OPHTHALMIC OPTICS

AND CLINICAL REFRACTION

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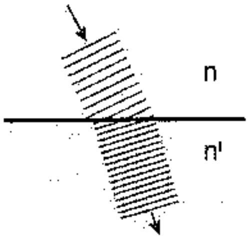
OPHTHALMIC OPTICS

Refraction of light at interfaces

Light slows down when entering refractive media.



$$\text{Refractive index} = n = \frac{\text{speed of light in vacuum}}{\text{speed of light in material}}$$

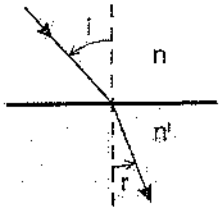
n is **always > 1**

n_{vacuum} = 1 (exactly)
n_{air} = 1.0003
n_{water} = 1.33

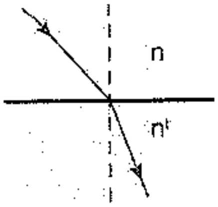
Wavefronts slow down and change direction when entering a refractive medium at any angle other than perpendicular.

Two laws of refraction:

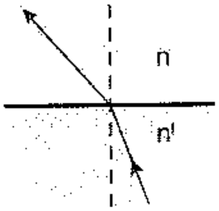
1. Snell's law $\boxed{n \sin i = n' \sin r}$
2. Incident ray, normal to the surface, and refracted ray all lie in the same plane.



When a light ray passes from a medium with a lower refractive index (n) to a medium with a higher refractive index (n'), it is bent **toward** the normal.

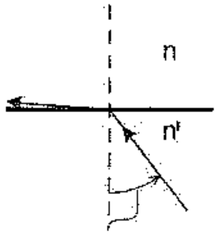


When passing from a higher refractive index (n') to a lower refractive index (n), it is bent **away from** the normal.

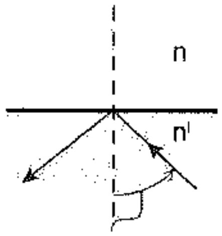


Critical angle

Only occurs when light passes from a **higher index** to a **lower index** medium.



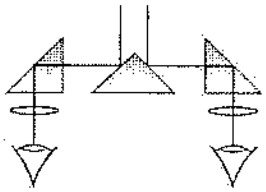
critical angle
(critical angle for
ordinary glass/air
interface = 41°)



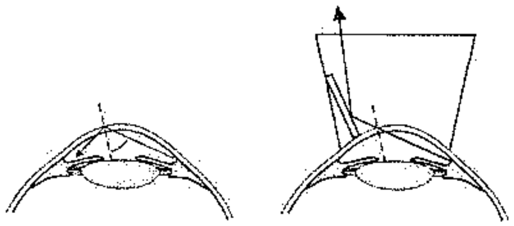
greater than critical angle; get
total internal reflection

See:
p77, prob 27

Examples of total internal reflection:

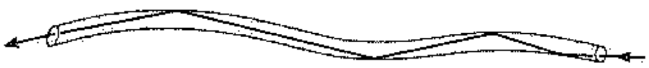


eyepieces of indirect
ophthalmoscope



gonioscopy

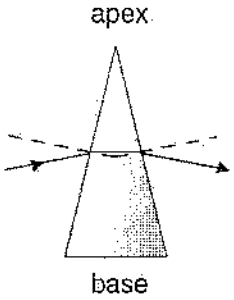
(by replacing air with glass or plastic, rays
which previously were totally internally
reflected can now exit from the cornea)



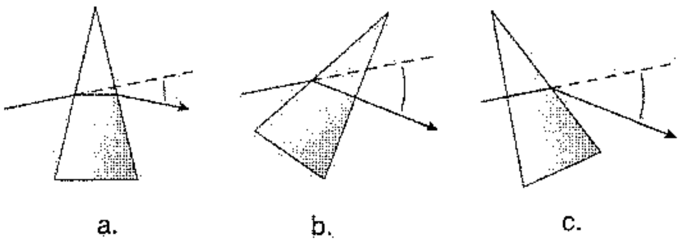
fiberoptics

See:
p55, prob 1
p93, prob 42

Prisms



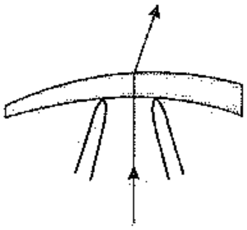
Prisms bend rays of light <u>towards the base</u> of the prism.



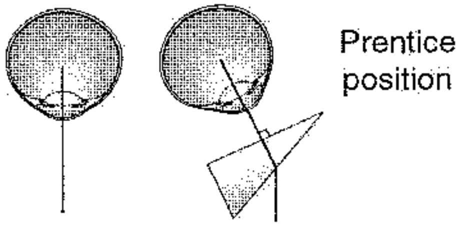
The total angle of deviation is <u>least</u> when equal bending occurs at each face of the prism ("minimum deviation position"), as in (a).

Calibration of prisms

Prism in spectacle lenses is measured in the <u>Prentice</u> postion, with one of the faces of the prism (the rear face against the nose cone of the lensmeter) being perpendicular to the light rays.

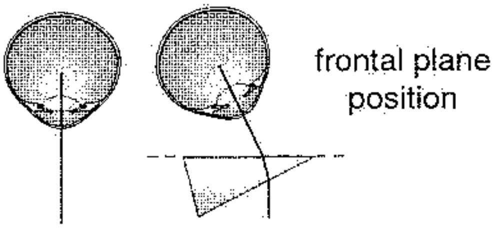


Orthoptic prisms made of glass are calibrated in the Prentice position. They should be held with the back surface perpendicular to the line of sight.



Glass prism

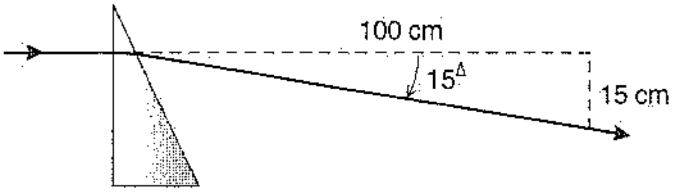
Plastic prisms, and prism bars, are calibrated by the angle of minimum deviation. Holding them with the rear surface in the frontal plane approximates this closely for distant fixation objects. For near fixation objects, the rear surface should be angled in slightly so as to be perpendicular to the direction of the fixation object. The shape of the prism base (right angle, isosceles) makes no difference in either case.



Plastic prism

Prism diopter

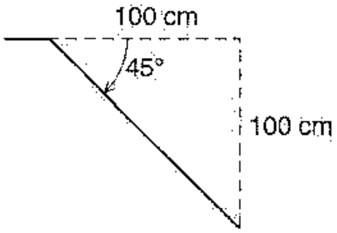
The power of a prism in prism diopters ($^{\Delta}$) is equal to the displacement in centimeters of a light ray passing through the prism, measured 100 centimeters from the prism.



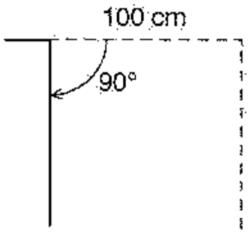
15^{Δ} prism

30^{Δ} should never be referred to as 30 "diopters". Although the term 30 "prisms" may occasionally be used, the correct term is 30 "prism diopters".

As can be seen from these diagrams, **prism diopters** of deviation are related to **degrees** of deviation in a trigonometric manner (degrees = $\tan^{-1} \Delta/100$), not a linear manner.

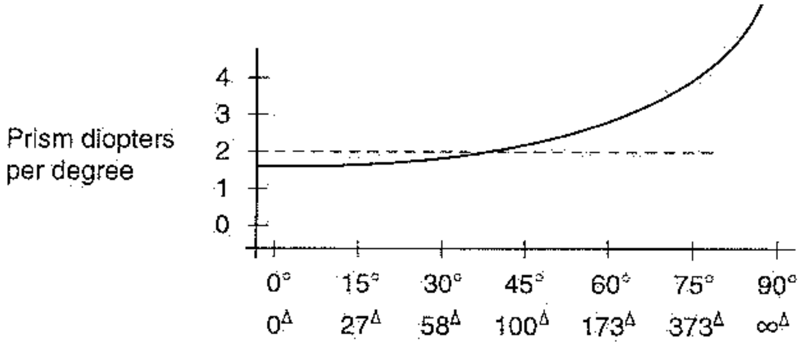


A 45° angle is equal to 100^{Δ}.



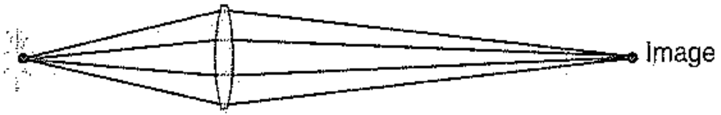
A 90° angle is equal to an infinite number of prism diopters.

For angles under 45° (or 100^{Δ}), each degree (°) of angular deviation equals approximately 2^{Δ}. Beyond 45° (or 100^{Δ}), however, this approximation is no longer valid, and, as one approaches 90°, each degree approaches an infinite number of prism diopters.

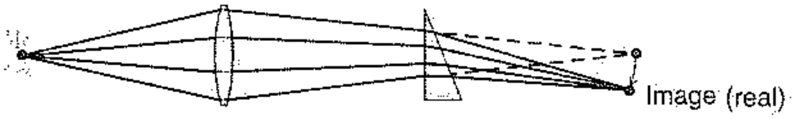


Displacement of images by prisms

Consider an image of a point of light formed by a lens:

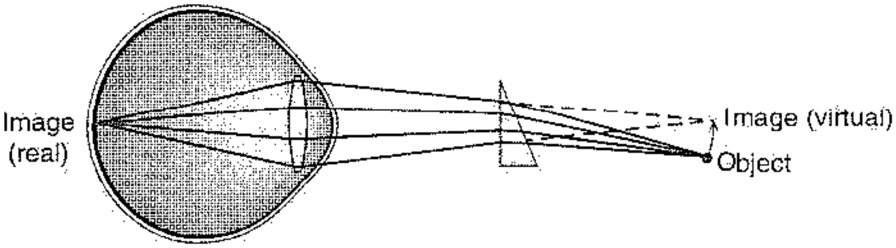


Introduce a prism:



Note that the image has been displaced **toward the base** of the prism. **Real** images, like individual light rays, are displaced toward the **base** of the prism.

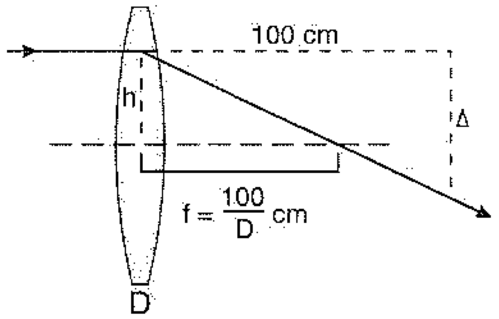
But, if we turn the light around, and make the image the object, and view the object through the prism:



An image of the object is formed by the prism, a **virtual** image, which is displaced toward the **apex** of the prism. Virtual images are in general displaced toward the **apex** of prisms, although the light rays themselves are always bent toward the base.

See:
p55, prob 2
p79, prob 28

Prismatic effects of lenses (Prentice's rule)



A lens has **no** prismatic power at its optical center; that is, a ray passing through the optical center of a lens passes through undeviated.

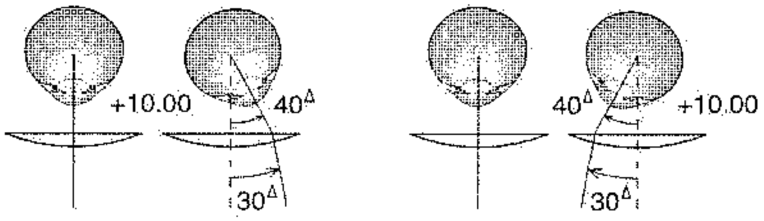
By similar triangles: $\frac{\Delta}{h} = \frac{100}{\frac{100}{D}}$

Prentice's Rule

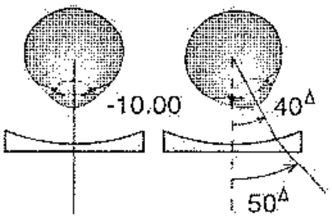
$$\Delta = h_{cm} D$$

The prismatic power of a lens at any point on the lens is equal to the distance of that point from the optical axis in centimeters multiplied by the power of the lens in diopters.

Prismatic effect of glasses on strabismic deviations



Plus lenses <u>decrease</u> the measured deviation, whether ET, XT, or HT.



Minus lenses <u>increase</u> the measured deviation, whether ET, XT, or HT.

The true deviation is changed by approximately:

(2.5) (D) %
where D = the bilateral spectacle lens power.

For example, an exotrope of 40^{Δ} wearing -10.00 sphere glasses will measure:

(2.5) (10) = 25% more exotropia,

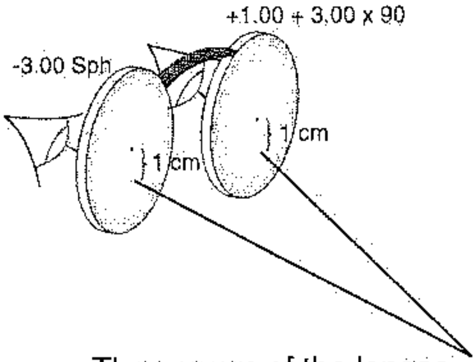
for a total of 50^{Δ} of XT (see righthand drawing above). Remember the **3M** mnemonic:

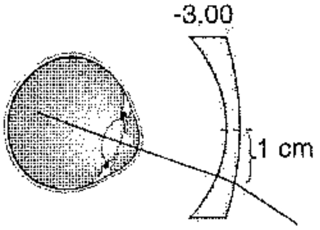
Minus Measures More.

See:
p55, prob 3

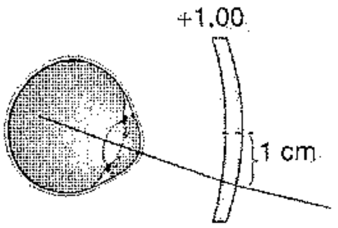
Induced prism in anisometropia

If a patient with no ocular misalignment reads 1 centimeter below the optical centers of his single vision glasses, with the different lens powers as shown, what prismatic effect is induced by the glasses?





$\Delta = h\ D$
$\Delta = (1)\ (3.00)$
$\Delta = 3^{\Delta}$ BD



$\Delta = h\ D$
$\Delta = (1)\ (1.00)$
$\Delta = 1^{\Delta}$ BU

The powers of the lenses acting in the **vertical** meridians are used.

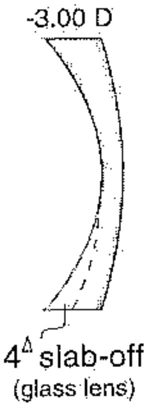
Total prismatic effect in the reading position = 4^{Δ} of vertical prism.

If measured in the reading position while wearing these glasses, will the patient show a right hyperdeviation, or a left hyperdeviation? A **left** hyperdeviation.

Think of the effect of the lenses in deviating the lines of sight as the lines of sight pass from the eyes out through the lenses. Or think of what type of prism will be necessary to **neutralize** the induced deviation (will need BU on the right, or BD on the left). **Behind** the glasses, the right eye may try to turn upward, and the left eye downward, to compensate for the **optically-induced** left hyperdeviation.

Most patients adapt (physiologically) or learn to fuse small vertical deviations. If they **cannot**, there are several ways to compensate for the problem:

1. Contact lenses **instead** of glasses
2. Lower both optical centers to compromise vertical imbalance between distance and near vision
3. Prescribe dissimilar segments
4. "Slab-off" prism (bicentric grinding)

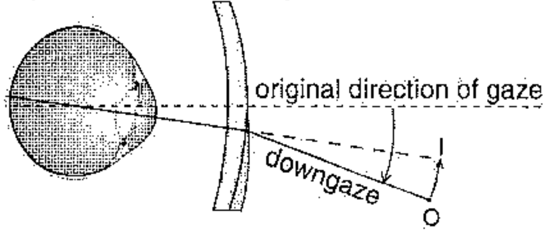


The slab-off prism is always taken off the more minus or less plus glass lens. (Except with modern plastic lenses, where the slab-off is taken off the **mold**, effectively **adding** base-down prism to the more plus or less minus lens; this is called "reverse slab.") It is better to **measure** (by prism and cover test in the reading position) than to try to calculate, the amount of slab-off prism needed.

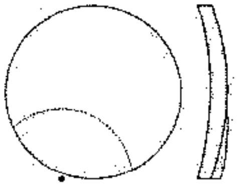
See:
p57, prob 4
p81, prob 29

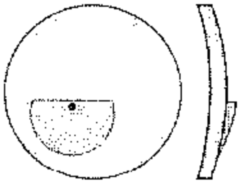
Bifocal segments — prismatic effects

Image jump — produced by sudden introduction of prismatic power at the **top** of the bifocal segment. The object which the eye sees in the inferior field when looking straight ahead suddenly jumps upward when the eye turns down to look at it:



If the optical center of the segment is at the top of the segment, there is no image jump:


round-top seg
maximum
image jump


flat-top seg
minimal
image jump

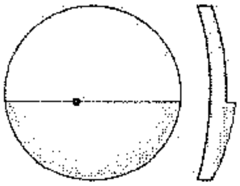
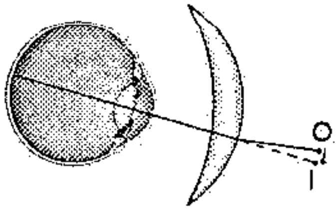
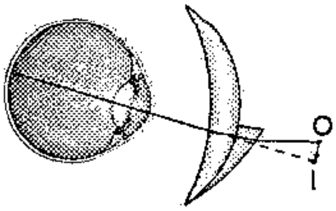
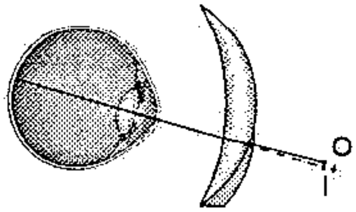

Franklin (Executive®) seg
no
image jump

Image displacement — produced by the **total** prismatic power acting **in the reading position** (the total prismatic power of the **lens plus the bifocal segment**).

With plus lenses:

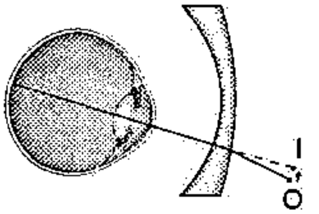


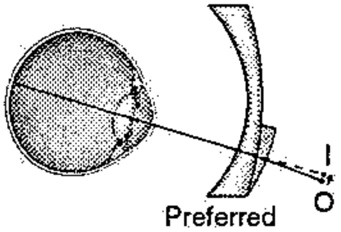




Preferred
(round-top)

With minus lenses:





Preferred
(flat-top)

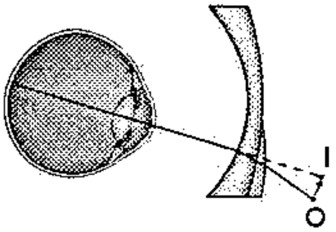
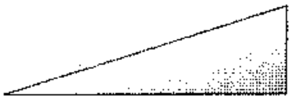


*Image displacement is more bothersome than image jump for most people, and minimizing image displacement should take precedence when choosing the type of add.

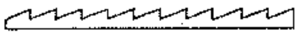
See:
p57, prob 5
p81, prob 30

Fresnel prisms

Fresnel (pronounced freh nell') prisms are equivalent to side-by-side strips of long, narrow, thin prisms.



conventional prism

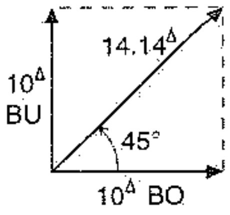


Plastic Fresnel prisms are available as Press-On™ prisms from 0.5^{Δ} to 40^{Δ} for application to the rear surface of spectacle lenses. They are convenient and lightweight, but are difficult to clean, requiring periodic replacement.

Visual acuity suffers by one or two lines with the higher power prisms, because of glare and chromatic aberration.

Oblique Prisms

Horizontal and vertical prisms may be combined into an oblique prism by ordinary vector addition.



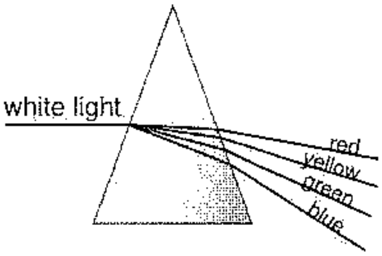
In this case, for a left eye, an oblique Fresnel prism of 14^{Δ} could be prescribed with base **up and out** in the 45 degree meridian. Note that each meridian has **2** directions as far as prism base directions are concerned, unless one prescribes prism bases from 0 to 360 degrees.

Prescribing oblique prism, rather than separate vertical and horizontal prisms, saves thickness, weight, and cost in spectacles.

See:
p57, prob 6
p81, prob 31

Prisms – chromatic effects

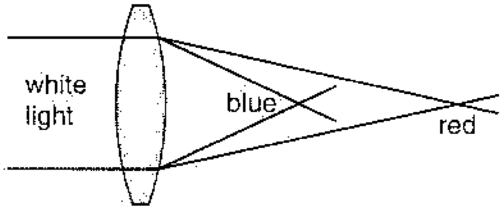
Because the refractive index of transparent materials is slightly different for different wavelengths of light, white light is **dispersed** into its component colors by prisms.



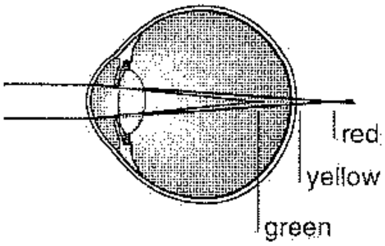
Blue rays are bent more strongly than red rays.

Chromatic aberration of lenses

Simple plus lenses likewise bend blue rays more than red rays, leading to the optical aberration known as **chromatic aberration**. The blue rays come to focus closer to the lens than the red rays.



Chromatic aberration occurs strongly in the human eye, with almost **3.00 D** difference in the focus of the far ends of the visible spectrum (1.50 D is usually stated in textbooks). This is the basis of the red-green test for refinement of the sphere in clinical refraction (duochrome test, bichrome test).



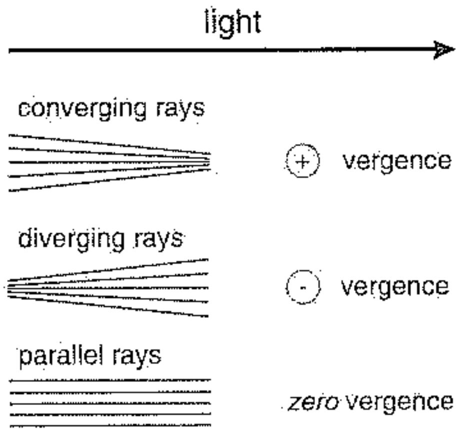
Sphere is adjusted until the black letters on the red and green halves of the test chart are equally clear, indicating that the red rays are focused as far **behind** the retina as the green rays are focused **in front**. Yellow light, midway between the red and green, will then be in perfect focus on the retina, the optimum focus when viewing with white light. The red and green filters usually used create a chromatic spherical difference of only 0.50 D, requiring visual acuity of 20/30 or better to distinguish a blur difference. Balance with the red-green test should always be approached from the fogged direction (red clearer) to minimize accommodation.

See:
p59, prob 7

Vergence

Extremely important concept.
Used primarily in **ophthalmic** optics.

Definition — A measure of the spreading (or coming together) of a bundle of light rays coming from (or heading toward) a **single point**.

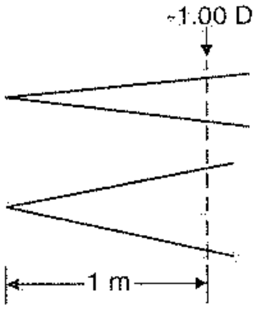


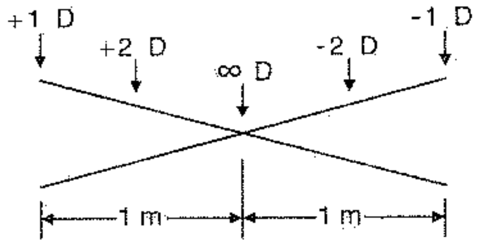
Direction of light travel must be specified!

Light from the sun — zero vergence? **No**. Light from each **point** on the sun has practically zero vergence by the time it reaches us. If all the light from the sun had zero vergence, the sun would appear as a pinpoint spot of light. If light from every point of an **extended** object (such as the sun) has zero vergence, the light from the object as a whole is said to be **collimated.**

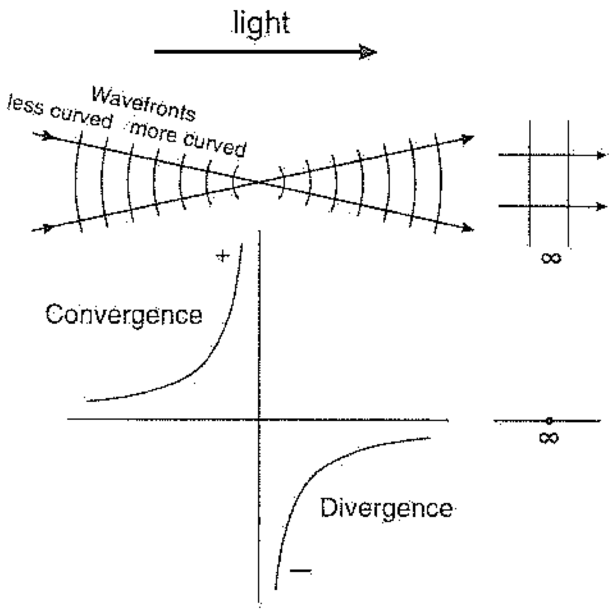
Converging light — rare in nature; requires an optical system to produce it.

Units — **diopters** — the reciprocal of the distance, in meters, to the point where the rays would intersect if extended in either direction.



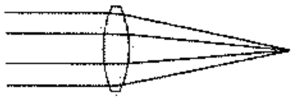


Vergence cannot be measured by angles, for which angle would we use?

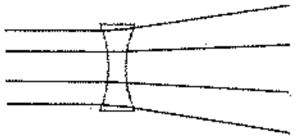


Alternatively, vergence may be thought of as a measure of the curvature of the wavefront. The more curved the wavefront, the greater the vergence. Curvature is defined as the reciprocal of the radius, so in fact the units are entirely equivalent.

Lens power defined in terms of vergence (U+D=V)



Lenses **add** vergence to light.



The **amount** of vergence added to the light is defined as the power of the lens, measured in diopters. (As is turns out, the lens adds the same amount of vergence to the light regardless of the vergence of the light to begin with.)

Thus by definition:

$$\boxed{U \quad + \quad D \quad = \quad V}$$

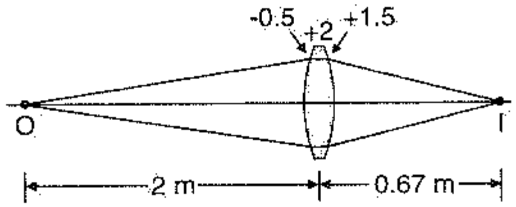
BASIC LENS FORMULA

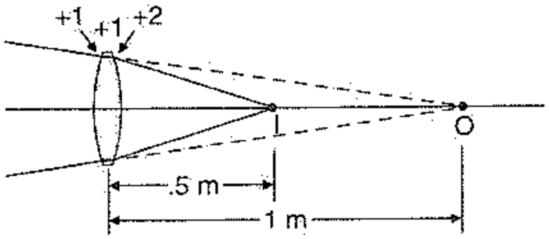
("Vergence formula")

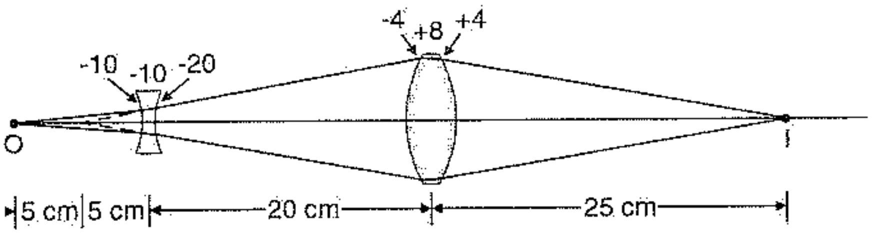
vergence of light entering the lens	amount of vergence added to the light by the lens (power of the lens)	vergence of light leaving the lens

(Easier to use than the lens formula from high school physics:
$1/p + 1/f = 1/q$)

Vergence examples:



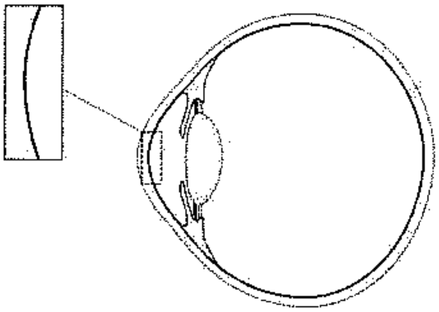




See:
p59, prob 8
p83, prob 32
p85, prob 34

Power of a spherical refracting surface in fluid

To determine whether a spherical refracting surface has plus or minus power, enclose the surface within an imaginary rectangle:



Determine the shape of the “lens” which the rectangle carves out of the material with the **higher** refractive index. If this “lens” has a plano-convex shape, the surface has plus power. If it has a plano-concave shape, the surface has minus power.

The refracting power in diopters of a spherical surface may be calculated by:

$$\boxed{D_s = \frac{|\,n' - n\,|}{r}}$$

where
$|\,n' - n\,|$ = difference in refractive index
r = radius of surface (in meters)

Does the back surface of the cornea have plus or minus power? **Minus** power (see diagram). If the radius of the back surface is 7 mm and the refractive indices of the cornea and aqueous are 1.37 and 1.33 respectively, what is the power of the back surface?

See:
p95, prob 44

$$D_s = -\left(\frac{|\,1.37 - 1.33\,|}{0.007}\right) = -5.7 \text{ D}$$

Power of a thin lens immersed in fluid

The refracting power of a thin lens is proportional to the **difference in refractive index** between the lens and the medium.
If the power of an intraocular lens is marked as +20 D, what would the power of the lens be if measured in air?

$$\frac{D_{air}}{D_{aqueous}} = \frac{n_{IOL} - n_{air}}{n_{IOL} - n_{aqueous}}$$

$$\frac{D_{air}}{+20} = \frac{1.49 - 1.00}{1.49 - 1.33}$$

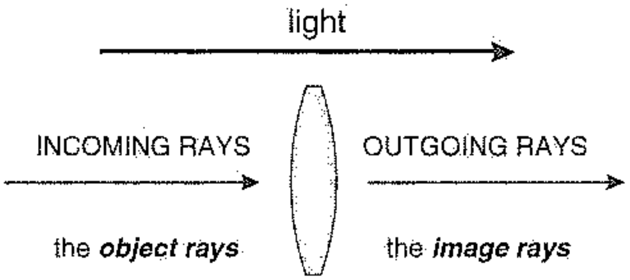
$$D_{air} = +61 \text{ D}$$

See:
p61, prob 11

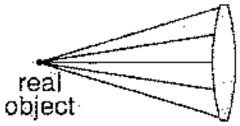
Refractive indices

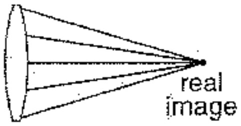
air	1.00
water, aqueous, vitreous	1.33
keratometric	1.3375
cornea	1.37
crystalline lens	1.42
plastic (PMMA, CR-39)	1.49
crown glass	1.52
polycarbonate	1.59
high-index plastic	up to 1.66
high-index glass	up to 1.81

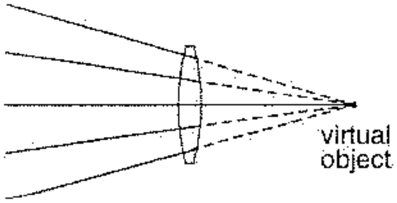
Real vs. virtual objects and images

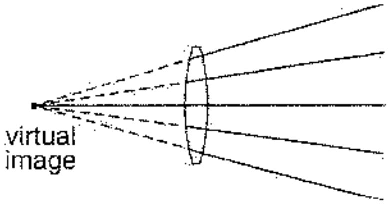


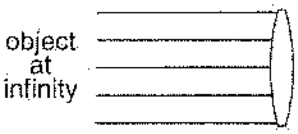
Although the object **rays** exist only on the incoming side of the optical system, and the image **rays** exist only on the outgoing side, **object "space"** and **image "space"** extend infinitely far in both directions. That is, the object does not have to be on the same side as the object rays, and the image does not have to be on the same side as the image rays.

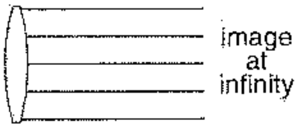






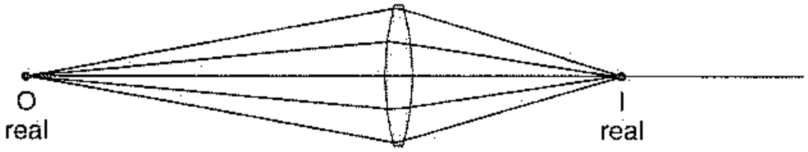


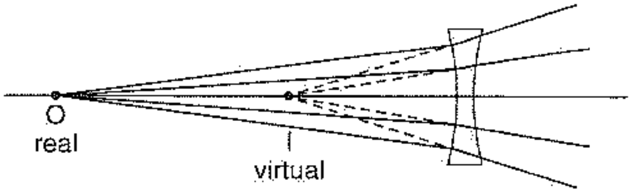


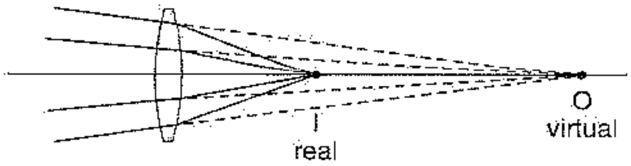


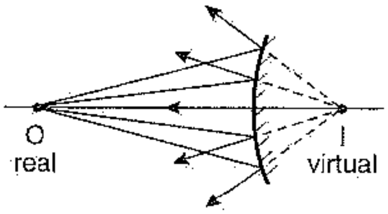
If the object or image is located on the same side as its respective rays, it is called **real**; if it is on the opposite side from its respective rays, it is called **virtual**. Virtual objects or images are located through **imaginary** extensions of the respective rays through the lens.

Examples:


O
real
I
real


O
real
I
virtual


I
real
O
virtual


O
real
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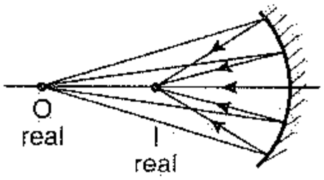
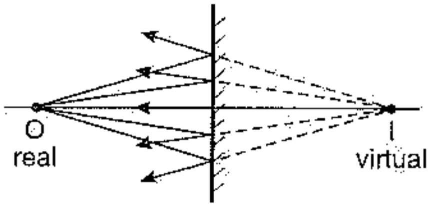
virtual

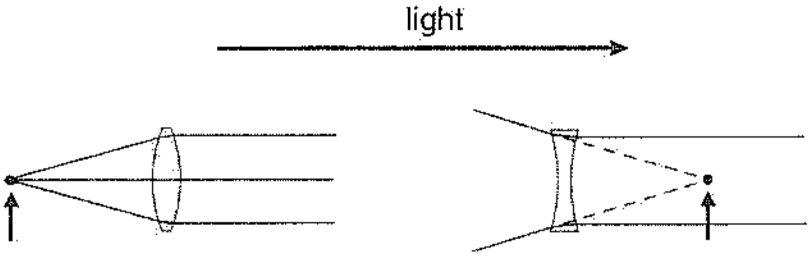

O
real
I
real


O
real
I
virtual

Focal points and focal lengths

Each lens had two focal points, an **anterior** focal point on the side of the incoming rays, and a **posterior** focal point on the side of the outgoing rays. In ophthalmic optics, the terms "primary" and "secondary" focal points are often used.

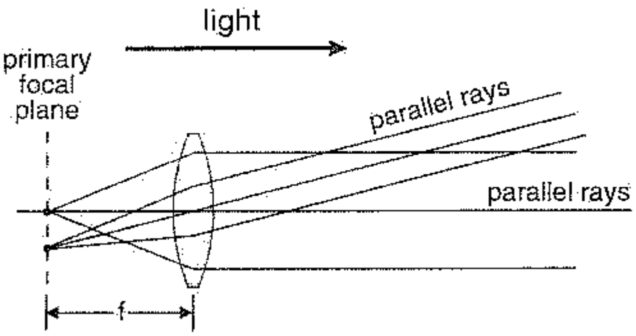
The **primary focal point** is the point along the optical axis at which an object must be placed for parallel rays to emerge from the lens (forming an image at infinity).



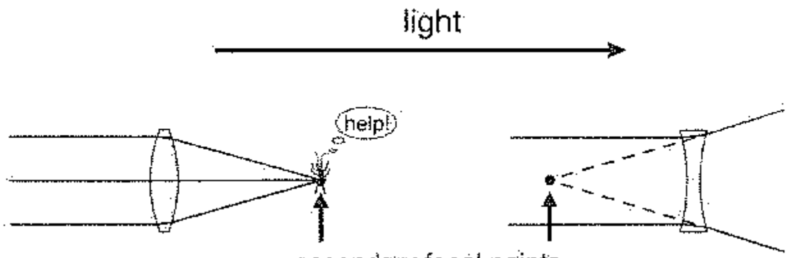
primary focal points

The primary focal plane is perpendicular to the optical axis and passes through the primary focal point. Any object point in the primary focal plane will be imaged at infinity.

Note that all the rays of the light to the right of the lens in the diagram are **not** all parallel to each other. The light to the right of the lens is said to be **collimated.**



The **secondary focal point** is the point along the optical axis where parallel incident rays are brought to focus.



