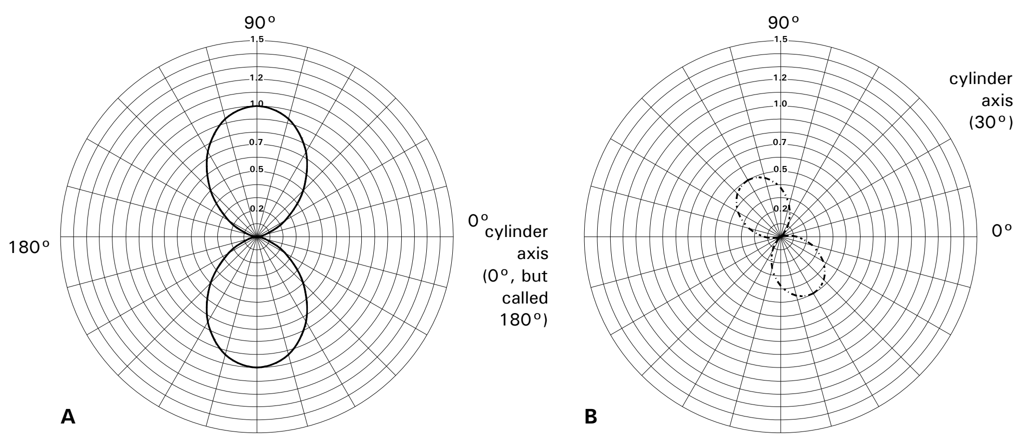
The usual scientific convention is followed, with the angle origin (0°) being to the right (but there is a wrinkle, about which more shortly), and the angle increases in the counterclockwise direction.

It is difficult to express minus values on a chart in polar coordinates—a "minus" radius would put the point on the opposite side of the chart, where it would just look like the (plus) value for an angle 180° from the actual angle.

To escape this difficulty, here I will plot minus values of the refractive power as a dotted line. And we see that in figure 22, panel B, the plot for a sphere lens with a refractive power of -0.5 D (a diverging lens).

3.4 Cylinder lenses

A cylinder lens has a surface that is a portion of a cylinder (which may or may not be exactly a right circular cylinder). A cylinder lens exhibits a certain power (its "rated" power) in one direction (perpendicular to its axis). Along its axis, it exhibits zero power. At intermediate angles, it exhibits intermediate values of power[3].



Cylindrical lens (refractive power +1.00 diopter, axis "180°")

Cylindrical lens (refractive power -0.50 diopter, axis 30°)

Figure 3. Cylinder lens—power plot

[3] Although the "power" at an oblique angle has some odd properties.

We see this illustrated in figure 3 for two cylinder lenses, one with a plus power and one with a minus power (and a smaller magnitude, and a different axis angle).

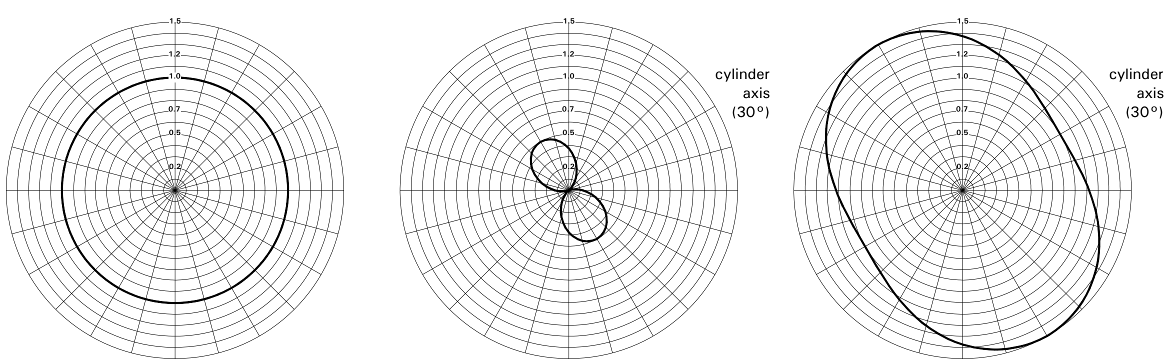
Imagine that we combine a sphere lens and a cylinder lens (and we assume here the convenience of the fanciful "thin lens" conceit, which, although impossible to have in practice, makes all the math work out in a very simple way).

In the direction of the cylinder lens axis, where the cylinder lens has zero power, there is no effect of the cylinder lens on the overall result. In the direction at right angles to that, the "stated" power of the cylinder lens combines with that of the sphere lens (taking into account the applicable algebraic signs) and so we have a power different from that of the sphere lens alone (perhaps even of the opposite sign).

Before we continue, let me mention the small wrinkle about angles. The axis of the cylinder angle can only vary over the range 0° to 180°, with 0° and 180° having exactly the same significance. In scientific work, that angle is called "0°". In ophthalmic practice, it is called 180°. (Still, on instruments, the "zero" on one aide of an axis angle scale is often marked 0 and the one on the other side 180.)

In any case, the angle of the axis is as seen by the refractionist looking at the subject, and 0° (and 180°) is horizontal.

In figure 4, we see one example of the combination of a sphere and a cylinder component.



A — Sphere component (+1.00 D)

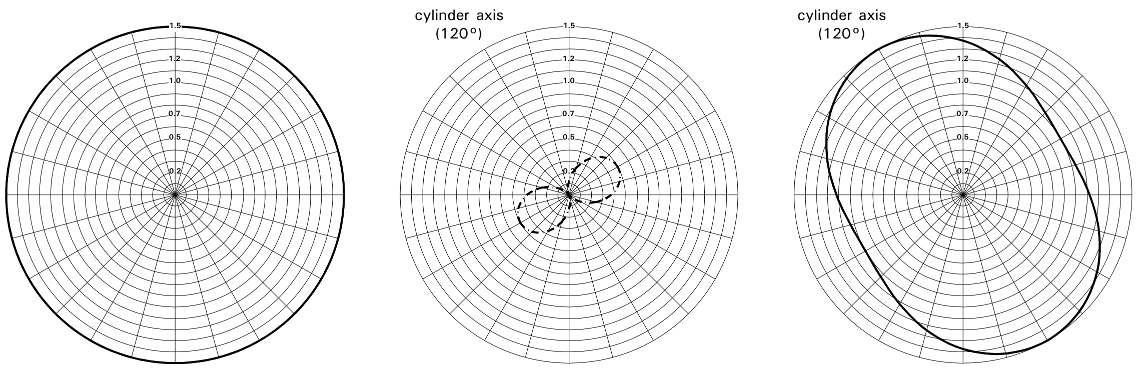
B — Cylinder component (+0.50 D, axis 30°)

C — Lens net refractive power

Figure 4. Composite lens—power plot

In figure 5 we see a different example.

Note that the result here is identical to the previous case.[4] This is reminiscent of the two ways we might make an ellipse. We might start with a circle of small diameter, and stretch it in the direction of the ellipse's major axis. Or we might start with a circle of large diameter, and shrink it in the direction of the ellipse's minor axis.[5]



Sphere component (+1.50 D) | Cylinder component (-0.50 D, axis 120°) | Lens net refractive power

Figure 5. Composite lens—power plot

We can of course make a single lens that will exhibit this overall behavior (and of course do so in the corrective lens itself). A simple version (not found in modern ophthalmic practice) would have a front surface that is a portion of a sphere and a rear surface that is a portion of a cylinder. Note that this would have the result shown regardless of which of the two "recipes" we thought of as leading to it.

4 HUMAN VISION

4.1 Accommodation

Ideally, the human eye can focus on objects at a wide range of distance, from very near to "infinity". This is called *accommodation*.

Typically, with advancing age, the eye's accommodation ability can become compromised (and the same may be true of young people as a result of congenital malformation of the eye or of various ailments). Several types of deficiency are common.

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[4] The specific mathematical variation of the power of a cylinder lens with angle makes this equivalence exact.

[5] Notwithstanding this metaphor, the plot of the power of such a composite lens is not an ellipse.

Hyperopia ("far-sightedness") is the deficiency in which the total range of accommodation is "offset out", such that distant objects (even at "infinity") can be focused on but the near limit is not nearly as close as is normal.

Myopia ("near-sightedness") is where the total range is "offset in", such that close objects can be focused on but the far limit is not to infinity.

Presbyopia (the term means "old person's seeing") is the deficiency in which the total range of accommodation (the *accommodation amplitude*) is decreased. The remaining limited range may be in the far, intermediate, or near regimes, in the individual case.

4.2 Astigmatism

Astigmatism is the deficiency in which the refractive power of the eye's lens is not the same in different directions. An illustrative result is that if we have astigmatism and look at a cross of thin lines on a card, we can focus so that the vertical line is sharp, or the horizontal line is sharp, but not both at the same time. For a point on an object, the eye cannot produce a point image.

4.3 Corrective lenses

We can overcome basic deficiencies in accommodation with the use of a corrective lens. For farsightedness, we can use a sphere corrective lens with a a plus power; this will shift the range of focus in the "nearer" direction. For nearsightedness, we can use a sphere corrective lens with a minus power; this will shift the range of focus in the "farther" direction.