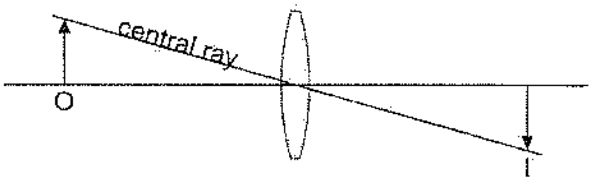
secondary focal points

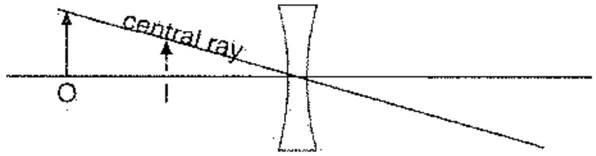
The focal length is the distance from the ideal thin lens to each of its focal points. It is equal, in **meters,** to the reciprocal of the dioptric power of the lens. A 3 D lens has a focal length of 1/3 m or 33.3 cm.

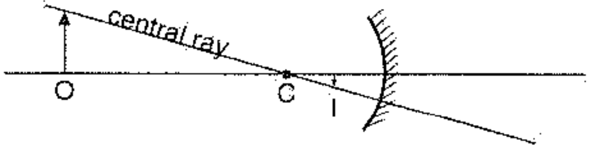
Ray tracing — the central ray

Images formed by lenses or mirrors may be located along the optical axis either by the vergence formula (U + D = V) or by ray tracing. The vergence formula is usually easier to apply, but the **size and orientation** of the image are more easily appreciated by **ray tracing**, for only a single ray is required: the **central ray**. The central ray passes from the tip of the object through the optical center of the lens, extending infinitely far in both directions. Its intersection with the image plane locates the tip of the image.

Examples:



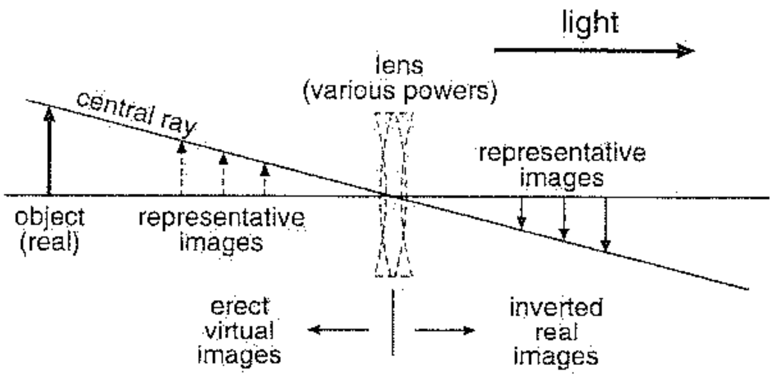




(the central ray for mirrors passes through the center of curvature of the mirror)

The central ray only has meaning for extra-axial object and image points. The corresponding points of the object and image (tips of the arrows) must **always** fall on the central ray.

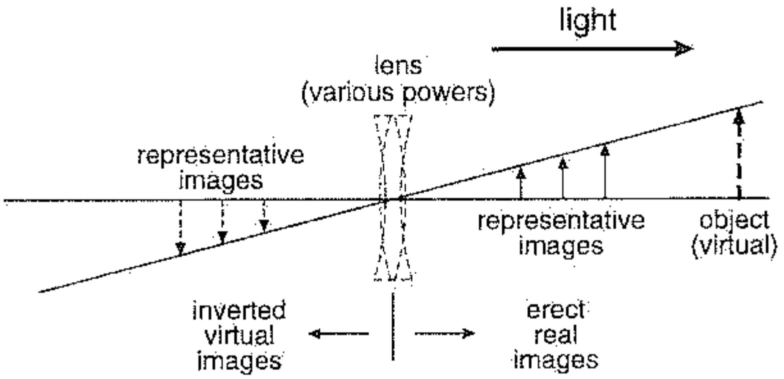
As is immediately obvious from the central ray concept, images on the same side as the object have the same orientation as the object (erect); those on the opposite side of the lens are inverted.



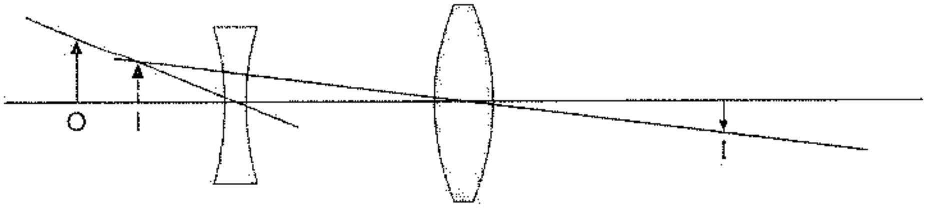
See:
p59, prob 9
p61, prob 12
p85, prob 34

Ray tracing — the central ray, cont.

Do not fall into the trap of thinking that all virtual images are erect and all real images are inverted. Consider the situation with a virtual object:



For multiple lens systems, the central rays are drawn in succession for each object-image pair:



By similar triangles formed by the central ray, it is immediately obvious how large the image is with respect to the object, for the sizes of the object and image are in the same ratio as the distances of the object and image from the lens. The farther away an object or image is, the larger it is.

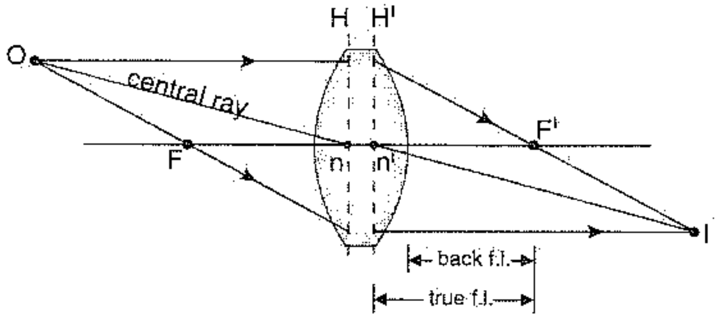
Thick lenses

Only the ideal thin lens in air may be described by its optical center and its two focal points. The ordinary lens with thickness must be described by the location of six "**cardinal points**":

2 principal points (usually referred to as principal planes H and H')

2 nodal points (n and n')

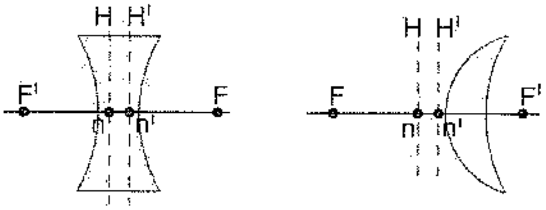
2 focal points (F and F')



Refraction "occurs" at the principal planes (H and H'), as shown.

The **true focal lengths** are measured from the principal planes, not from the lens surfaces. The lensmeter measures the back vertex power, which is the reciprocal of the back focal length.

The **central ray** heads toward the first nodal point and emerges from the second nodal point parallel to its original direction.



The nodal points (and principal planes) are reversed with respect to the focal points in minus lenses, and they may even fall outside the lens in meniscus lenses.

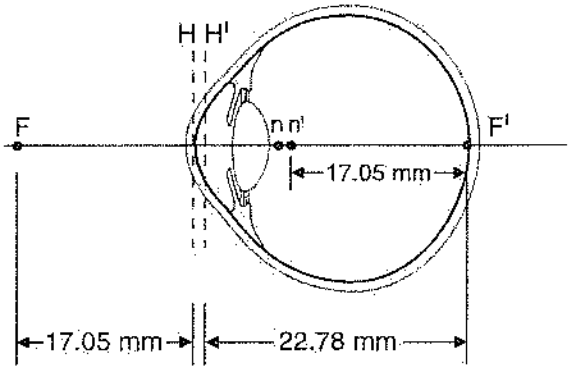
The nodal points of a lens coincide with the principal planes unless the refractive medium is different on the two sides, in which case the nodal points and one of the focal points shift toward the medium with the higher refractive index (as in the eye; see next page).

Any optical system involving multiple lenses, mirrors, or refractive media may be reduced, using the simplifying technique of "Gaussian optics," to a single system having two nodal points, two principal planes, and two focal points.

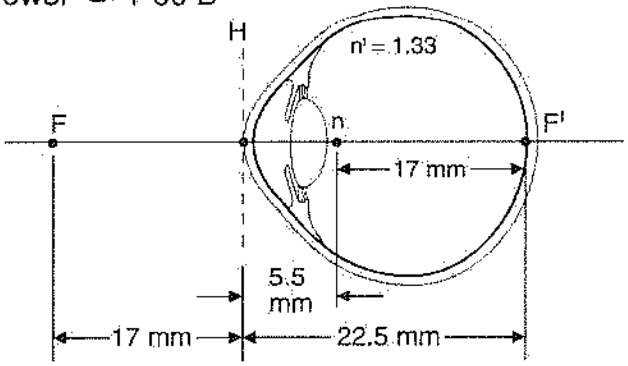
The schematic eye

(approximate parameters for calculation purposes)

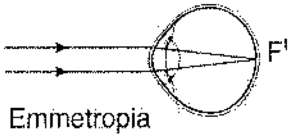
Gullstrand's eye
power = + 58.6 D



The reduced schematic eye
power = + 60 D

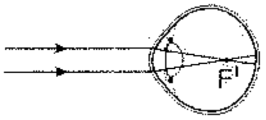


Refractive errors

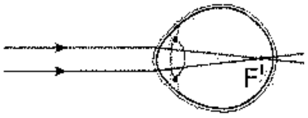


Emmetropia
(no refractive error)

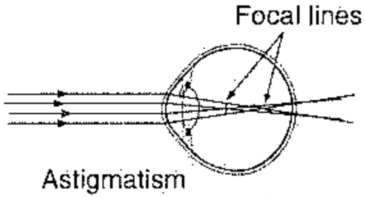
Defined by the position of the secondary **focal point** (F') or **focal lines** with respect to the retina, when accommodation is fully relaxed.



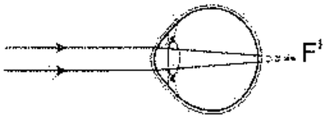
Refractive myopia



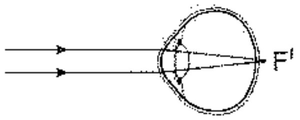
Axial myopia
(long globe)



Astigmatism
(compound myopic, with both principal meridians being myopic)



Refractive hyperopia
(aphakia is extreme example)



Axial hyperopia
(short globe)

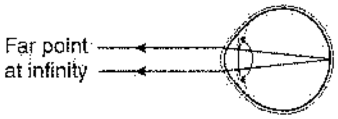
Far points and far lines

These are very different from **focal** points and **focal** lines as illustrated above. Focal points and focal lines are never more than a few **millimeters** away from the retina (about 1/3 mm per diopter of refractive error).

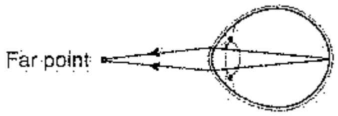
Far points and **far** lines are centimeters, meters, or kilometers away from the retina (they are actually measured from the cornea or from the spectacle plane), or even at infinity.

Far points and far lines are located, in the non-accommodating eye, by turning the light around and tracing rays of light from a **single point on** the retina out through the optics of the eye to the point or lines where they come to focus.

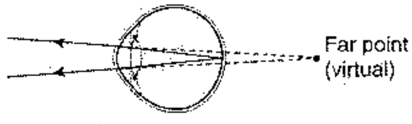
These are called **far** points or **far** lines because they generally represent the farthest away that the eye can see clearly with accommodation completely relaxed. Note that the hyperopic eye has a **virtual** far point. We sometimes say incorrectly that the hyperopic eye can see "beyond" infinity.



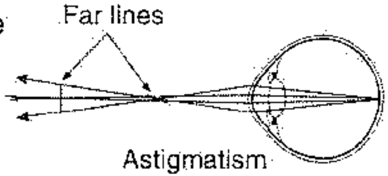
Emmetropia



Myopia

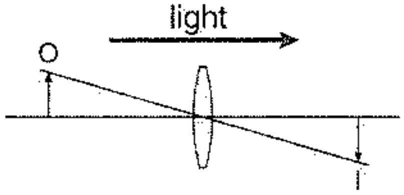


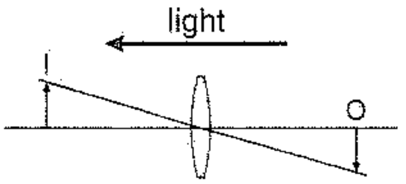
Hyperopia



Astigmatism
(compound myopic in this case)

Conjugate points and planes





Each pair of object-image points in an optical system constitutes a pair of **conjugate** points.

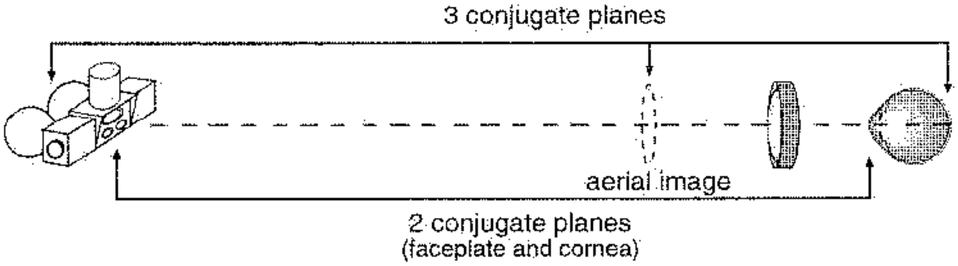
If the light is turned around, the object and the image switch places exactly. There exist an infinite number of pairs of conjugate points, and likewise an infinite number of pairs of conjugate planes.

Examples of conjugate planes

Projection screen and retina — in the same manner that an image of the projected slides is formed on the retinas of each person in the audience, there are very faint images of each person's retinas dancing about on the projection screen.

Direct ophthalmoscope — patient's retina conjugate to examiner's retina.

Indirect ophthalmoscope — three planes are conjugate to each other: the patient's retina, the aerial image plane, and the examiner's retina:



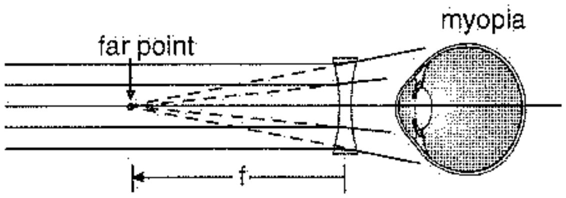
Also the plane of the faceplate of the indirect ophthalmoscope is conjugate to the plane of the patient's cornea, allowing the light source and the observer's pupils to be imaged onto the patient's cornea, discretely separated from one another to avoid back-reflection into the observation pathway. These images of the light source and the observer's pupils are also small enough to fit within the patient's pupil.

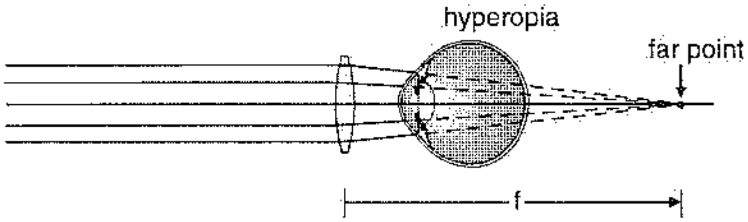
Far point in the non-accommodating eye — is conjugate to the patient's retina. Therefore, any object placed **or imaged** at the far point will be re-imaged sharply in focus onto the retina.

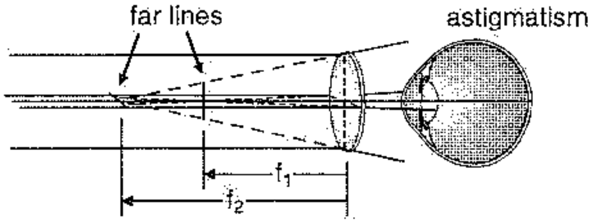
See:
p63, prob 13

Correction of ametropia using the far point concept

1. Locate the far point of the eye.
2. Choose a lens whose secondary focal point coincides with the far point.

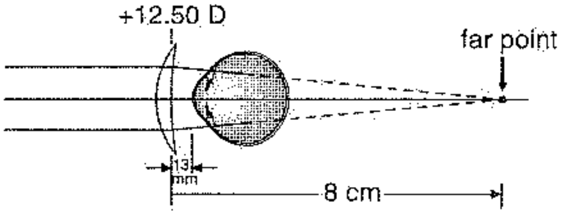


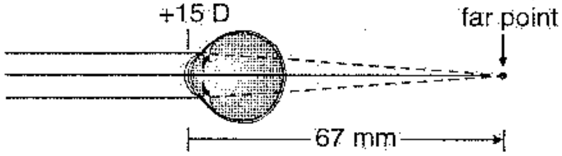




Vertex distance conversion

1. Locate the focal point of the present lens; this is the far point of the eye.
2. Determine the distance of the new lens from the far point; this is the focal length of the new lens required.
3. Take the reciprocal of the focal length of the new lens to determine the power of the new lens.





See:
p63, prob 15
p83, prob 33

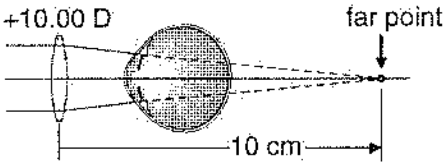
Lens effectivity

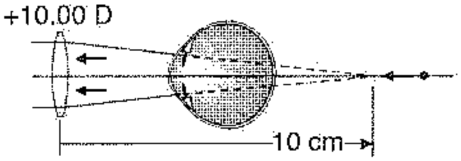
1. Plus lenses*

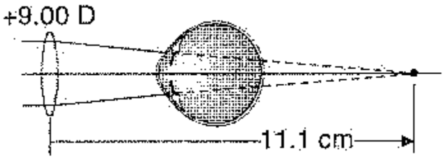
Moving plus lenses forward **increases** effective plus power.

(Aphakic patients often slide their glasses down their noses to see more clearly at near.)

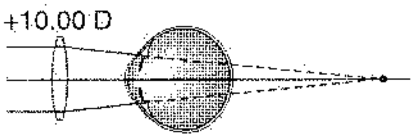
To maintain proper distance correction, a plus lens will have to be **decreased** in power (giving it a longer focal length) if it is moved forward.

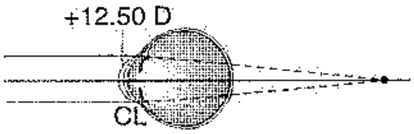




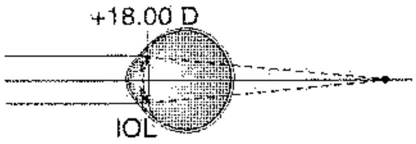


Moving plus lenses toward the eye **decreases** effective plus power. Therefore the lens must be increased in power (giving it a shorter focal length) to maintain the same correction for distance.

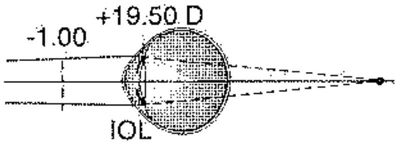




Note that it requires about +18.00 D of IOL power to give the same correction as +10.00 D of spectacle lens power. As an approximation, we use 1.25 to 1.50 D for IOL power per 1.00 D of spectacle lens power.



For example, if we wish to achieve -1.00 D of myopia in an eye calculated to need a +18.00 D IOL for emmetropia, we should implant a +19.50 D IOL.

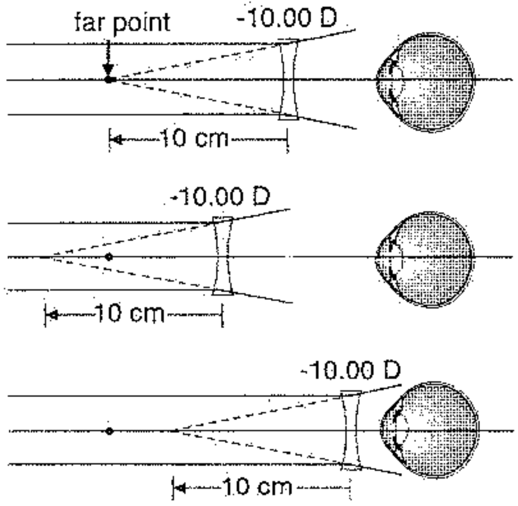


Lens effectivity, cont.

2. Minus lenses*

Moving minus lenses forward **decreases** effective minus power (**adds** effective plus power!). The focal length will have to be shortened to maintain the same distance correction.

Moving minus lenses toward the eye **increases** effective minus power. The focal length will have to be lengthened to maintain the same distance correction.



Note:

The above examples of changes in lens effectivity are all for **distant** objects.

The same relationships hold for **near** objects, **except** when **low power plus lenses** are moved forward or backward. In this case the effects are the **opposite**. This begins to occur at near distances equal to twice the focal length of the plus lens. (For details, see Rubin ML. The sliding lens paradox, or the unexpected effect of longitudinal ("to-and fro") motion of plus spectacle lenses. Surv Ophthalmol 17(3):180-195, 1972.)

Accommodation

Accommodation — increased convexity of the crystalline lens adds plus power to the eye, usually thought of as acting at the cornea for calculation purposes.

Amplitude of accommodation — the total number of diopters which an eye can accommodate.

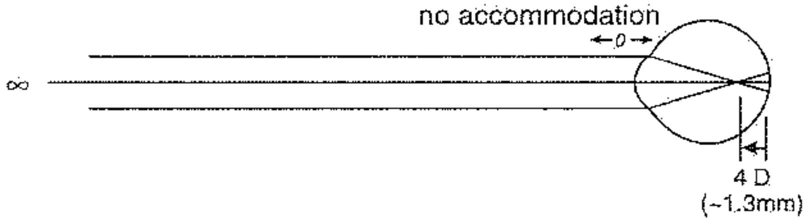
Far point — the point on the line of sight which is conjugate to the retina when accommodation is completely relaxed.

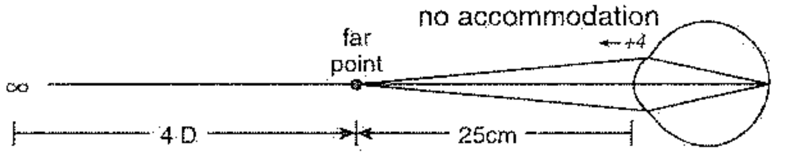
Near point — the point on the line of sight which is conjugate to the retina when accommodation is fully active.

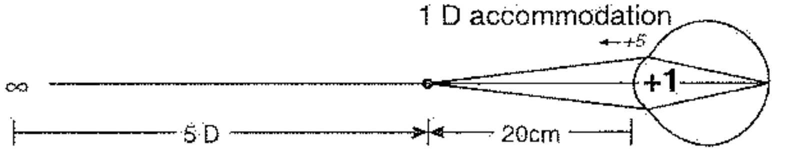
Range of accommodation — the linear extent of clear vision obtainable via accommodation. The far point can exist "beyond" infinity as a virtual far point behind the eye, but the range of accommodation cannot, for clear vision is not obtained with the eye focused "beyond" infinity.

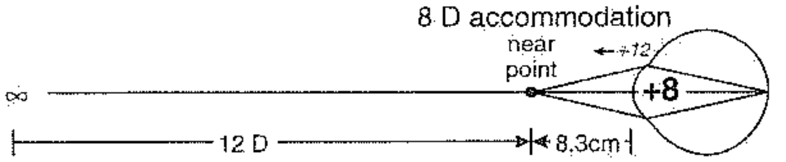
Examples:

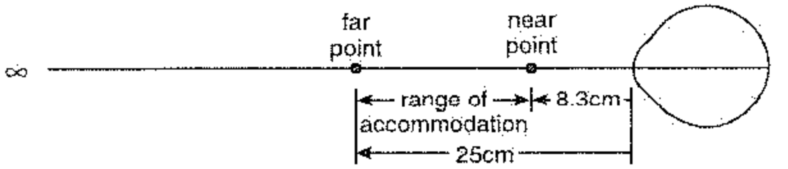
1. Eye with 4 D of myopia and an amplitude of accommodation of 8 D.





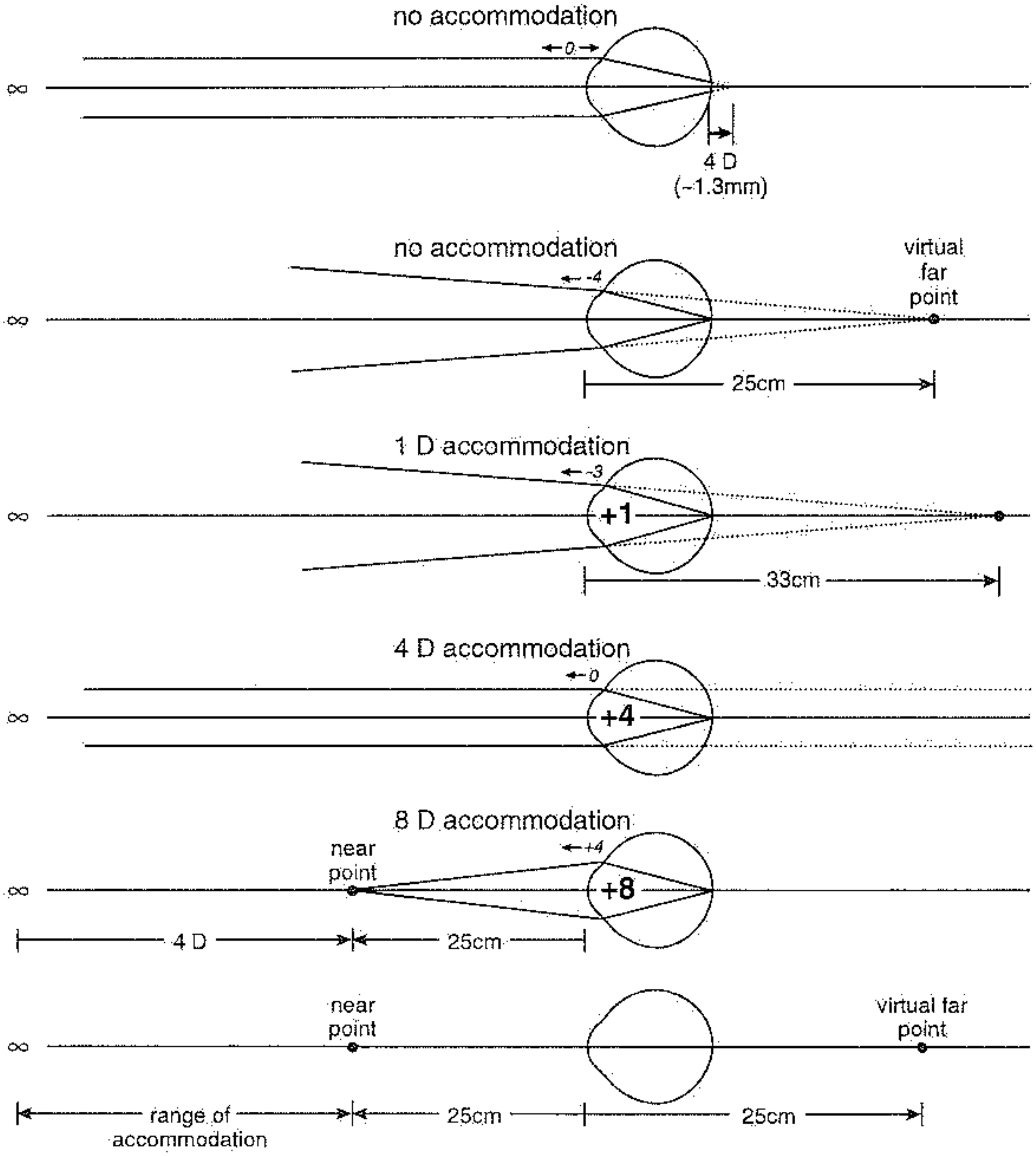






See:
p73, prob 25
p93, prob 41

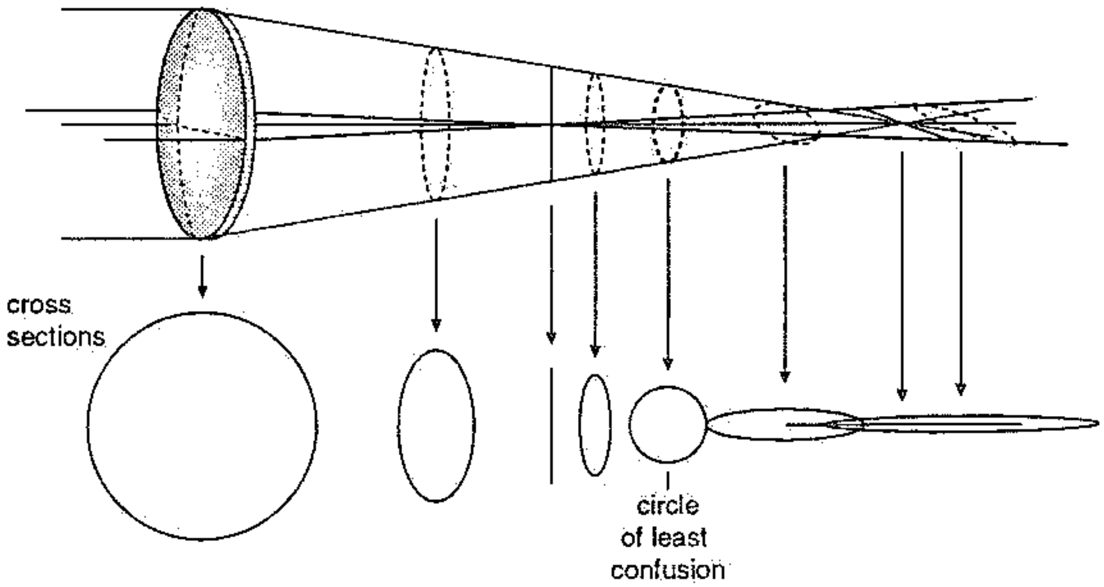
2. Eye with 4 D of hyperopia and an amplitude of accommodation of 8 D.



Resting level of accommodation — in the absence of visual stimuli, the eye assumes an accommodative posture approximately 1 D inside the far point, at the so-called "dark focus". This phenomenon helps explain "night" myopia and "empty field" myopia. Activation of the sympathetic nervous system is apparently involved in driving the accommodative state from the resting level to the far point in ordinary seeing.

Presbyopia — the loss of accommodative amplitude with age. Various factors contribute, including hardening of the crystalline lens, loss of elasticity of the anchoring fibers between the ciliary muscle and the choroid, and simply the progressive increase in the diameter of the crystalline lens with age.

Astigmatism



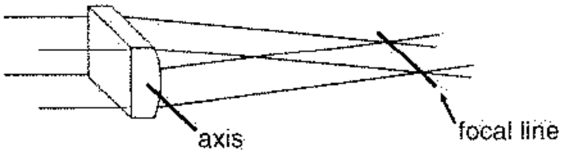
Conoid of Sturm — the geometric figure formed by the rays

Interval of Sturm — distance between the two focal lines

Circle of least confusion — the circular cross section of the conoid of Sturm, lying halfway between the two focal lines **dioptrically.** Why is it a circle? Because the aperture of the lens (or pupil of the eye) is circular.

Note that each focal line is formed by the power of the lens acting 90° away from the focal line.

Plano-convex cylindrical lens

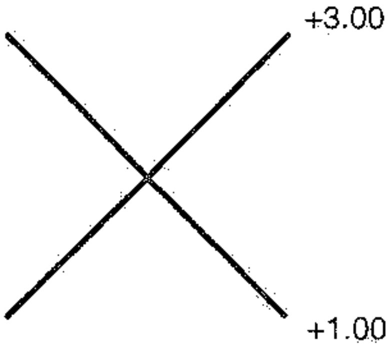


Focal line is formed by the power acting in the vertical meridian. The axis meridian of a planocylinder has **no** power.

Astigmatic imagery of an **extended** object

Cross diagram of an astigmatic lens

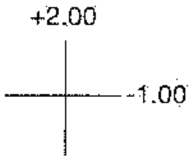
The two principal meridians are labeled with the power acting **in** these meridians:



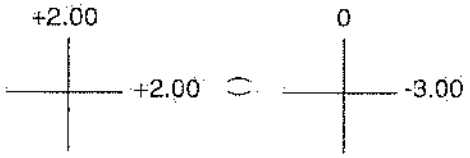
+3.00 D acting in the 45° meridian

+1.00 D acting in the 135° meridian

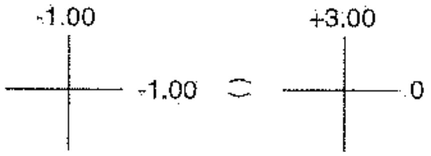
Equivalent combinations:



+2.00 x 180 ⊂ -1.00 x 90
(combination of two cylinders)



+2.00 Sph ⊂ -3.00 Cyl x 90
(spherocylinder, minus cylinder form)



-1.00 Sph ⊂ +3.00 Cyl x 180
(spherocylinder, plus cylinder form)

See:
p65, prob 16
p87, prob 37

Transposing

new sphere = old sphere + old cylinder

new cylinder = same as old cylinder, with opposite sign

new axis = change old axis by 90°

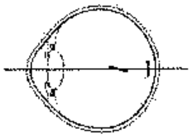
Combination of cylinders at oblique axes

— complicated trigonometric calculation

— calculate with overrefraction microcomputer

— **or** simply read combination through lensmeter

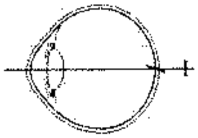
Astigmatism Types



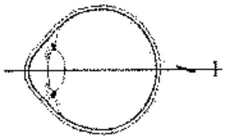
compound
myopic

simple
myopic

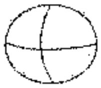
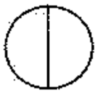
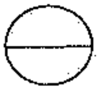
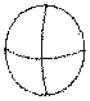
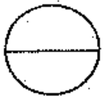
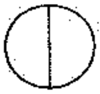
mixed



simple
hyperopic



compound
hyperopic

	cornea	typical age	axis of correcting plus cylinder (± 20°)	axis of correcting minus cylinder (± 20°)
"with the rule"		young		
"against the rule"		old		

oblique

symmetrical

asymmetrical

See:
p65, prob 17
p75, prob 26

Spherical equivalent

The average sperical power of a spherocylindrical lens.

$$\boxed{\text{spherical equivalent} = \text{sphere} + 1/2\ \text{cylinder}}$$

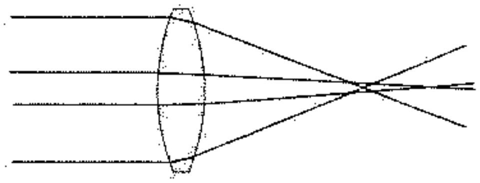
The spherical equivalent of a refractive correction places the circle of least confusion on the retina.

See:
p65, prob 18
p87, prob 36

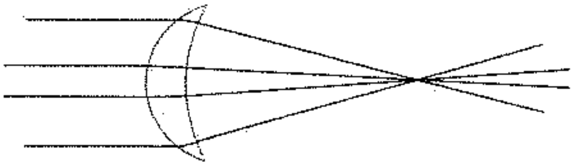
Important lens aberrations

Spherical aberration

Most spherical lenses, such as the biconvex form, refract peripheral rays more strongly than paraxial rays, bringing the peripheral rays to focus closer to the lens.



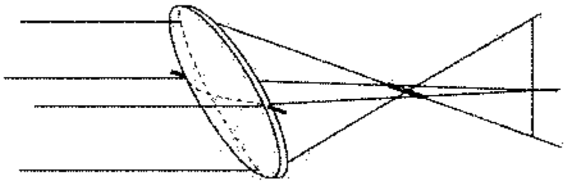
This is called spherical aberration. It may be reduced either by "bending" the lens to a plano-convex shape or meniscus shape, or by using aspheric lens surfaces.



Spherical aberration produces the bulls-eye retinoscopic reflex in young children, with the peripheral portions of the pupil myopic (against movement) with respect to the central portion of the pupil, at neutralization.

Astigmatism of oblique incidence

Tilting a spherical lens produces astigmatism.



Tilting a **plus** lens induces **plus** cylinder with axis in the axis of tilt (horizontal in the above drawing).

Tilting a **minus** lens induces **minus** cylinder with axis in the axis of tilt.

A small amount of additional sphere of the same sign is induced as well. For example, tilting a +10.00 lens 20° about the 180° axis produces a power of +10.41 + 1.38 x 180.

Undercorrected myopes frequently tilt their glasses by raising the temples to gain increased minus cylinder and sphere effect.

An emmetropic child retinoscoped from the side, (horizontally displaced from the line of sight) will show astigmatism against-the-rule (**correcting** plus axis at 180°, or **correcting** minus axis at 90°).

See:
p67, prob 19

Contact lenses — calculation of power

Overrefract over a trial lens and add the finding to the power of the trial lens.

If trial lenses are not available, **calculate** power by:

1. **Soft contact lenses:**
   a. Convert spherical equivalent of the refraction to zero vertex distance for the power of a spherical soft contact lens.

2. **Rigid contact lenses:**
   a. Obtain **K readings** and **refraction**
   b. Choose **base curve** slightly steeper than low K (usually +0.50 D steeper, or 1/3 of the astigmatism steeper, whichever is greater). Tears form a +0.50 D (or greater) "tear lens", preventing apical touch.
   c. Convert refraction to:
      1. minus cylinder form (the minus cylinder will be formed by the tears and may be disregarded from this time on)
      2. zero vertex distance
   d. Subtract the +0.50 D (or greater) spherical tear lens from the sphere value of the refraction to obtain the final sphere value for the contact lens.

• • • • • • • • • • • • • • • • • • •

Example:

K readings	Refraction
44.25 / 45.87	+ 11.50 + 1.00 x 35 (at 13 mm vertex distance)

choose base curve **44.75**, + 0.50 D steeper than low K

convert refraction to minus cylinder form:
+ 12.50 - 1.00 x 125

convert sphere of refraction to zero vertex distance:
+ 15.00 - ....

subtract value of spherical tear lens from calculated sphere:
+ 15.00 - (+0.50) = **+ 14.50 D Sphere**

See:
p67, prob 20
p95, prob 43

Intraocular lenses — calculation of power

Use formula for calculation:

1. Theoretic formula

   Derived from optical principles, using assumed anterior chamber depth.

   Examples:
   Binkhorst
   Colenbrander
   Hoffer
   Holladay

2. Empiric formula

   Derived by regression analysis from clinical results.

   Examples:
   SRK, SRK II

SRK power for emmetropia:

P = A - 2.5 (L, axial length in mm) - 0.9 (K, av. keratometry in D)

(A is a constant, approximately **117**, a function of the IOL used. Also depends on position of placement of the IOL, and usually assumes "in the bag" placement of PC IOL's. This "A constant" may be personalized by analysis of individual results.)

The SRK II is a modification of the original SRK to improve accuracy in long and short eyes:

SRK II emmetropia power, **P = A1 - 2.5 L - 0.9 K**

If $L < 20.0$, then $A1 = A + 3$
If $20.0 \leq L < 21.0$, then $A1 = A + 2$
If $21.0 \leq L < 22.0$, then $A1 = A + 1$
If $22.0 \leq L < 24.5$, then $A1 = A$
If $L \geq 24.5$, then $A1 = A - 0.5$

3. Combination formula

   Derived from theoretic optics, with regression analysis to optimize results for long and short eyes.

   Example:
   SRK/T

Data necessary:

1. Axial length in mm (A-scan biometry)
2. Keratometry readings
3. Desired postoperative refraction

See:
p95, prob 45

Intraocular lenses, continued

Errors from measurement:

1. Axial length
   0.1 mm error ≈ 0.25 D error

2. Keratometry:
   0.25 D (0.05 mm) error ≈ 0.25 D error

If we wish to leave an eye myopic, and we only know the calculated IOL power for emmetropia, we can implant a **higher** power IOL. As an approximation, for implants around 18 D, we use +1.25 to +1.50 D added IOL power for each diopter of desired spectacle-plane myopia.

Most A-scan machines have software that will calculate lens implant power for emmetropia and a range of desired postoperative refractions using several formulas. While both theoretic and regression analysis formulas are accurate for normal-sized eyes, theoretic or combination formulas may be better for unusually long or short eyes because they are based on optical principles.

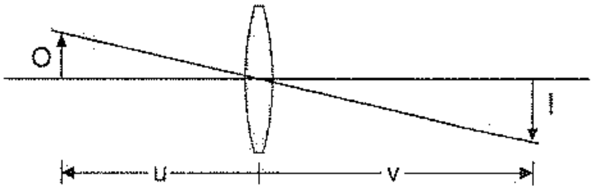
When calculating IOL power for secondary lens implantation and IOL exchange, remember that ultrasound velocity varies with aphakia, cataract, and IOL material, and affects axial length measurement. For example, ultrasound velocity in the aphakic eye is 1532 meters/second (m/s), and in the cataractous eye is about 1550 m/s. Ultrasound velocity in the pseudophakic eye is even more varied (2718 m/s for PMMA, 980 m/s for silicone), and settings on the ultrasound unit must be modified if accurate axial lengths are to be obtained. The exact axial length can be calculated by measuring the axial length of the pseudophakic eye at aphakic velocity (1532 m/s), if the ultrasonic velocity in the IOL material and central thickness of the IOL are known. (See Am J Ophthalmology 115:536-7, 1993)

Magnification

Transverse magnification (linear, lateral)

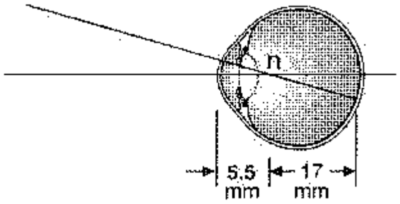
Central ray forms similar triangles:

$$\boxed{\text{Mag} = \frac{I}{O} = \frac{v}{u}}$$



See:
p69, prob 21

Central ray for the eye passes through "the nodal point"

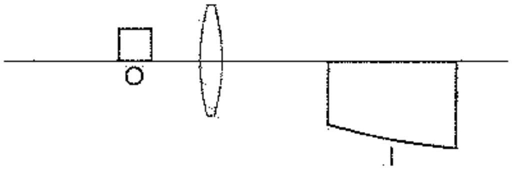


See:
p63, prob 14

Axial magnification

Magnification **along** the axis.

Is always the square of the transverse magnification (between any given pair of conjugate planes).



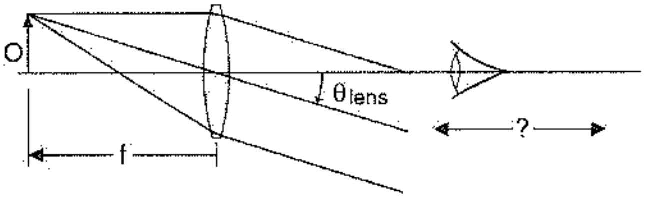
Causes **distortion** in 3-D images, as in indirect ophthalmoscopy or when using fundus viewing lenses with the slit lamp (see page 109).

Angular magnification

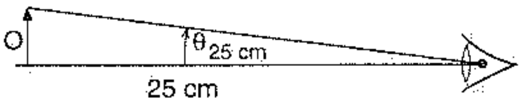
Used:

1. **With objects and images at infinity** (although they are infinitely large, they have a finite angular size).

2. **When viewing with an eye** (because of different powers and lengths of eyes, we cannot know the size or distance of the retinal image; we must rely on angles).



How should the magnification produced by this lens be expressed?



By comparing the angular size produced (Θ_{lens}) to a reference angle ($\Theta_{25\ cm}$)

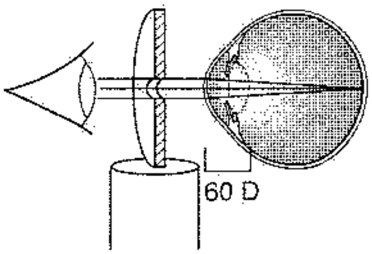
$$\text{Mag} = \frac{\Theta_{lens}}{\Theta_{25\ cm}} = \frac{\tan^{-1}(O/f)}{\tan^{-1}(O/25)} \approx \frac{25\ \text{cm}}{f} = \frac{\mathbf{D}}{\mathbf{4}}$$

Magnification of a **simple magnifier**

Direct ophthalmoscope magnification:

The examiner uses the optics of the patient's eye as a simple magnifier to examine the patient's retina.

$$\text{Mag} = \frac{60\ \text{D}}{4} = 15\ \text{X}$$



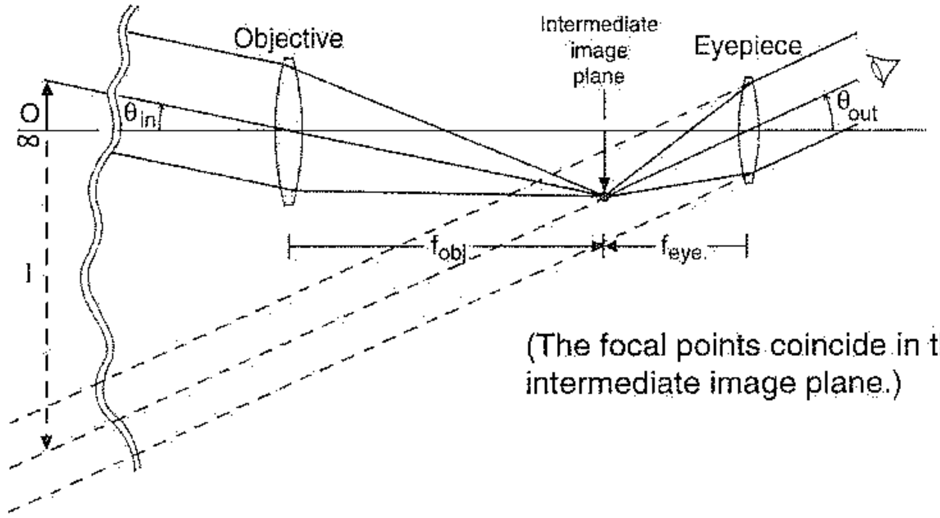
See:
p69, prob 22

This indicates that the patient's retina appears 15 times larger than if it were cut out of the eye and held at 25 cm.

Angular magnification, continued

Astronomical telescope

Forms an inverted image and has few uses in ophthalmic optics.

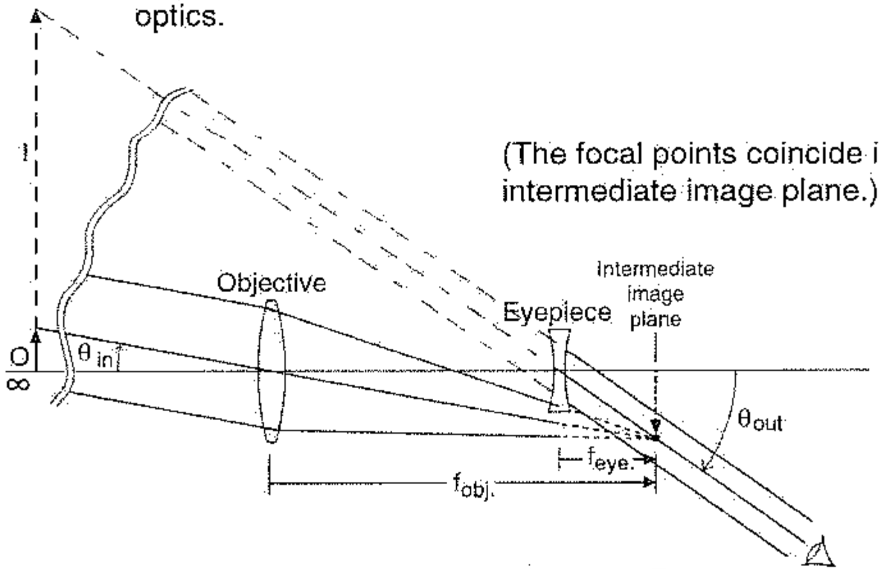


(The focal points coincide in the intermediate image plane.)

$$\textbf{Mag} = \frac{\Theta_{out}}{\Theta_{in}} \approx \frac{f_{obj}}{f_{eye}} = \frac{D_{eyepiece}}{D_{objective}}$$

Galilean telescope

Leaves images upright; frequently used in ophthalmic optics.



(The focal points coincide in the intermediate image plane.)

$$\textbf{Mag} = \frac{\Theta_{out}}{\Theta_{in}} \approx \frac{f_{obj}}{f_{eye}} = \frac{D_{eyepiece}}{D_{objective}}$$

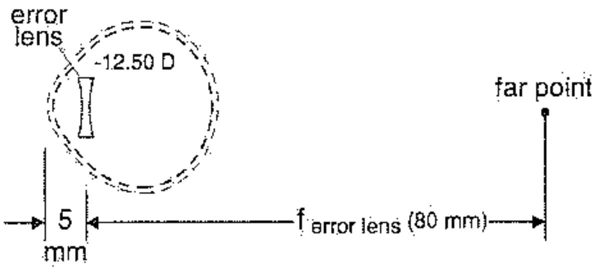
See:
p89, prob 38
p91, prob 39

NOTE for all telescopes: zero vergence **in** gives zero vergence **out**

Angular magnification, continued

Corrected aphakic eye (magnification considerations)

The refractive error of an aphakic eye can be thought of as a single -12.50 D lens **in air** acting at the seat of ametropia, 5 mm behind the cornea. The primary focal point of the -12.50 D lens is the far point of the eye.



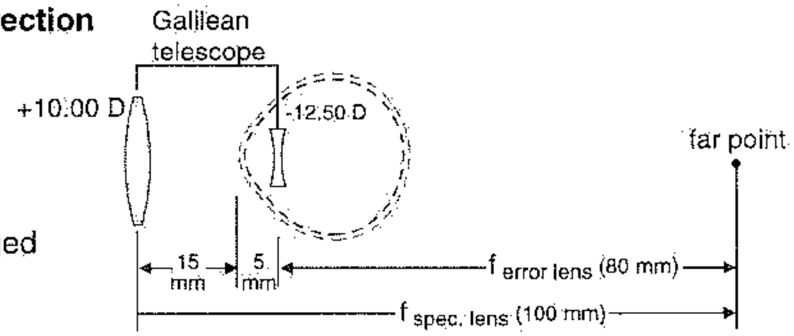
The secondary focal point of the corrective lens must coincide with the far point, thereby creating a Galilean telescope with magnification determined by the ratio of the eyepiece power to the objective power, as shown below:

Spectacle lens correction

$$\text{Mag} = \frac{12.50}{10.00}$$

$$= 1.25\ \text{X}$$

= 25% enlarged

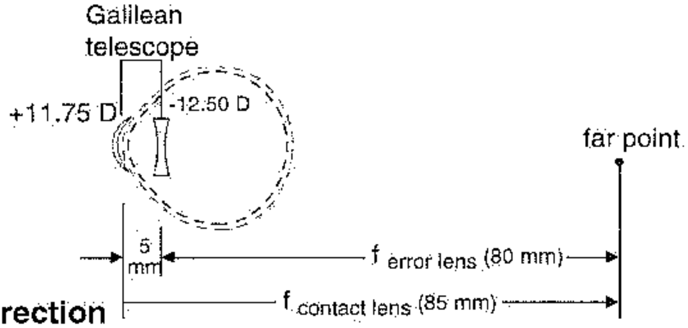


Contact lens correction

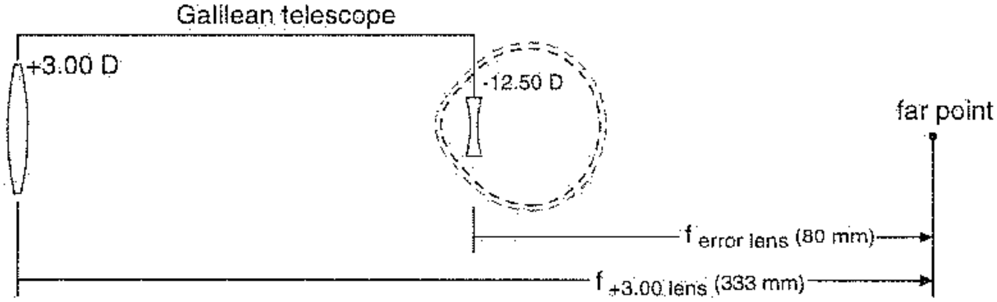
$$\text{Mag} = \frac{12.50}{11.75}$$

$$= 1.06\ \text{X}$$

= 6% enlarged



Hand-held +3.00 D lens correction



See:
p71, prob 23

$$\text{Mag} = \frac{12.50}{3.00} = 4.2\ \text{X}\text{, or 320\% enlarged}$$

Angular magnification, continued

Ordinary spectacle lenses

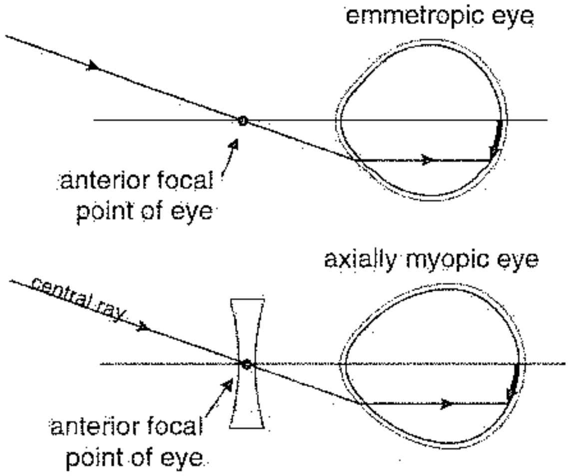
A spectacle lens at a vertex distance of 12 to 13 mm changes the retinal image size by about 2% per diopter of power, with respect to the retinal image size in the uncorrected state.

	type of telescope	example	% change	Mag
Plus lenses magnify	Galilean	+ 4 D	8% larger	1.08 X
Minus lenses minify	reverse Galilean	- 4 D	8% smaller	0.92 X

Up to 6 to 7% overall image size difference (aniseikonia) between the two eyes can usually be tolerated. This corresponds to a spectacle-lens-corrected **refractive** anisometropia of 3 to 4 diopters of sphere. Children are very tolerant of aniseikonia and adapt partially, or fully, automatically. DO NOT undercorrect children for fear of aniseikonia, for you risk amblyopia and permanent visual loss.

Knapp's rule

In **axial** anisometropia (i.e. unilateral high myopia), equal image sizes on the two retinas are obtained by correcting the refractive error by a spectacle lens placed at the anterior focal point of the eye, approximately 16-17 mm in front of the cornea. (In **axial** ametropia, the **optical power** of the eye is normal, and the anterior focal point is in the normal position 16-17 mm in front of the cornea.)



Same image height as in the emmetropic eye, **whatever** the necessary power of the minus lens

Highly myopic eyes may have stretched-apart photoreceptors, however, and a **larger** retinal image in the highly myopic eye may be desirable. It is impossible to determine this in young unilateral high myopes who cannot respond to special aniseikonia tests, and many practitioners use contact lens correction instead of glasses. Contact lens correction avoids the anisophoria that glasses correction produces in such cases.

Low vision aids

Prerequisites for optimal determination and demonstration:

Assessment of patient's needs
Visual acuity known (linear or reading acuity is more useful than single optotype acuity)
Visual field status
Assortment of aids

Available aids for near – Plus lens*		
	Advantages	**Disadvantages**
High add in bifocal		
+ 4 to +20 D	Large field of view.	Short reading distance, expensive.
High power single vision lens		
+ 4 to +20 D, full frame or half-eye. Monocular or binocular (with base-in prism)	Large field of view.	Short reading distance, expensive.
Hand-held magnifier		
usually +5 to +20 D	Variable eye-to-lens distance. Easy to carry. High rate of acceptability.	Small field of view with lens held away. Difficult to manipulate by patients with tremors, arthritis, etc.
Stand magnifier		
About +4 to +50 D. Fixed focus (requires accommodation or a reading add in addition) or focusable (can adjust for refractive errors or presbyopia).	Greater eye-to-lens distance than spectacle. Easy to manipulate. Favorite of older patients.	Smaller field of view than spectacle. Bulky, especially if light source is built in.

* see next page

Low vision aids, continued

***Kestenbaum's rule** — (estimation of strength of plus lens necessary to read ordinary newspaper print (without accommodation))

At a normal reading distance of 40 cm (16 in), newspaper print (8 point, Jaeger 5, 1 M) requires a linear (not single letter) visual acuity of approximately **20/50**. This reading distance also requires plus power of +2.50 D for proper focus. Coincidentally, **the reciprocal of the Snellen acuity is equal to the plus dioptric power required.**

A patient with 20/100 distance visual acuity would have to hold the newspaper print at 20 cm so that it would appear twice as large as at 40 cm. This reading distance of 20 cm would require plus power of +5.00 D, either from accommodation or from a plus lens reading aid. Again, the plus power required is equal to the reciprocal of the Snellen acuity (100/20 = 5), illustrating the generality of this relationship.

If reading vision is measured in terms of M units with the Sloan reading cards at 40 cm, the plus lens power necessary for reading 1 M print (newspaper print) is equal to M x 2.5 D.

Available aids for near – loupes

Loupes (close-focus telescopes)	Advantages	Disadvantages
Prefocused (e.g. surgical loupes). An "add" (lens cap) over a distance telescope brings working distance in from infinity.	Long working distance, leaves hands free.	Small field of view. Limited depth of field, especially with higher powers. Requires precise head positioning without tremor. Expensive.

Available aids for near – electronic displays for reading

	Advantages	Disadvantages
Closed circuit television (CCTV) Reading material is moved about in the field of the camera and is displayed at a magnification as high as 40 X.	Contrast reversal (white on black) possible for less glare.	Non-portable.
View-Scan® Linear sensor is moved over reading material, painting magnified image on screen.	High magnification. Contrast reversal possible. Manual dexterity required.	Expensive.
Magni-Cam® Hand-held (cigarette-pack-sized) video camera is scanned across material to be viewed.	Relatively inexpensive. Contrast reversal simple. Can view uneven surfaces. Camera is PORTABLE and can be battery powered.	Limited field of view. Requires television and some manual dexterity.
Large print computer display programs Fixed size or variable. Can reverse contrast.	Built-in rectilinear orientation.	Reading material must be available on disc or stored in computer. Large monitors are more expensive. Difficult to scan at high magnification.
Mentor Horizon® Text is scanned into device and is automatically displayed as a continuous line-of-text format (like Times Square).	Black on white or reverse contrast. Variable size and speed of display. Good for patients who are avid readers (e.g., students and lawyers).	Expensive. Not portable. Separate scanning step is time-consuming.

Available aids for near – Non-optical aids

	Advantages	Disadvantages
Large-type watches / talking clocks		
	Readily available. Inexpensive models available.	Talking models conspicuous.
Large numeral calculators		
	Inexpensive.	
Large numeral telephone dials		
	Inexpensive. Readily available.	Conspicuous.
Large print books and periodicals		
	Available through libraries.	Not all titles available. News is out of date in large print periodicals.
Black ink marking pens		
	Inexpensive. Readily available.	Conspicuous.
Signature guides		
	Inexpensive.	Conspicuous.
Masking devices for reading (e.g. "Typoscope")		
	Inexpensive	Conspicuous.
Illumination control		
Patients usually need increased contrast: halogen lamps.	High contrast. Readily available. Inconspicuous.	Some models expensive.

Distance low vision aids

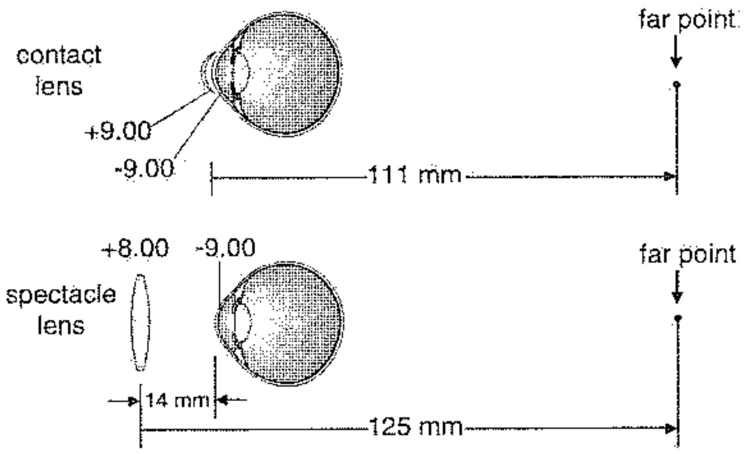
	Advantages	Disadvantages
Telescope		
Monocular or binocular. Hand-held or spectacle mounted. Fixed- or adjustable-focus.	The only magnifying distance aid available. Portable. Some states allow driver's license with telescopic aid, despite poor acuity.	Restricted field of view. Limited to about 8X because of difficulty in finding object, and swimming of field with movement. Cosmetically obvious.
Absorptive lenses		
For glare control in presence of media opacities or albinism.	Relatively inexpensive.	Cosmetically obvious.
For partial dark adaptation in patients with congenital achromatopsia and in some cases of age-related maculopathy.	Relatively inexpensive.	Cosmetically obvious.
Night vision telescopes		
For patients with poor scotopic vision (e.g. Retinitis pigmentosa)	Aids mobility during scotopic conditions.	Cosmetically obvious. Limited field of view. Bulky. Expensive.

Accommodation through corrective lenses

The difference in vertex difference between spectacle lens and contact lens correction for a given eye requires different powers for these lenses. The difference in power is greater with higher degrees of ametropia. This difference in power, in conjunction with the different vertex differences, produces different transverse magnification in the two situations (see "Corrected aphakic eye" on page 40). The **axial** magnification is also different, though, creating a difference in the accommodative requirement for a given viewing distance.

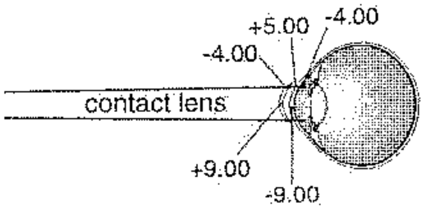
Hyperopes must accommodate more through glasses than through contact lenses, and myopes must accommodate less through glasses than through contact lenses. This is best understood by an example.

Assume a highly hyperopic eye corrected with a +8.00 D spectacle lens or a +9.00 D contact lens:



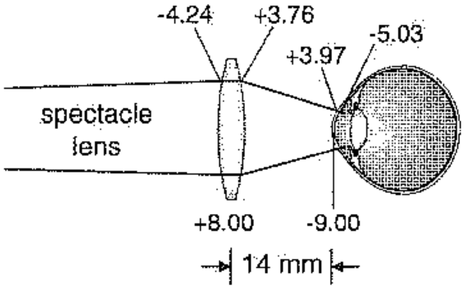
For simplicity, assume that the refractive **error** is measured at the corneal surface (-9.00 D), and that accommodation occurs just inside the corneal surface.

With a contact lens, the light from an object 25 cm from the cornea will arrive at the contact lens with a vergence of -4.00 D, and leave the contact lens, striking the cornea, with a vergence of +5.00 D. The refractive error of -9.00 D acts on the light, leaving -4.00 D of vergence entering the eye. Thus the eye must accommodate only 4.00 D to see the near object clearly through the contact lens.



Accommodation through corrective lenses, continued

In the case of spectacle correction, light from a near object 25 cm **from the cornea** will arrive at the spectacle lens with a vergence of -1 / (0.25 - 0.014) = -4.24 D.



By the vergence formula U + D = V, the vergence leaving the spectacle lens is +3.76 D, and is +3.97 D by the time it reaches the cornea.

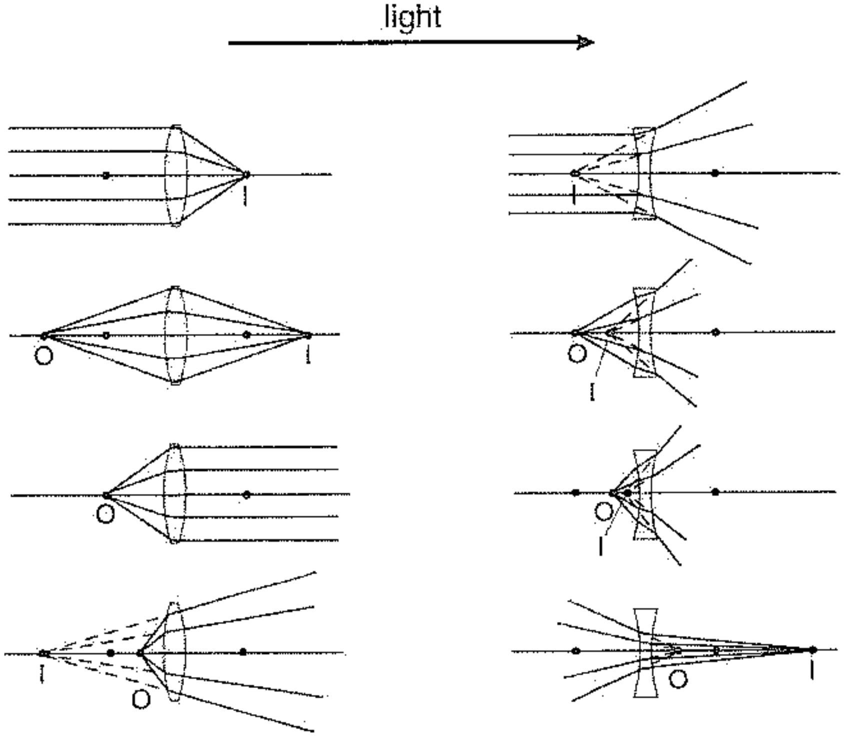
The -9.00 D of refractive error acts upon the light at the cornea, leaving -5.03 D of vergence entering the eye. The eye must therefore accommodate 5.03 D to see the near object clearly through the spectacle lens.

In this example, the increased 1.03 D of accommodative demand created by the spectacle lens can easily be clinically significant in the early presbyopic years. Such a patient switching from contact lenses to glasses will suddenly appear to have exacerbated presbyopia. The reverse is true with myopia: glasses decrease the accommodative demand compared to contact lenses. Switching a mid-life-crisis myope with incipient presbyopia from glasses to contact lenses is asking for problems!

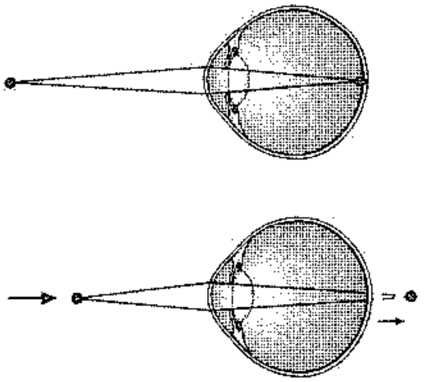
See:
p71, prob 24

Object - image movement

In any optical system, if an object is moved from one position to another, the image or images of the object move **in the same direction** relative to the light, not usually at the same speed, but always in the same direction.



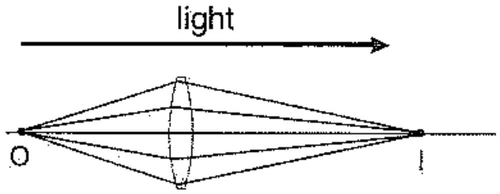
In the eye:

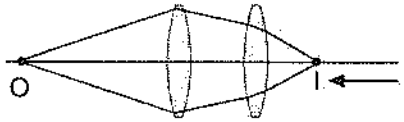


In the operating microscope:

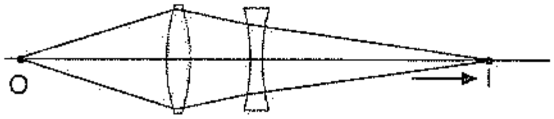
Moving the 'scope up fogs the surgeon, allowing relaxation of accommodation.

Image movement caused by introduction of lenses

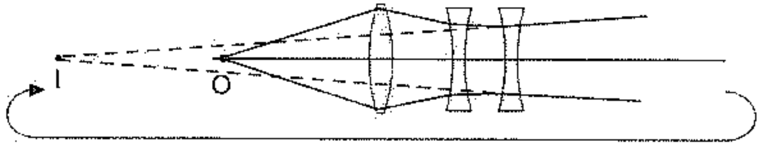




Introducing plus power pulls all "downstream" images against the light.

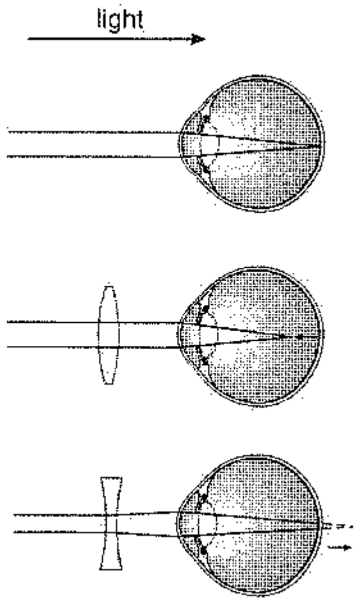


Introducing minus power allows all "downstream" images to slide with the light.

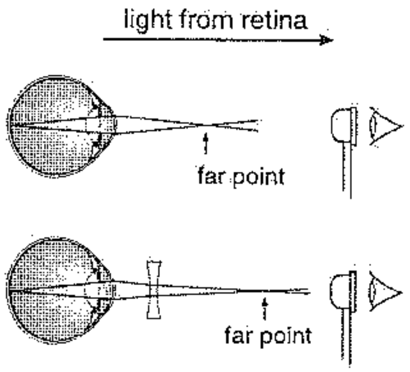


Images can never move **through** lens power that is added. Instead, to get to the other side of the lens, the image moves "through" infinity and comes back in from the other side.

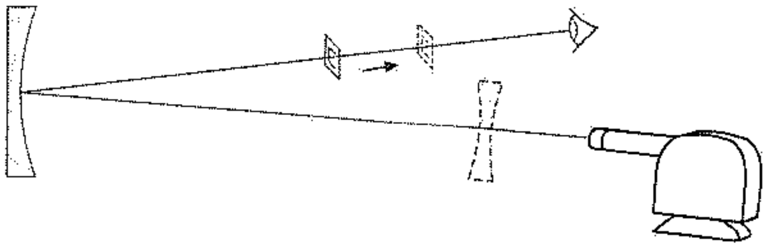
In the eye:



In retinoscopy:



For remote refraction:



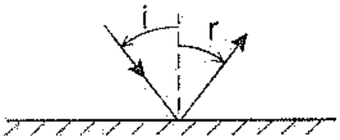
See:
p93, prob 40

Mirrors

Laws of reflection —

Angle of reflection is equal to the angle of incidence.

The incident ray, the normal to the surface, and the reflected ray all lie in the same plane.

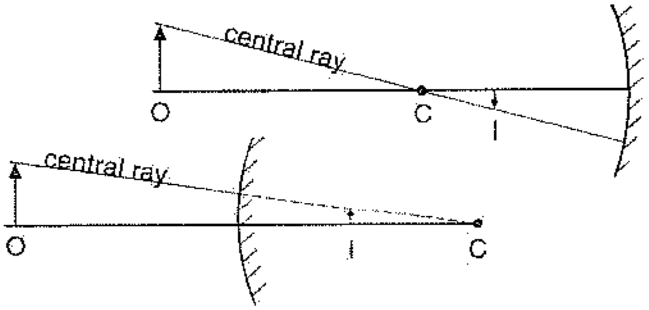


Mirrors may be thought of as lenses which flip over the image space, by reversing the direction of the light.

Convex mirrors — add **minus** vergence (like minus lenses)
Concave mirrors — add **plus** vergence (like plus lenses)
Plane mirrors — add **no** vergence (simply reverse direction)

The vergence formula (U + D = V) may be used to locate the images formed by mirrors, remembering that mirrors reverse the direction of the light at the same time that vergence changes.

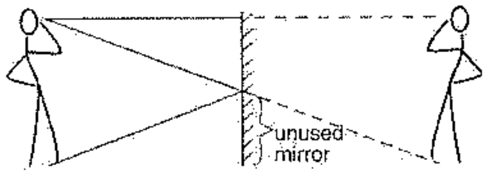
Central ray — passes through the **center of curvature**, not through the center of the curved mirror.



Plane mirror

Forms erect virtual image of real objects, located as far behind the mirror as the image is in front.

Need only a half-length mirror to see entire self in:



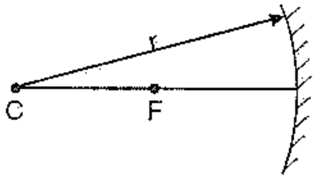
Holding a hand mirror farther away from the face does **not** enlarge the field of view.

Mirrors, continued

Reflecting power

The **reflecting power** of a mirror in **diopters** is equal to the reciprocal of the focal length, with the focal length always being half the radius of curvature. There is no refractive index to worry about.

$$D_{\text{reflecting}} = \frac{1}{f} = \frac{1}{\frac{r}{2}} = \frac{2}{r}$$

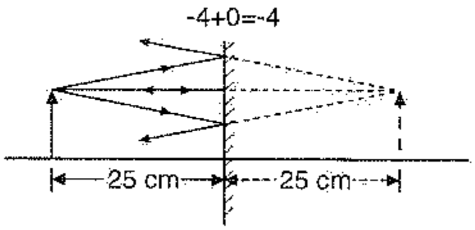


See: p61, prob 10

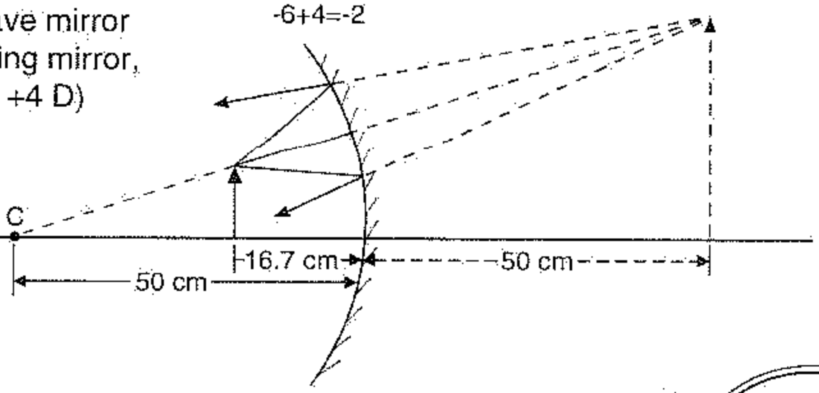
The primary focal point and the secondary focal point along a chosen optical axis for a mirror coincide with one another.

Mirror vergence calculations

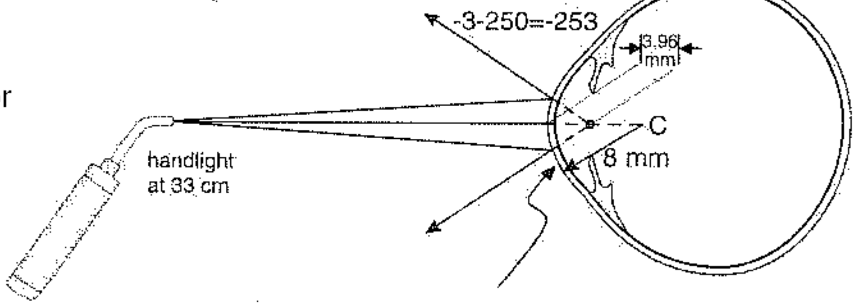
plano mirror



concave mirror (shaving mirror, about +4 D)



convex mirror (cornea)



The **reflecting** power of the cornea =
2/r = 2/0.008 = 250 D, or -250 D, because the convex surface adds minus vergence.