We can overcome astigmatism with the use of a cylinder lens with appropriate power and the appropriate axis angle.

In reality, both sphere and cylinder components are combined in a single corrective lens to deal with the overall visual syndrome.

5 THE PRESCRIPTION

5.1 General

An eyeglass prescription is a specification for the lenses in the glasses. It is done in terms of the model we saw above, in which the overall refractive pattern of the lens is described in terms of the joint effect of two hypothetical lenses, one sphere and one (only present if there is a correction for astigmatism) cylinder.

Recall that, as we saw in figures 4 and 5, the identical lens result can be conceptually implemented with either of two conceptual “recipes”; for that particular example, we could combine:

- A sphere lens with power +1.00 D
- A cylinder lens with power +0.50 D and axis 30°

or

- A sphere lens with power +1.50 D
- A cylinder lens with power –0.50 D and axis 120°

Recall that in reality the way the lens is actually made may not directly follow either of those “recipes”.

5.2 Format of the prescription

In a prescription, there is a line (or section) for each eye. In each, for single-vision eyeglasses (not bifocals), there are three parameters stated:

- The power of the sphere component (could be zero). This is normally in increments of 0.25 D.

If there is a cylinder component:

- Its power (normally in increments of 0.25 D)
- The angle of its cylinder axis (normally in increments of 5°, from 5° through 180°.

Often, the indicators OD (from the Latin, *oculus dexter*) and OS (*oculus sinister*) are used for the right and left eyes, respectively. (OU—*oculus uterque*—indicates both eyes.)

We will give our first complete example in the “plus cylinder” system.

There a complete prescription might look like this:

OD +1.25 +0.50 X 130

OS +1.50 +0.75 X 25

Sometimes the decimal points are omitted (and all powers stated to two decimal places), so it would look like this:

OD +125 +050 X 130

OS +150 +075 X 25

There are many other variations in style.

For the very same pair of lenses, under the “minus cylinder” system, the prescription might look like this:

OD +1.75 −0.50 X 40

OS +2.25 −0.75 X 115

5.3 Two systems of notation

Either the :puls cylinder” form or the “minus cylinder” form could be used (at our choice) as the premise for specifying a certain lens **behavior** in a prescription. But it turns out that when the prescription is written by an ophthalmologist (a physician and surgeon specializing in the eyes), it would be in the first form (the cylinder component always having a plus power), called the “plus cylinder” form.

When the prescription is written by an optometrist (a Doctor of Optometry, qualified and certified to examine eyes and issue eyeglass prescriptions), it would be in the second form, (the cylinder component always having a minus power), called the “minus cylinder” form.

This is not only the result of accidental historical “diversity”. At one time, licensed optometrists were, in many states, not allowed to prescribe nor administer any medication, which in most cases included the “drops” that could be used by ophthalmologists to disable the eye’s accommodation mechanism so that its attempt to keep the image on the retina in focus would not disrupt the refraction process.

At an earlier time, the prescription was thought of not as just an optical specification for the corrective lens but actually a recipe for the lens construction.

Also at that time., it was most common, in making corrective lenses to have the cylinder component executed on the front of the lens, and “mechanical” considerations suggested that this be done with a plus cylinder component.

Again thinking of the prescription as a “recipe” for making the lens, an ophthalmologist would prefer to write the prescription in plus cylinder form. And that form would most directly come from a refraction using plus cylinder lenses.

And the most convenient strategy for doing a refraction called for the eye’s accommodation mechanism to be disabled. And there were medications that would do that. In that *modus operandi*, it was essentially equally convenient to refract for the cylindrical component using plus or minus cylinder lenses in the refractor. So this all worked out well for an ophthalmologist.

But not so well for an optometrist, who most likely could not use such medication.

That being the case, the best strategy for avoiding attempts of the eye's accommodation mechanism to change the focus of the eye while it was being measured worked most conveniently using minus cylinder trial lenses.[6] And the prescription form that flowed most directly from that used minus cylinder notation.

But what about when the lens was to be made, most conveniently with a plus cylinder component? Well, of course lens makers were well equipped to change the form of the "specification" from a minus cylinder basis (on a prescription written by an optometrist) to a plus cylinder basis (needed to set up the equipment to grind the front of the lens).

Now, today, almost all of those fascinating situations have moved into folklore. In most states, optometrists can (if they wished) administer medication to disable the eye's accommodation mechanism while the eye was being "refracted". And today, it is most common to execute the cylinder component on the back surface of the lens, where the same "mechanical" considerations alluded to earlier suggest the use of a minus cylinder component.

But the die was cast. Ophthalmologists have refractors equipped with (only) plus cylinder lenses in their lens wheels, and trial lens sets that include (only) plus cylinder lenses; optometrists have refractors equipped with (only) minus cylinder lenses in their lens wheels, and trial lens sets that include (only) minus cylinder lenses.

6 BACK TO THE REFRACTOR

6.1 Basic concept

As I mentioned at the outset, a manual refractor is essentially an eyeglass simulator. It allows the refractionist to establish the same optical properties as would a pair of eyeglass lenses, changing them in order to determine what parameters produce the best result to the subject.

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[6] This is discussed in detail in the companion article, "Plus and minus cylinder notation in ophthalmology and optometry", probably available where you got this.

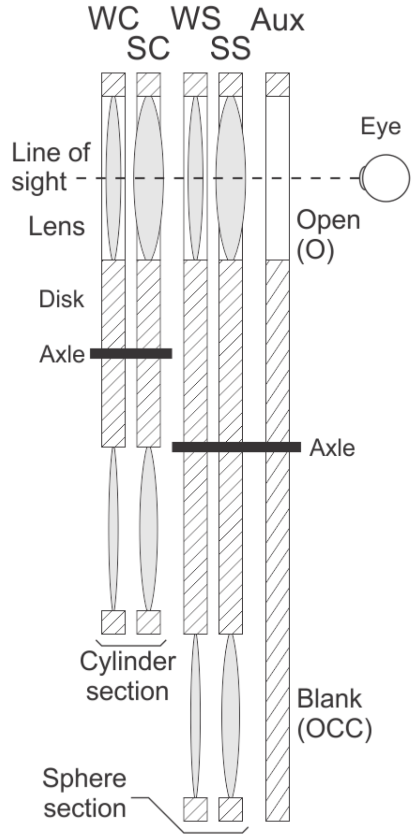

Figure 6. Refractor lens disks typical arrangement

6.2 The lens disks

6.2.1 *Introduction*

Figure 6 illustrates, schematically, the heart of the refractor: its lens disks, in a typical arrangement.

We see the disks and the lenses on them in cross-section. The symbols WC, SC, WS, SS, and Aux indicate, respectively, the *weak cylinder*, *strong cylinder*, *weak sphere*, *strong sphere*, and *auxiliary lens* disks.

6.2.2 *The sphere section*

On each eye unit, in what I will call the “sphere section”, a pair of adjacent rotatable disks puts into place one of a number of sphere lenses (perhaps 12) from each disk. One disk (called the “weak sphere” disk) has lenses with powers separated by a small increment, perhaps 0.25 D. The other disk (the “strong sphere” disk) has lenses separated by a greater increment, perhaps 3.00 D The overall result in a net sphere power variable over a large range in steps of 0.25 D.

Both plus and minus net powers are provided, on both sides of a “zero-power” position, although not usually symmetrically (for example, a range of -19.00 D through +16.75 D, 144 values in all). The power in effect is indicated in a little window, the markings in black for plus powers and red for minus (zero gets both). A clever system allows markings on both disks to collaborate to form an indication of the total power in place.

6.2.3 *The cylinder section*

In the immediately adjacent “cylinder section” of the refractor, a similar arrangement of two adjacent rotatable disks (the “weak cylinder” disk and the “strong cylinder” disk), smaller in diameter than the disks in the sphere section, puts into place one of a number of cylinder lenses (perhaps 5) from each disk, with different powers. The combination of the two lenses results in a net cylinder power variable over a modest range (typically 0.00 D through 6.00 D) in steps of 0.25 D.

Note that if, as is often the case, the cylinder disks held 5 lenses each, the section would not show the cross section of the lens opposite the line of sight, but I show it just to help illustrate the configuration.

Note that, for each pair of lens disks, the “strong” lens disks are the closest to the eye. Also note that the two disks of each pair are closely spaced, and the two sections are fairly closely spaced. This all plays a role in moderating a certain problem I will discuss later.

A single knob steps the disk pair in steps (0.25 D per step). Again, the power in effect shows in another little window (this time directly from an indicator wheel). Another knob rotates all the cylinder lenses so as to vary the angle of the cylinder axis of the lens in place (it turns the rest of them, too, but this doesn’t do anything).

On a particular refractor, all available cylinder lens powers will be either minus or plus, deepening on the variant of the refractor model (in turn usually depending on whether it was ordered by an optometrist of an ophthalmologist). The two variants are called the “minus cylinder” and “plus cylinder” models.

Consistent with the convention used for the indications on the sphere power wheel, on the plus cylinder instruments, the numbers in the cylinder power indicator window (including the zero) are all black; on the minus cylinder instruments, the numbers (including the zero) are all red.[7]

6.2.4 *The zero lenses*

Each of the four lenses has a "0" position. There are theoretical reasons why it is desirable to implement these as actual glass lenses, with their surface powers and thickness such that their vertex power is zero. But in all refractors I am aware of, the "0" positions of the lens disks are implemented as just an open hole.