Important relationships to remember

location in
review notes

p.6 Prentice's Rule

$$\boxed{\Delta = hD}$$

Δ - prism diopters
h - distance from optical axis in cm
D - diopters of lens power

p.12 Vergence Formula

$$\boxed{U + D = V}$$

U - vergence of the object rays entering the lens
D - vergence added by the lens (lens power)
V - vergence of the image rays leaving the lens

p.14 Power of a spherical **refracting** surface

$$\boxed{D_s = \frac{|n' - n|}{r}}$$

D_s - surface **refracting** power (use imaginary rectangle to determine sign)
$|n' - n|$ - difference in refractive index
r - radius of the surface in meters

p.14 Refractive indices:

air	1.00
water, aqueous, vitreous	1.33
keratometric	1.3375
cornea	1.37
plastic (PMMA, CR-39)	1.49
crown glass	1.52
polycarbonate	1.59
high index plastics	up to 1.66
high index glass	up to 1.81

p.17 Focal length of lens

$$\boxed{f = \frac{1}{D}}$$

f - focal length in **meters**
D - lens power in **diopters**

p.25 Lens effectivity: use the **far point concept**

p.32 spherical equivalent

$$\boxed{\text{sph eq} = \text{sph} + \frac{1}{2}\,\text{cyl}}$$

p.37 Transverse magnification

$$\boxed{M_{\text{trans}} = \frac{\text{image height}}{\text{object height}} = \frac{\text{image distance}}{\text{object distance}}}$$

Important relationships to remember, cont.

p.21, 37 Nodal point of the average emmetropic eye: 17 mm from the retina

p.37 Axial magnification $\boxed{M_{axial} = (M_{transverse})^2}$

p.38 Magnification of a simple magnifier $\boxed{M_{angular} = \frac{D}{4}}$ D - lens power

p.39 Magnification of telescope $\boxed{M_{angular} = \frac{\text{power of eyepiece}}{\text{power of objective}}}$

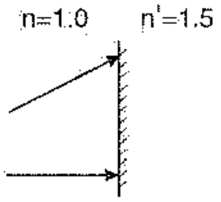
p.41 Magnification/minification from spectacle lens: about 2% per diopter of lens power

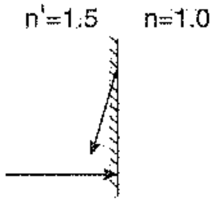
p.52 Reflecting power of spherical mirror $\boxed{D_{reflecting} = \frac{1}{f} = \frac{1}{r/2} = \frac{2}{r}}$

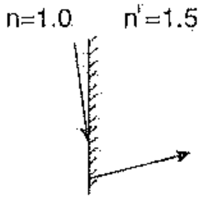
f - focal length in **meters**
r - radius of curvature in **meters**

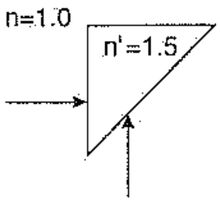
Problems

1. Complete the missing parts of the light rays, showing the correct direction of the bending at the interfaces:









2. A prism deflects a light ray 6 cm at a distance of 50 cm. What is its power measured in diopters?

If this prism is placed base up before the right eye of a patient without strabismus, which way will the image seen by the right eye seem to move to the patient? Which way will the image on the right retina move?

With this prism base-up before the right eye, will the patient measure to an examiner to have a right hypertropia or a left hypertropia?

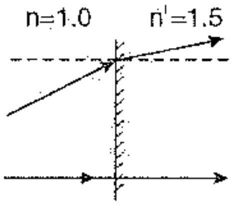
3. A patient with 40^{Δ} of exotropia wears the following glasses, properly centered:

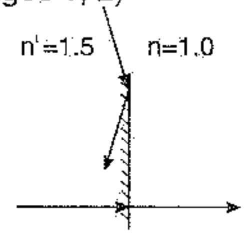
RE	-10.00 sphere
LE	plano

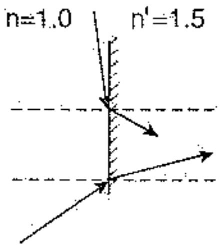
What will the exotropia measure at distance through the glasses with the right eye fixing (looking straight ahead)? With the left eye fixing?

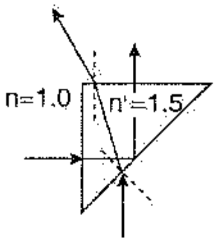
How far and to which side must the patient look with the right eye to decrease the measured exotropia to 30^{Δ}?

1. (see review notes pages 1, 2)









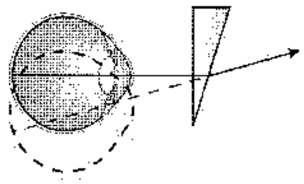
Remember the **critical** angle applies to light rays inside optical media. The top ray had to have been totally internally reflected.

2. (see review notes pages 4, 5, 7)

Zero diopters. In **prism diopters**, on the other hand, its power is 12^{Δ}, for the number of prism diopters is equal to the deflection measured 100 cm from the prism.

The image seen by the patient is a virtual image and moves **down**, toward the apex of the prism. The image on the retina is a real image and moves **up**, toward the base of the prism.

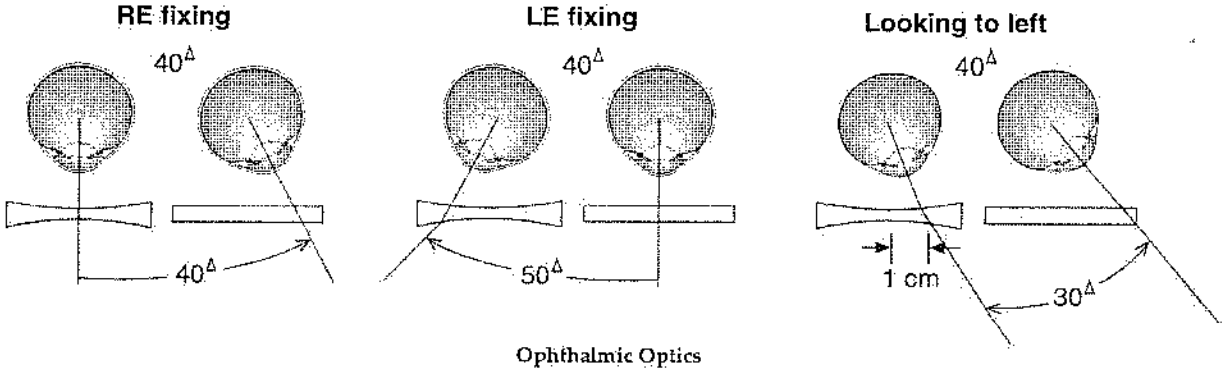
A **right** hypertropia. Think of what happens to the right line of sight as it emerges from the eye and travels through the prism. It is bent upward, measuring to the examiner as a right hypertropia. Although the patient's eye may **appear** to the examiner to have been **displaced** downward, the entire image of the eye has actually **rotated** so that the **image** is looking upward.



3. (see review notes page 6)

Right eye fixing: 40^{Δ}
Left eye fixing: about 50^{Δ} ($2.5 \times 10 = 25\%$ more than the true angle)

By looking left through the right lens 1 cm nasal to the optical center, base-in effect is encountered equal to (1 cm)(10 D) = 10^{Δ}, by Prentice's Rule, reducing the measured exotropia to 30^{Δ}. Note the apparent incomitance induced.



4. A patient reads 8 mm below the optical centers of her glasses with the following prescription:

   RE +3.00 sphere
   LE -2.00 + 1.00 x 180

   What prismatic effect do the glasses have in the reading position?

   Would the patient experience a right hyperdeviation (phoria or tropia) or a left hyperdeviation through the glasses in the reading position, assuming her visual axes behind the glasses are perfectly aligned in all direction of gaze?

   What are various ways this problem can be alleviated?

5. True or false:

   Flat-top bifocal segments:

   a. cause no image jump

   b. minimize image jump on minus lenses but not on plus lenses.

   c. decrease image displacement on plus lenses but not on minus lenses.

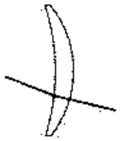
   d. are generally preferred for use on plus lenses.

6. A patient has X(T) 5^{Δ}, LH(T) 5^{Δ}. What power and orientation of Fresnel Press-On™ prism could be used on the left lens of the glasses to fully correct the deviation?

4. (see review notes page 7)

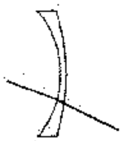
RE vertical meridian = +3.00 D

By Prentice's Rule:
(0.8 cm)(3 D) = 2.4$^\Delta$ BU



LE vertical meridian = -1.00 D

By Prentice's Rule:
(0.8 cm)(1 D) = 0.8$^\Delta$ BD



3.2$^\Delta$ BU RE
Net prism = right + left = 2.4$^\Delta$ + 0.8$^\Delta$ = **or**
3.2$^\Delta$ BD LE

Note that in this case the prism effects added in the same vertical prism direction. The net effect can be referred either to the right eye (base up), or to the left eye (base down).

This would create a **right hyperdeviation** in a straight-eyed patient.

Possible solutions:

Contact lenses

Dropping the optical centers of **both** lenses, to compromise the vertical imbalance between distance and near vision.

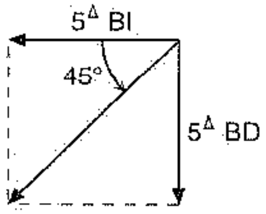
Slab-off prism from the left lens, because slabbing off **takes away base-down** prism. How much should be slabbed off? 3.0$^\Delta$, rounded to the nearest 0.5$^\Delta$.

Reverse slab added to the right lens, of 3$^\Delta$, **adding base-down** prism

5. (see review notes page 8)
a. false — cause **minimal** image jump. Only with Franklin type, or "Executive" style, bifocal segment is there **no** image jump, for here the optical center of the segment is precisely at the top of the segment.
b. false — flat-top segs have minimal image jump with **either** minus or plus lenses.
c. false — the opposite is true. Flat-top segs decrease image displacement on minus lenses but increase it on plus lenses.
d. false — round-top segs are generally preferred for use on plus lenses, because image displacement is usually more of a problem than image jump.

6. (see review notes page 9)

left lens:



$5^2 + 5^2 = 50$ (Pythagorean Theorem)

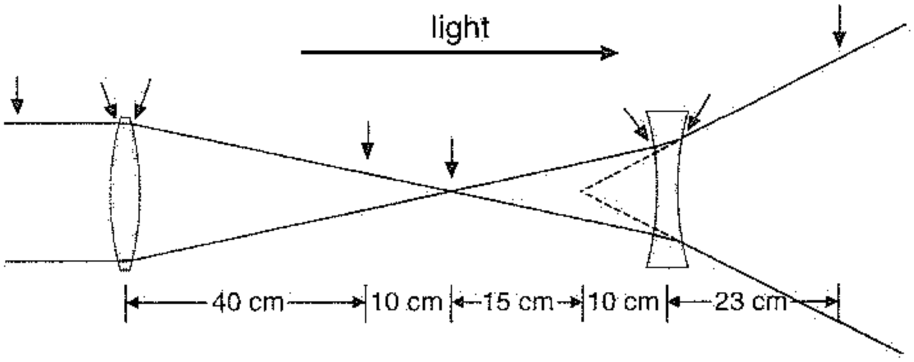
$\sqrt{50} \approx 7^\Delta$

7$^\Delta$ base **down and in** in the 45° meridian

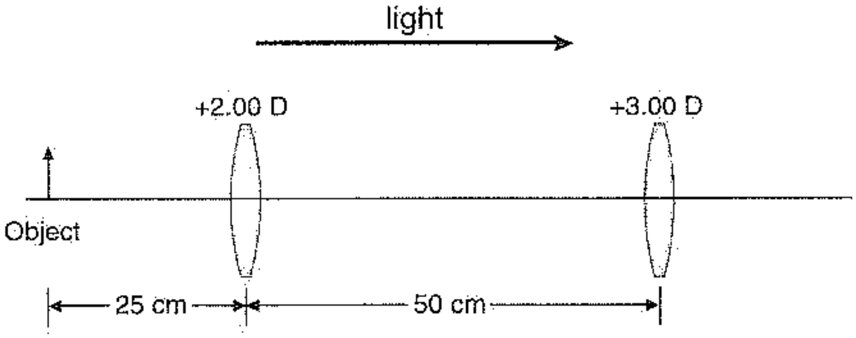
7. Is the refractive index of the ocular media lower for red light or for blue light?

   In the correct use of the red-green (duochrome) test for refraction of young adults, what should the patients **always** see when the test is first introduced?

8. What is the vergence of the light at each of the points indicated? What are the powers of the lenses?



9. Find by calculation the axial location of the final image formed by the following optical system:

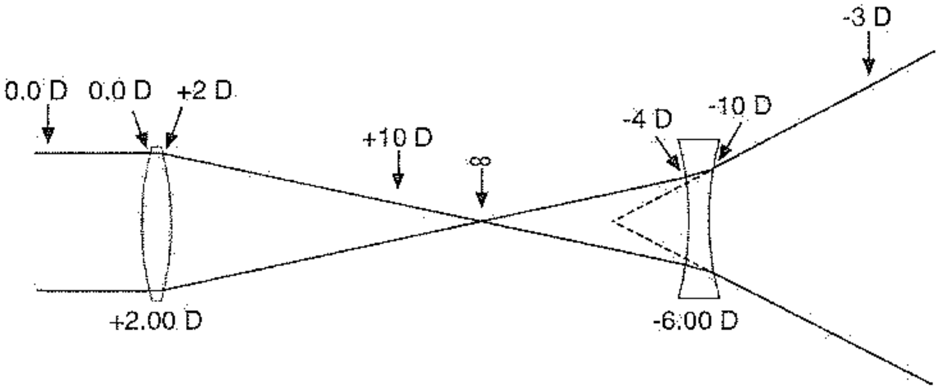


   Are the intermediate and final images upright or inverted?
   Real or virtual?

7. (see review notes page 10)
Lower for red light, with red light being refracted less strongly.

The letters on the red side should always be blacker and sharper than the letters on the green side when the test is first introduced. If the green side is sharper, accommodation is likely not controlled. Re-fog using the white chart.

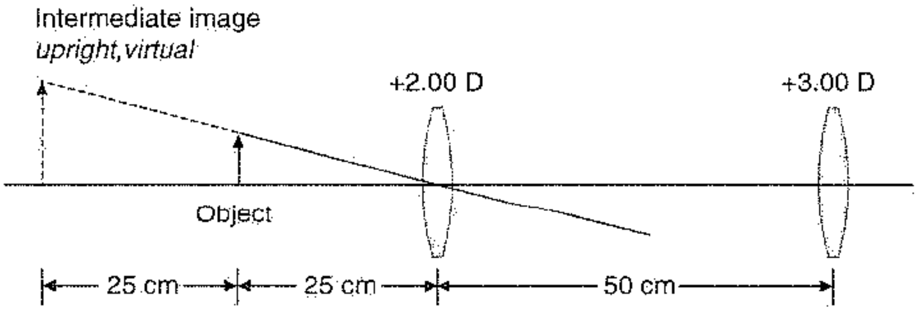
8. (see review notes pages 11, 12, 13)



9. (see review notes pages 12, 13, 15, 18, 19)

First lens: -4 + 2 = -2 (U + D = V)

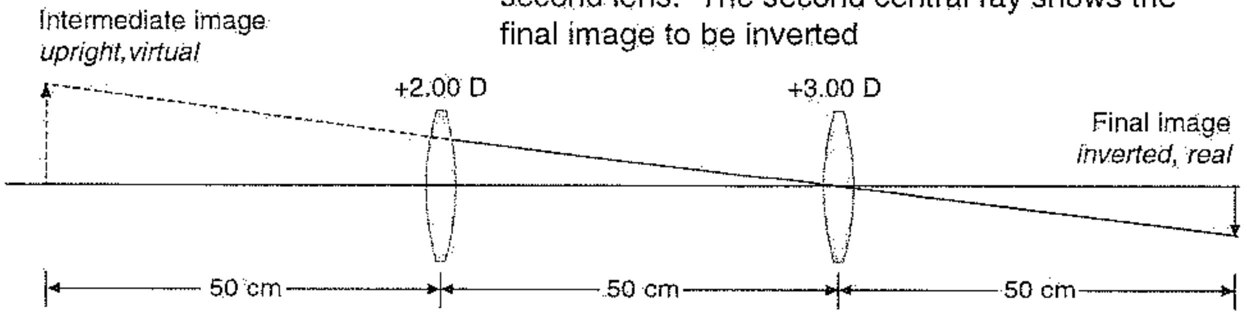
The image formed by the first lens is thus 50 cm to the left of the first lens. The central ray shows the image to be upright.



Second lens: -1 + 3 = +2 (U + D = V)

The vergence **entering** the second lens is -1 D, because the image formed by the first lens is 100 cm to the left of the **second** lens.

The final image is thus 50 cm to the right of the second lens. The second central ray shows the final image to be inverted



10. K-readings indicate a spherical cornea with radius of curvature equal to 8.0 mm. Given a "standardized" refractive index for the cornea of 1.3375, what is the refracting power of the cornea?

    What is the reflecting power of the same cornea?

11. A plastic intraocular lens is marked as +20 D. What would its power be if it were made of crown glass with the same thickness and surface curvatures?

12. How can one obtain an **inverted** virtual image, given a single lens (which may be plus or minus) and an **upright** object (which may be real or virtual)?

10. (see review notes pages 14, 52)

Refracting power $= \dfrac{|n' - n|}{r} = \dfrac{1.3375 - 1.00}{0.008 \text{ m}} = \dfrac{0.3375}{0.008} = +42.2 \text{ D}$

(The refracting power is **plus** because the higher refractive index medium has a convex surface.)

Reflecting power $= 1/f = 1/(r/2) = 1/0.004 = -250 \text{ D}$

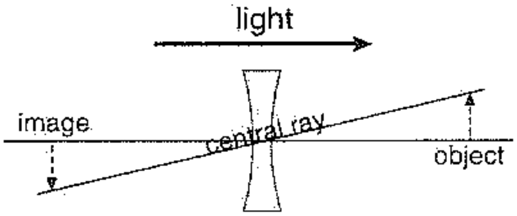
(The reflecting power is **minus** because the convex surface adds **divergence** to the light as it reflects it.)

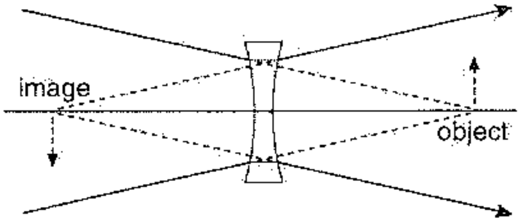
11. (see review notes page 14)

$$\frac{D_{glass}}{D_{plastic}} = \frac{n_{crown\ glass} - n_{aqueous}}{n_{plastic} - n_{aqueous}} = \frac{1.52 - 1.33}{1.49 - 1.33} = \frac{0.19}{0.16}$$

$$D_{glass} = \frac{0.19}{0.16}(D_{plastic}) = \frac{0.19}{0.16}(+20) = \mathbf{+23.75\ D}$$

12. (see review notes pages 15, 18)





For the image to be virtual, it must be located on the side of the incoming rays. For it to be inverted relative to the object, it must be on the opposite side of the lens from the object (think of the central ray concept). Therefore the upright object must be on the outgoing side of the rays, a "virtual object." The object rays entering the lens must therefore have plus vergence (traveling from left to right). The image rays leaving the lens have minus vergence, because the image is to the left of the lens. The lens therefore had to have added minus vergence, identifying it as a **minus** lens.

13. What planes are conjugate to one another in retinoscopy?

14. In neutralization in retinoscopy, how large is the image of the 3 mm retinoscope peephole on the patient's retina? Assume that the retinoscope is held approximately 67 cm from the nodal point of the patient's eye.

    If the optic disc is 1.5 mm in diameter, how large a retinal area, in terms of disc diameters, is being "looked at" at neutralization in retinoscopy?

15. A -20.00 D spectacle lens is moved 10 mm forward from its correct position. How does its **effective** power change (with respect to the distance refractive correction)?

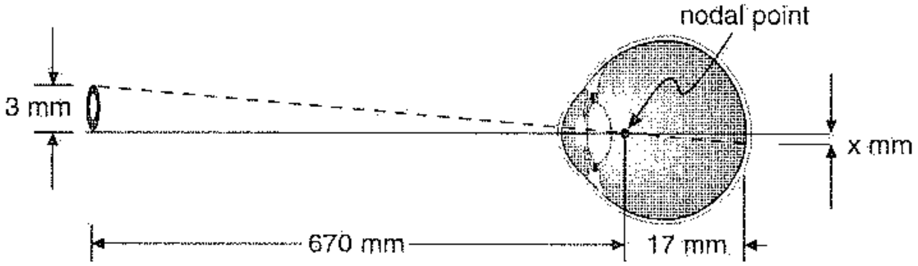
    What power would the lens have to be to provide the proper distance correction at the new vertex distance?

13. (see review notes page 23)

The retinoscopist is focused on the patient's pupil. The patient's pupil is therefore conjugate to the examiner's retina.

As the retinoscopic reflex is neutralized, the far point of the patient's eye is brought optically to coincide with the peephole of the retinoscope. Therefore, because the retina of the nonaccommodating eye is always conjugate to the far point (by definition), the patient's retina and the peephole of the retinoscope become conjugate to one another at neutralization.

14. (see review notes pages 21, 37)

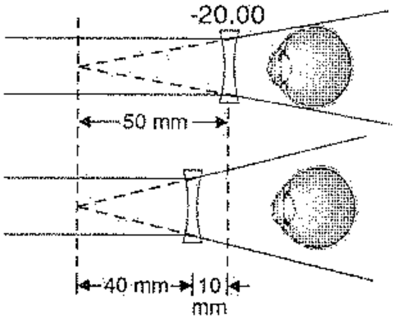


by similar triangles:

$$\frac{x}{3} = \frac{17}{670} \qquad x = \frac{3 \times 17}{670} = 0.08 \text{ mm}$$

$$\frac{0.08 \text{ mm}}{1.5 \text{ mm}} = 0.05$$, or **1/20th of a disc diameter**

15. (see review notes pages 24, 25, 26)

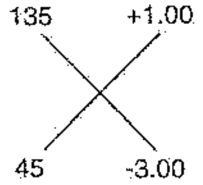


The effective power **decreases** as the lens is moved forward, because a higher minus lens would be required to provide the same correction.

High myopes, therefore, the same as high hyperopes, can gain "plus" power for reading by sliding their glasses down their noses.

$$\frac{1}{0.040} = \mathbf{-25.00\ D}$$ necessary for correction at the new vertex distance.

16. Use both cross diagrams and standard spherocylindrical notation to express the lens:



a. as the combination of two cylinders.
b. as a sphere combined with a minus cylinder.
c. as a sphere combined with a plus cylinder.

17. A postoperative aphake has K-readings of 48.25 @ 75 / 42.75 @165 six weeks after cataract surgery. Is the corneal curvature greater horizontally or vertically? Does this represent astigmatism with-the-rule or against-the-rule?

Which is the "flattest K"?

Which "o'clock" suture might be cut to help correct the postoperative astigmatism?

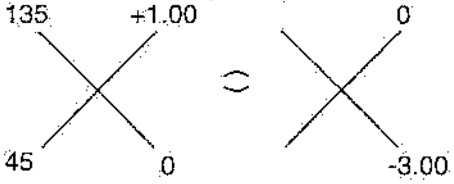
How does the amount of astigmatism in the spectacle plane relate to the astigmatism measured at the cornea?

18. If the cylinder is to be cut by 50% in the following prescription, and the axis is to be rotated to 90° to lessen distortion, what will the resultant prescription be if the spherical equivalent is to be kept constant?

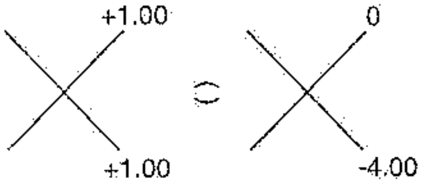
- 2.00 + 4.00 x 80

What is the spherical equivalent of this prescription?

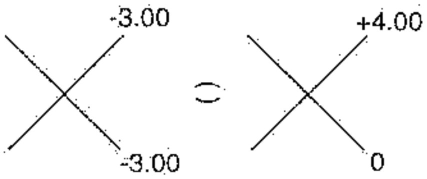
16. (see review notes page 30)



a.
+ 1.00 x 135 ≎ - 3.00 x 45
(combined cylinder form)



b.
+1.00 - 4.00 x 45
(spherocylinder, minus cyl form)



c.
-3.00 + 4.00 x 135
(spherocylinder, plus cyl form)

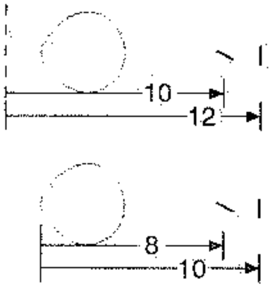
17. (see review notes page 31)
Curvature is greater vertically (the 75° meridian has the greater dioptric power). Astigmatism is therefore with-the-rule.

The 165° meridian has the flattest K, +42.75 D.

The 12:30 o'clock suture. The tight suture flattens the cornea locally (peripheral cornea), causing the cornea to bulge forward centrally over the pupil, steepening that meridian. (Demonstrate with a bowed index card.)

In the **hyperopic** patient the astigmatism in the spectacle plane is always **less than** the astigmatism measured at the cornea, particularly noticeable in high hyperopes such as aphakes, where the spectacle lens power is typically 2/3 to 3/4 of the corneal cylinder. The opposite is true for myopes.

Think this through using the far point concept of refractive error correction (review notes page 24) (see the construction to the right for a case of aphakia with astigmatism).



$$\text{Astig}_{\text{glasses}} = \frac{1}{0.10} - \frac{1}{0.12}$$

$$= 10 - 8.3 = 1.7 \text{ D}$$

$$\text{Astig}_{\text{CL}} = \frac{1}{0.08} - \frac{1}{0.10}$$

$$= 12.5 - 10 = 2.5 \text{ D}$$

18. (see review notes page 32)
-1.00 +2.00 x 90
Add half as much sphere algebraically as you take away in cylinder. Rotating the cylinder axis has no effect on the spherical equivalent.
Spherical equivalent = **plano**

19. A spectacle-corrected hyperope increases the pantoscopic tilt of her glasses by raising the temples. What is the resultant residual refractive error?

20. You are ordering a rigid contact lens for a unilateral aphake, but you do not have an aphakic contact lens to refract over. K-readings are 44.00 / 46.25. With a plano contact lens trial set you determine that an 8.2 mm lens with base curve of 44.75 D gives the proper fit. The spectacle refraction at a vertex distance of 13 mm is +11.00 + 1.50 x 90. What power contact lens do you order?

    Why doesn't the power of the contact lens suddenly change when it becomes bounded by tears on one side?

19. (see review notes page 33)

Increasing the pantoscopic tilt of a plus lens adds plus cylinder axis 180 as well as a small amount of additional plus sphere. The resultant residual refractive error will therefore be, because the eye is now too powerful in all meridians, especially the 90° meridian, **compound myopic astigmatism with-the-rule.**

20. (see review notes page 34)

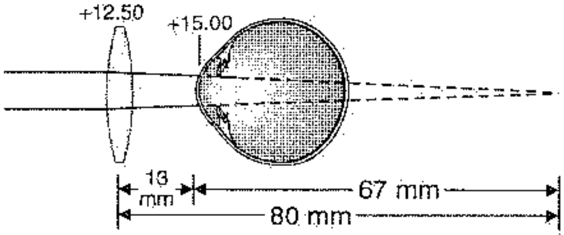
Note that the chosen base curve is 0.75 D steeper than low K (44.75 - 44.00), creating a +0.75 D spherical "tear lens."

Transpose the spectacle refraction to minus cylinder form:

+11.00 +1.50 x 90 transposes to +12.50 - 1.50 x 180

Now ignore the minus cylinder, for it will be provided automatically by the tears (a cylindrical "tear lens").

Convert the +12.50 sphere at 13 mm to the new sphere at zero vertex distance:



The sphere at the cornea will have to have a focal length of 67 mm. Its power must therefore be: 1 / 0.067 = +15.00 D.

The spherical tear lens already provides +0.75 D at the cornea, so the necessary contact lens power is +15.00 - (+0.75) = **+14.25 D**.

The power of the contact lens **can** be thought of as changing, actually becoming more powerful, as its concave surface is almost fully neutralized by the tears. The power of the air-tear interface, on the other hand, is greatly **decreased** by the plastic replacing the air. The net effect is essentially zero change, so that the full power of the contact lens can simply be thought of as being added to the eye. (See review notes page 14 and problem #10.)

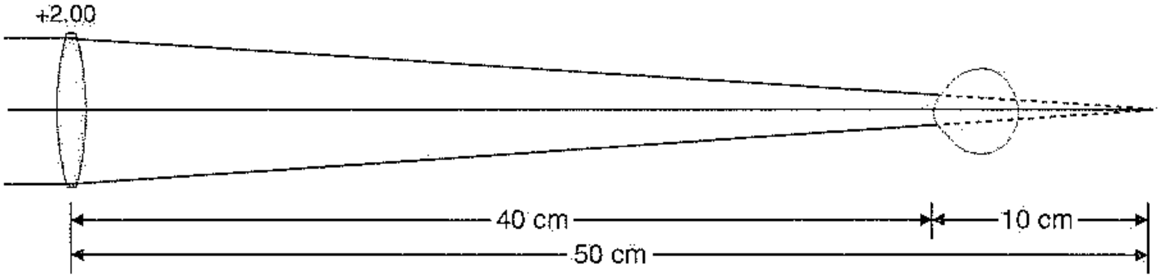
21. You perform cataract surgery on your mother, and she reads the 20/20 line on the first postoperative visit by holding a +2.00 D lens 40 cm from her aphakic eye. She insists on a contact lens as soon as possible, so you take great pride in calculating the necessary vertex distance correction and order the appropriate contact lens through a local optician. Two weeks later she returns, wearing the contact lens and complaining of floaters. Vision is 20/100. What power contact lens did you order, and why is the vision worse?

22. What is the defined magnification of a +20 D indirect ophthalmoscopy condensing lens when used as a simple magnifier?

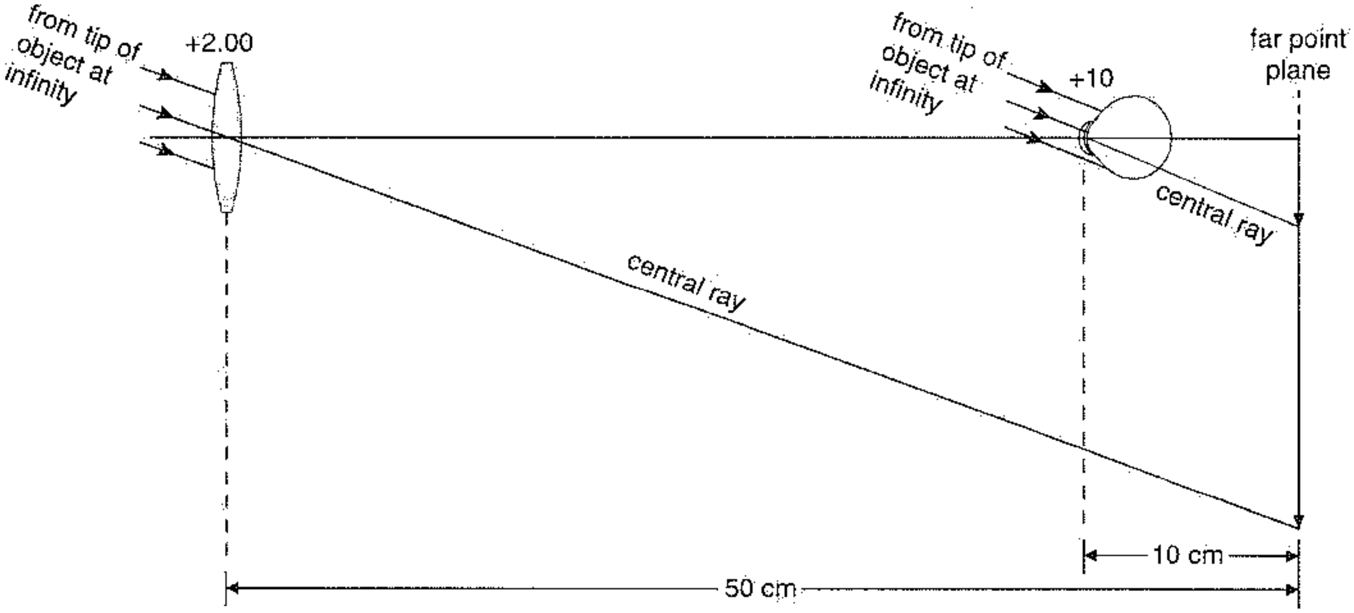
    What is the reference distance used for this definition, and what does this defined "magnification" mean?

    If the reference distance had been chosen as 40 cm, what would the magnification of the above lens have been?

21. (see review notes pages 24, 37)



The correct lens must have a focal length of 10 cm, so it must have a power of +10.00 D (neglecting the power of the tear lens for this problem).



By similar triangles, the size of the image formed in the far point plane is 50/10, or 5 times larger with the +2.00 D lens than with the + 10.00 D contact lens. The + 2.00 D lens therefore gives 5 times the magnification of the +10.00 D contact lens, and 20/20 vision with the +2.00 D lens is **equivalent** to 20/100 vision with the contact lens.

22. (see review notes page 38)

$$\frac{20}{4} = 5\text{ X, as a simple magnifier}$$

The reference distance is 25 cm. With the above lens, the magnified image would subtend an angle 5 time as large as the angle subtended by the object held at 25 cm from the eye.

With greater reference distance, the constant image size with the magnifier would be compared to a smaller angular size without the magnifier, and the defined magnification of the lens would have been greater, in the ratio of 40/25.

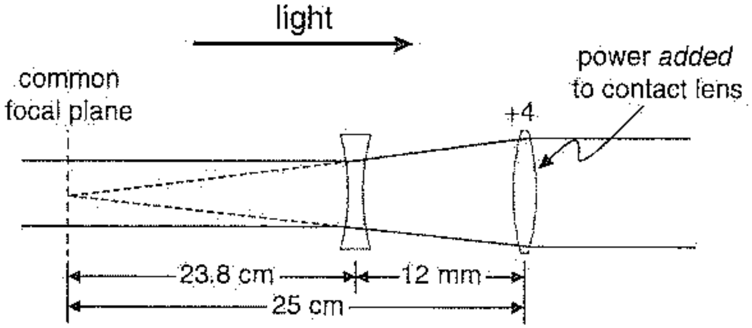
$$\frac{40}{25} \times 5 = \mathbf{8\ X}$$

23. A monocular aphake corrected with a contact lens still complains of unequal image size between the two eyes. You decide to try a spectacle lens/contact lens combination to decrease the size still further in the aphakic eye. You overplus the contact lens by 4.00 D. At a vertex distance of 12 mm, what power spectacle lens is appropriate, and how much minification does this combination provide?

24. A bilateral high myope is fully corrected for distance with glasses of -20.00 D OU at a vertex distance of 12.5 mm. How much accommodation is required to see clearly at 40 cm from the glasses, with the assumption that accommodation occurs just inside the cornea?

23. (see review notes pages 39, 40)

A reverse Galilean telescope is being used to provide the minification (or "magnification" of less than 1). The minus lens is in front, and the plus lens is behind, separated by the vertex distance of 12 mm. The focal planes of the two lenses must coincide to produce a telescope:



The minus lens must therefore have a focal length of 23.8 cm, or a power of -4.20 D, rounded to **-4.25 D**.

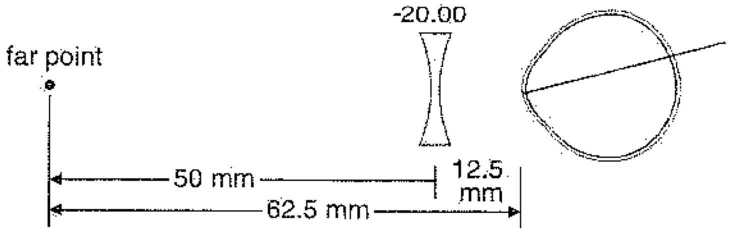
The "magnification" of this reverse Galilean telescope will be equal to the power of the eyepiece divided by the power of the objective:

4.00 / 4.25 = 0.94 X

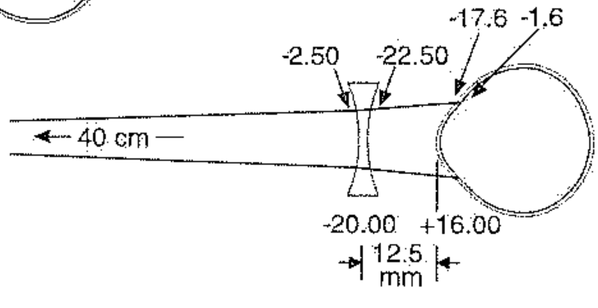
0.94 X represents **6% minification** produced by this arrangement.

24. (see review notes pages 47, 48)

This problem requires that vergence of light from the object at 40 cm be traced through the corrective lens and through the refractive error assumed to act at the cornea.



The refractive error at the cornea will be the reciprocal of 62.5 mm, in meters, or 1 / 0.0625 = +16.00 D.



Tracing the vergence from the object at 40 cm through the corrective lens and through the refractive error leaves -1.6 D of vergence entering the eye. The patient will therefore have to accommodate only 1.6 D to see clearly at 40 cm. This illustrates the fact that high myopes need only low power reading adds when they become presbyopic.

Remember that plus spectacle lenses require more accommodation than contact lenses; minus spectacles require less.

25. a. An eye with an amplitude of accommodation of 6 D has its near point at 50 cm. What is the full refractive correction, and where is the far point?

b. What is the **range** of accommodation of this uncorrected hyperope with an accommodative amplitude of 6 D?

c. (Same eye) If the far point of an eye is 25 cm behind the eye, and the near point is 50 cm in front of the eye, what is the amplitude of accommodation?

d. (Different eye) If the far point is 20 cm in front of the eye, and the near point is 12.5 cm in front of the eye, what is:

1) the distance refractive correction?

2) the amplitude of accommodation?

3) the far and near points when wearing the distance correction?

4) the range of accommodation when wearing the distance correction?

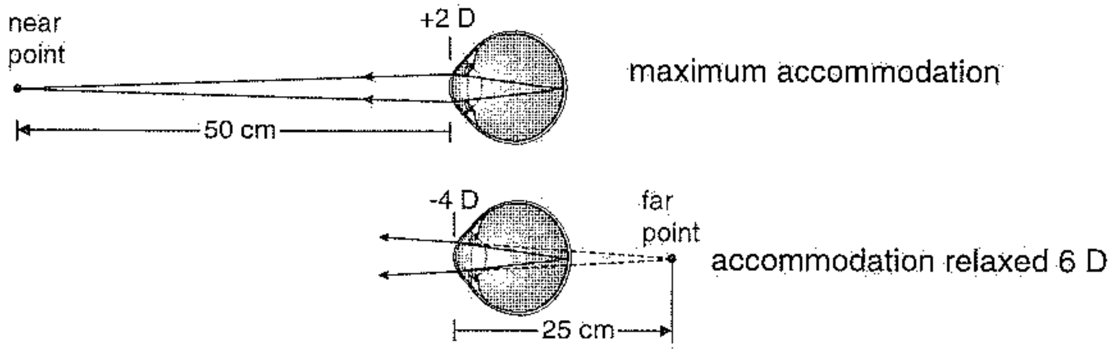
25. (see review notes page 28)

a. There are two ways to work problems involving far points, near points, and amplitudes of accommodation:

1) **Working through infinity**

All 6 D of accommodation are being used at the near point of 50 cm. It took only 2 D to focus from infinity to 50 cm, so when the eye was focused at infinity, 4 D of accommodation were active, indicating **4 D of hyperopia**. The far point of a 4 D hyperope is a virtual far point **25 cm behind the eye** (see review notes page 19).