6.2.5 *The auxiliary lens disk*

There is actually a third disk in the "sphere" section, the auxiliary lens disk (Aux in the figure), located closest to the eye. It contains various special lenses and filters, including a plus sphere lens of power 0.125 D (but marked "+.12") to apply a "half step" additional plus sphere power.

It also has an open hole (often designated "O") that is normally left in position when none of the special lenses are in use. Another position is just blank (often designated "OCC", for "occluded"), and can be put in place to completely block the vision of that eye while the other eye is being tested. Both these are suggested by the figure.

6.3 Conversion between equivalent forms

If we have a prescription in either "plus cylinder" or "minus cylinder" form, we can easily convert to the other form, this way:

- Add the present sphere and cylinder powers (observing the signs). The result is the new sphere power.
- Reverse the sign of the cylinder power; the result is the new cylinder power.
- Add or subtract 90° to/from the current cylinder axis angle (so that the result will be non-zero and plus but not over 180°). The result is the new cylinder axis angle.

6.4 Sphere-cylinder interaction

If we consider a subject with astigmatism, when the refractor operator ascertains the sphere power that provides the "best" vision, that typically occurs when the sphere power allows the subject to focus equally well (albeit not perfectly) along both meridians of his

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[7] Thus one can quickly ascertain by a quick glance at your ophthalmologist's instrument whether, perhaps just starting his practice, he bought it from an optometrist that was retiring.

astigmatism; that is, to have equal but opposite focusing error in the two directions.

Then, in the “cylinder” phase of the measurement, when a certain cylinder power has been introduced (and let’s assume that it is at nearly the “appropriate” axis angle), it corrects the focus along one meridian but not the other. Thus, the sphere power now set into the refractor is no longer optimal.

To overcome this effect, the operator, when changing the cylinder power, may make a compensating change in the sphere setting. The magnitude would be half the change in the cylinder power; the sign would be opposite the sign of the change in cylinder power.

Typically, the available changes in cylinder power are in steps of 0.25 D, and the steps in sphere power are likewise 0.25 D. Thus, for a “one step” change in cylinder power, a truly rigorous operation would call for a “half step” change in sphere power—not directly available. In many cases, this subtlety may be ignored.

However, the truly fastidious operator may wish to take advantage of a “half step” increment in sphere power (actually, nominally +0.12 D) that can be applied with the auxiliary lens mechanism.

There are many subtleties in actual refraction technique, including in the area just mentioned, that are beyond the scope of this article.

6.5 Axial location of the nearest lens

The effect of a lens on vision correction is determined by both its power and by its distance from the eye. It is the custom in vision correction to, whenever possible, position the back vertex of the nearest actual lens (the lens on the strong sphere disk) at a fixed, standardized distance (ordinarily about 14 mm) in front of the front vertex of the cornea of the eye.

In order that the power of the lens determined by the use of the refractor is correct in this context, the instrument must be used with this standard distance between the front of the subject’s cornea and what is spoken of as the reference plane of the instrument. The adjustment for this is made with a knob that moves the instrument headrest.

The refractor is usually equipped with two small “periscopes” that allow the operator, while standing in front of the instrument, looking through a small part, to sight across the cornea and observe its position on a scale.

In figure 7, we see this on a Topcon VT-10 Vision Tester refractor:

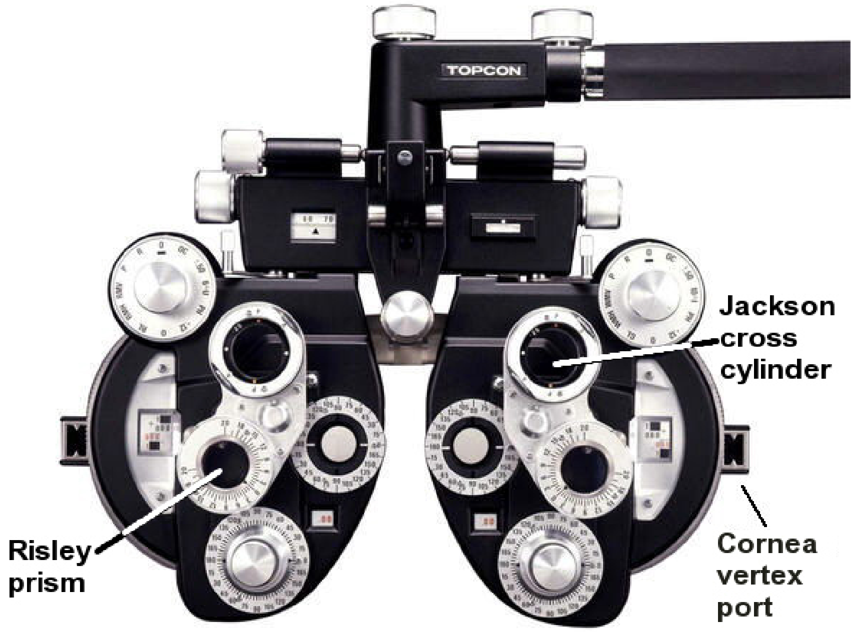

Figure 7. Topcon VT-10 Vision Tester

6.6 The Jackson Cross Cylinder (JCC)

The Jackson Cross Cylinder (JCC) unit is a clever system (the *Jackson cross cylinder*) to make rapid incremental changes in the cylinder lens power and axis to allow most effective "bracketing" of the best result (the familiar "which is better, one [click] or two" scenario). This unit is on one leg of a two-position turret on the front of the refractor, and is swing into the line of set when it is needed. We can see this on figure 7.

This unit is described in detail in Appendix A.

6.7 The Risley prism

On the other leg of the turret is a Risley prism unit. This is essentially a prism whose power can be adjusted and whose orientation can be adjusted. It is used to determine the needed prism component of the corrective lens prescription (not often encountered). This component is to correct troubles with the eyes readily converging on the same object. This vision flaw and the details of the Risley prism are beyond the scope of this article.

7 THE ADDITIVITY PROBLEM

7.1 Introduction

In the preceding I intimated that the net vertex power exhibited by two lenses in the line of sight was the sum of their individual vertex powers. And in fact, in using the results of a refractor determination, we actually assume that, along the direction of the power meridian of the cylindrical lens(es), the net vertex power is the sum of the usually four) individual lens powers.

But in fact this is not so. It would be so if all the lenses were the "thin" lenses so beloved to optical theory lecturers (those have center thicknesses of zero!) and if all four were in exactly the same location.

But of course we are dealing with real, physical lenses, with non-zero center thicknesses, and even when placed as close together as is mechanically possible (and prudent), they are not "in the same place". The result is that the net vertex power of the "train" is not the sum of the vertex powers of the participants.

It is said that the powers of the lenses in such a situation are not "additive".

The consequence is that, if a corrective lens is made that exhibited sphere and cylinder components as described in the prescription developed by the refractor setup, it will not in fact have the same power (in both meridans) as the refractor setup, the one that produced the best vision. Thus the corrective lens will not be what exactly what is really needed.

7.2 Tillyer's solution to this problem

Edgar D. Tillyer, the lens design ace at American Optical Company for many years, in the early 1900s pondered this problem in the context of trial lens practice (where there were only two lenses, a sphere lens and a cylinder lens, in the "train" in the trial frame).

He determined (and later proved convincingly in his 1923 patent on this matter) that if we adopt and then follow certain constraints on the design of the sphere lenses, and separately for the cylinder lenses, in a trial lens set, then, when we have both a sphere lens and a cylinder lens "in train" in a trail frame, the net vertex power exhibited by that lens train will be the sum of the powers **marked** (note that word!) on both lenses. In fact, on the cylinder lenses, that will not be the actual vertex power of the lens, but rather the power that it would contribute to the power of a two-lens train where the sphere lens follows the Tillyer "rules".

Thus, trial lens sets that were exactly "additive" could be designed, and in fact American Optical Company sold trial lens sets that were "additive", based on Tillyer's scheme (and in fact bore his name). They are still thought of, by optometric instrument aficionados, as the best trial lens sets ever made.

7.3 Ah, but in a refractor

When the refractor emerged a few years later, this problem again presented itself, but now with the prospect of there being four lenses “in train” (maybe even five).

Tiller’s patent assured us that his scheme could be extended to trains of any number of lenses, and that the needed calculations for constraints on lens designs to attain to would be able to be done by anyone familiar with lens design. But it wasn’t immediately apparent what it would mean to extend his scheme to trains of more than two lenses. And eventually, two researchers proved mathematically that in fact that could not be done!

But the good news is that by using what we can think of as a “reasonable generalization of Tillyer’s design rules”, and then by placing the sphere lenses with the largest magnitude of power (those being on the “strong sphere” disks) as close to the eye as possible, and by making the spacing between the lenses as small as possible, the departure in the actual joint power of the lens train from that suggested by the sum of the “power indications” of the participating lenses can be held to a very small, and potentially not troublesome, amount.

And that is what we are led to believe was first done in the American Optical No. 589 Phoroptor, and its descendants.

7.4 In modern refractors

In the AO No, 589 Phoroptor, the cylinder lenses were in a separate hosing from the sphere lenses, and accordingly, the inter-lens spacing between the weak sphere lens and the strong cylinder lens was a bit larger than we night have wished to make this situation work out the best for us.

Staring with the AO 590 Phoroptor, all four lens disks were very closely spaced (as suggested by figure 6), which in fact assists in our aspiration to approach true additivity.

7.5 Those old zero lenses

One of the collateral conditions of Tillyer’s scheme, discussed clearly in his patent, was that when the needed power of the sphere lens in a trial lens setup was zero, we must still have a glass lens, following the constraints adopted for the design of all sphere lenses for the Tillyer scheme, but specifically designed to have zero power (easily done). And for the “zero” cylinder lens to be able to be “marked” zero, it would also have to be a real glass lens, not a hole in the disk.

But, as I mentioned above, in all of the refractors in this dynasty that I know off, all the "zero" lenses, in any of the four or five positions, were just open holes.

It can in fact be shown that using open holes as the zero lenses in the train causes a greater additivity error than if actual "glass" zero lenses were used. But the increase in error is not very large for reasonable setups.

8 NEAR VISION EFFECTIVITY ERROR

8.1 Introduction

In the field of ophthalmics, the refractive power or lenses is stated in terms of their back vertex power. Recall that this is defined as the reciprocal of the back focal length (bfl), which is the distance from the back vertex of the lens to the point where the rays originating at a point on an object "at infinity" converge to a point image.

But if we analyze a lens system with an object at a "near" distance (as when the subject is regarding a near object through the lens), the behavior of the lens (in terms of the relationship between object and image distances is not (necessarily) that suggested by the "rated" back vertex power. This discrepancy is described as *near vision effective error* (NVEE).

8.2 The context

The matter is often discussed in the context of a corrective lens proper, but it of course also applies in the case of the "simulated corrective lens" created by a refractor.

The phenomenon arises because the lens is not the thin lens so beloved to optical theory lecturers, but rather has a finite thickness. In fact, in the case of the refractor, the "lens" is a compound lens with two elements, or four elements if we think in terms of the power of the refractor system with respect to the power meridian direction of the cylinder lenses (if any) in the train. Thus the discrepancy is exacerbated in the refractor.

8.3 About "vergence"

In the discussion to follow, I will use for the first time in this article the term *vergence*, a term not that often heard, so I thought I would take a moment to discuss it.

Vergence is a general term in optics that embraces both of the more-familiar terms *convergence* and *divergence*, and is used to quantify either in the analysis of a lens system. It is generally applied to the rays originating at a single object point as they are observed at some later place in a lens system. It can be thought of as describing the rate at which the rays converge or diverge at that place.

The sign of the vergence is plus for convergence and minus for divergence. If we consider convergence, the value of the vergence is the inverse of the distance from the point of reference to the subsequent place at which the rays from such a single point on an object will converge to an image point. If we consider divergence, the value of the vergence is the inverse of the distance from the point of reference to the point, if we were to project the diverging rays backward, at which the projected rays would converge to a point (a virtual image model).

Vergence is denominated in the unit *diopter* (D), just as for the power of lenses or lens surfaces (and the two are closely related [8]).

8.4 Quantifying the near vision effectivity error

To quantify the near vision effectivity error (NVEE), we first consider the lens of interest, with an object at the "chosen" near distance being observed. We calculate where the image of a point on that object would be formed, and take the reciprocal of its distance from the back vertex of the lens as the vergence of the light rays (at that back vertex) in this first situation.

Then we consider a fictional thin lens, with power the same as the rated rear vertex power of our actual lens, and located at the location of the rear vertex of that actual lens. We calculate where the image of the point on the imagined object would be formed, and take the reciprocal of its distance from the back vertex of the lens as the vergence of the light rays (at that back vertex) in this second situation.

The difference between these two vergence values is the *near vision effectivity error*. The sign convention is that the error is negative if the vergence with the lens of interest is less than the vergence with the hypothetical thin lens. We can think of this situation as the actual lens having a lesser effective power for the viewing of a near object than its "rated" back vertex power.

How this value is used in lens planning is beyond my ken.

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[8] For a lens system regarding an object at infinity, the vergence of the rays as they leave the back vertex of the lens system is the same as the back vertex power of the lens system.

9 HISTORICAL EVOLUTION

9.1 Introduction

Many inventors have contributed to the refractor as we know it today, and many firms have manufactured these instruments.

But there are three major evolutionary dynasties. I will discuss one briefly here. Readers interested in more detailed information about the instruments of this dynasty will find that in the companion article, "Evolution of the optometric refractor—the deZeng-American Optical-Reichert dynasty", probably available where you get this.

9.2 The deZeng-American Optical-Reichert-and sort of Leica dynasty

9.2.1 *Background—trial lens refraction*

Before the development of the refractor, what is called the *trial lens* system was the usual way of refracting a person to determine the proper prescription for corrective lenses. It remains in use today in several special situations.

In this technique, the subject wears a trial frame, essentially a special pair of eyeglasses with interchangeable lenses.

The refractionist places lenses of varying power, taken from a set of several hundred, in the trial frame. A sphere lens is placed at the back of the frame, nearest the eye, and a cylinder lens (when required), is placed in the front of the frame, in a holder that can be rotated to change the axis direction of the cylinder lens.

When the combination of lenses (and axis settings for the cylinder lenses, if applicable) that produces best vision has been determined, that prescription is written directly from that setup.

9.2.2 *Henry L. deZeng II*

Henry L. deZeng II of New Jersey was a prolific inventor in the fields of optical devices and what we would today recognize as optometric instruments. His own form (eventually known as the DeZeng-Standard Company) manufactured and sold these instruments.

In the area of refraction of the eye, deZeng developed successively more sophisticated instruments, gradually sneaking up on what we would today recognize as the refractor.

At one stage of his work, he developed elaborations of the trial frame, including in them various collateral units used to test for and quantify various special vision problems.

These units were too heavy and bulky to be "worn" by the subject, and so they were supported by a table or floor stand.

This line of improvement eventually lead to what, at least in the deZeng line of evolution, was the first true refractor.

9.2.3 *Actual refractors of the dynasty*

So now it is time for us to move beyond "abstract" discussions of refractors and look at a couple of pivotal members of the Dezeng-American Optical-Reichert dynasty.

9.2.4 *The DeZeng No. 570 Phoro-Optometer*

The first of deZeng's instruments that we would consider today to be a refractor was the DeZeng No. 570 Phoro-Optometer, introduced in 1915. We see it in figure 8.

The two canister-like units each contain three disks, each of which has eight sphere lenses of differing powers. The sides of the housings are open, and the edges of the disks are serrated, allowing them to be moved with the finger to put a selected one of the lenses on each into the line of sight.

By manipulating the three disks, a range of sphere powers, both minus and plus, could be established. The current powers of all three lenses could be read though a single small window, allowing the sphere power being introduced to be "easily" determined (with a bit of signed number arithmetic).

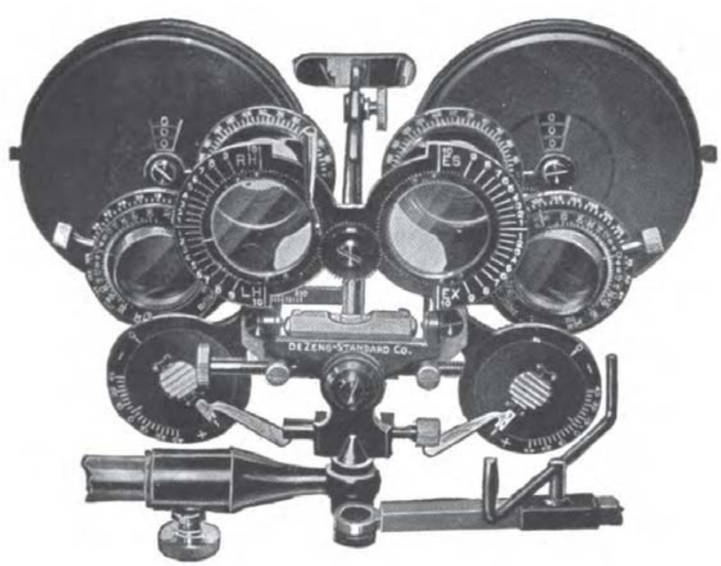

Figure 8. DeZeng No. 570 Phoro-Optometer

As to the cylinder lens component, in the basic form of the instrument this was done (just as with a trial frame) by placing "loose" cylinder lenses in a rotatable receptacle in front of the sphere lens section.

9.2.5 *The No. 589*

We will jump ahead a bit. In 1925, the American Optical Company bought deZeng's firm, and introduced deZeng's latest design, the No. 588 Phoroptor. Among other new features, it was supported from an overhead stand, which turned out to be much less intrusive to the subject. But I will skip past any further discussion of this to its successor.

In 1934, American Optical introduced the No. 589 Additive Effective Power Phoroptor. It made many both functional and aesthetic improvements to the design of the No. 588. We see a typical one in figure 9.

Figure 9. American Optical No. 589 Phoroptor

Although quite stylish in it own way, it was still very much the child of its deZeng ancestors.