2) **Turning the light around**



Consider the vergence of light from the retina leaving the eye: At the near point, with all 6 D of accommodation active, the vergence leaving the eye is +2 D. If accommodation is then relaxed completely, the vergence leaving the eye is changed by -6 D, going from +2 to -4 D. The vergence of the light leaving the eye in the relaxed state is always exactly equal to the refractive error. In this case it is -4 D, indicating 4 D of hyperopia. Again, the far point of a 4 D hyperope is a virtual far point 25 cm behind the eye.

b. The **range** of accommodation extends from infinity to the near point at 50 cm, corresponding to the actual range of clear vision. The 4 D used by the patient to reach infinity from the far point does not contribute to the **range** of accommodation in this case.

c. The amplitude of accommodation is 6 D, figuring backward from the example above. One should be able to determine any one of these quantities (near point, far point, amplitude of accommodation, refractive correction) when given the others.

d.
1) -5.00 D
2) 3 D
3) far point = infinity; near point = 33 cm
4) infinity to 33 cm

26. For the following refractive or keratometric measurements, determine the type and orientation of astigmatism (e.g. compound myopic with-the-rule), and determine the spherical equivalent.

- 4.00 + 4.00 x 180

- 1.00 + 5.00 x 40

plano + 2.00 x 100

43.00 @ 80
45.00 @ 170

+ 2.00 - 4.00 x 90

- 1.00 - 2.50 x 10

+5.00 - 0.50 x 125

46.50 @ 30
42.50 @ 120

Also give the plus and minus cylinder corrections for the pairs of keratometric readings.

26. (see review notes page 31)

- 4.00 + 4.00 x 180

simple myopic astigmatism
against-the-rule
sph eq = -2.00 D

+ 2.00 - 4.00 x 90

mixed astigmatism
against-the-rule
sph eq = 0.00 D

- 1.00 + 5.00 x 40

mixed astigmatism
oblique
sph eq = +1.50 D

- 1.00 - 2.50 x 10

compound myopic astigmatism
with-the-rule
sph eq = - 2.25 D

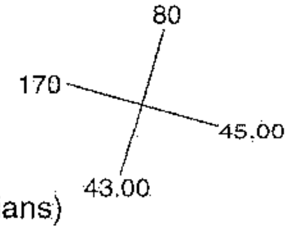
plano + 2.00 x 100

simple hyperopic astigmatism
with-the-rule
sph eq = +1.00 D

+5.00 - 0.50 x 125

compound hyperopic astigmatism
oblique
sph eq = +4.75 D

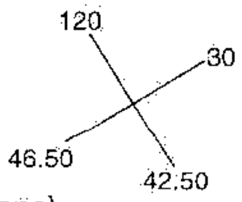
43.00 @ 80
45.00 @ 170
(powers **in**
principal meridians)



type is undefined
against-the-rule
sph eq = 44.00 D

plus cylinder **correction**:
+ 2.00 x 170
minus cylinder **correction**:
- 2.00 x 80

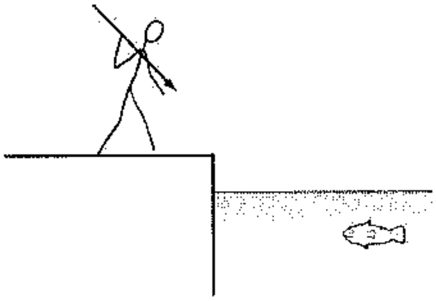
46.50 @ 30
42.50 @ 120
(powers **in**
principal meridians)



type is undefined
oblique
sph eq = 44.50 D

plus cylinder **correction**:
+ 4.00 x 30
minus cylinder **correction**:
- 4.00 x 120

27. A fisherman attempts to spear a fish as shown at the right.

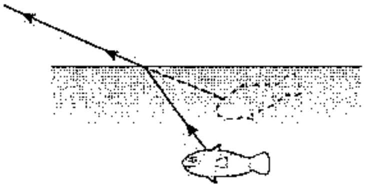


a. Should he aim above or below the fish as he sees it?

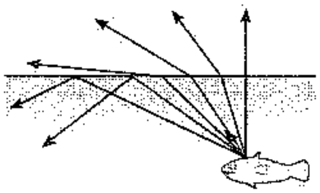
b. How far away from the fisherman must the fish be before disappearing because of total internal reflection?

27. (see notes page 2)

a. Below the fish. Light passing from the fish to the fisherman's eyes is bent away from the normal, and the fisherman sees a virtual image of the fish (dotted) above the actual location of the fish.



b. The fisherman will **always** see the fish. Trace the rays fanning out from a point on the fish's back. Some of the rays will be refracted; some will be totally internally reflected. One of the refracted rays will always reach the fisherman no matter how far away the fish is. The **amount** of light may limit the fisherman's view, but total internal reflection will not.



28. A 10^{Δ} prism is placed BO before the left eye of a patient with perfectly straight eyes (orthotropia) at distance and near.

    a. Which way will a distant object appear to move, to the patient's left eye, when the prism is introduced?

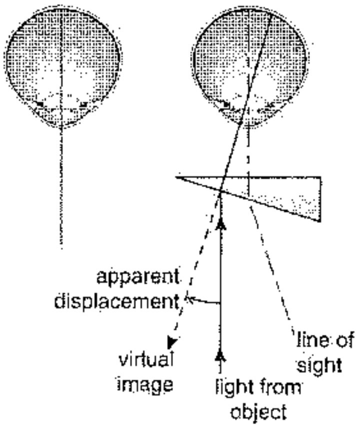
    b. Which way will the patient's left eye appear to be displaced to an examiner sitting facing the patient?

    c. If the prism is held 2 cm from the patient's eye, how far does the patient's eye appear to be displaced to the examiner?

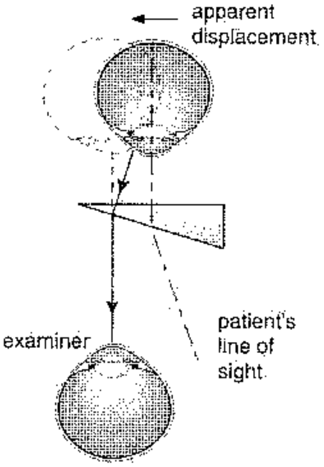
    d. Will the patient have to converge or diverge to compensate for the prism? What type of deviation will be apparent to the examiner by cover-uncover testing, with the prism in place?

28. (see notes pages 4, 5, 55, 56)

a. To the patient's right, toward the apex of the prism, for the image seen by the left eye is a virtual image, and virtual images are displaced toward the **apex** of prisms. Note that the retinal image, a real image, is displaced temporally, toward the base of the prism.

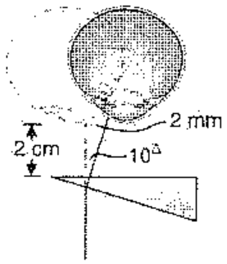


b. Nasally, again toward the apex of the prism, for the examiner's view of the patient's eye is also a virtual image. Note that although the patient's eye appears **displaced** nasally, it also appears to the examiner as being rotated slightly temporally (before the patient makes a compensatory (fusional) eye movement).



c. 2 mm. Because 10^{Δ} of deviation displaces light rays 10 cm at 100 cm from the prism, the displacement at 2 cm is

$$(2/100) \times 10 \text{ cm} = 0.2 \text{ cm} = 2 \text{ mm}.$$



d. Converge, because the left line of sight has been directed outward by the prism (see top diagram). The patient will appear to have an exophoria by cover-uncover testing, for the fusion-free position measured anterior to the prism is an exodeviation.

29. A patient's right eye refraction is - 3.00 + 1.00 x 180 before cataract extraction and IOL placement, and + 2.00 +2.00 x 90 afterwards. If the patient was orthophoric in the reading position 10 mm below the optical centers of his glasses before the surgery, will you expect a right hyperdeviation or left hyperdeviation in the reading position after the surgery? How much?

30. True or false:

Round-top bifocal segments:

a. Minimize image jump.

b. Have round tops because they are placed on meniscus lenses.

c. Decrease image displacement on plus lenses and increase image displacement on minus lenses.

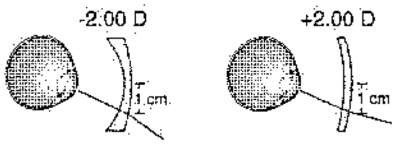
d. Are generally preferred for use on minus lenses.

31. A patient has 5^{Δ} of left hypertropia and 8^{Δ} of exotropia. With a single 7^{Δ} prism over the right eye, which orientation will best correct fully the patient's hypertropia? What will be the residual deviation?

29. (see notes pages 6, 7, 57, 58)

A right hyperdeviation of 4^Δ. The dioptric power in the vertical meridian of the glasses was -2.00 D, and after the surgery is +2.00 D.

The net change in vertical prism effect in the reading position, in going from 2^Δ BD to 2^Δ BU, is 4^Δ, with the right line of sight now being directed higher than before, causing a right hyperdeviation of 4^Δ.



Pre-op	Post-op
$\Delta = hD$	$\Delta = hD$
$\Delta = 1(2)$	$\Delta = 1(2)$
$\Delta = 2^\Delta$ BD	$\Delta = 2^\Delta$ BU

30. (see notes pages 8, 57, 58)

a. False — They maximize image jump. The optical center of the segment is far below the top of the segment, giving maximum base-down effect at the top of the segment.

b. False — They have round tops because they are brought to a feather edge on the spherical surface of the spectacle lens. The cylinder is ground on the **opposite** side of the spectacle lens, usually on the **back** side, which creates a "minus cylinder" type of lens.

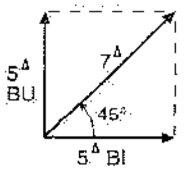
c. True

d. False — Round-top segments create image jump **and** increase image displacement on minus lenses. They are preferred on plus lenses where they decrease image displacement, although they still cause image jump. Image jump is usually better tolerated than image displacement.

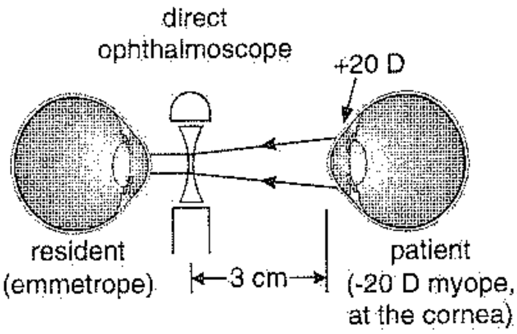
31. (see notes pages 9, 57, 58)

Before the right eye, a 5^Δ base-up prism is needed to correct the relative right hypotropia. For the exotropia, base-in prism will be helpful.

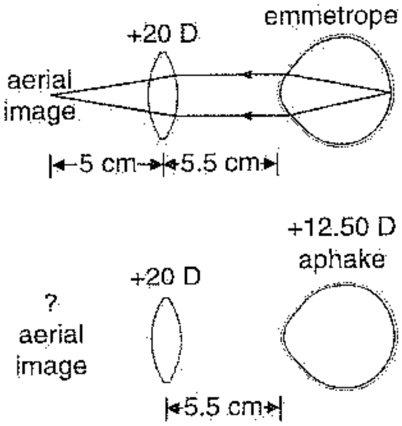
By drawing the vector diagram at the right, and by applying the Pythagorean theorem, it can be seen that the 7^Δ prism with base up and in in the 45 degree meridian will supply 5^Δ of base-in prism. The residual deviation of the patient will be 3^Δ of exodeviation, which can probably be fused.



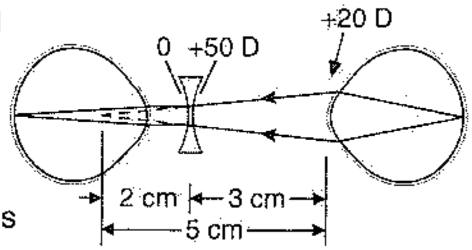
32. An emmetropic ophthalmology resident examines a -20 D myopic eye with a direct ophthalmoscope. If the bundles of light emerging from the patient's eye have a vergence of +20 D, and the ophthalmoscope is 3 cm from the patient's eye, what corrective lens must be dialed into the ophthalmoscope to give the resident a clear view of the patient's retina?



33. A +20 D indirect ophthalmoscope condensing lens is held 5.5 cm from the patient's cornea to achieve proper illumination through the patient's pupil. The aerial image of an emmetrope's retina is imaged 5 cm in front of the condensing lens. Where is the aerial image of a +12.50 D aphake? Assume the refractive error of the aphake is measured with respect to a spectacle plane 10 mm anterior to the cornea.



32. (see notes pages 11, 12, 13, 59, 60)



-50 D. The light emerging from the patient's eye with vergence of +20 D converges toward a point

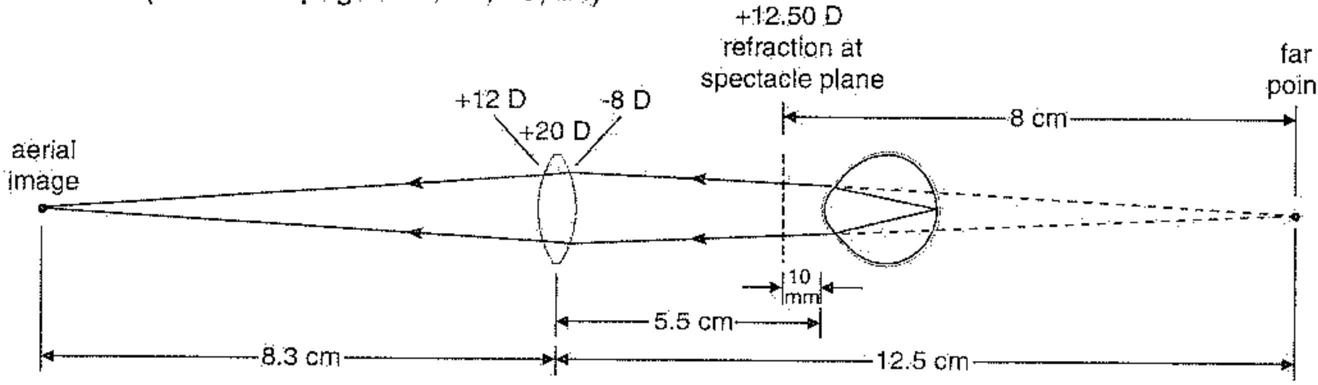
1/20 = 0.05 m = 5 cm

in front of the patient's cornea. By the time this light has traveled 3 cm to the ophthalmoscope, it is only 2 cm from its point of focus, therefore having a vergence of

1/0.02 = +50 D

A -50 D lens is therefore necessary in the opthalmoscope to neutralize this +50 D of vergence and thus provide zero vergence for the emmetropic resident.

33. (see notes pages 11, 12, 13, 24)



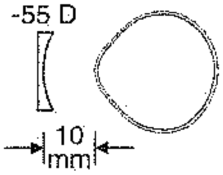
To find the position of the aerial image of the aphake's retina, the vergence of light entering the condensing lens must be known. If the aphakic eye's refraction is +12.50 D 10 mm anterior to the cornea, the far point of the eye is

1/12.50 = 0.08 m = 8 cm

behind the spectacle plane. Light emerges from the aphakic eye as if it came from the far point plane, so by the time the light travels to the condensing lens it has a minus vergence equal to the reciprocal of the distance of the condensing lens from the far point plane. This distance is 12.5 cm, so the vergence entering the condensing lens is -8 D. By the vergence formula U + D = V, the vergence of the light leaving the +20 D condensing lens is +12 D, so the aerial image is formed

1/12 = 0.083 m = 8.3 cm in front of the condensing lens.

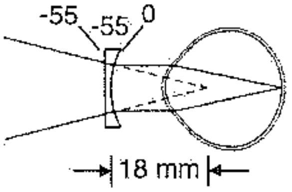
34. A Hruby lens, -55 D, is held 10 mm in front of the cornea of an emmetropic eye. Where is the image of the posterior pole formed by this lens? Is the image inverted or upright? Real or virtual?



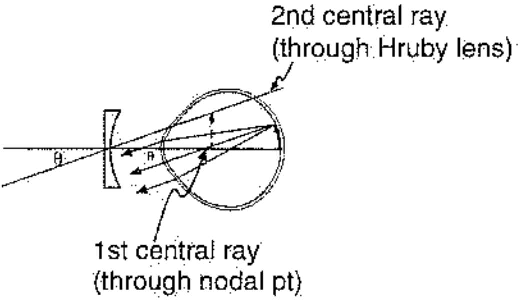
35. A patient wearing a -20.00 D spectacle lens is still 1.00 D myopic. Can the residual myopia be corrected by moving the spectacle lens forward or backward? Which way? How far must the lens be moved?

34. (see notes pages 13, 15, 18)

Light from the retina of the emmetropic eye enters the Hruby lens with a vergence of zero, and leaves with a vergence of -55 D. This places the image of the retina 1/55 = 0.018 m = 18 mm behind the lens, 8 mm behind the front of the cornea. This is where the slit lamp microscope must focus.



To determine whether the image is upright or inverted, two central rays must be drawn. The first is drawn from the tip of an arrow on the retina through the nodal point of the eye. A second central ray must then be drawn through the center of the Hruby lens. The second central ray is parallel to the first because all rays leaving the eye from the tip of the arrow are parallel to each other, for the eye is emmetropic. All such rays make a constant angle Θ with the optical axis. The object for the Hruby lens is therefore at infinity, and all rays from the tip of the arrow, including the second central ray through the optical center of the Hruby lens, come in to the lens at the angle Θ as drawn. The image formed by the Hruby lens is to the right of the lens and must have its tip on the central ray, so it is upright.

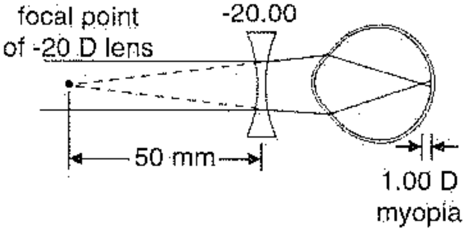


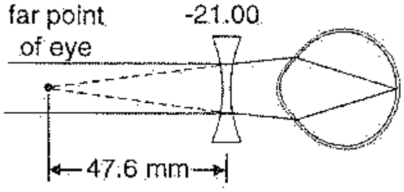
The image is virtual, for it is on the opposite side of the lens from the image rays and must be found by imaginary extensions of the image rays backwards (see top diagram).

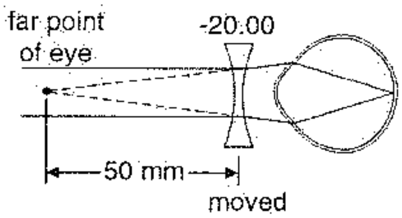
35. (see notes pages 24, 25, 26)

If the patient's total refractive error is 21.00 D of myopia, we know where his/her far point is. It is at the secondary focal point of a -21.00 D lens placed at the same position as the present -20.00 D lens. The focal length of the -21.00 D lens is 1/21 = 0.0476 m = 47.6 mm.

To correct the eye with the -20.00 D lens, its secondary focal point (50 mm in front of the lens) must simply be placed at the far point of the eye, so the -20.00 D lens must be moved **toward** the eye 2.4 mm.







36. K-readings for an eye are:

42.50 @ 80
44.50 @ 170

The best refraction in the spectacle plane with spheres only is -3.00 D. Assuming that this is equal to the spherical equivalent, what is the patient's approximate refractive correction in the spectacle plane, expressed:

a. as a cross diagram

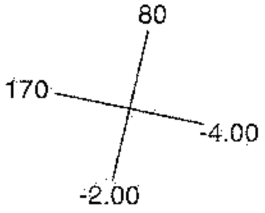
b. in plus cylinder form

c. in minus cylinder form

37. An eye's refraction in the spectacle plane 15 mm from the cornea is -12.50 +2.50 x 90. What is the refraction at the cornea? Note how the cylinder changes as well as the sphere. (Hint: convert each principal meridian separately.)

36. (see notes pages 29, 30, 31, 65, 66, 75, 76)

The difference between the K-readings is 2.00 D, so there is astigmatism at the corneal plane of 2.00 D. In the absence of a large accompanying spherical error, there will be approximately 2.00 D of astigmatism in the spectacle plane as well (see next problem). The cross diagram of the refractive correction must therefore have 2.00 D difference between the two principal meridians, and the **average** of the two principal meridians (the spherical equivalent) must be equal to -3.00 D. Also more minus power must be in the 170 degree meridian than in the 80 degree meridian to neutralize the K-readings. The cross diagram is therefore:

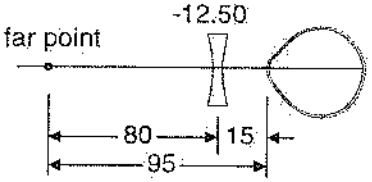


plus cylinder form:
- 4.00 + 2.00 x 170

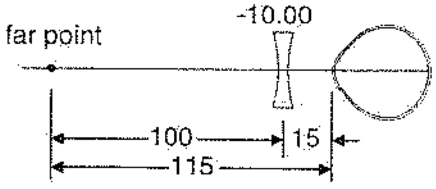
minus cylinder form:
- 2.00 - 2.00 x 80

37. (see notes pages 30, 24, 65, 66)

The two principal meridians of the refractive correction -12.50 + 2.50 x 90 are -12.50 D and -10.00 D. Each of these must be converted from 15 to 0 mm vertex distance.



1 / 0.095 = -10.5 D

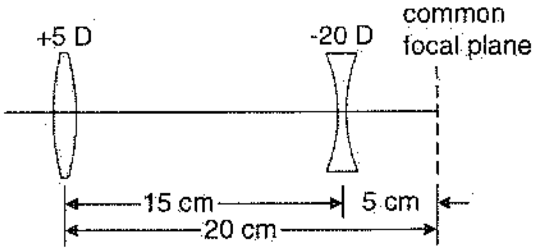


1 / 0.115 = - 8.7 D

The principal meridians of the refractive correction at the cornea must thus be -10.5 D and -8.7 D, indicating 1.8 D of astigmatism. The refraction at the cornea is therefore approximately **-10.50 + 1.75 x 90**. In the presence of high myopia, astigmatism measured in the spectacle plane is significantly greater than when measured at the cornea. The reverse is true with high hyperopia and aphakia; the cylinder in the spectacle plane is less (typically 2/3 to 3/4 of the cylinder indicated by the K-readings at the cornea).

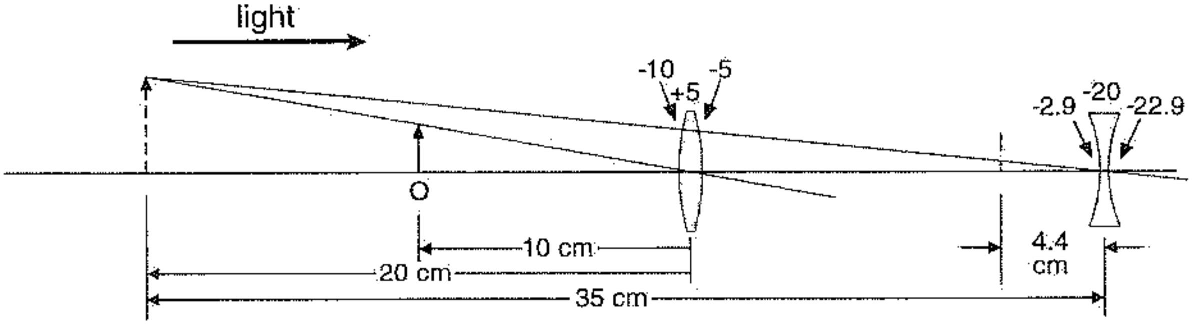
38. Two lenses, +5 D and -20 D, are used to make a Galilean telescope. The angular magnification of the telescope, for distant objects, is equal to the power of the eyepiece divided by the power of the objective (20/5 = 4 X). What about near objects? Where does the telescope form an image of an object 10 cm from the +5 D lens, and what is the transverse magnification?

38. (see notes pages 39, 13, 37)



The focal planes of the two lenses must coincide in a Galilean telescope, so the telescope is formed as follows:

Using the vergence formula $U + D = V$, we can trace the image of an object at 10 cm through the system as follows:



The final image is inside the telescope, 4.4 cm from the -20 D lens, and is a virtual, upright image. To find the overall magnification, the magnification for each lens (image/object distance) is calculated, and the two are multiplied together:

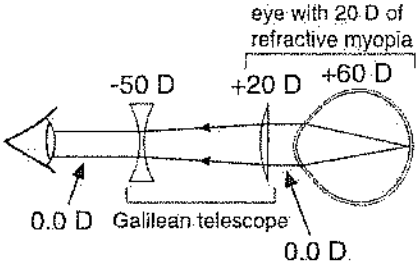
$$\text{Transverse magnification} = (20/10) \times (4.4/35) = 0.25\text{ X}$$

(As it turns out, the transverse magnification for finite object/image distances is the reciprocal of the angular magnification for Galilean telescopes. This apparent inconsistency may be reconciled if one understands that the angular magnification of a system depends on the location of the point of observation. If we calculate the **angular** magnification of the above telescope for the **finite distance** object, with the point of observation being at the **minus lens**, we will obtain:

$$\text{image angle/ object angle} = (0.25\text{ Object} / 4.4) \div (\text{Object}/25)$$
$$= (0.25/4.4) \div (1/25) = \frac{0.25\ (25)}{4.4} = 1.4\text{ X}$$

By repeating this calculation as the object distance goes to infinity, we will find that the angular magnification goes to 4 X. With telescopes only, the **transverse** magnification is constant, independent of object distance. With **most** optical systems, magnification changes between one pair of conjugate planes and another.)

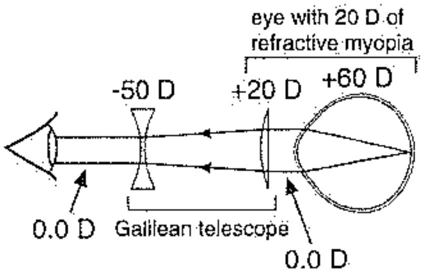
39. An eye's refraction is -20.00 D, measured at the cornea. An emmetropic ophthalmology resident views the posterior pole of the eye with a direct ophthalmoscope held 3 cm from the patient's cornea. This requires a -50 D lens dialed into the ophthalmoscope (see problem 32). What is the magnification with which the resident sees the posterior pole? Assume the eye's refractive error is **refractive** rather than axial.



39. (see notes page 39)

The patient's refractive error is +20.00 D, acting as the objective of a Galilean telescope. The -50 D is the eyepiece. The Galilean telescope's magnification, therefore, is

50/20 = 2.5 X.



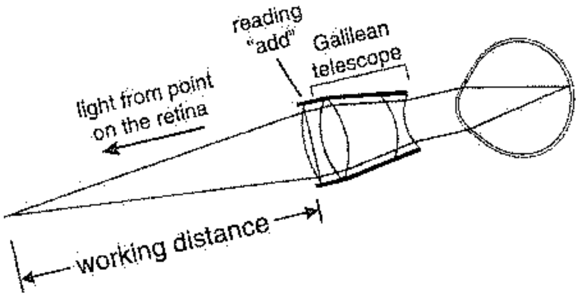
The posterior pole will thus appear 2.5 X larger than if the patient were emmetropic. The magnification afforded by the optics of the patient's eye itself, acting as a simple magnifier, is 60/4 = 15 X. The overall magnification, therefore, is the product of the two magnifications,

2.5 x 15 = 37.5 X.

This means that the retinal details will appear 37.5 times larger than they would appear if the retina were cut out of the eye and held at 25 cm.

(If the eye's refractive error were **axial** rather than refractive, the magnification produced by the Galilean telescope would be the same, but the power of the "emmetropic" component of the eye would only be 60 - 20 = 40 D, yielding a "simple magnifier" magnification of only 40/4 = 10X. In this case the overall magnification would be 2.5 x 10 = 25 X.)

40. A surgical loupe may be thought of as a Galilean telescope in combination with a reading add, with the focal length of the reading add being the working distance of the loupe. The working distance may be lengthened by using a lower power add (with a longer focal length). If, instead, a minus lens is added to the **rear** of the loupe, will the working distance be lengthened or shortened?

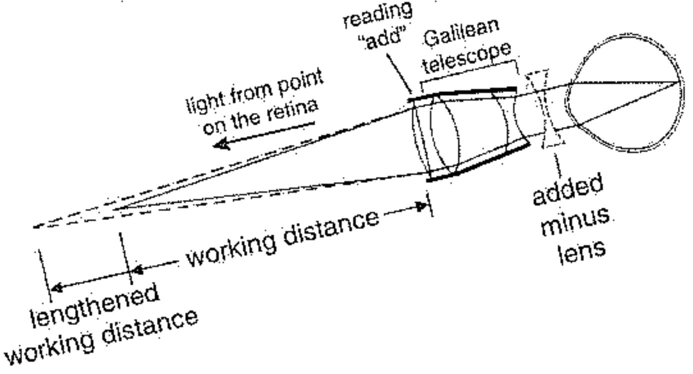


41. A presbyope has a range of accommodation from 4 m to 1 m and goes without distance glasses. What power reading glasses are necessary to allow clear and comfortable vision at 40 cm, leaving half the accommodative amplitude in reserve?

42. The eyepieces of indirect ophthalmoscopes have plus lenses, +2 to +2.5 D depending on the make of the instrument. Why are these lenses necessary for young ophthalmology residents? Can they not accommodate this amount to see the aerial image as they ordinarily do to view near objects?

40. (see notes page 50)

Lengthened as well. Turn the light around and think of it traveling from the surgeon's eye to his or her far point. Minus power added **anywhere** in the optical system causes downstream images to slide with the light. The far point, which represents the image of the surgeon's retina, will therefore move away from the loupe, lengthening the working distance. Plus lenses pull images against the light; minus lenses let them slide with the light.

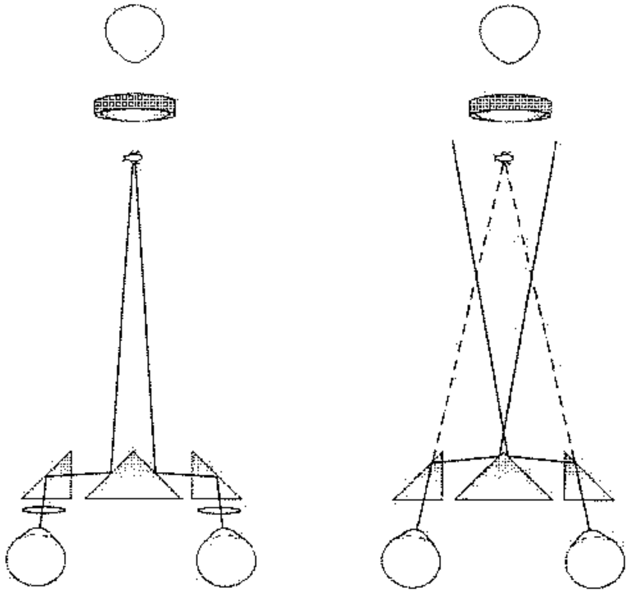


41. (see notes page 27)

The **amplitude** of accommodation is 0.75 D in accommodating from 4 m (0.25 D in from infinity) to 1 m (1 D in from infinity). Half of the patient's accommodative amplitude is therefore 0.37 D. To see clearly at 40 cm, a total of 2.50 D of plus power is necessary. The patient is already 0.25 D myopic, and can comfortably supply 0.37 D of accommodation. The plus power to be supplied by the reading glasses will therefore be 2.50 - 0.25 - 0.37 = 1.87 D.

42. (see notes page 2)

Young indirect ophthalmoscopists can certainly accommodate the 2 to 2.5 diopters, but **convergence** accompanies accommodation. Because the PD has been reduced by reflecting prisms in the ophthalmoscope to approximately 15 mm, even a small amount of convergence will produce esotropia and diplopia. The reflecting prisms in the indirect ophthalmoscope, therefore, effectively give the examiner accommodative esotropia, which is "treated" by plus lenses in the eyepieces.



43. An eye has K-readings of 44.50 @ 90 and 46.50 @180. A rigid contact lens of -2.00 D is fit to the eye 0.75 D steeper than low K. Overrefraction yields +1.00 + 1.00 x 90. Assuming that the contact lens is not warped and corrects all of the corneal astigmatism, what is the spectacle refraction, in plus cylinder form, when the contact lens is not worn?

44. For contact lens base curves in the range of 41 to 46 D, what is the relationship between diopters of refractive power and millimeters of radius curvature? That is, how many diopters correspond to each mm or 0.05 mm of radius of curvature? Use the standardized keratometric refractive index of 1.3375.

45. An IOL formula calls for a +18.00 D IOL for emmetropia. To achieve a refraction of -2.00 D myopia, approximately what power IOL should be implanted?

43. (see notes pages 34, 67, 68)

Vertex distance changes can be disregarded at these low powers of spectacle/contact lens corrections. The astigmatic overcorrection indicates the presence of lenticular astigmatism "uncovered" by the contact lens correction of the corneal astigmatism. The corneal cylinder (the difference between the K-reading) is 2.00 D, corrected by a tear lens of –2.00 cyl x 90 when the contact lens is in place. A +0.75 D sphere tear lens is also present, because the contact lens was fit 0.75 D steeper than low K. The power of the contact lens itself is –2.00 D. Adding these various powers to the overrefraction yields:

+ 1.00 + 1.00 x 90	overrefraction
– 2.00 x 90	cylindrical tear lens
+ 0.75	spherical tear lens
– 2.00	contact lens
– 0.25 – 1.00 x 90	
or	
– 1.25 + 1.00 x 180	

44. (see notes page 14)

Diopters of surface power are related to **meters** of radius of curvature by the relationship $D_s = | n - n' | / r$. Using the keratometric index of refraction of 1.3375, we can solve for the radius of curvature in meters for a given surface power: $r = 0.3375/D_s$. For $D_s = 41$ and 46 D respectively, r = 8.23 and 7.34 mm. Over this 5 D range, therefore, radius changes by 8.23 - 7.34 = 0.89 mm, with power going up as radius goes down. The number of diopters per mm = 5/0.89 = 5.62 D/mm. The number of diopters per 0.05 mm = 5.62 x 0.05 = 0.28 D, or about a quarter diopter per 0.05 mm change in radius.

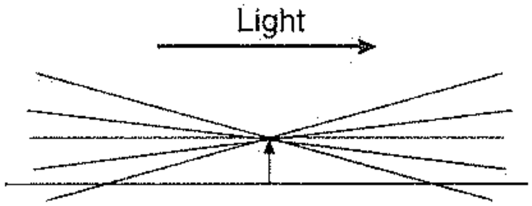
45. (see notes page 35, 36)

As an approximation, for IOL's in the +18.00 D range, is to change the calculated IOL power for emmetropia by 1.25 to 1.50 D for each diopter of desired ametropia. To achieve -2.00 D of myopia, +2.50 to +3.00 D of power should be added, for a resultant IOL of +20.50 or +21.00 D.

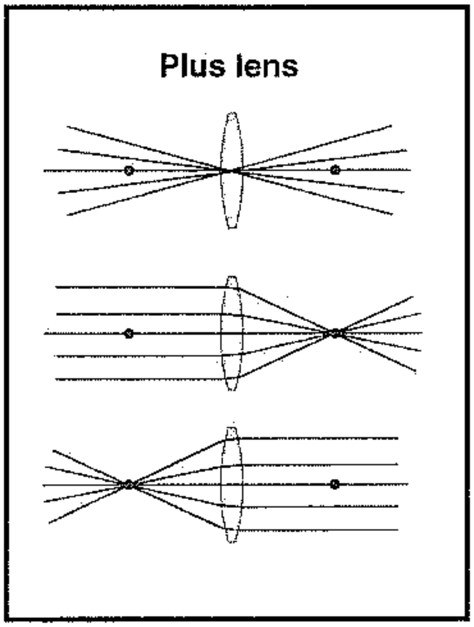
Ray Tracing

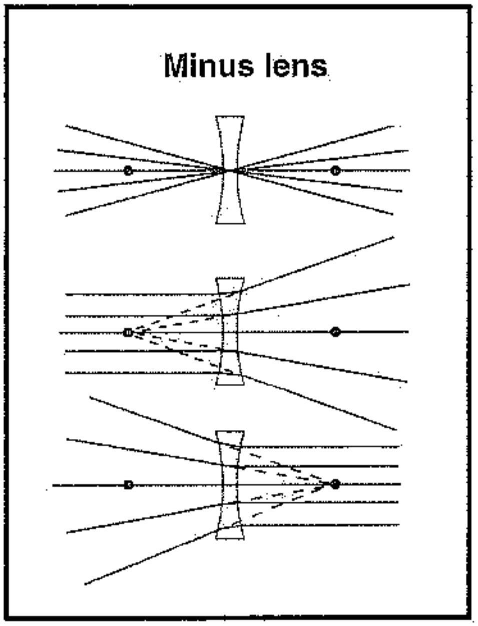
Ideal thin lenses and ideal mirrors
"First order" optics

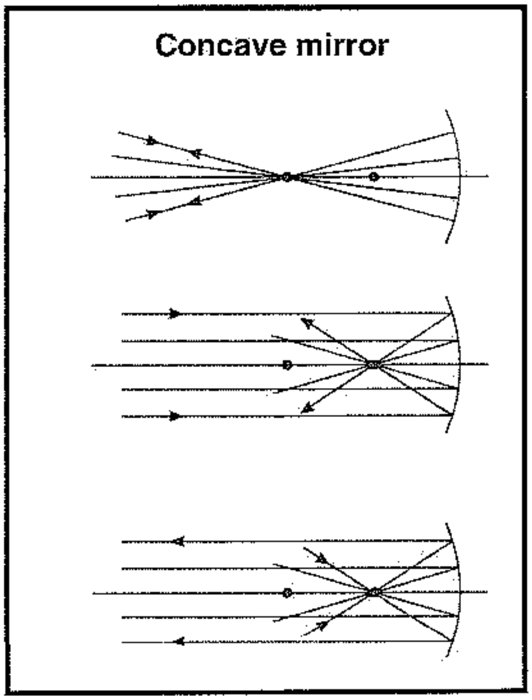
Available rays:

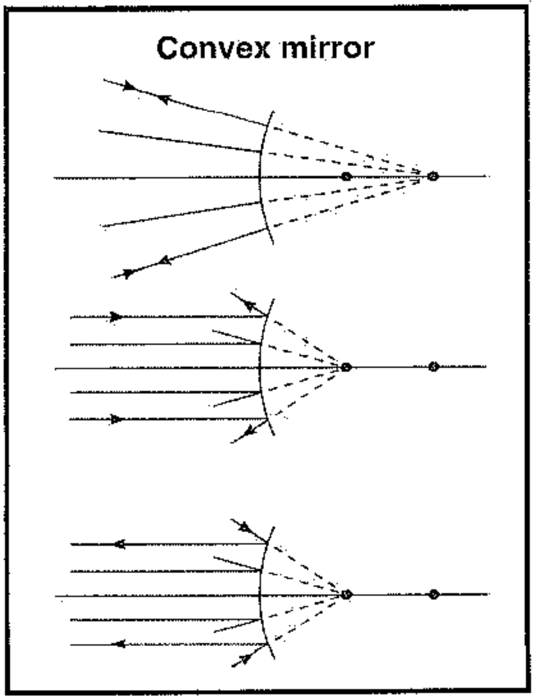


Available paths:


Plus lens

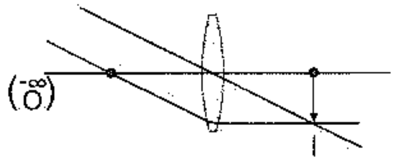

Minus lens

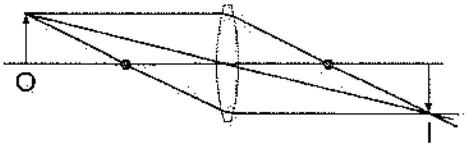

Concave mirror

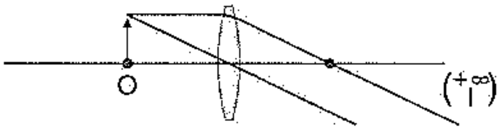

Convex mirror

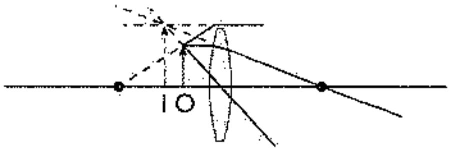
Ray Tracing, cont.