Figure 10. American Optical Model 590 Phoroptor

9.2.6 *The Model 590*

The Model 590 Phoroptor, (note the subtle difference in the nomenclature, with “model) was introduced by American Optical in 1948. We see one in figure 10.

This model took an entire new design approach in many different ways, essentially moving beyond the DeZeng design tradition. It was in effect the prototype of the modern line of Phoroptor instruments.

It had many subtle features that did not propagate to its children (perhaps because they were two costly to manufacture and were not that valuable to the users).

9.2.7 *The RxMaster*

In 1956, American Optical introduced the RxMaster Phoroptor series of refractors. Figure 11 shows a typical one.

Figure 11. RxMaster Phoroptor

It carried forward many of the improvements of the Model 590, but in an entirely new overall design.

9.2.8 *The Ultramatic RxMaster*

In 1967, American Optical introduced the Ultramatic RxMaster Phoroptor series of refractors. We see a typical one in figure 12.

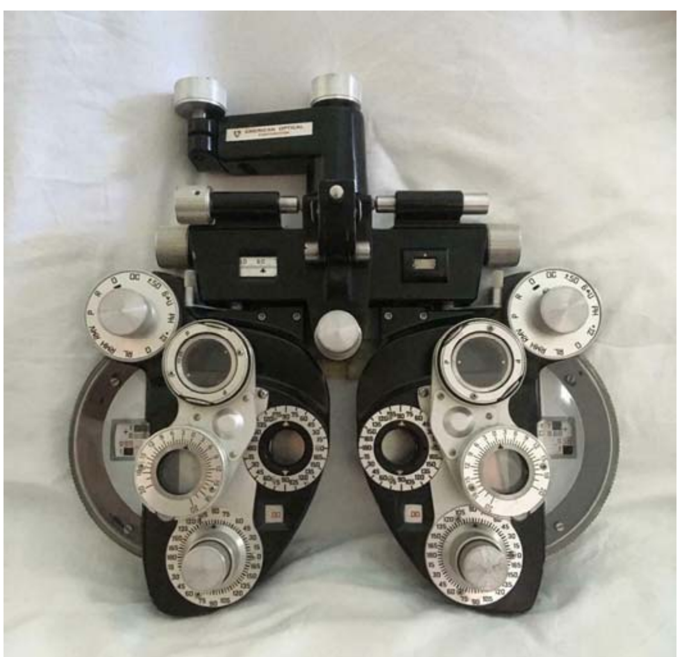

Figure 12. Ultramatic RxMaster Phoroptor

It closely followed the general design of the RxMaster, but with a number of improvements, including an important advance in the way the sphere power was set.

Essentially this same model is still offered today.

9.2.9 *Reichert, and maybe Leica.*

In 1982, American Optical sold its refractor business to Reichert (its current name is Reichert Technologies, but over the years that has changed a bit in the wake of corporate reorganization and such). Reichert continued to make the Ultramatic RxMaster Phoroptor, and has added a number of new features and modest design changes. For a while, Reichert became an element of Leica, the famous maker of cameras, optical instruments, and the like, and for a while, the Ultramatic RxMaster Phoroptor was sold under the “Leica” tradename.

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Appendix A

The Jackson cross cylinder

In the use of a manual refractor, the optimal optical parameters are determined empirically. To ascertain an initial value for the sphere power, lenses of different sphere power are put in place with the sphere disk until the subject reports that the most clear vision is obtained. The setting will typically be refined by "bracketing": if the subject reports that +1.50 is better than +1.75, and that +1.50 is better than +1.25, then +1.50 is chosen.[9] It is here that we first encounter that classical patter, "which is better, one or two".

A similar approach is used to get an initial choice for the cylinder power and cylinder axis for astigmatism correction. But in this regime, the perceptual impact of less-than-ideal correction is a bit more subtle than in basic sphere correction (where the result is an "out of focus" appearance). Further, the cylinder axis control on the refractor, being continuous, does not lend itself to simple back-and-forth change between two "bracketing" values.

To improve the "bracketing" process with regard to the cylinder correction, modern (since the 1930s) manual refractors are usually equipped with an ingenious mechanism called the *Jackson cross cylinder* mechanism (sometimes, "crossed cylinder", better grammar, actually).

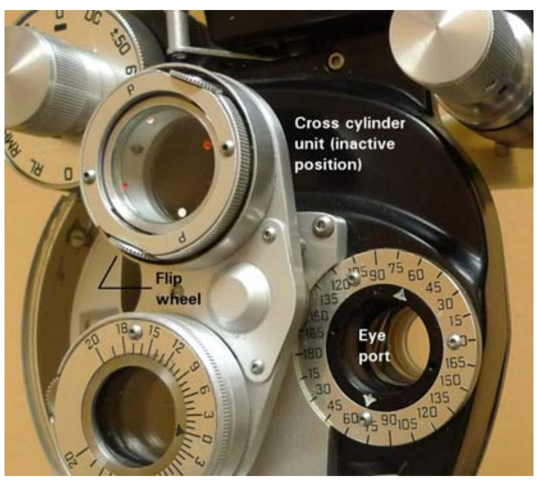

Figure 13. Cross cylinder unit

Photo by Kelly Smith
used by permission
Annotations by this author

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[9] If two adjacent trial values are reported by the subject as giving the same result, the more plus is usually chosen, as this seems to be the best in term of practical eye accommodation (this is called the "push plus" approach).

In figure 13, we see it on the right eye portion of a manual refractor (I think it is a Woodlyn). It is mounted on a swing arm, and in its inactive position (shown here) is not in the optical path for the eye.

After the initial cylinder power and axis settings are made, the cross cylinder unit is swung into place in front of the eye port.

The centerpiece of the unit is the cross cylinder lens. This lens has a plus cylinder power with one axis, and a minus cylinder power of the same magnitude with its axis at right angles to the axis of the plus power aspect. A common magnitude for that power is 0.25 D (although other values are sometimes implemented).

In figure 14, we see this in our familiar polar plot:

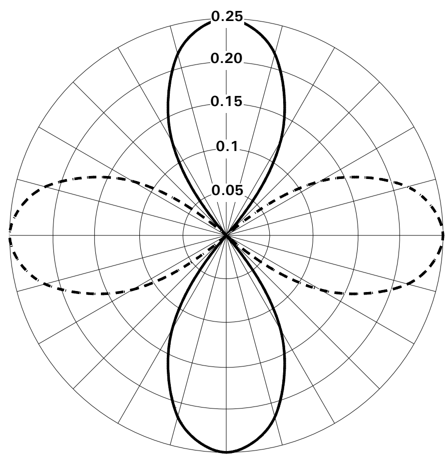

Figure 14. Cross cylinder power polar plot—±0.25 D

As before, the dotted line represents minus values of the refractive power in the respective direction.[10]

In figure 15, the arrangement of the cross cylinder unit is illustrated.

In the center, we see the cross cylinder lens, in a mounting ring. Here, for convenience, we have adopted a more symbolic representation of the lens' power arrangement. The plus cylinder aspect is shown by a black bar; its length is proportional to the magnitude of the power, the direction of the bar shows the direction of the peak of that power. (The plus cylinder axis is at right angles to the length of the bar.)

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[10] It may be difficult to grasp the significance of a lens exhibiting a plus cylinder power along one meridian and a minus cylinder power along the opposite meridian. It may be helpful to realize that the lens shown above is equivalent to a lens with sphere power of +0.25 diopter and a cylinder power of –0.50 diopter with its axis at 90°, or a lens with sphere power of –0.25 diopter and a cylinder power of +0.50 diopter with its axis at 0°

The minus cylinder aspect is shown by the white bar in the same way.

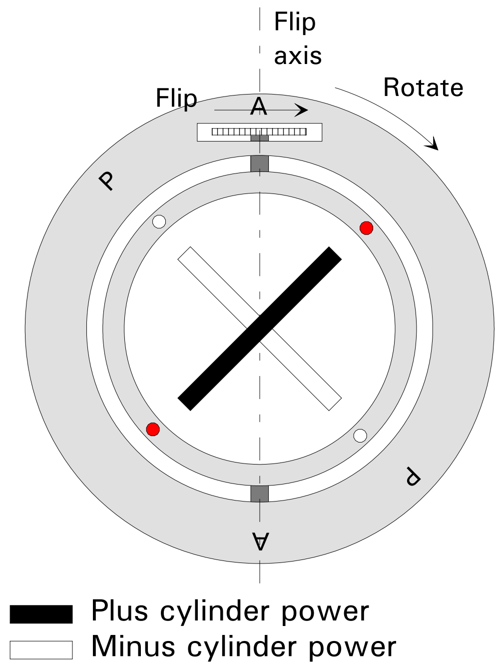

Figure 15. Cross cylinder unit

The red dots (They will look black if you are seeing this in black and white) show the direction of the plus power meridian); the white dots the direction of the minus power meridian. (Of course, in the literature, the red dots are usually described as showing the minus cylinder axis, and the white dots the plus cylinder axis.) [11]

The lens mount is itself mounted in a "gimbal" way in an outer ring, and there is a small knurled wheel on the axle that allows the lens to be flipped over. (Commonly there is one at each end, as seen in figure 13.) A detent on the axle encourages snappy action and assures that the lens will hold either position once put in it.

The outer ring can also be rotated, allowing us to orient the lens with respect to the direction of the cylinder lens in place, in different ways for different tasks. In later refractors[12], the outer ring is mounted on an underlying ring that rotates as the cylinder lens axis is rotated. Thus, once we have established a certain relationship between the orientation of the cross cylinder lens and the cylinder lens, that will be preserved as we change the cylinder axis.

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[11] In the U.K. the opposite convention is often used, perhaps a result of misunderstanding about the meaning of the notation, axis *vs*. power meridian.

[12] Said to have the "yoked cross cylinder" feature.

The notations “A” and “P” (often the “A” is not marked) have to do with two orientations of the cross cylinder lens with the cylinder lens, used for the two different functions of the cross cylinder unit—more about that shortly. A ball detent makes those two orientations mechanically stable.

Now, let’s see this wondrous gadget at work. Our first task will be to refine the choice of cylinder power. We have already put in place a cylinder lens with what we think is about the correct power, and have set its axis to what seems to be a good first position.

We swing the cross cylinder unit it place, and rotate it so that the “P” indicator aligns with the current cylinder axis. (The “P” is evocative of “refine the cylinder power”.)

We will follow the optical action on figure 16.

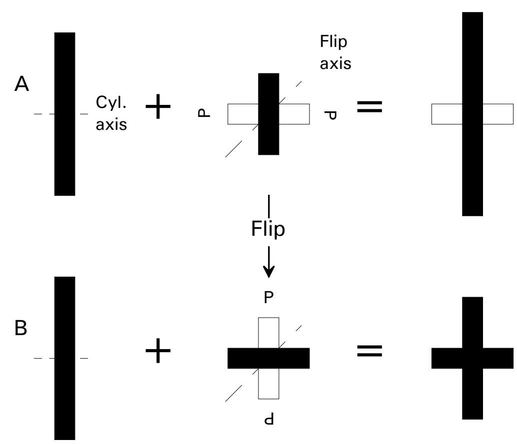

Figure 16. Cross cylinder—refinement of cylinder power

In panel A, we see the initial setting of the cross cylinder unit. On the left, we see a bar representing the basic cylinder lens that is in place (we assume its axis to be horizontal). In the center we see the cross cylinder lens. On the right, we see the joint effect of the two. Note that the presence of the cross cylinder lens has:

- **Increased** the effective (plus) cylinder power over the power of the cylinder lens proper by the magnitude of the cross cylinder powers (for example, 0.25 D).
- Added a minus cylinder aspect at right angles to the plus power.

The operator says, “which is better, one . . .”

With that, the operator flips the cross cylinder lens (we move to panel B of the figure), and says “. . . or two?”

Now note that now the presence of the cross cylinder lens has now:

- **Decreased** the effective (plus) cylinder power over the power of the cylinder lens proper by the magnitude of the cross cylinder powers (for example, 0.25 D).
- Added a plus cylinder aspect at right angles to the plus power.

If the subject reports that there is no difference, we can conclude that the power of the cylinder lens proper is the optimum cylinder lens power—situations "one" and "two" have "bracketed" the optimum value.

If the subject prefers "one" (the situation in panel A), then clearly more cylinder power is optimum. The operator puts in a higher cylinder power and repeats the process until an optimum has been reached. The converse is true if the subject prefers "two" (the situation in panel B).

Note that neither situation "A" nor "B" represent any change in the overall sphere power of the optical path.

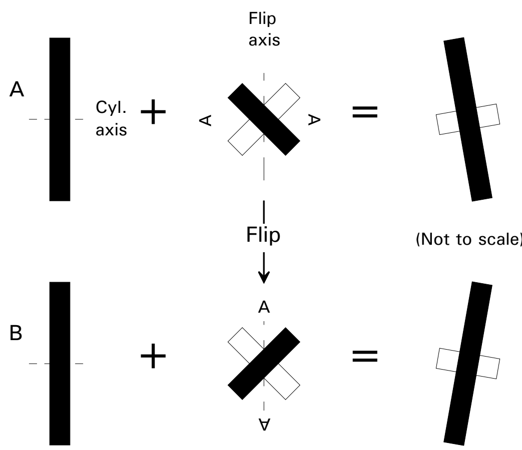

Figure 17. Cross cylinder—refinement of cylinder axis

Next, we will use the cross cylinder unit to refine our choice of cylinder axis. We rotate the unit so that the "A" indicator aligns with the current cylinder axis. (The "A" is evocative of "refine the cylinder axis".) Again, the ball detent makes that alignment stable.

We will follow the optical action on figure 17 (note that in the third part of each panel the drawing is not rigorously to scale).

Note that, initially (panel A) the presence of the cross cylinder lens has:

- Rotated the axis (and the power direction) of the cylinder correction slightly counterclockwise.

- Added a minus cylinder aspect at right angles to the plus power (essentially inconsequential).

The operator says, “which is better, one . . .”

With that, the operator flips the cross cylinder lens (we move to panel B of the figure), and says “. . . or two?”

Now the presence of the cross cylinder lens has:

- Rotated the axis (and the power direction) of the cylinder correction slightly clockwise.
- Added a minus cylinder aspect at right angles to the plus power (essentially inconsequential).

If the subject reports that there is no difference, we can conclude that the axis of the cylinder lens proper is the optimum cylinder lens axis—situations “one” and “two” have “bracketed” the optimum value.

If the subject prefers “one” (the situation in panel A), then clearly a cylinder axis greater than that now in place (that is, farther counterclockwise) is optimum. The operator increases the cylinder axis and repeats the process until an optimum has been reached.

The converse is true if the subject prefers “two” (the situation in panel B).

Note that again neither situation “A” nor “B” represent any change in the overall sphere power of the optical path.

Historical background

Sir George Gabriel Stokes developed a variable-power cylinder lens, which he described in an 1849 paper, suggesting its use to determine the optimal cylinder power to correct astigmatism. It comprises two cylinder lenses, one with a plus power, and the other with a minus cylinder power of the same magnitude.

The two lenses are mounted together so that the relative orientations of their axes could be varied. When the two axes are aligned, the net power (cylinder and sphere) is zero. When the two axes are at right angles, the situation is that illustrated in figure 14: along one meridian there is a plus cylinder power of a certain magnitude (the magnitude of the power of either component lens), and along the other meridian, at right angles, there is a minus cylinder power of the same magnitude.

With some other angle between the two components, the composite lens presents an intermediate plus cylinder power on one meridian, and the same minus cylinder power on the opposite meridian.

Note that in this situation, the overall result can be considered equivalent to a lens with both either:

- A plus sphere component and a minus cylinder component, or
- A minus sphere component and a plus cylinder component

The use of a Stokes lens to determine the optimum cylinder power in eyeglasses was done in a context where the optimal sphere power was found by placing sphere lenses with varying power, from a set, into an eyeglass-like holder worn by the subject. A Stokes lens was then added to the mix, with its “setting” (angle between the axes of its components) adjusted to vary the cylinder effect, and its overall angle adjusted to vary the cylinder axis. And of course, a sphere component was also added, which had to be taken into account in recording the overall indicated prescription.

Edward Jackson, in 1897, published a paper in which a Stokes lens, fixed at the “cylinder axes at right angles” state, could be used (by “flipping”) to increment and then decrement the power of a “trial” cylinder lens, allowing for convenient “bracketing” to ascertain the optimal cylinder power (just as we saw above in figure 16). Thus a Stokes lens, with the axes of the two elements fixed at right angles, became the “Jackson cross cylinder” lens.

Twenty years later, in 1907, Jackson published another paper in which he showed that this same “cross cylinder” setup could be also used to make incremental changes in the effective axis of a cylinder lens, allowing for convenient “bracketing” to ascertain the optimal cylinder axis (just as we saw above in figure 17).

The use of the Jackson cross cylinder arrangement on manual refractors emerged some time in the 1930s.

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Appendix B

Plus and minus cylinder refractors

B.1 Introduction

In the body of this article I described that ordinarily a given refractor will be arranged to provide a range of plus cylinder powers or a range of minus cylinder powers, but not both. I pointed out thet the "plus cylinder" refractors are ordinarily used by ophthalmologists, and the minus cylinder refractors by optometrists. What's with this? The story is a complicated one.

B.2 The duality of plus and minus cylinder powers

The prescription for a corrective lens (when correction for astigmatism is involved) can be expressed either in terms of a sphere power with a certain plus cylinder power with a certain axis direction, or in terms of a sphere power along with a certain minus cylinder power with a certain axis direction. The two, for all practical purposes, can describe the identical needed behavior of the corrective lens. But why might the prescriber choose to consistently use form or the other (and to order a phoropter arranged to most directly deliver its result in that form)?

B.3 Two refraction techniques

B.3.1 Accommodation by the eye

The human visual system, faced with an out-of-focus image, tries to attain good focus by *accommodation*; that is, by changing the shape of the crystalline lens of the eye, done by way of the ciliary muscle, which surrounds the lens capsule.

When refraction is done (either with a refractor or trial lenses), the eye's attempt to accommodate, by shifting its focus state, can interfere with some of the maneuvers of the refraction procedure. Thus we must in some way disable, or frustrate, the eye's attempt at accommodation.