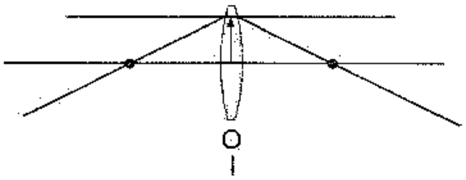
Plus lens

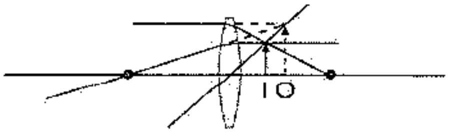


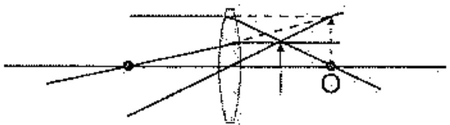


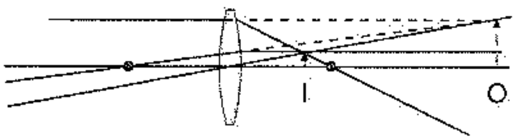


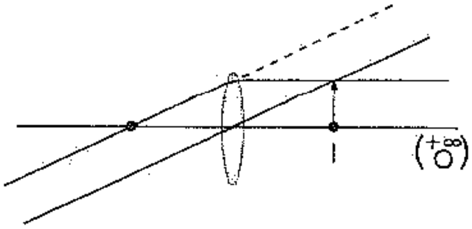




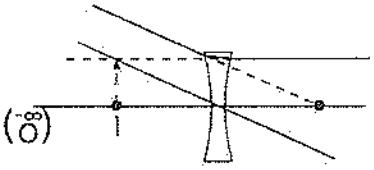


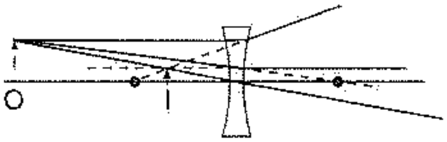


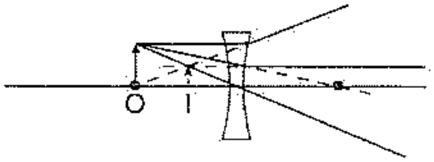


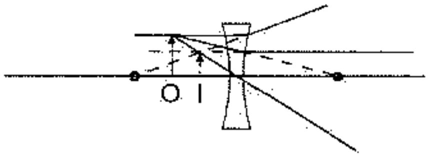


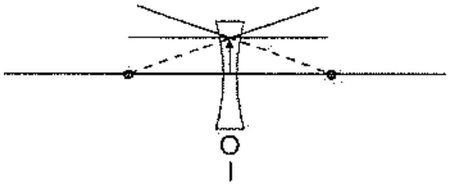
Minus lens

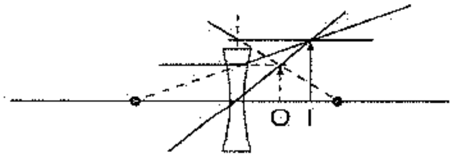


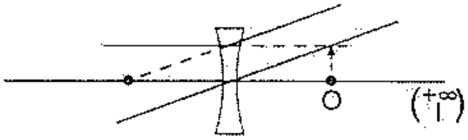


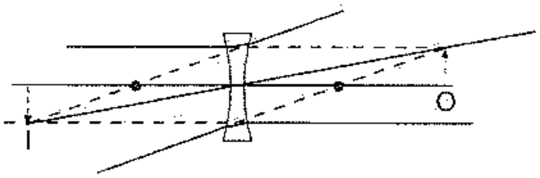


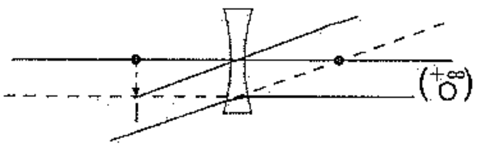












Ophthalmic Instruments: Optical Principles

Trial lenses

"Additivity" — combined lenses should add correctly. Curves, thicknesses, and spacings are chosen to optimize additivity.
  Trial frames (numbers face forward):
    Sphere - rear cell
    Cylinder - middle cell
    Low power lenses - front cell

"Corrected curves" — refers to choice of front and back curves to minimize astigmatism of oblique incidence
- **Not** usually a feature of trial lenses
- Results in meniscus form for spectacle lenses.

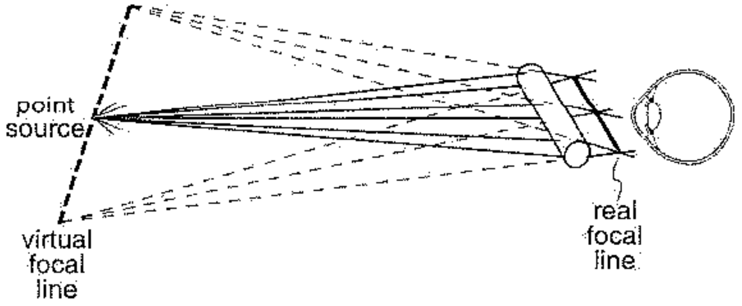
Additivity error — More significant with high-power corrections

Also present in phoropters, where up to 4 lenses must add together.

Some Japanese-made trial lenses are meniscus lenses, designed for additivity as well as having corrected curves.

Walking-around trial with trial frames does **not** simulate glasses fully because of aperture and magnification differences.

Maddox rod

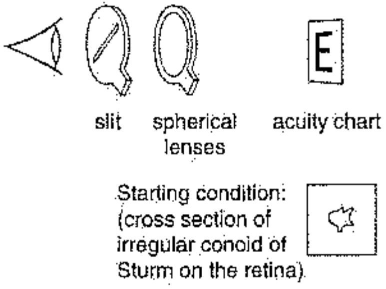


Light from a point source is focused by the high-power cylindrical rod into a real focal line so close to the eye that the eye cannot focus on it. What the eye **does** see is the other focal line of the conoid of Sturm, a virtual focal line passing exactly through the position of the original point source. The Maddox rod (single rod or multiple side-by-side rods) thus converts the point of light viewed through the rod into a line of light, with the line exactly perpendicular to the axis of the Maddox rod.

Alternatively, the line of light seen through the Maddox rod can be thought of as the point of light grossly defocused in only one direction by the high-power cylindrical Maddox rod, in the direction perpendicular to the axis of the rod.

Stenopeic slit

An elongated pinhole aperture sometimes useful for initial refraction of eyes with irregular astigmatism.

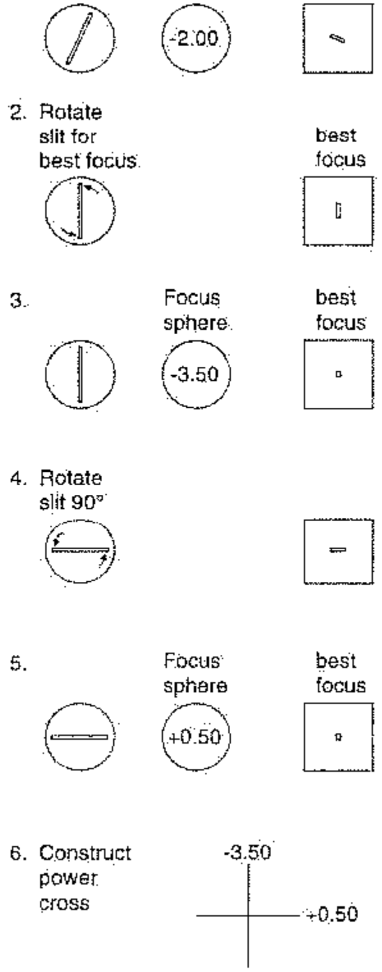


Starting condition: (cross section of irregular conoid of Sturm on the retina)

Minimizes refractive blur in one meridian (perpendicular to the slit), so that refractive error in the meridian of the slit can be neutralized with spherical lenses.

Use **visual acuity chart** for all judgements of best focus.

Refracting Steps:



1. Apply slit at arbitrary meridian — Focus sphere — best focus
2. Rotate slit for best focus — best focus
3. Focus sphere — best focus
4. Rotate slit 90°
5. Focus sphere — best focus
6. Construct power cross
7. Attempt refinement with cross cylinder

Refractive Findings:

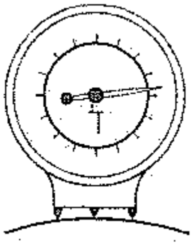
First principal meridian:
-3.50 @ 90
(*or* -3.50 x 180)

Second principal meridian:
+0.50 @ 180
(*or* +0.50 x 90)

Combined refraction:
-3.50 +4.00 x 90
(*or* +0.50 -4.00 x 180)

Lens clock

Geneva Lens Measure determines curvature, but dial reads in diopters of surface power. Conversion from curvature to surface power uses n = 1.523, the refractive index of crown glass.



Plastic lenses require special lens clocks with non-scratching pins and calibration using the refractive index of that material (n=1.49 for CR39 plastic lenses).

The primary clinical use of lens clocks is the detection of plus cylinder spectacle lenses (cylinder ground on the front surface) in the original glasses of a dissatisfied refraction patient.

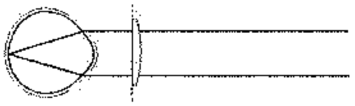
Lensmeter

Used to measure the power of spectacle or contact lenses.

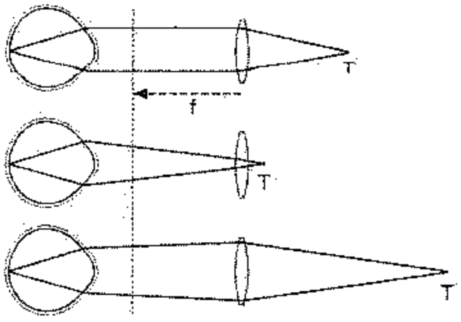
"Lensmeter" is the generic term; "Lensometer" is a trade name.

Based on the **optometer principle** (shown at right), with the addition of a telescope for precise detection of parallel rays at neutralization.

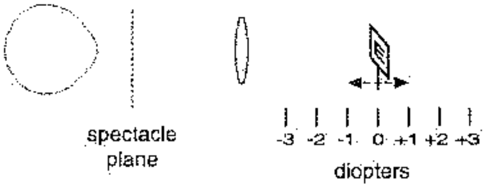
Trial lens



Optometer principle

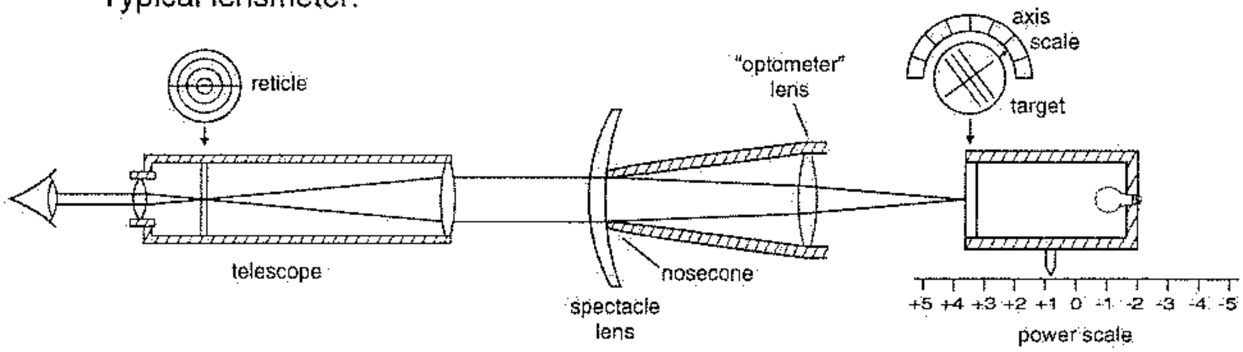


Optometer



Lensmeter, cont.

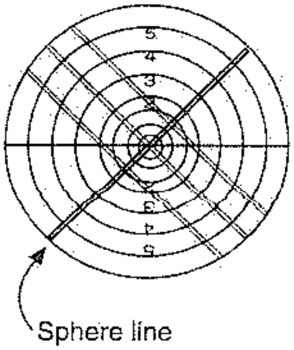
Typical lensmeter:



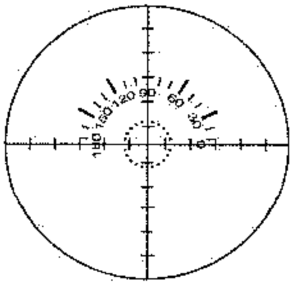
Vergence is varied at the tip of the nosecone, by longitudinal movement of the target assembly, until the target becomes focused on the reticle of the telescope. This focus only occurs when zero vergence enters the telescope, indicating that the spectacle lens has exactly neutralized the vergence emerging from the nosecone. The power of the lens is then read from the power scale, which indicates the negative of the vergence emerging from the nosecone.

Telescope prevents examiner's refractive error from causing significant error in measurement. For best accuracy, adjust eyepiece by setting power on zero and rotating eyepiece out to fog yourself. Then rotate **in just** until best focus.

American cross target



European dot target



Distance measurement:

Back vertex power (temples away from you).

Add measurement:

Front vertex power (temples toward you, measuring **difference** between top and bottom segments). (Makes significant difference with high plus lenses.)

Prism measurement:

Displacement of target pattern indicates direction of prism base.

If displacement goes off scale, add neutralizing prism **anywhere** between spectacle lens and telescope.

New lensmeters:

Projection models - project target pattern onto a large screen.

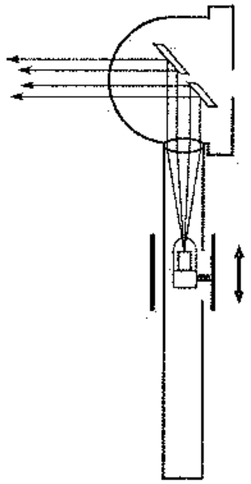
Electronic readout models.

Automatic models - do not neutralize; measure **deflection** of light rays.

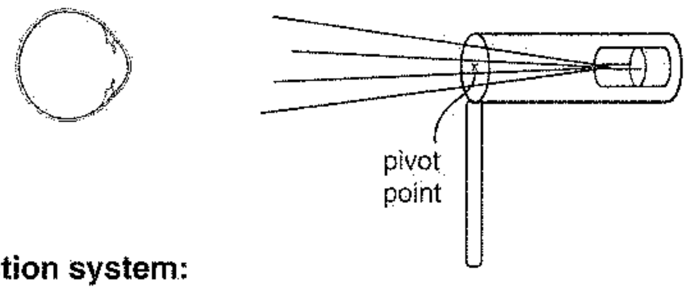
Retinoscope

Objective measurement of refractive errors.
Detects when far point has been moved to the peephole.

Cross section

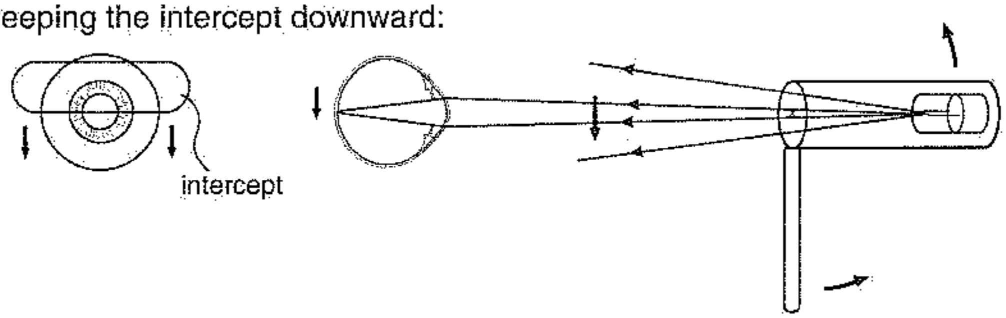


Illumination system, plano mirror effect (sleeve up):



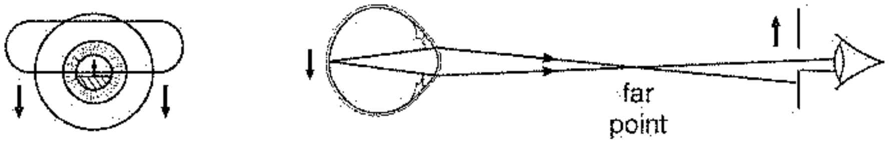
Detection system:

Sweeping the intercept downward:

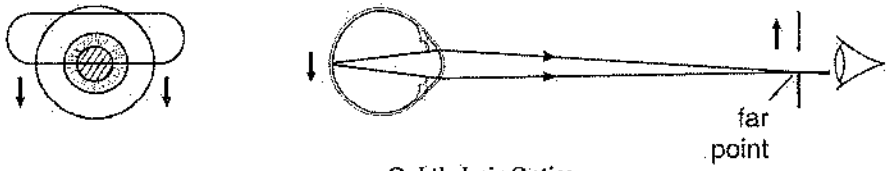


"With" movement (far point is beyond peephole; light entering the examiner's eye comes from top of patient's pupil):

"Against" movement (far point is in front of peephole; light entering the examiner's eye comes from bottom of patient's pupil):



Neutralization (far point is at peephole; light entering examiner's eye comes from patient's entire pupil at once):



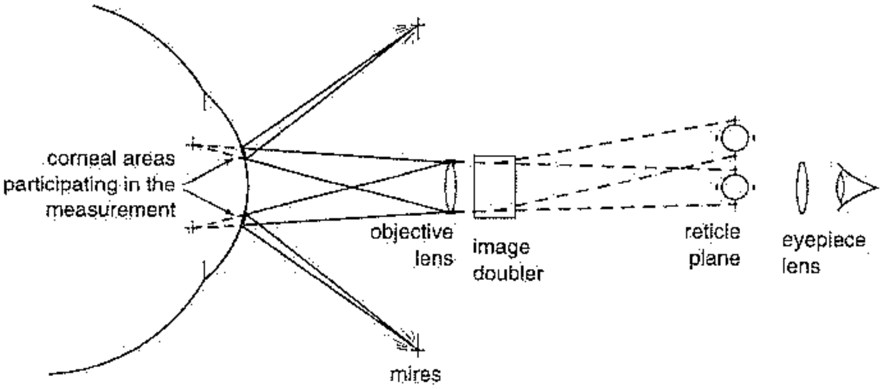
Keratometer

Determines corneal curvature by measuring the size of a reflected "mire".

Doubling of image avoids problems from eye movements.

Radius scale is exact. Diopter scale is derived from the radius scale using the formula for surface power D = (n - 1) / r, where n = 1.3375, an empirically derived "standardized" refractive index for the cornea.

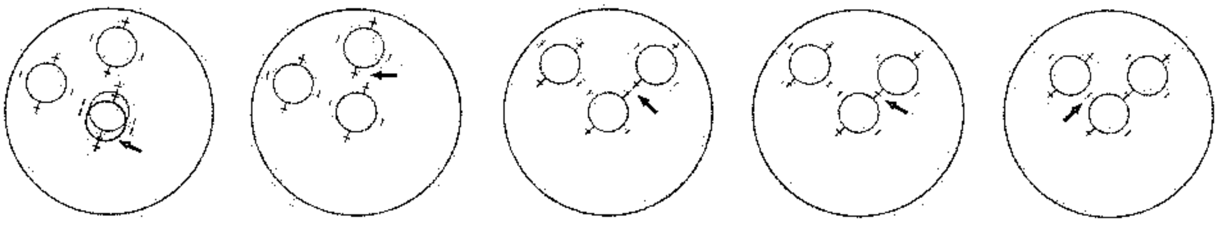
Keratometers "look" only at an annulus of the cornea about 3 mm in diameter.



Bausch & Lomb keratometer

(Constant mire size, variable image doubling)

View of mires of Bausch & Lomb-type keratometer



Before to-and-fro adjustment; doubling of central image.

Non-aligned with a principal meridian; plus marks are skewed.

Rotated to become aligned with a principal meridian; plus marks are in line with each other.

Doubling adjusted optically for coincidence of plus marks, thus measuring curvature in one principal meridian.

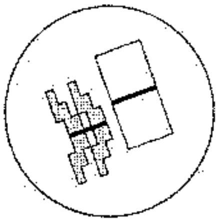
Doubling adjusted optically for meridian 90° away, thus measuring curvature in other principal meridian.

Keratometer, cont.

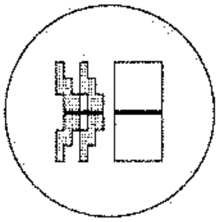
Javal-Schiötz ophthalmometer

(Variable mire separation, constant image doubling)

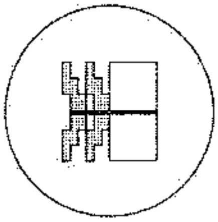
View of mires of Javal-Schiötz ophthalmometer (Haag-Streit)



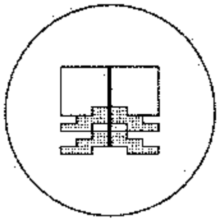
Non-aligned with a principal meridian; central line is skewed.



Rotated to become aligned with a principal meridian.



Mires physically moved closer until images touch, thus measuring curvature in one principal meridian.



Mires rotated 90°; amount of overlap yields amount of astigmatism (each step equals 1 diopter).

Automatic keratometers

Use principles similar to those used in automatic lensmeters, measuring amount of deflection of reflected rays.

Surgical keratometers

Attach to operating microscopes.

Several variations, including simply a ring of lights.

Terry™ keratometer has constant object size, constant two-meridian doubling, and achieves variable image size using the zoom magnification of the microscope.

Amblyoscope (synoptophore, troposcope)

Separate target for each eye, a type of haploscope.

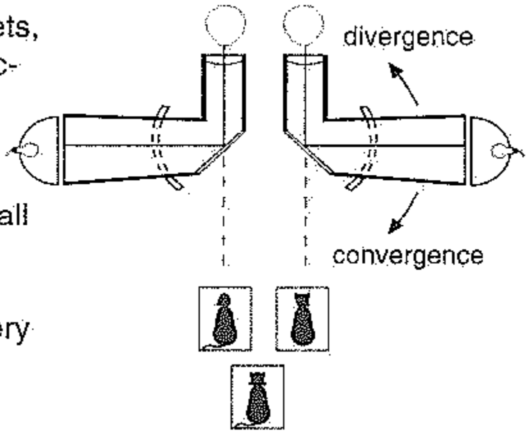
Horizontal, vertical, and torsional adjustments.

Measurements:

Objective angle — Any two targets, alternate flashing, adjust to no objective movement, like alternate prism and cover test.

Subjective angle — Large **dissimilar** targets, simultaneously viewed, adjust to subjective superimposition.

Fusional vergence amplitudes — Large **fusable** targets with both large and small distinguishing features, simultaneously viewed. Diverge from subjective angle until lose fusion; note break and recovery points. Do same with convergence.



Subjective angle = objective angle:
normal retinal correspondence (NRC)

Subjective angle = zero, in tropic patient:
anomalous retinal correspondence (ARC)
(harmonious)

Subjective angle between zero and objective angle:
anomalous retinal correspondence (ARC)
(non-harmonious)

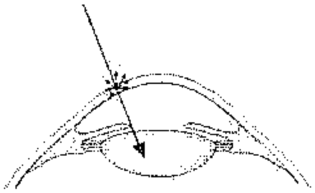
Slit lamp

Illumination system:
  Illuminated slit is imaged precisely over the common pivot point of the illumination and viewing arms.

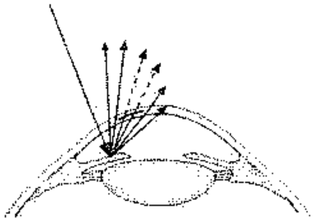
Viewing system:
  Binocular stereo microscope.
  Eyepieces are individually focusable.
  Use central pivot focusing stick.

Magnification change:
  Alternative eyepieces
  Alternative objectives
  Galilean magnification changer
  Zoom system

Examination techniques

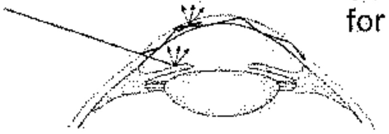


A. Direct illumination

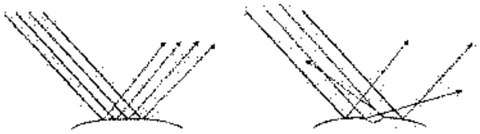


B. Retroillumination

(Decenter beam for B and C)



C. Sclerotic scatter

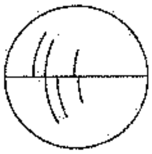


D. Specular reflection

Pachymeter

Used to measure corneal thickness or
  A.C. depth.

Types:
  - Optical
    Attachment to slit lamp
    Image doubling

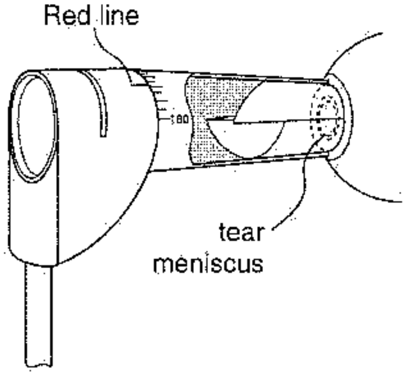


  - Ultrasonic

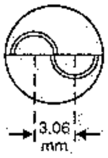
Applanation Tonometer

Split-field plastic prism separates two half fields by 3.06 mm.

Increasing force against eye expands the fluorescein-filled tear meniscus, until inner edges of semicircular bands are aligned.



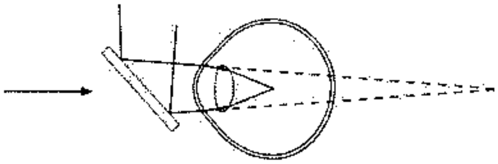
Applanated area is 3.06 mm in diameter, where force in **dynes** x 10 = intraocular pressure in mm Hg.

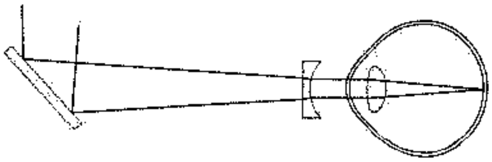


If significant astigmatism is present, applanated area will be an ellipse. To compensate, rotate prism to align **minus** cylinder axis with red line, and proceed.

Fundus lenses

Without special lens, slit lamp can only view half of the way back from the crystalline lens to the retina.

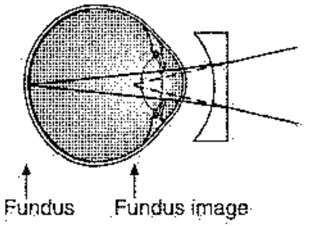




Fundus lenses, cont.

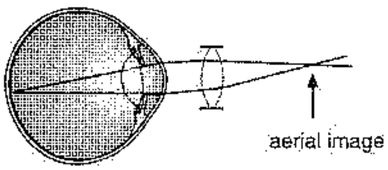
Hruby lens

-55 D, upright image



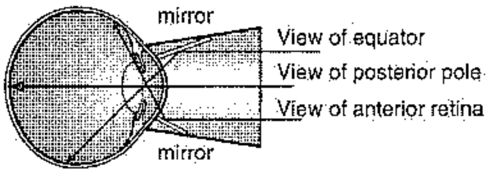
Volk 90 D lens

indirect ophthalmoscopy, inverted image



Goldmann contact lens

-64 D, upright image; 1 or 3 mirrors give reversed images of anterior chamber angle and fundus periphery

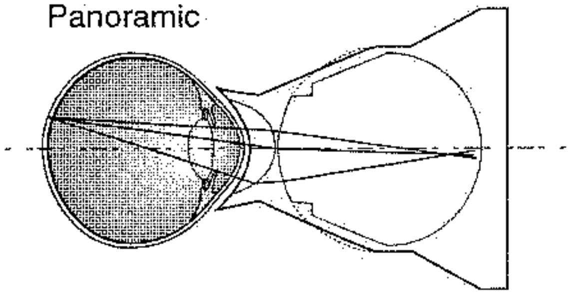


Panfundoscope

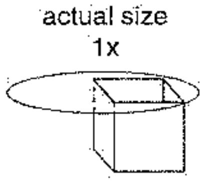
High plus lenses

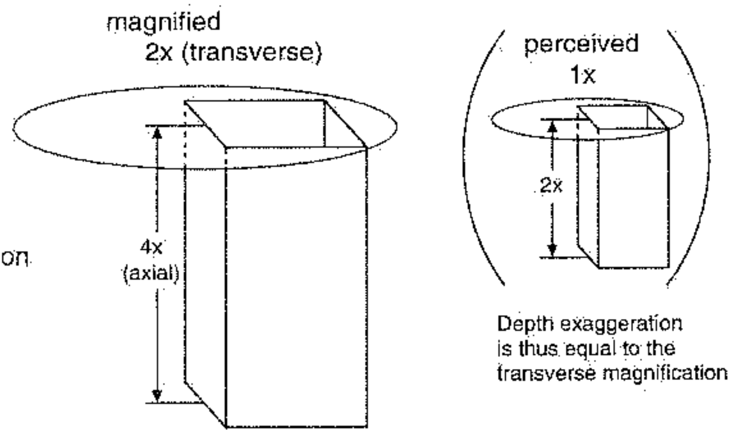
Inverted image

Panoramic



Depth exaggeration when using fundus lenses





Depth exaggeration is thus equal to the transverse magnification

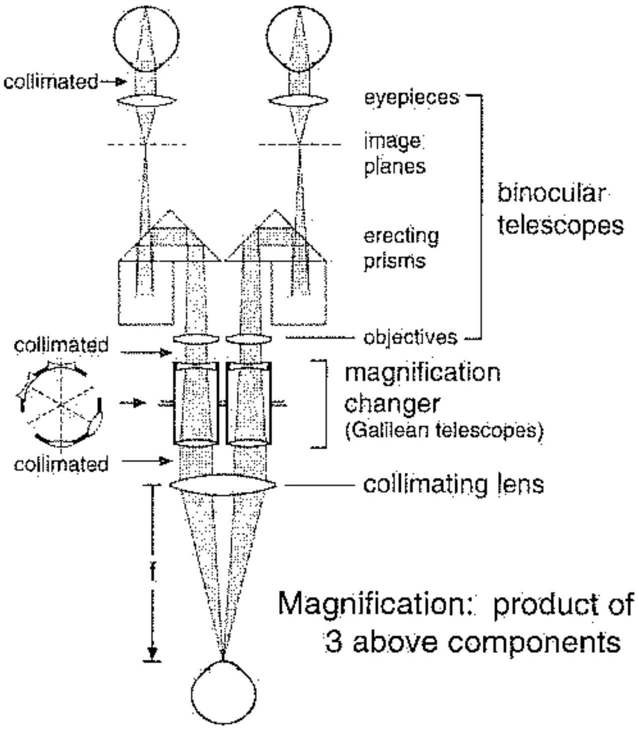
Relative depth exaggeration

Hruby	1.02
Goldmann	0.93
Volk 90	0.66
Panfundoscope	0.70

Operating microscope

Components:

Binoculars — magnify and reduce PD
Magnification changer — Galilean or zoom
Collimating lens — focal length determines working distance



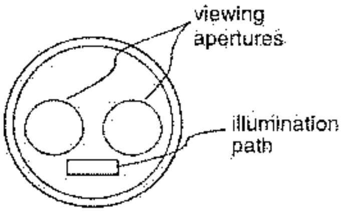
Magnification: product of 3 above components

To achieve parfocality:

1. Focus up-and-down under highest magnification.
2. Change to low magnification and focus eyepieces from fogged direction (screw out, then in to focus).

"Coaxial" illumination:

Illumination and viewing paths all pass through collimating lens, but separated.



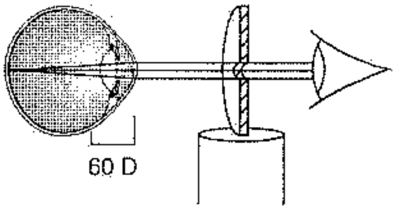
Collimating lens from below

Direct ophthalmoscope

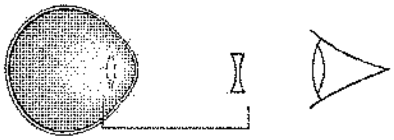
Magnification:

Examiner uses the optics of the patient's eye as a simple magnifier

$$\text{Mag} = \frac{60\text{ D}}{4} = 15\text{ X}$$

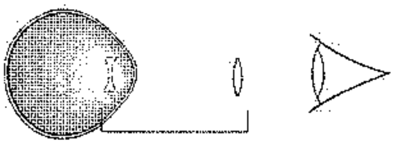


In myopic patient:



Galilean telescope:
extra magnification

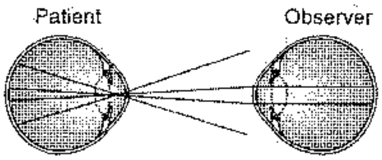
In hyperopic patient:



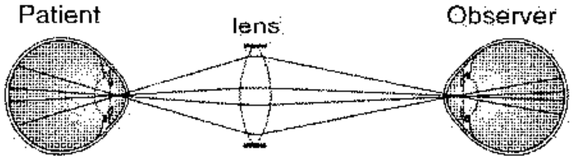
Reverse Galilean telescope
minification

Field of view:

direct scope ≈ 7° field of view
(peripheral rays are lost)



indirect scope ≈ 25° field of view
(condensing lens captures peripheral rays)



Focusing reticles on the retina:

For ametropes, requires **projection** system in illumination pathway.

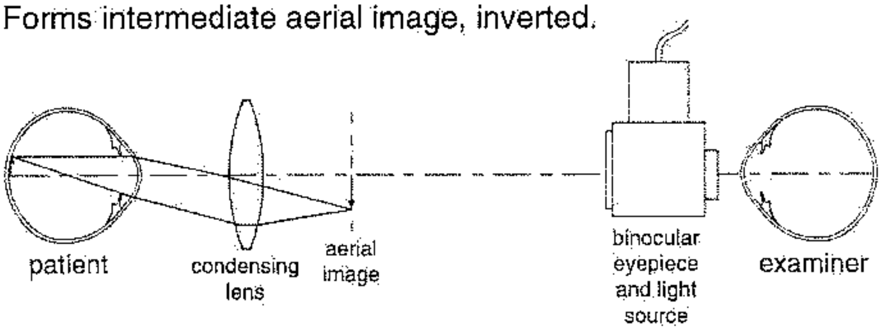
Available in:

Oculus Visuskop
Keeler Projectoscope
Propper Autofoc

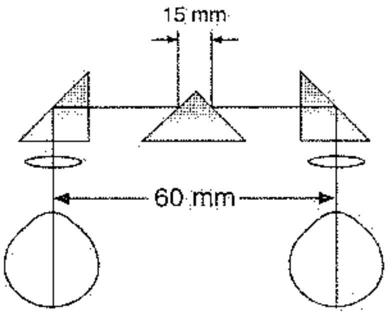
With ordinary ophthalmoscope, interpose correcting trial lens between ophthalmoscope and patient's eye to render the patient roughly emmetropic. Works well.

Binocular indirect ophthalmoscope

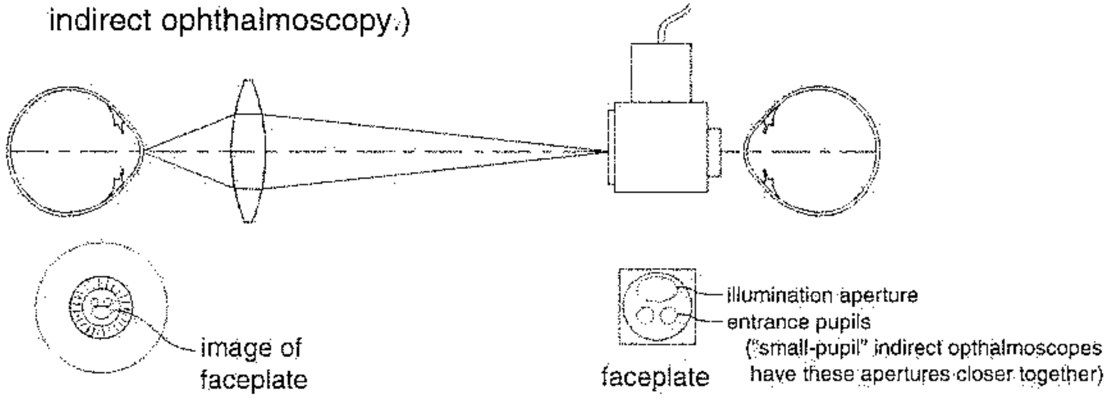
Forms intermediate aerial image, inverted.