B.3.2 Clycloplegic refraction

One approach is to instill into the eyes a *cycloplegic medication*[13], which seriously disables the ciliary muscle (induces *cycloplegia*), and thus keeps the eye's focus state fixed. That state is with the ciliary muscle relaxed, which puts the lens into its greatest focal length (as

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[13] This medication is usually also a *mydriatic*—it causes the eye's pupil to dilate (open wide). This has its own advantage in the refraction process.

for focus on an object at a great distance, ideally and theoretically at an infinite distance).

It turns out that, with cycloplegia in effect, the cylinder aspect of the refraction can be essentially equally-well conducted with either plus or minus cylinder lenses. (Not all would agree!)

But, at the time the practice of refraction was being “normalized”, another consideration led to a preference for using plus cylinder lenses in cycloplegic refraction.

I will put off explaining that “other consideration” just now so as not to slow down the real story. I will discuss it later, in section B.5.

B.3.3 Manifest refraction

In this technique, cycloplegia is not used. The name suggests that this is the refraction “as seen” (manifest), meaning without interference with the eye’s accommodation action by cycloplegia.

Here, we still need to avert interference with the measurement process by the eye’s action of accommodation, as it tries to maintain good focus. This is done by a clever ploy, involving what is spoken of as “fogging” the eye.

The process is complicated to explain, and to allow this appendix to come to a conclusion, I will separate it into appendix Appendix C.

But the bottom is that the process works more handily if minus cylinder lenses are used in the refraction.

So, in fact, when conducting manifest refraction, it is seen as desirable to use minus cylinder lenses.

What about the notion that if we use minus cylinder lenses in the refraction, the prescription will be written in “minus cylinder” form, and in turn, that will suggest (if the lens is made in the once-common practice), the use of a minus cylinder surface on the front of the lens, which is not desirable?

Well, that is all just folklore. Even in “the day”, lens makers were well able to covert a prescription in “minus cylinder” form to “plus cylinder” form, so it could be used as a recipe for making the lens.

B.4 Why the difference by profession?

Above we saw the basic differences between clycloplegic and manifest refraction. And overall, cycloplegic refraction was the easiest to actually do—the “maneuvers” we less tricky than for manifest refraction (even when the latter was done with minus cylinder lenses).

However, under the medical practice laws of the various states (which differed greatly), there were (still are) are certain things that a licensed ophthalmologist (who had to start off with “MD” or “DO” training) can do that a licensed optometrist (whose training, while very extensive, is not that of an MD or DO) may not do.

And in many states, at an earlier time, one of those prohibited things was to prescribe or administer “medication”. The definition of “medication” varied from state to state, but in many cases included that which was used to induce cycloplegia.

So, in those states, licensed optometrists, unable to induce cycloplegia, were forced to us the less-convenient manifest form of refraction.

> The licensed optometrist associations in the various states were typically supportive of relieving those restrictions. By now, we should be able to imagine that the licensed ophthalmologist associations in the various states were not in general supportive of relieving those restrictions.

Of course, in fact, today, in all (think) states, licensed optometrists are permitted to prescribe, and administer, a range of medications, including the medication used for cycloplegia.

And the result of that was that the profession of optometry settled into the use of minus cylinder technique in refraction.

But that doesn’t tell us why, in the profession of ophthalmology, where the practitioners have essentially always been free to use cycloplegia, and the situation mentioned above does not apply, the profession settled into the use of plus cylinder technique.

B.5 Why the preference for plus cylinders in ophthalmology?

But that doesn’t tell us why, in the profession of ophthalmology, where the practitioners have essentially always been free to use cycloplegia, and the situation mentioned above does not apply, the profession settled into the almost exclusive use of plus cylinder technique. Maybe this is the reason.

“In the day”, it was generally the view that the prescription was not just a specification for the overall optical performance of the eyeglass lens but in fact a recipe for making it. And in that era, when the eyeglass lens was made, it was common to have a sphere surface (which determined the sphere power) ground into the back surface of the lens, and a cylinder surface (which determined the cylinder power), if applicable, ground into the front of the lens.

And at the time, it was at the time for various reasons considered desirable for this cylinder surface to be convex (a plus cylinder) rather than concave (a minus cylinder). (Remember, either kind can be used to get the desired effect.) For one thing, a concave surface on the front of a an eyeglass lens makes the glasses look really funny.

So, given the view of the time that the prescription was a "recipe" for making the lens, working backward from that it became desirable for the prescriptions to be written in "plus cylinder" form.

And, again working backward, since the prescription notation was most handily derived directly from the refraction procedure, it became most common to use plus cylinders in that process.

And so it became standard practice, in the field of ophthalmology, to use plus cylinder practice in refraction.

Maybe.

B.6 A bit of a postscript

Now, it was later realized that better optical performance would be attained if both the sphere and cylinder components of the lens power were done by the rear surface of the lens. This required a surface that was in fact a section of a torus, said to be a *toric* surface.

Grinding that was more challenging than for a sphere or cylinder surface, but schemes for doing that were invented and made it practical to use this more desirable design. Both sphere and cylinder aspects of that rear surface curve are minus. The front surface is sphere, and is convex (plus) so the lens will have the desirable "meniscus" form whether its sphere power is plus or minus.

But, in ophthalmology, the die was cast.

B.7 In historical refractors

For whatever reason, the earlier refractors (at least in the "dynasty" mentioned in the body of the article) were seemingly all made in only the "minus cylinder" form.

And today, for someone looking to acquire a modern refractor on the used market, they will probably find far more minus cylinder machines offered than plus cylinder machines. Perhaps more optometrists retire, or go out of business, than ophthalmologists.

An interesting note in one of the US patents covering the American Optical Model 590 Phoroptor was that the cylinder lens section was specifically designed so that it could readily be removed to gain access to the lens disks “for interchanging plus and minus cylinders”.

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Appendix C

"Eye fogging" in manifest refraction

C.1 Introduction

In manifest refraction, we do not use cycloplegia to disable, or at least frustrate, the eye's attempt to accommodate as different cylindrical powers are put in place with the refractor.

Rather, in most practice, a clever ploy is used instead, one that is spoken of as "fogging the eye".

C.2 The procedure

C.2.1 Introduction

Let's first consider an eye whose lens system has a greater power in one meridian than the opposite one (that is, which has astigmatism), and which in addition has a "relaxed" focal length that is too great for the dimensions of the eye (that is, the eye suffers as well from hyperopia).

Imagine that this eye is regarding a point source of light at a great distance. Because of the inconsistency of refractive power in the different meridians, rather that the light rays from the point source being converged into a point image at some point, here (theoretically) two line images are formed. one (horizontal) at a point behind the retina, and the other (vertical) at a point farther behind the retina.

We see a fanciful oblique presentation of that in this figure [14].

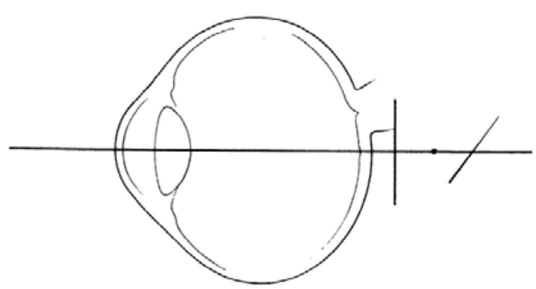

Figure 18.

This is predicated on the refractive power of the eye's lens system being greatest in the horizontal meridian and thus being the least in the vertical meridian.

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[14] The figures in this section were adapted from those in a paper by Jay H. Kaufman, and may be original with him. They are used here under the doctrine of fair use.

Of course, no actual images can be formed behind the retina (which is opaque), but just imagine that this problem has been magically relieved.

C.2.2 My avatar

Before I proceed, I must note that, in actual refraction, the object is not a point source but rather a test chart of some sort (perhaps a Snellen chart or its equivalent). Thus the actual image situation (theoretically, behind the retina) is much more complex that a pair of two line images. But we will magically still follow the adventures of the images created from a single point on that test chart–initially as two line images at right angles, at different places on the axis.

Now as we, in the subsequent scenes of this drama, approach neutralization of the subject's astigmatism, the two line images move closer to each other, axially, and become shorter, approaching and eventually becoming a point image.

But, to help us follow the action, following the actors, I will continue to draw the "image result" as two line images at right angles, albeit eventually closer together axially. I think of this as an avatar for the entire image result.

Now back to the drama.

C.2.3 "Fogging" the eye

The first step in the refraction process is to put a sphere lens of substantial power in front of the eye. The result is that our two heroes, the two line images, are now created farther forward, perhaps even, theoretically, in front of the eye, like so:

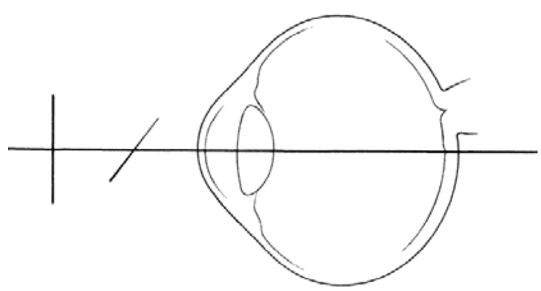

Figure 19.