Binocular eyepiece reduces PD to about 15 mm. Stereopsis would thus be reduced 4-fold if the axial magnification of the aerial image did not compensate for this.



Formation of images of examiner's pupils at the patient's cornea, centered in the patient's pupil. Critical to avoid corneal reflection (Gullstrand principle of reflex-free indirect ophthalmoscopy.)



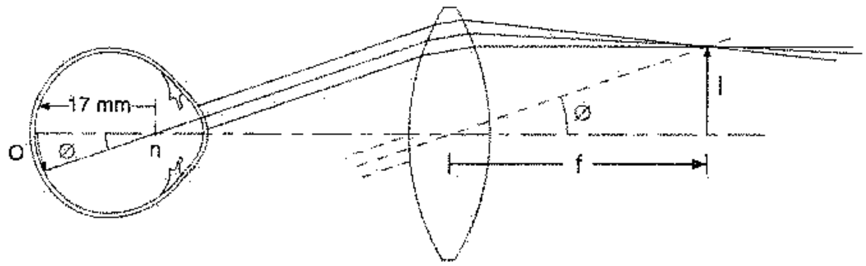
Binocular indirect ophthalmoscope, cont.

Magnification of the aerial image:

For emmetropic eye, by similar triangles, magnification equals:

$$\frac{\text{focal length of the lens}}{\text{nodal point to retina distance}} = \frac{\text{focal length of the lens}}{\text{focal length of the eye (in air)}}$$

$$= \frac{\text{power of eye}}{\text{power of lens}}$$



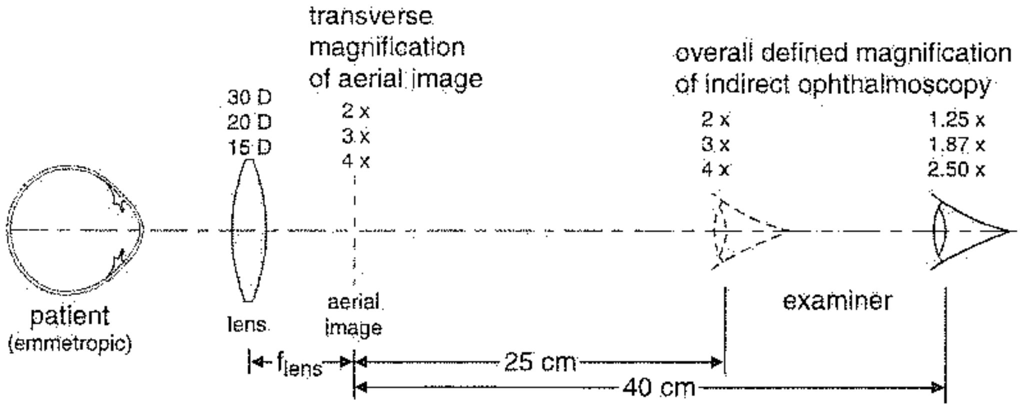
Axial mag = $(\text{transverse mag})^2$

With 20 D lens:

$$\text{transverse mag} = \frac{60}{20} = 3\text{ X}$$

$$\text{axial mag} = (3)^2 = 9\text{ X}$$

But eyepieces reduce depth by 4-fold, so axial mag only **appears** 9/4 = 2.25 X.



Halogen bulb

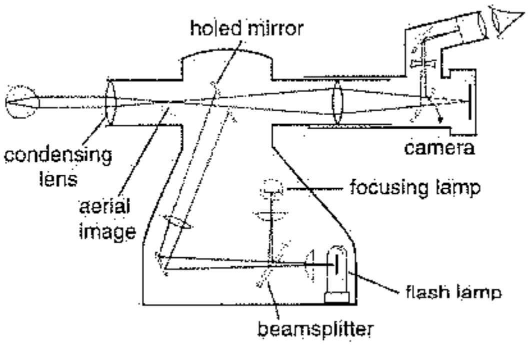
Intense brightness and whiteness.

Halogen gas combines with evaporated tungsten and returns it to the filament, keeping the envelope clean and prolonging filament life.

Fundus camera

Uses principle of indirect ophthalmoscopy.

Holed mirror corresponds to face of indirect scope, conjugate to patient's pupil.



Aerial image is re-imaged onto camera film, similar to image formed on examiner's retina with indirect ophthalmoscope.

Standard field of view is 30°.

Wide-angle cameras up to 60° are available, with up to 148° view being possible with contact type of objective lenses.

Physical Optics

Introduction: Beyond Vergence Calculations

Light is that portion of the electromagnetic spectrum which stimulates the human eye, producing visual sensations. Our definition of light is intimately connected with our perceptions of the world through our visual system. The **Early Greeks** (500 B.C.) recognized the sensory nature of light, but in the form of a **Tactile Theory**. They believed that the eye sends out invisible probes to sense what we see. This theory, abandoned around 1000 A.D., was replaced by an **Emission Theory**, in which bright objects give off light. The Greeks' egocentric model of vision did not prevent them from investigating angles of incidence and refraction, the magnifying properties of a glass globe, and the construction of burning glasses.

The Dark Ages introduced a long hiatus in the understanding of optics. A resurgence occurred in 1621, however, by Snell's formulation of the **Law of Refraction** (Figure 1). Two theories of the nature of light then evolved: the **Corpuscular Theory**, of Isaac Newton, which served to explain many aspects of reflection and the nature of color; and the **Wave Theory,** largely developed by Huygens, which could account for many aspects of the behavior of light as it passes from one material to the next (Figure 2). James Clerk Maxwell, in the 19th century, greatly extended the power of the Wave Theory of light by explaining how a moving charge produced an electromagnetic disturbance in the form of propagated waves (Figure 3).

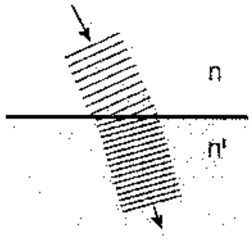


Figure 1
Refraction of light

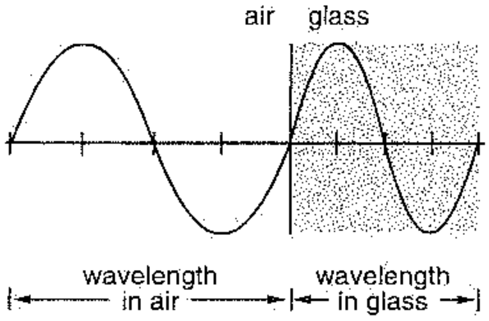


Figure 2
Light wave crossing an interface

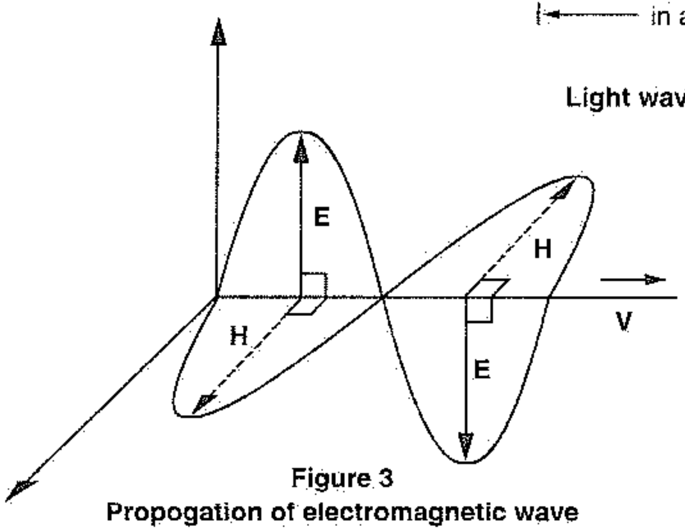


Figure 3
Propogation of electromagnetic wave

Physical Optics: Quantum Theory

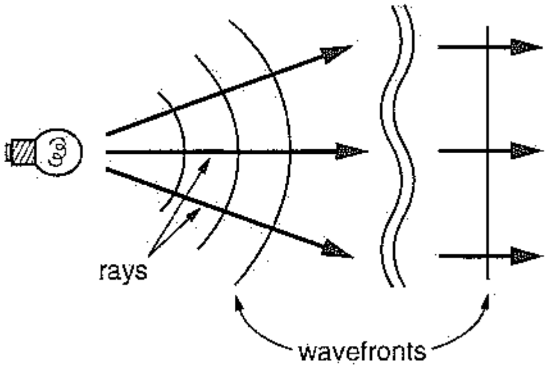


Figure 4
Light rays and wavefronts

Geometric optics deals with the behavior of light rays (Figure 4), an artificial but powerful construct that can be used when the size of the optical element (be it lens or mirror) is large with respect to the wavelength of the electromagnetic wave. As the scale becomes smaller and smaller, the geometric interactions between electromagnetic radiation (light) and matter (atoms and electrons) begin to break down. As the scale becomes still smaller, Quantum Theory is employed to explain the interactions between matter and energy. **Quantum Theory** states that all interchanges of energy and mass occur through the exchange of quanta (small packets of energy).

Quantum mechanics relates the wave properties of light (frequency, wavelength, velocity) with the photon properties of light (energy content). What we call color (a visual perception) is directly related to the frequency of oscillation of the electromagnetic field (Table 1). "Sodium yellow" light has a frequency of 5×10^{14} (almost a billion trillion) cycles per second, with a corresponding wavelength in vacuum of 589 nanometers.

Table 1

Approximate Color Associations

Color	Wavelength, nm (in vacuum)
(Infrared)	>700
Red	620
Orange	610
Yellow	580
Green	540
Blue	480
Violet	450
(Ultraviolet)	<400

Physical Optics: Quantum Theory, continued

As the frequency increases, the electromagnetic radiation changes its color toward blue, and the energy of this radiation increases in direct proportion to the increase in frequency. Blue light has more energy than red light, as well as a shorter wavelength (Figure 5).

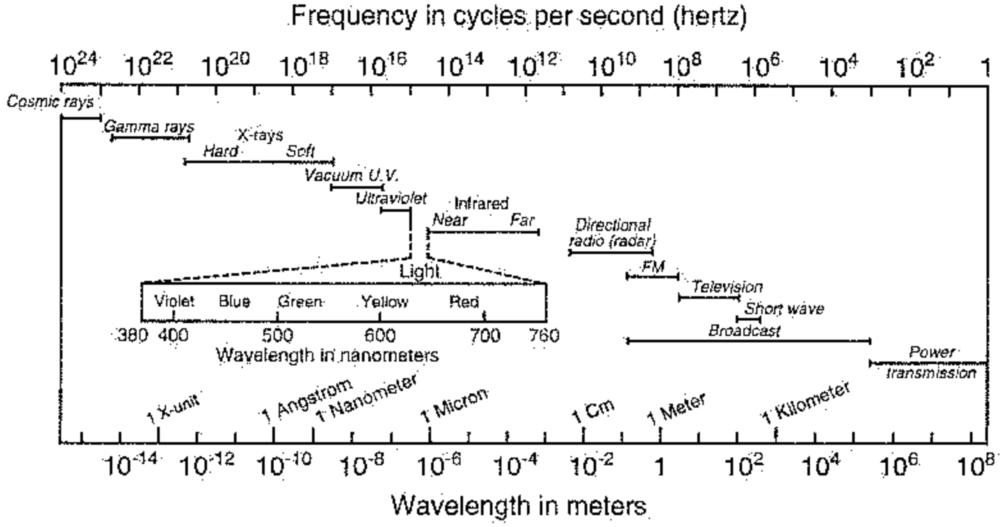


Figure 5
Electromagnetic radiation spectrum
(adapted from the IES Lighting Handbook, ed 4, New York, 1966, with permission from the Illuminating Engineering Society of North America)

Absorbance, Transmittance, Reflectance

Light that passes through a transparent medium may be partially absorbed by that medium. The fraction of light that is absorbed is the **absorbance**. **Transmittance** is the fraction of light which passes through a transparent medium, and may be wavelength dependent. For a given wavelength, absorbance plus transmittance equals 1.0. **Reflectance** is the proportion of the incident light that is neither transmitted nor absorbed by the medium, but rather is reflected.

Illumination, Luminance

Illumination refers to light shining upon an object (Figure 6a). Natural sources of illumination include the sun and stars.

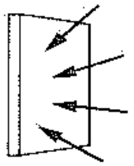


Figure 6a
Illumination

Luminance refers to the light reflected by, or radiated by, an object (Figure 6b).

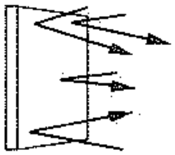


Figure 6b
Luminance

Brightness, like color, is a perception, and is not precisely defined.

Photometry

Relative measures of brightness can be quantified, and the **photometric units** of measure (Table 2, upper) are based upon the magnitude of the response of the eye, which differs at various wavelengths (Figure 7).

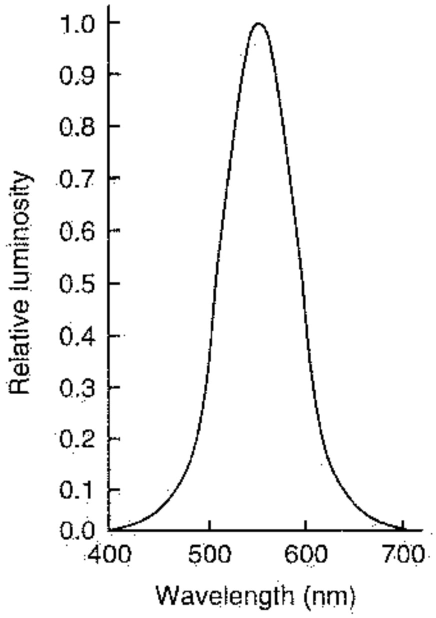


Figure 7
Photopic luminosity curve

Radiometry

Radiometric units, on the other hand, are not based on perception, but rather on a direct measurement of radiation intensity per unit area (Table 2, lower). A given amount of radiometric energy or power, weighted by the **photopic luminosity** curve, yields the photometric value. Several different units of measure are encountered in the ophthalmic literature with regard to intensity of illumination (watts or lumens), energy transfer (millijoules), differential sensitivity (decibels), or illumination.

Table 2

Photometric Units

Luminous Energy	lumen-seconds (weighted energy)
Luminous Flux	lumen (weighted power)
Luminous Flux Density	lumens/square meter
Luminance	apostilb

Radiometric Units

Radiant Energy	watts-seconds (energy)
Radiant Flux	watts (power)
Radiant Flux Density	watts/square meter
Radiance	watts/solid angle

Absorption and Emission

An electromagnetic wave is generated by movement of a charged particle. This charge movement can occur as an electron transition from one energy level to the next.

A quantum of energy absorbed by an atom, resulting in a higher level of internal energy, is usually immediately released as the atom returns to its ground state. This results in the release of light in a random direction and phase from each atom. **Black Body** radiation describes the spectrum of light emitted when a black object is heated. Initially, predominantly red light is given off, but finally the object becomes "white hot."

Another form of radiation can occur from materials that exhibit **fluorescence**. An atom absorbs energy and does not immediately release its energy to return to the ground state as in black body radiation. Instead, it drops to an interim state, then drops to ground state as it emits energy of a frequency corresponding to the energy difference between the intermediate state and the ground state. The **excitation light** is always of higher frequency (and hence, higher energy) than the **emitted light**. For example, in ophthalmology, fluorescein dye absorbs blue light and re-radiates the energy as yellow-green light.

A very special form of radiation can occur when the excited atom makes a temporary transition to a **metastable energy region**. When triggered by a passing quantum of energy, the energy from the metastable atomic state is radiated with the same phase and direction of propagation as the quantum that triggered its release. A chain reaction occurs, resulting in an intense pulse of coherent light. A broadband absorption system, a metastable state, and subsequent coherent radiation of light with the same frequency, direction of propagation, phase, and polarization are the elements that form a **Laser**.

Laser Light

Laser light has some very special properties. The light that is emitted is highly monochromatic. It can be created in **pulses**, where the power is delivered over a short time, or as a **continuous wave**. The laser's radiative transition from the metastable state to the resting level determines the energy of each photon, and thus the frequency of the radiation, because the frequency is directly proportional to the energy of the photons (and vice versa).

Laser-Tissue Interactions

The frequency of light emitted by a laser is determined by the material that is used in its construction. How the light emitted by the laser interacts with tissue is largely determined by the frequency of the laser. Each tissue in the eye will interact more or less with a given wavelength of laser light, and therefore will absorb more or less of the energy.

Photocoagulation

When the energy transfer occurs sufficiently slowly, thermal effects predominate. **Photocoagulation** occurs when the local tissue temperature becomes high enough for tissue coagulation to occur. This tissue interaction is exploited for retinal laser surgery (Table 3). It is necessary for the laser energy to be delivered to the desired tissue without undesirable tissue interaction occurring in the preceding layers. For example, the cornea, with a very high water content, readily transmits the visible wavelengths of the krypton and argon lasers, but absorbs some of the light emitted by the Nd:YAG infrared laser and all of the ultraviolet light emitted by the argon-fluoride excimer laser. The argon blue emission (488 nm) is absorbed by xanthophyll pigment within the retina, and should be avoided in treating subretinal lesions. The red emissions of krypton (647 nm) interact less with the retina, penetrate blood better, and interact most strongly with melanin in the retinal pigment epithelium, allowing the energy to be delivered deep within the retina.

Table 3

Commonly Used Ophthalmic Lasers

Material	Wavelength, nm (in vacuum)	Mode of Tissue Interaction Employed in Ophthalmology	Comments
Erbium:YAG	2940	Ionizing (?) (Photoablation)	"ablates" water-containing tissue
Holmium:YAG	2100	Ionizing (?) (Photoablation)	
Nd:YAG	1064	Ionizing (Photodisruption)	
"Diode" laser	810-840	Thermal (Photocoagulation)	
Krypton Red	647	Thermal (Photocoagulation)	deep penetration
Krypton Yellow	568	Thermal (Photocoagulation)	
Krypton Green	530	Thermal (Photocoagulation)	
Argon Green	514	Thermal (Photocoagulation)	
Argon Blue	488	Thermal (Photocoagulation)	undesirable xanthophyll interaction
Excimer ArF	193	Photochemical Decomposition (Photoablation)	breaks chemical bonds within proteins

Several factors can be controlled by the operator during photocoagulation. The **power level** is the total power output of the laser, that is, energy delivered per second by the entire beam. This beam may be masked to produce a **spot size,** the diameter of which is specified in microns. Changing the spot size does not change the power density, in watts per unit area, but simply changes the area that is irradiated. The spot size affects the rate of temperature rise within the tissue, because as the energy is transferred to the spot of retina irradiated, the surrounding tissue cools it, with smaller spots cooling more quickly than large ones. Consequently, it is necessary to decrease the power level when changing to larger spot sizes. The **duration** of a laser pulse is specified in milliseconds. Increasing either power level or duration results in more energy per unit area being delivered over the duration of the pulse. Finally, the beam of radiation exiting the laser tube can be diverged and then focused, forming a large cone angle, so that the **power density** is lower anterior and posterior to the point of focus, thus limiting the amount of energy transfer per unit volume anterior and posterior to the tissue plane that is to be treated.

Photovaporization

Photocoagulation requires a 10-20 degree Celsius increase in retinal temperature to produce the desired "burn." Large temperature increases can lead to **photovaporization**, via steam formation.

Photodisruption

The Nd:YAG laser uses convergent optics to bring a very short, intense pulse of light into focus within a small volume of tissue. **Photodisruption** then results, ionizing tissue by stripping the electrons from atoms, creating a plasma shock with an associated wave. This shock wave, in turn, cuts tissue without significant thermal effects. By delivering high concentrations of energy with a convergent optical system in a very short pulse, the Nd:YAG laser causes very minimal thermal effect when used for descission of the posterior capsule following cataract surgery. Instead, the shock waves from the photodisruption can cause corneal trauma or retinal tears, both complications of a YAG capsulotomy.

Photoablation

The excimer laser is a high-energy ultraviolet laser producing the predominant tissue interaction of **photoablation**. Extremely short pulses produce ablation by photodecomposition of the irradiated tissue, and limit the adjacent thermal damage to a depth of much less than 10 microns. Similar effects occur with extremely short-pulse, high powered pulses of infrared holmium and erbium lasers interacting with the cornea and lens.

Reflection

When light encounters the interface between media of different refractive indices, not all of the light is refracted. Some of the light (an amount which is somewhat proportional to the difference in the indices of refraction) is **reflected**. The amount of light reflected is also determined by the incident angle, and is at a minimum when the angle of incidence is zero (perpendicular to the interface). In the eye, the greatest difference in refractive index occurs at the air/ tear interface, where about 2% of perpendicularly incident light is reflected. Each surface of spectacle lenses reflects about 4% of the light. **Mirrors**, designed for high reflectivity, can have the aluminum coating on either the front or the back. Rear surface mirrors (such as bathroom mirrors) are easy to clean, but only reflect about 70% of the light and suffer from a ghost reflection from the front surface. Front surface mirrors are highly reflective (up to 95%), and are free of the ghost image.

Reflection: Ophthalmic Applications

The amount of light reflected increases as the incident angle increases, approaching 100% for grazing incidence. The everyday significance of this is apparent by the sunset being reflected by bodies of water. **Specular microscopy** exploits the difference in refractive index across the endothelium/aqueous interface to permit visualization of the corneal endothelium within the patch of reflected light.

Coherence and Interference

One result of the wave nature of light is that wavefronts, separated and recombined from different directions, can combine either constructively (when they are in phase) or destructively (when they are out of phase). Light is coherent when the ability for wavefronts to interfere is present. Laser light, created in an arrangement where all the light has uniform frequency, phase, and polarization, is highly coherent. **Temporal coherence** is a measure of the uniformity of the frequency of the light, and represents the time over which the wavefront remains sufficiently stable to interfere with itself. **Spatial coherence** is the ability of an optical system to create interference within some volume of space, by geometric considerations.

Coherence: Ophthalmic Applications

One familiar application of spatial coherence is in the creation of interference fringes used in **testing retinal function** (Figure 8). By changing the geometry (separation) of the interfering beams, the spatial frequency of the interference patterns on the retina is changed to measure different levels of grating visual acuity. The creation of interference patterns on the retina is practically independent of the focusing system of the eye, and the interference fringes are degraded less by cataracts than are the images formed by ordinary light passing through the whole pupil.

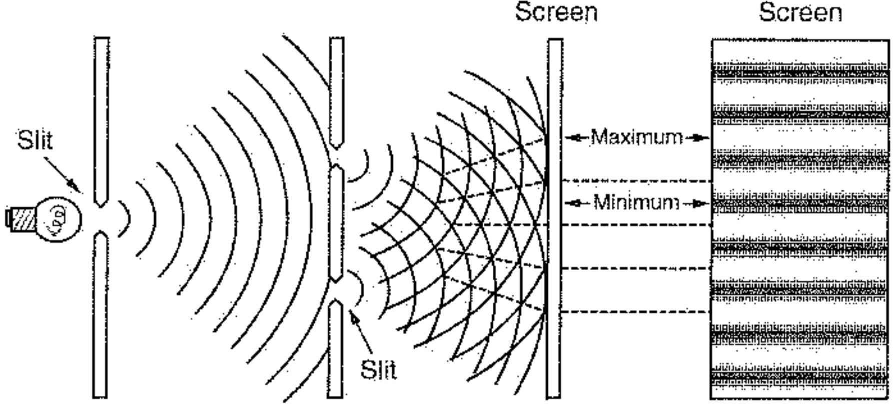


Figure 8
Interference fringes from spatially coherent light

Interference: Ophthalmic Applications

An **antireflection coating** is another application of interference in ophthalmic optics (Figure 9). In order to decrease the reflection from the surfaces of spectacle lenses, a thin coating of a material with a different refractive index is applied to the lens so that the thickness of the coating is one quarter of a specified wavelength. The index of refraction of the coating is selected so some light will be reflected at the air/coating interface, and an equal amount will be reflected at the coating/lens interface. The latter wavefront will exit the coating/air interface one-half wavelength out of phase with the former wavefront, resulting in destructive interference and thus no reflection of energy at that wavelength.

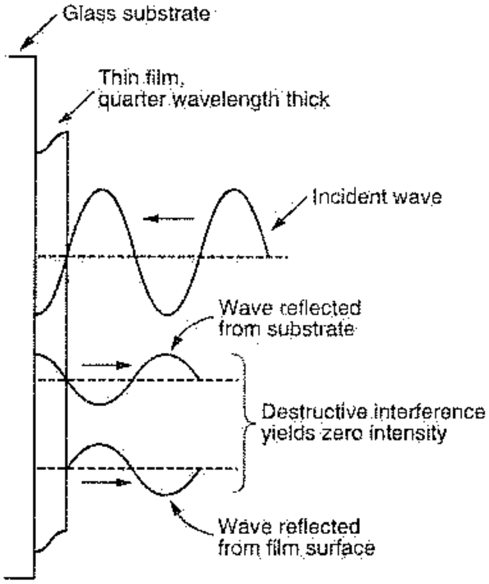


Figure 9
Antireflection coating

Interference: Ophthalmic Applications, continued

Another application of interference in ophthalmic optics is the use of **narrow band interference filters** in fluorescein angiography (Figure 10). An interference filter is made by selecting a thickness of glass, or coating on the glass, that is a multiple of the desired wavelength of light, and then partially coating both sides of the material with a reflecting substance. Multiple reflections of the desired wavelength will exit in phase and will constructively combine. Other wavelengths will exit out of phase and destructively interfere.

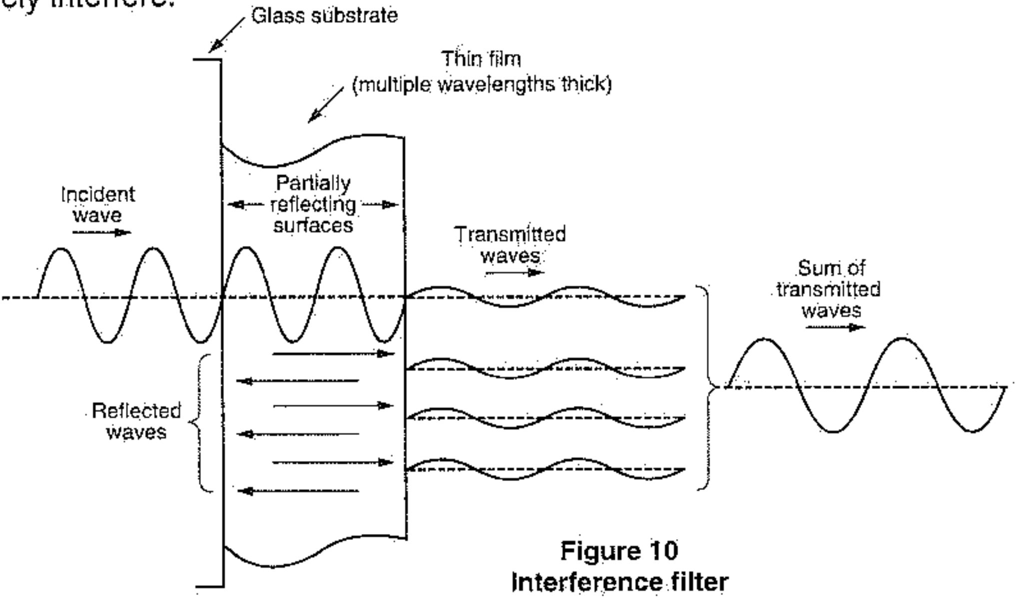


Figure 10
Interference filter

Fluorescein Angiography

In **fluorescein angiography**, an "**excitation filter**" allows light centered about 480 nm (blue light) to excite the fluorescein molecule, as well as illuminate the remainder of the eye. The radiation spectrum of fluorescein is from 500 to 600 nm, with a maximum about 520 nm. On the return path, a "**barrier filter**" permits the desired wavelength of 520 nm to pass, but blocks the background blue light, preventing it from flooding the image.

Scattering

The interaction of electromagnetic radiation with isolated atoms and molecules can induce resonance. Isolated atoms characteristically are resonant in the ultraviolet. At frequencies below resonance, in sparse media, energy is absorbed and subsequently re-radiated at the same wavelength but in a different direction ("scattering"). As the frequency of radiation approaches the resonant frequency, more and more interactions occur, and the percentage of light that is scattered increases. The light that is scattered off the incident axis is polarized.

Scattering: Ophthalmic Applications

Scattering is responsible for the "optical section" phenomenon of slit beam illumination of the eye. It is also the mechanism responsible for our blue skies and our red sunsets, as the blue light is most scattered by the atmosphere, arriving to the observer from all directions. The red portion of the spectrum passes through the atmosphere without being scattered significantly and therefore still appears to come from the general direction of the sun.

Polarization Phenomenon

The electromagnetic wave consists of perpendicular electric and magnetic fields that are mutually perpendicular to the direction of propagation. **Polarized light** is composed of radiation in which the electric fields are constrained to a specific orientation. Polarizers are made from materials that are **birefringent**, having different refractive indices for different orientations of the electric field vector. They are arranged to pass light of a specific electric field orientation, and deflect or absorb the remainder of the light. **Plane (linear) polarizers** permit properly oriented transverse fields of plane waves to pass, while a **circular polarization filter** produces light with a continuously spinning electric field.

Polarization: Ophthalmic Applications

Polarized light occurs frequently in nature, arising from transmission through crystalline matrices, from scattering, and from reflection at characteristic angles. Ophthalmic applications of polarization are numerous. **Polarized sunglasses** darken the sky by blocking the horizontally polarized component of the scattered light from the sky, and also selectively block reflections from horizontal surfaces. **Crossed polarizers** are employed in ophthalmic imaging systems to reduce unwanted reflections. **Vectographic images**, when viewed through glasses that have polarizing filters oriented at ninety degrees to each other, permit independent stimulation of the right and left eyes for binocular vision tests (suppression and stereopsis tests). The **Haidinger brushes** are a sensory phenomenon in which "propellers" are observed when viewing rotating plane polarized light. The "propeller" rotates as the linear polarizer rotates. The test may be performed through cataractous media, and serves as a test of macular function. Finally, many materials, including glass and plastic, exhibit **photoelasticity**. That is, they become birefringent when subjected to stress. When a spectacle lens, mounted in a frame, is viewed between crossed polarizers, areas of high stress are apparent, suggestive of risk for breakage.

Diffraction

As a wavefront of light passes an obstruction, the wavefront fans out beyond the edge of the obstruction. Each portion of the wavefront that passes beyond the obstruction serves as a secondary radiator, creating wavefronts that interfere with each other. The interference created by the aperture of an optical system limits the resolution that can be obtained with the system. The **diffraction limit** of an optical system is the smallest spot image that can be observed and is a function of the diameter of the aperture relative to the wavelength of the light. Longer wavelengths are more subject to diffraction than shorter wavelengths.

Diffraction: Ophthalmic Applications

One ophthalmic application of diffraction is the use of **diffractive lenses**, also known as **binary optics**. Although the lines of Fresnel prisms only cause blurring by diffraction, a specially designed pattern of steps may be etched into the back of a contact lens or intraocular lens to create a diffractive lens. The light diffracted by the steps creates a second focal point for the lens, creating a multifocal lens, allowing simultaneous distant and near far points for a presbyopic individual.

CLINICAL REFRACTION

Visual acuity measurement

Minimum separable acuity

The acuteness of vision is measured as the angle subtended by the smallest detail the eye can perceive. A **Point Source** of light, such as a star, cannot be used as a stimulus, as the imperfections of the eye and limitations from diffraction will convert the point of light into an extended image on the retina. Even the smallest star will be seen, therefore, if it is bright enough. While being able to see one star may not be a good test of visual acuity, the ability to see two closely spaced stars as distinct is a good test.

In addition to the quality of the image-forming capabilities of the eye, the sensitivity and density of the photoreceptor array determine the limit of visual acuity. Photoreceptors measure the average light flux across their area. For the pair of stars to be resolved, their detail must be spread over more than one photoreceptor, and the brain must be able to detect the differential response of these photoreceptors to light. How does photoreceptor density relate to visual acuity?

The astronomer Robert Hooke noted in 1705 that the smallest angle at which two closely spaced stars could be resolved was between 30 seconds and one minute of arc. Helmholz, in 1860, proposed that the standard for visual acuity be based on one minute of arc. Anatomists of his time measured the photoreceptor density and estimated their spacing at one minute of arc. Helmholz reasoned that to detect a detail one minute of arc in size, one unstimulated photoreceptor must lie between two stimulated photoreceptors.

Hartridge, in 1922, recognized that the images of point sources were larger than the area of a single photoreceptor, and proposed the **contrast sensitivity** theory of visual acuity, still currently accepted. The middle photoreceptor must receive perceptibly more or less stimulation than its neighbors, rather than be simply “on” or “off”.

The cones in the fovea actually subtend about 20 seconds of arc. Given the aberrated images on the retina, however, the smallest detail that can be resolved must be somewhat larger than 20 seconds of arc, in order to allow a less stimulated photoreceptor to be between two more intensely stimulated photoreceptors. Observed minimum separable acuity measurements are in close agreement with predictions based on anatomy and contrast sensitivity theory.

Vernier acuity

Vernier acuity, in which the smallest break in a line or contour is detected, is 5 to 10 times better than the limits posed by the photoreceptors. This paradoxical resolution, where the detected stimulus is smaller than the photoreceptor spacing, is still not explained.

The **Amsler Grid**, when held at 30 centimeters, tests the central 20 degrees of the visual field with a grid where each square subtends one degree of arc. Any distortion of the retina, say from blood under the retina, will result in an apparent distortion of the lines. The amount of distortion that can be detected is very small, a manifestation of vernier acuity in reverse.

Minimum legible visual acuity: optotype testing

Optotypes are figures or letters that can be read and identified. Acuity measurements based upon the smallest print or figure correctly recognized are measures of minimum legible visual acuity. The first eye chart used for vision testing was published by **Jaeger** in 1854. Twenty different sized types were used to test at near in order to record the smallest type that could be read. The test distance was not specified. Jaeger near cards are still used in many clinics.

Distance measurement of minimum legible visual acuity was promulgated by **Snellen** in 1862, with his publication of "Optotypes." By specifying both the stimulus (size and shape of the characters) and the test distance, Snellen was able to standardize the measurement of visual acuity.

Snellen acuity

Snellen used a standard visual angle of one minute of arc (following Helmholz), with each letter subtending five minutes of arc in vertical size, at a specified distance. All Snellen letters subtend five minutes of arc at the stated distance. The largest letters on the chart are large because their stated distance is large; but if the chart were moved to that distance, the angular size of those letters would be five minutes of arc.

Snellen initially advocated a test distance of 20 Paris feet (21 feet 4 inches English measure), but later revised the charts for 6 and 5 meter test distances. Snellen thought it important to specify the testing distance, not just the visual angle subtended by the test object. His method of notation is still used today: the numerator corresponds to the testing distance, and the denominator the distance at which the test letters subtend an angle of five minutes of arc.

LogMAR acuity and alternative optotype sets

A simpler method would be to record visual acuity in minutes of arc (ie; 20/20 = 1 minute; 20/40 = 2 minutes, etc). Statistical analysis is enhanced when the logarithm of the minimum angle of resolution (**LogMAR**) is recorded. LogMAR charts have an equal number of letters per line, with a geometrically decreasing size of letters and spaces between letters from the top to the bottom of the chart. The charts, however, have a drawback: the top row of letters is so wide (2 feet wide at a 10 foot test distance) that it cannot be readily projected.

Not all letters that are the same size are equally recognizable. Louise Sloan identified ten letters of the alphabet that are recognized with approximately equal ease. These letters are used in multicenter clinical trials such as the ETDRS study. Letters also vary in the prominence of vertical or horizontal strokes. In the presence of astigmatism, this can cause errors in the measurement of refractive error. Consequently, the Landolt C was adopted as the international standard in 1909. Both the gap and stroke of the C subtend one minute of arc in width, with the orientation of the gap either up, down, right, or left. The Landolt C yields slightly better visual acuity than the same size letters.

Snellen himself proposed use of the "Tumbling E" or "Illiterate E," where the subject indicates the direction the E is turned. Other optotypes include the **Allen figures** (pictographs of a telephone, tree, etc), the **Lippman HOTV letter set** (letters that do not suffer from mirror image reversals), and the **Lea figure set** (pictographs of a circle, square, house, and apple). These figures can often be used at an earlier age (18-24 months) than the tumbling E (often not used reliably until 36 months of age because of horizontal reversal errors).

Equipment used for measuring visual acuity

A number of options are available for measuring "visual acuity," or more properly, minimum legible visual acuity. Wall charts can be printed, hung on the wall at the specified test distance, and illuminated from the front, or printed on translucent material and lighted from behind. Similarly, pocket size charts can be printed for measuring vision at near, such as the **Rosenbaum Pocket Vision Screener**. Projected visual acuity charts can either be manually operated, or automatically advanced to a desired letter size. A computer-controlled video display can be used (**Mentor BVAT**) to not only advance to a desired size, but also to present the letters randomly to prevent memorization of the chart. Calibration of these devices requires adjusting the size of the letters for the actual room size and test distance. To calibrate a projector, multiply the distance from the patient to the chart in meters by 29.1 to obtain the linear height of the 20/400 letter in millimeters.

Vision Screeners are table-top instruments that allow distance vision to be tested with a small, self-contained unit. Plus lenses in these instruments optically place the test letters at 20 ft, 30 ft, or infinity. Occasionally, instrument myopia occurs, resulting in falsely poor visual acuity being measured. Accommodation is stimulated by knowledge that the target is near, despite optically being placed at a distance. The patient accommodates, resulting in blurred vision. When retested using a distance wall chart, the vision is better.