Of course, these hypothetical images, being located in front of the lens, are "virtual", but that doesn't make them of any less value to us at this point. The important thing is that they are so far removed from the retina that the image on the retina is gravely blurred, probably beyond recognition, as if the scene were being viewed through a thick fog. And in fact, this action is spoken of as "fogging" the subject's view.

The accommodation system, unsatisfied with this image not being on the retina, tries to move them back by an increase in the eye lens's focal length. but it runs out of range with the situation still almost as seen just above, maybe like so:

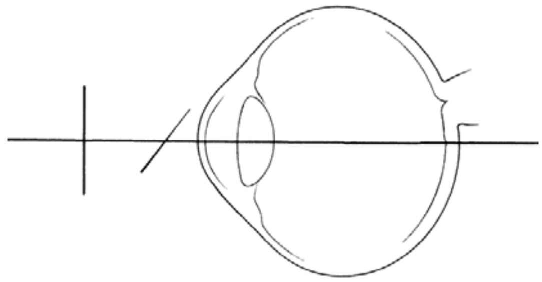

Figure 20.

The subject's view of the test chart is still severely "foggy".

We next reduce the power of the sphere lens, at one point leading to a situation like this:

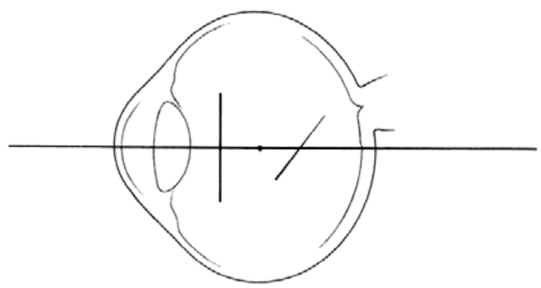

Figure 21.

Perhaps now the subject can begin to see the test chart, although still very badly out of focus. The accommodation system tries to move these images (on the average) onto the retina, but again that would require an increase in the focal length of the eye lens, and it is already at its greatest focal length. The accommodation system is "against the maximum focal length stop". And we want to keep it there.

We continue to decrease the power of the sphere lens until we get a situation like this:

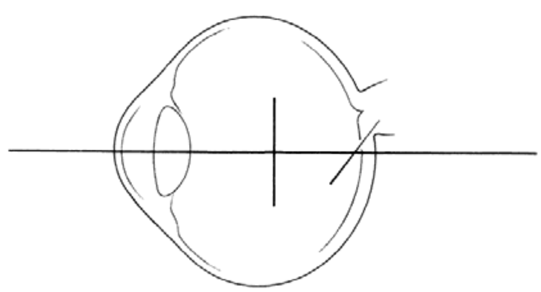

Figure 22.

Note that in reality the two line images now are smaller than in the prior figure. But my convention is to use the graphic presentation of the line images at constant size as the avatar for the entire situation downstream from the lens.

Now the rearmost (horizontal) line image lies almost on the retina (so the horizontal line image on the retina will be only slightly out of focus), but the frontmost line image (vertical) is still quite a way from the retina, so the vertical line image on the retina is substantially out of focus.

And again, the diligent accommodation system attempts to, "on the average", put the two line images on the retina. But again, that would require an increase in the focal length of the eye lens, and it is already at its greatest focal length.

So the accommodation system remains frustrated, and thus cannot change the focal length of the eye's lens as the remaining steps of the refraction take place.

Interestingly enough, although at this point both line images can be seen, the horizontal one a bit blurred, but neither as if "seen through a fog", this situation is still described in optometric jargon as the eye "still being fogged". That is really a metaphor for, "The accommodation system cannot do what it is inclined to do, which would mess up what we are doing."

C.2.4 Neutralizing the astigmatism—minus cylinder lenses

Now we begin to neutralize the astigmatism. We put in place a minus cylinder lens of small power with its axis vertical (and thus its power is in the horizontal direction). Its effect is the reduce the discrepancy between the overall power of the lens system between the (in this case) horizontal and vertical meridians. The result is that the axial separation between the two line images is reduced (the vertical line image being moved toward the retina.

Then we perhaps have this:

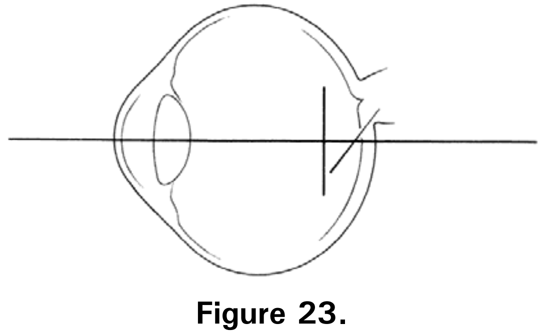

Figure 23.

W continue increasing the magnitude of the minus cylinder power until we have this:

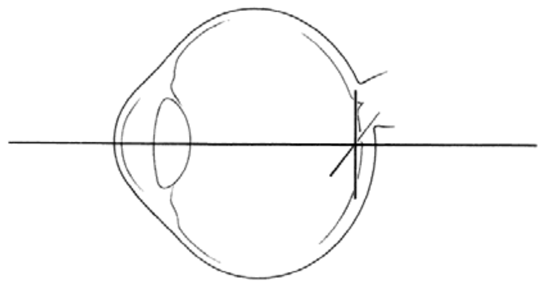

Figure 24.

In reality, the two line images have now shrunk to infinitesimal size, so it is a point image that is created. Still, for consistency, I continue to show the two line images, at constant size, as the avatar for what is happening.

Here, the astigmatism is completely neutralized, but the image is not quite on the retina, and thus is still a little out of focus.

So we decrease the sphere power a little until we have this:

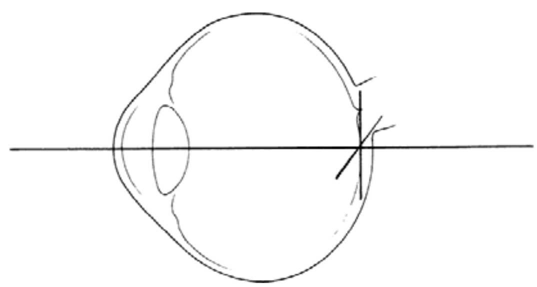

Figure 25.

Again, in reality, it is a point image that now lies on the retina, even though I show our familiar characters, the two line images, at constant size so they can be recognized.

We have neutralized all the refractive errors in the eye, and write down the sphere lens combination we have in the refractor as the cylinder part of the prescription for this eye.

C.2.5 Neutralizing the astigmatism—plus cylinder lenses

Now suppose we did this using plus cylinder lenses. We will start when we have again achieved this situation (as described earlier):

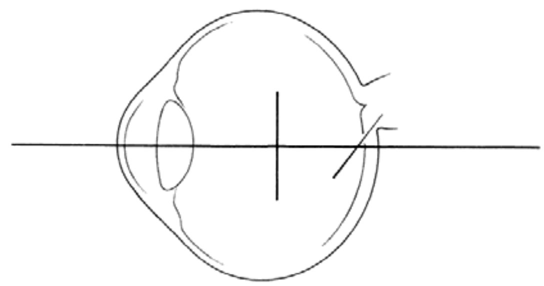

Figure 26.

Now we start to neutralize the astigmatism by putting a plus cylinder lens in front of the eye, with its axis horizontal (and thus its power is in the vertical direction). As before, its effect is the reduce the discrepancy between the overall power of the lens system between the (in this case) horizontal and vertical meridians. In particular, it increases the overall power in the vertical direction. The result is that the axial separation between the two line images is reduced (the horizontal line image being moved away from the retina).

We then might have this:

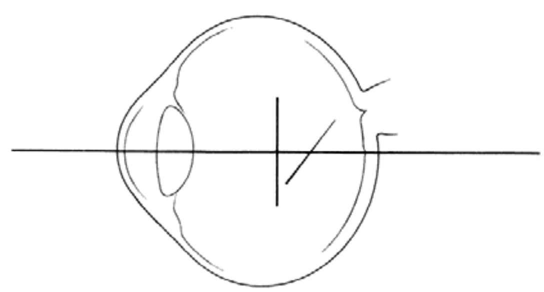

Figure 27.

But now neither of the line images are in very good focus, and it will be hard for the subject to report on changes seen with regard to teh effect of the astigmatism. So we must now decrease the power of the sphere lens to again put the rearmost (horizontal) line image near the retina.

As we continue to increase the plus cylinder power toward the value that will completely neutralize the astigmatism, we will again need to decrease the plus sphere power to keep the entire image (here represented by the two line images) in a reasonable state of focus.

C.3 So what of it?

The clear difference between these two scenarios is that, if we neutralize the astigmatism with plus cylinder lenses, we have to keep fiddling with the sphere power, whereas if we neutralize the astigmatism with minus cylinder lenses, we don't. And that is a clear advantage.

Is that easier than using clycloplegia? Maybe so, maybe not.

But to an optometrist who was, at the time, prohibited from using clycloplegia, that was of no importance., The important point is that, using manifest refraction (no clycloplegia), the minus cylinder technique is the more convenient.

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