Clinical tips for measuring vision

It is customary to measure unaided vision (vision without correction, abbreviated sc), or if spectacles are available, to measure vision with correction (abbreviated cc). Each eye is tested separately. If vision is worse than 20/20, vision is then measured through a pinhole (abbreviated PH), to screen for refractive error. If bifocals or reading glasses are available, measure near vision as well (specify type size and distance at which it is read). A large capital V is written, with either sc or cc at its base, and then to the right of the top portion of the V, the right eye acuity (followed by PH and pinhole acuity). Under the right eye acuity, the left eye acuity is similarly recorded.

		PH	
V$_{sc}$	20/20 20/40	— $20/20^{-2}$	(Indicates that vision **without** correction is 20/20 RE and 20/40 LE, pinholing to $20/20^{-2}$ in LE.)
V$_{cc}$	$20/15^{-2}$ 20/20		(Vision **with** correction.)
W	+2.00 + 0.50 x 180 =20/20 plano + 1.00 x 010 =20/20		add +2.00 = J1 @ 14" +2.00 = J1 @ 14" (Glasses that patient is **wearing** along with vision is obtained.)

Specifying levels of vision

For vision in the 20/15 to 20/400 range, use projected letters, but if the vision is worse than 20/400, a different method is called for. Hold a large optotype (Snellen 20/200 E) and approach the patient, then record the distance at which the letter is first recognized. For example, if the Snellen 20/200 E is first recognized at 4 ft, the vision is recorded as 4/200. Note that 10/200 is equivalent to 20/400, so testing with a 20/200 optotype is only necessary at distances within 10 feet.

The arms of the 20/200 letter are approximately the same width as fingers, and so the fingers on your hand can approximate a 20/200 letter. If the patient can count fingers from 5 ft away, the vision is recorded as CF 5', and is approximately 5/200. If the patient's vision is too poor to record with the 20/200 E or finger counting, often hand motion can still be detected. If the patient can see a hand waving at 6 feet, the vision is recorded as HM 6'.

"Light perception with projection" indicates that the patient can not only detect the presence of light, but can localize it to a quadrant. If he or she cannot localize to all quadrants, it is important to record this fact, as it may provide a clue as to the location of intraocular disease (eg: tumor or retinal detachment). "Bare light perception" indicates that the patient can sense the presence of light, but cannot say which direction it is coming from. "No light perception" ("NLP") means the absence of visual perception even with the brightest light shined in the eye. The other eye has to be occluded with more than a patch (usually the examiner's hand is used), and the light source is usually the indirect ophthalmoscope on high illumination.

Levels of vision (examples)

20/15
—
—
20/400
8/200 (=CF @ 8')
—
—
1/200 (=CF @ 1')
6"/200
HM 6'
—
—
HM 1'
HM 3"
LP with proj. all quadrants
LP with proj. temp and inf.
LP without proj.
bare LP
NLP

Near vision

(at a comfortable
reading distance
for patient)
J1 @ 14"
J2 @ 12"
J3 @ 15"
J10 @ 4"
Reading card @ 8"
(reads the title only)
No J

Measurement of vision in children

No Peeking! It is important not to rely on the child to hold an occluder or fingers over the eye, but to occlude the eye with a patch or tape. The Tumbling E usually can be used with children beyond the age of three, but is subject to errors of right and left reversal.

Children old enough to follow commands but too young to read can often be tested with Allen figures or a matching test such as the HOTV or Lea set. Children too young for optotypes can be tested by seeing if they will reach for small objects. If successful, vision is recorded as "picks up (kind of small object, and specify size) at (specify distance)".

Vision in children

E game
Allen cards @ __ft (x/30)
picks up small objects
tolerates patch
optokinetic nystagmus
follows light
blinks to light

Development of Visual Acuity

Vision at birth can only be recorded as an "intact pupillary light reflex" and "blinks to light." The ability to look at and follow a light develops during the first month, and should be fully developed by three months of age. When testing vision monocularly, it is very important to note the change in behavior as the patch or occluder is moved to the other eye. If the child "objects to occlusion," it is likely that the eye being occluded sees significantly better than the fellow eye.

Expected Visual Acuity

age	visual acuity	FPL*	VEP**
at birth	20/150-1000	20/400	20/600
6 mo.	20/400	20/100	20/20
1 yr.	20/200		
2 yr.	20/70		
3 yr.	20/30		
4 yr.	20/25		
6 yr.	20/20		
10 yr.	20/15		

*forced-choice preferential looking technique

**visual evoked potential technique

Another visual response that can be measured at a very early age is **Optokinetic Nystagmus**. The OKN drum is spun slowly across the visual field (one revolution in three to five seconds), and presents a compelling stimulus for the child to follow the stripes if they can be resolved. If the vision is too poor to resolve the stripes, then no optokinetic nystagmus (the following motion followed by a fast refixation motion) will be induced. The width of the stripes can be decreased until the OKN response is no longer observed. The smallest stripe width resolved is assumed to be the threshold for the OKN response. OKN response suggests that visual acuity at birth is approximately 20/400.

Children attend more to patterned objects than to blank objects, if the pattern can be resolved. This behavior is used in **Forced-Choice Preferential Looking (FPL)** measures of vision. The Teller Acuity Cards® permit testing with progressively narrower gratings until the child no longer shows a preferential response. The narrowest gratings that the child consistently looks at becomes a measure of the threshold of grating acuity. Grating acuity may overestimate visual acuity because of the redundancy of the stimulus. The grating acuity threshold for 6-month-old children is approximately 20/100.

Visual acuity may also be measured using **Visual Evoked Potentials (VEP)**. The EEG signal is recorded over the occipital cortex while the child is presented with an reversing black and white checkerboard stimulus of progressively decreasing size. As the stimulus size decreases, at some point the EEG response disappears. Such estimates suggest the potential for 20/20 vision as early as 6 months. This does not mean the child has 20/20 vision, however, because the association areas of vision, adjacent to areas 17 in the occipital cortex, have not yet developed.

From these various measurement techniques, it is clear that children are not born with the ability to see 20/20. The normal three year old can see 20/30, and the six year old, 20/20. At birth, the normal levels of vision are significantly worse. If the child's eyes are not straight, or if each eye does not fix on a light, or if each eye does not follow a light, by three months of age, an ophthalmologic evaluation should be performed.

Factors Affecting Visual Acuity

Patient age, refractive error, and media clarity are not the only factors that affect visual acuity. Pupil size has an effect on visual acuity. Very small pupils decrease visual acuity because of diffraction. And, as the pupil diameter increases beyond about 2.5 mm, aberrations of the eye can result in decreased visual acuity.

Effect of Refractive Error on Visual Acuity

How much does refractive error decrease visual acuity? With moderate to large sized pupils, spherical errors of a quarter diopter, and astigmatic errors of one half diopter, result in roughly one line decrease in visual acuity in the 20/15 to 20/25 range on the eye chart.

Effect of Eccentric Fixation on Visual Acuity

The portion of the retina being used also affects visual acuity, for as the distance from the center of the fovea increases, the resolving power decreases. About one disc diameter from the center of the fovea, acuity measures 20/70, and three disc diameters from the fovea, acuity is 20/200.

Effect of Contrast and Light Level on Visual Acuity

Contrast, or how black the letters are compared to the whiteness of the background, affects acuity as well. Visual acuity is usually measured at greater than 90% contrast, although the contrast will decrease if a projector is used and there is dust on the lenses and mirrors. The brightness of the projector bulb also makes a difference, as the brighter the background, the better the acuity. When there is plenty of light and the cones of the fovea are adequately stimulated, the **"photopic" visual acuity** is measured. As background illumination decreases to the point that the cones can no longer function, a central scotoma of about one degree in size develops, as there are no rods in this area. **"Scotopic" visual acuity** is about 10 to 100 times worse than "photopic" acuity, and appears to be at a maximum 5 to 10 degrees away from the fovea, where the rod concentration is greatest.

Shining a bright light directly into the eye can bleach the photoreceptors and temporarily decrease visual acuity. It is important to measure and document visual acuity before ophthalmoscopic examination of the macula, because it can take some time for the vision to return to normal when macular disease is present.

Effect of Glare on Visual Acuity

Glare, or stray light within the eye, decreases contrast and lowers visual acuity. Glare can arise from scattered light from cataracts or corneal scars, or from reflected light within the eye from drusen, an albinotic fundus, or medullated nerve fibers. Photoreceptors are more sensitive to light passing through the center of the pupil than through peripheral areas, a phenomenon known as the **Stiles-Crawford effect**. This helps protect the eye from the effects of glare.

Contrast Sensitivity Testing

The contrast sensitivity of the eye is defined as how faint an image can be and still be recognized appropriately. Typically, small patches of gratings (coarse to fine) are displayed at various levels of contrast. Not all spatial frequencies (the spacing of the gratings) are equally affected by alteration of contrast.

Contrast sensitivity testing measures the ability of an individual to just detect the presence of a grating. Both the level of contrast and the grating frequency are plotted over a range of frequencies. Normal subjects have variation in their threshold as the spatial frequency of the grating varies. Consequently, the result of contrast sensitivity testing is a graph, rather than a single number as reported for visual acuity. Contrast sensitivity provides a more complete description of a patient's visual performance, but is more difficult to interpret than the single ratio of a Snellen visual acuity.

Causes of Abnormal Contrast Sensitivity

Cataracts can result in altered contrast sensitivity, but such contrast sensitivity deficits are not specific for cataracts, because retinal and optic nerve disease can produce similar responses. Contrast sensitivity can be degraded even in the presence of normal visual acuity, such as in the patient with retrobulbar optic neuritis who reports that everything is "washed out". Before contrast sensitivity testing, there was no objective way to measure this loss of contrast as evidence of progression or regression of disease.

Techniques to Measure Contrast Sensitivity

There are several commercial systems available to measure contrast sensitivity. **Vistech Consultants**, Inc. makes a wall chart that tests several spatial frequencies at several levels of contrast. The **Pelli-Robson test** presents large letters at progressively less contrast until the patient can no longer read them. The **Mentor BVAT** has an optional joystick and printer to automatically generate and print the contrast sensitivity curve.

Glare Disability Testing

Light off to the side of where the patient is looking can be scattered by an opacity and fall on the fovea. The foveal image is washed out, and the patient experiences a loss of contrast sensitivity. A familiar example is the difficulty seeing while driving toward the sun in a car with a dirty windshield. A similar decrease in vision from glare occurs with cataracts. The decrease in visual performance arising from glare is specific to cataract or corneal disease, and is the best way to document visual disability from early cataracts. The measurement of visual disability arising from scatter arising in the anterior segment is called glare disability testing.

Methods to Measure Glare Disability

One early glare test was the **Miller-Nadler Glare Test**, a near test of Landolt C's of different contrast with a surrounding white background glare source. Another method of documenting the decrease in visual acuity with glare is provided by mounting a bright glare source adjacent to a visual acuity display. By measuring the visual acuity with the bright light off, and again while on, the decrement of visual acuity can be measured, documenting the amount of glare disability.

A popular commercial glare tester is the **Mentor BAT (Brightness Acuity Test)**. This small, hand-held device looks like an ice cream scoop with a hole in the back. The patient holds the bowl facing toward the eye, and looks through the hole in the back of the bowl to the usual visual acuity display. A light can then be turned on which illuminates the inside of this bowl, creating a glare source, and the decrement in visual acuity can be documented.

Glare testing is indeed the best way to document disability from early cataracts, and thus is the best way to justify earlier cataract surgery. An advantage of commercially available instruments is the standardization of testing. For example, should a patient's cataract be removed on the basis of glare disability alone, and a poor result obtained, that patient may claim that you performed surgery inappropriately. A result from a commercial glare tester would be more helpful in defending against this claim than a notation in the chart stating that you tested for glare using your own methods.

Methods of Estimating Potential Postoperative Visual Acuity

Another related problem in the evaluation of patients with early cataracts is determining whether or not visual acuity is decreased on the basis on the immature cataract or because of retinal disease.

Experienced examiners will frequently use a **direct ophthalmoscope** to view the retina and judge the clarity of the media directly, although without a great deal of accuracy or reproducibility. **Indirect ophthalmoscopy** is used to make an estimate of the health of the retina. The indirect ophthalmoscope facilitates a good view of the retina by using only a small portion of the patient's pupil, allowing the examiner the opportunity to look through a small hole in the immature cataract.

Other clinical tests to estimate the level of vision expected following cataract surgery include the **pupillary light reflex**, which should be normal even in the presence of dense cataract. **ERG** and **VEP** testing can be performed with bright flashes to determine whether there is functional retina behind the cataract. **Ultrasonography** can be used to determine that the retina is attached behind a dense cataract and that there are no tumors or masses.

Entoptic Imagery

Entoptic imagery tests have also been used to assess retinal function behind cataracts. The **Purkinje vessel pattern** arises when a bright spot of light is moved back and forth over the sclera or closed lid with a hand-held transilluminator, creating shadows of the retinal blood vessels on the retina. The patient's perception of these Purkinje vessel patterns does not correlate with foveal acuity, however, because there are no vessels that pass directly across the fovea.

Another entoptic imagery test is the visualization of **Sheerer's "flying corpuscles."** The flying corpuscles are simply leukocytes that are visualized as white spots that appear, move in arcuate paths, and then disappear. The leukocyte is relatively transparent, and as it squeezes through the retinal capillary, the leukocyte passes light to the relatively dark-adapted photoreceptors underlying the column of red blood cells, resulting in a moving pattern of white spots. The normal eye should see 20 to 40 of these flying corpuscles within its central visual field, reportedly predicting 20/40 or better visual acuity, but this measurement is somewhat subjective and does not correlate precisely with foveal visual acuity because of the lack of blood vessels or leukocyte paths directly across the fovea.

Color perception has also been used to test the vision potential behind a very dense cataract, but this information is only useful when color perception is absent. If color perception is completely absent, it is likely there is severe optic nerve or retinal disease present. Normal color can be perceived by the cones outside the fovea, so intact color vision does not indicate that an intact fovea is present.

Direct Acuity Measurement Through Cataractous Media

Newer quantitative methods of assessing retinal function behind cataracts involve direct acuity measurement, using patterns formed directly on the retina. The ordinary pinhole aperture, located in the spectacle plane, can provide some measure of potential acuity by isolating a small part of the eye's optics and avoiding scattered light from the cataract which washes out the image on the fovea. This same method can be employed more efficiently by optically moving the "pinhole" to a clear portion of the cataractous lens. Selectively projecting the light through a clear portion of the cataract minimizes the glare effects from the cataract.

Instruments to Estimate Potential Vision through Cataractous Media

Two types of stimuli can be projected through pinhole apertures. The **Rodenstock Retinometer** and the **Haag-Streit Visometer** produce interference fringes that are projected onto the retina. The **Potential Acuity Meter** from Mentor, in which Dr. Guyton still has a financial interest, projects a single beam of white light through a clear space in the cataract. This beam of light carries with it an image of a visual acuity chart by which a direct Snellen acuity measurement is obtained.

Clinical results of the Potential Acuity Meter, otherwise known as the PAM, and the interference fringe instruments, suggest that the instruments work reasonably well in predicting the final level of visual acuity. Typical accuracy figures suggest that if pre-operative visual acuity is 20/200 or better, post-operative vision can be predicted within two lines 91% of the time. If the pre-operative visual acuity is 20/300 or worse, however, it will be difficult to locate a clear space to project the light through the cataract, and accuracy falls off quickly. However, because most patients (95% or so) have healthy retinas behind their cataracts, it is not important to assess the rate at which people see well after it is predicted they will. The rates of falsely-poor and falsely-good predictions must be used to assess the value of these instruments.

Truly good predictions occur when the beam of light is projected through a clear space in the cataract and the healthy retina yields good acuity. This is the normal response. Truly poor predictions occur when the beam is projected through the cataract onto the retina, the retinal function is poor, and the patient provides a response predicting poor vision following cataract surgery.

Falsely poor predictions can arise when the beam of light does not pass through a clear opening in the cataract, and instead is blocked.

This can be guarded against by using the slit lamp microscope to monitor that the beam enters the eye and disappears cleanly into the vitreous. When the beam is blocked, the retina is not tested, and even though the potential for good vision may be present, that potential is not demonstrated. Finally, falsely good predictions occur when the instrument predicts good vision following surgery, and yet such vision is not obtained. Unfortunately, falsely good predictions occur in the presence of the same diseases we wish to detect.

The interference fringe instruments are more likely to be associated with falsely good readings in the presence of a macular scotoma, because of the larger, redundant stimulus size. Both the PAM and the interference fringe instruments yield falsely good predictions in the presence of macular edema. Macular edema causes light scattering within the retina, and the larger the pupil, the more such scattering will occur. The potential acuity instruments effectively concentrate all the light toward each image point into a single bright ray that is less degraded by scattering. Finally, irregular refraction arising from corneal surface irregularity is effectively bypassed by the pinhole effect. After the surgery, the irregular cornea is still present, and poor visual acuity can result.

If a falsely good prediction should occur, it is important to determine the cause. First, repeat the potential acuity test. If poor vision is now measured, a hidden surgical complication may have occurred. If this is not the case, check the retinoscopic reflex for irregular astigmatism, or for a prominent rim of posterior capsule protruding into the pupillary space. A rigid contact lens can correct the former, while a capsulotomy can correct the latter.

The Effect of Color on Visual Acuity

Just as refraction and media clarity can affect visual acuity, the color of light used to form the image can have an effect. The Corning Glass Company developed a line of sunglasses that not only darken in outdoor light, but also cut off the blue end of the spectrum. These were first promoted for patients with retinitis pigmentosa, where the blue end of the spectrum is felt to be more damaging to the retina. Since blue light is scattered more than red light, it was thought that patients with early cataract might also benefit from these "Corning Photochromic Filter" lenses. The "CPF" lenses, as well as other "blue blocking" glasses, do indeed block the blue end of the spectrum, but we are not particularly sensitive to blue light to begin with. The blue blocking lenses have actually been shown not to improve visual acuity, but some patients claim to be more comfortable with them.

The eye has significant chromatic aberration, and naturally focuses for yellow light. Even if the eye is refracted properly for each color, best acuity is achieved with either yellow or white light. Blue light yields the poorest visual acuity, because there are no blue cones in the very center of the fovea.

Pinhole Pearls

The major use of the pinhole aperture in ophthalmology is determining "pinhole" visual acuities. The pinhole effectively nullifies small amounts of refractive error by increasing the depth of focus of the eye, reducing the size of all blur circles. If visual acuity improves through a pinhole, a refractive error is probably the cause of the decreased acuity. The most effective pinhole diameter for nullifying refractive errors is approximately 1.2 mm, "neutralizing" up to 3 D of refractive error. Smaller pinholes introduce diffraction blurring and drastically decrease the amount of light entering the eye. Larger pinholes are more easily located by the patient but do not effectively neutralize refractive error. A 2 mm pinhole can "neutralize" only about 1 D of refractive error. Taking a pinhole vision of an aphakic eye requires a +10.00 or +11.00 D lens in addition to the pinhole aperture.

A pinhole aperture is also valuable **after** the best refractive correction has been obtained, if vision is not as good as expected. Further improvement of vision with the pinhole implicates scattering from corneal or lenticular irregularities as the cause of the decreased vision. The pinhole allows looking through only a small portion of the eye's optical system, an irregularity-free "window." If vision **decreases markedly** with a pinhole, suspect retinal disease involving the photoreceptors (with slow regeneration of rhodopsin in response to lower light level).

Other uses of the pinhole aperture include a makeshift visual aid for presbyopes or cyclopleged patients, and a makeshift magnifier, allowing reading material to be held much closer than otherwise, without going out of focus.

A pinhole may be used for gross refraction. If a distant object becomes smaller as the pinhole is moved **away** from the eye, the eye is myopic. If the object becomes larger, the eye is hyperopic. If a distant object moves in the same direction as the pinhole as the pinhole is moved **across** the pupil ("with" movement), the eye is myopic. "Against" movement indicates the eye is hyperopic.

By placing a pinhole near the anterior focal point of the eye (about 16 mm in front of the cornea) and looking at the sky or a white screen, irregularities within the eye's optics can be seen as shadows cast upon the retina. Even dust particles in the tear film may be seen moving with each blink. (Imaging a point source of light into the same position gives even better "entoptic" shadows.)

Pinhole pearls, continued

Double pinhole apertures have been used since 1619 (the Scheiner principle) to detect and measure refractive errors. If the two bundles of light rays passing through the two pinholes do not come to focus at the retina, a double image will be seen. The object may be moved, or lenses may be placed before the eye, until the double image disappears, thereby determining the refractive error in the meridian of the double apertures.

"Pinhole" goggles were once used in an attempt to limit eye movements in post-operative retinal detachment patients. The benefit of such pinhole goggles was questioned by many, especially in view of the limited field of vision and resultant hazard in navigating.

Retinoscopy (basic plus cylinder technique)

1. Set phoropter to +1.50 sph and zero cyl both eyes.

2. If **manifest** RNS, both of patient's eyes should be open; he or she should look just past your ear at a fixation light at the end of the room. The patient must be fogged (overplussed), relative to the wall chart, at all times in both eyes. Learn to retinoscope patient's right eye with your right eye and the left eye with your left eye.
   If **cycloplegic** or **aphakic** RNS, occlude patient's other eye and have him or her look directly at the retinoscope light. No need to worry about fogging the other eye.
   If **strabismic** patient, occlude the other eye.
   If patient is under anesthesia, locate appropriate line of sight by observing the corneal light reflex.

3. Use working distance best for you, as far away as comfortable.

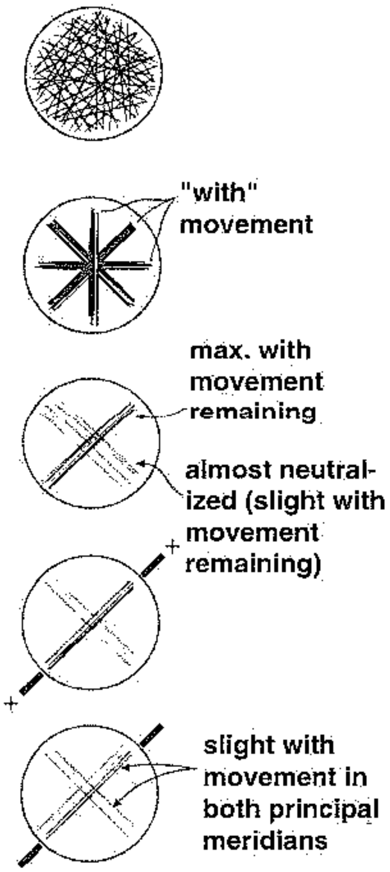
4. Observe retinoscopic reflex in various meridians with retinoscope sleeve all the way **up** (Copeland 'scope). Always sweep the streak perpendicular to itself.

   a. Add **minus sphere** until obtain "with" motion in all directions. (If reflex is dull and motionless, try high plus or high minus correction.) (Dial **up** for minus sphere.)

   b. Add **plus sphere** (go in plus direction by dialing down) until **almost** neutralize the reflex in the first meridian which neutralizes (leave a small amount of with movement).

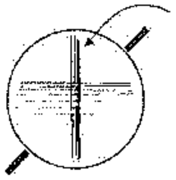
   c. Rotate streak approximately 90° and set plus cylinder **axis parallel** to remaining with movement. (May drop sleeve temporarily to help "enhance" remaining with movement, helping to define the axis position for **high** cylinders. Do not forget to raise sleeve before next step.)

   d. Add plus cylinder until **almost** neutralize the remaining with movement (in the second principal meridian).



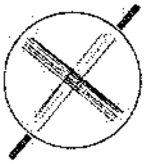
Retinoscopy (basic plus cylinder technique), cont.

e. **Refine axis.** Sweep 45° to either side of axis, moving in slightly to pick up more with movement if necessary. Move axis **toward** the "guide line", that is, toward the narrower, brighter reflex.



move axis toward this "guide line" by 5° or so until sweeps are balanced 45° to either side of axis

f. **Refine cylinder power** by moving in, sweeping in both principal meridians, and backing off to see if both meridians neutralize equally. If not, change sphere or cylinder appropriately.



5. After both eyes are done, dial in -1.50 D of sphere (6 clicks up). If your working distance is shorter than usual, you may find that 7 clicks up is optimal for the best visual acuity, but still use 5 or 6 clicks if you are going to refine the refraction subjectively.

subtract working distance

DONE

6. Record retinoscopy results as follows:

RNS +3.00 + 1.00 x 055 = 20/40+2
+1.00 + 2.25 x 165 = 20/15 = retinoscopy

CRNS = Cyclopentolate retinoscopy
HRNS = Homatropine retinoscopy
ARNS = Atropine retinoscopy

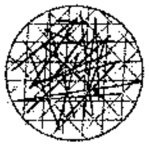
Retinoscopy (basic minus cylinder technique)

1. Set phoropter to +1.50 sph and zero cyl both eyes.

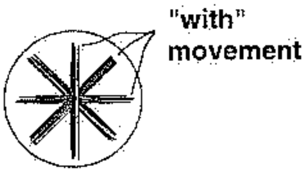
2. If **manifest** RNS, both of patient's eyes should be open; he or she should look just past your ear at a fixation light at the end of the room. The patient must be fogged (overplussed), relative to the wall chart, at all times in both eyes. Learn to retinoscope patient's right eye with your right eye and the left eye with your left eye.
   If **cycloplegic** or **aphakic** RNS, occlude patient's other eye and have him or her look directly at the retinoscope light. No need to worry about fogging the other eye.
   If **strabismic** patient, occlude the other eye.
   If patient is under anesthesia, locate approximate line of sight by observing the corneal light reflex.

3. Use working distance best for you, as far away as comfortable.

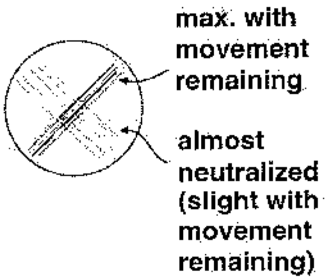
4. Observe retinoscopic reflex in various meridians with retinoscope sleeve all the way **up** (Copeland 'scope). Always sweep the streak perpendicular to itself.



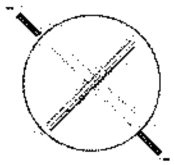
   a. Add **minus sphere** until obtain "with" motion in all directions. (If reflex is dull and motionless, try high plus or high minus correction.) (Dial **up** for minus sphere.)



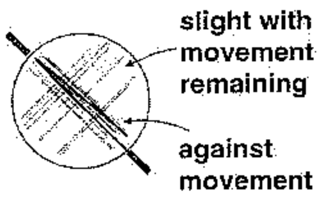
   b. Add **plus sphere** (go in plus direction by dialing down) until **almost** neutralize the reflex in the first meridian which neutralizes (leave a small amount of with movement).



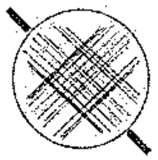
   c. Set minus cylinder **axis 90°** to remaining with movement. **Judge** perpendicularity, do not look at numbers. (May drop sleeve temporarily to help "enhance" remaining with movement, helping to define the axis position for **high** cylinders.)



   d. Continue adding **plus sphere** (dial down) until **almost** neutralize the with movement in the orthogonal meridian. The first meridian now shows against movement.

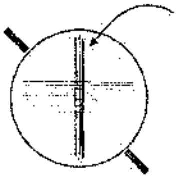


e. Neutralize the against movement in the first meridian by adding **minus cylinder.** Continue through the dead zone until observe **slight** with movement, the correct endpoint.



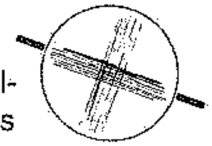
slight with movement in both principal meridians

f. **Refine axis.** Sweep 45° to either side of axis, moving **in** slightly to pick up more with movement if necessary. Move axis **away from** the "guide line", that is, away from the narrower, brighter reflex.



move axis <u>away</u> from this "guide line" by 5° or so until sweeps are <u>balanced</u> 45° to either side of axis

g. **Refine cylinder power** by moving in, sweeping in both principal meridians, and backing off to see if both meridians neutralize equally. If not, change sphere or minus cylinder appropriately.



5. After both eyes are done, dial in -1.50 D of sphere (6 clicks up). If your working distance is shorter than usual, you may find that 7 clicks up is optimal for the best visual acuity, but still use 5 or 6 clicks if you are going to refine the refraction subjectively.

subtract working distance

DONE

6. Record retinoscopy results as follows:

RNS +3.00 - 1.00 x 150 = 20/40+2
+1.00 - 2.25 x 165 = 20/15 = retinoscopy

CRNS = Cyclopentolate retinoscopy
HRNS = Homatropine retinoscopy
ARNS = Atropine retinoscopy

Subjective refraction (cross cylinder method) (plus cylinders)

1. Start with retinoscopic finding. If not available, use old correction.

2. Take vision (using **your** chart in **your** room).

3. Adjust sphere to the most plus or least minus which gives best visual acuity. Try plus sphere first; ask "Is this better or worse?" If no improvement, try minus sphere; ask "Is this better, or just smaller and darker?"

4. Use cross cylinder to refine cylinder axis and power:
   a. Use a line on the chart 1 or 2 lines larger than the patient can read.
   b. (If no cylinder is present, **look for one** by testing with cross cylinder at 90° and 180°, then at 45° and 135°.)
   c. Refine **axis** first.
      1. Position cross cylinder axes 45° to principal meridians.
      2. Flip cross cylinder; ask "Which is better, 1 or 2 (3 or 4, etc)?"
      3. Leave cross cylinder in the preferred position and rotate the cylinder axis 5° or so **toward** the **+ axis** (white) of the cross cylinder.
      4. Repeat until converge on axis.
   d. Refine **cylinder power.**
      1. Align cross cylinder axes with principal meridians.
      2. Flip cross cylinder; ask "Which is better, 1 or 2 (3 or 4, etc)?"
      3. Leave cross cylinder in the preferred position. If the + axis of the cross cylinder in the preferred position is aligned with the axis of the correcting cylinder, add **more** plus cylinder to correction. If + axis of cross cylinder is 90° to axis of correction, subtract plus cylinder from correction.
      4. Keep track of cylinder power added or subtracted, and compensate at the same time by adding half as much sphere power in the opposite direction (to keep the "circle of least confusion" on the retina).
   e. Recheck axis and cylinder power refinement until no further change is necessary. (Tricking the patient is usually necessary to do cross cylinder refinement well. Reversing the presentation of flip choices will often reveal that the patient has been leading you in a circle.)

5. Find best sphere by "fogging" (add plus sphere by dialing down) until vision blurs; then unfog until best acuity is **barely** reached. (Adding too much minus sphere will cause the letters to become smaller and darker. Ask "Is this better, or just smaller and darker?" as unfog.)

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6. If patient has equal corrected vision in both eyes, consider binocular balancing.
7. Consider adding another -0.25 D sph to final refraction as determined above in order to move the corrected far point from 4 meters to infinity.
8. If correction is greater than 5 to 7 D, plus or minus, determine vertex distance (especially with **aphakic** corrections).

Subjective refraction (cross cylinder method) (minus cylinders)

1. Start with retinoscopic finding. If not available, use old correction.

2. Take vision (using **your** chart in **your** room).

3. Adjust sphere to the most plus or least minus which gives best visual acuity. Try plus sphere first; ask "Is this better or worse?" If no improvement, try minus sphere; ask "Is this better, or just smaller and darker?"

4. Use cross cylinder to refine cylinder axis and power:
    a. Use a line on the chart 1 or 2 lines larger than the patient can read.
    b. (If no cylinder is present, **look for one** by testing with cross cylinder at 90° and 180°, then at 45° and 135°.)
    c. Refine **axis** first.
        1. Position cross cylinder axes 45° to principal meridians.
        2. Flip cross cylinder; ask "Which is better, 1 or 2 (3 or 4, etc)?"
        3. Leave cross cylinder in the preferred position and rotate the cylinder axis 5° or so **toward** the - **axis** (red) of the cross cylinder.
        4. Repeat until converge on axis.
    d. Refine **cylinder power**.
        1. Align cross cylinder axes with principal meridians.
        2. Flip cross cylinder; ask "Which is better, 1 or 2 (3 or 4, etc)?"
        3. Leave cross cylinder in the preferred position. If the - axis of the cross cylinder in the preferred position is aligned with the axis of the correcting cylinder, add **more** minus cylinder to correction. If - axis of cross cylinder is 90° to axis of correction, subtract minus cylinder from correction.
        4. Keep track of cylinder power added or subtracted, and compensate at the same time by adding half as much sphere power in the opposite direction (to keep the "circle of least confusion" on the retina).
    e. Recheck axis and cylinder power refinement until no further change is necessary. (Tricking the patient is usually necessary to do cross cylinder refinement well. Reversing the presentation of flip choices will often reveal that the patient has been leading you in a circle.)

5. Find best sphere by "fogging" (add plus sphere by dialing down) until vision blurs; then unfog until best acuity is **barely** reached. (Adding too much minus sphere will cause the letters to become smaller and darker. Ask "Is this better, or just smaller and darker?" as unfog.)

---

6. If patient has equal corrected vision in both eyes, consider binocular balancing.
7. Consider adding another -0.25 D sph to final refraction as determined above in order to move the corrected far point from 4 meters to infinity.
8. If correction is greater than 5 to 7 D, plus or minus, determine vertex distance (especially with **aphakic** corrections).

Reading adds

Estimate from patient's age; modify by knowledge of reading or working requirements.

Start with +1.25 as first add age 40-45.

Progress to +2.50 by age 60.

Use +2.50 for aphakes with good vision; +3.00 or more if poorer vision.

Adds up to +4.00 are readily available; higher adds cost more.

Best method to **determine**: Use **manifest** correction in **trial frame** and add appropriate plus sphere until clear vision is obtained at comfortable or required reading distance. Better to prescribe add that is too weak than too strong!

Prescribe **equal** add in both eyes unless rare circumstances.

Intermediate add in trifocals (not prescribed unless patient complains about intermediate distance) is usually equal to 1/2 of the full add.

If change distance correction (i.e. with nuclear sclerotic cataracts), it is often best to adjust add accordingly to keep reading distance the same.

If only reading glasses are necessary, consider "dime store magnifying glasses", which are actually very good quality and inexpensive (full size or half-eye). Power is sometimes marked by "focus number," the focal length in inches, as follows:

Focus number	Equivalent diopters
32	+1.25
26	+1.50
22	+1.75
20	+2.00
18	+2.25
16	+2.50
14	+2.75
12	+3.25
10	+4.00
8	+5.00

Recording refractions

RNS
+3.00 +3.00 x 15 = 20/40+2
+1.00 +2.25 x 105 = 20/15
= **manifest** retinoscopy

dilated RNS = dilated retinoscopy
CRNS = Cyclopentolate retinoscopy
HRNS = Homatropine retinoscopy
ARNS = Atropine retinoscopy

M
+1.00 +2.50 x 180 = 20/20 add +2.00 = J1 @ 12"
+2.00 Sph = 20/15 add +2.00 = J1 @ 12"
= manifest refraction

Dilated
+1.50 +2.50 x 180 = 20/20
+2.50 Sph = 20/15

Cycloplegic (agent)
+1.75 +2.50 x 180 = 20/20
+2.75 Sph = 20/15

note: reading adds should not be determined when dilated or under cycloplegia.

note: **Manifest** means **without cycloplegia**. This term is often used as synonymous with **subjective** refraction. This usage should not be continued. If the refraction is a cycloplegic one, it should be so specified. Subjective refinement of all refractions is **assumed** unless the refraction is identified specifically as a retinoscopy.

Cycloplegia

Patients for whom a cycloplegic refraction is indicated:

Probably any patient under age 15 before prescribing glasses. (Manifest refraction should rarely be relied upon under age 10 and usually need not be done.)

Hyperopes in general, up to age 35, especially if symptomatic.

Any patient with asthenopia suggestive of accommodative problems.

Patients who tend to accommodate during manifest refraction.

Remember before using cycloplegic drops:

Amplitude of accommodation cannot be measured afterward.

Reading adds cannot be determined.

Phorias and tropias are often affected.

Cycloplegic to use

Mydriacyl (0.5% or 1%) — Use with phenylephrine 2.5% for routine **dilation**. Usually not strong enough for cycloplegia in children.

Cyclogyl (1%) — Best drug for routine use in all children.

Homatropine (5%) — Occasionally used instead of Cyclogyl, but Cyclogyl is faster and usually more effective.

Atropine (0.5% or 1% drops or 1% ointment) — Only necessary for strabismus cases. (Used often for initial evaluation of strabismus in children, especially in children with heavily pigmented irides.)

How administered:

Mydriacyl — 2 drops into lower fornix; wait 20 to 30 min
Cyclogyl — 2 drops into lower fornix; wait 30 min
Homatropine — 2 drops into lower fornix; wait 1 hour
Atropine — 1 drop bid x 2 days, then x 1 on morning appointment (if ointment used, omit dose on morning of appointment)

(Note: use topical anesthetic before Mydriacyl, Cyclogyl, or homatropine.)

Duration of action: (highly variable) (mydriasis lasts longer than cycloplegia)

Mydriacyl — 2-4 hours
Cyclogyl — 6 - 24 hours
Homatropine — 8 hours - 2 days
Atropine — 2 days - 2 weeks

Cycloplegia, cont.

Toxicity

Allergic, or hypersensitivity, reaction

signs: conjunctivitis
swollen lids
dermatitis

See with **atropine**, less frequently with **scopolamine**. Rarely, if ever with Mydriacyl, Cyclogyl, or homatropine.

Hypnotic effect

See with **scopolamine**; occasionally with **Cyclogyl** or **homatropine.**

Systemic intoxication (atropine)

signs: fever, dry mouth
flushing of the face
rapid pulse
nausea, dizziness
if severe: delirium

Remember!
1 drop of 1% atropine = 0.5 mg atropine

Treatment: supportive measures;
physostigmine if severe

Prescribing

(Rough guidelines; some are controversial.)

If patient has good vision and is asymptomatic, do not give new glasses or change old ones.

Do not prescribe minor corrections (0.25 D cylinders, +0.50 sph OU, -0.25 sph OU) unless patient can definitely tell the difference.

For eyes with no useful vision, prescribe "balance" lenses (cheaper than plano lenses).

Recognized indications for tinted lenses are rare.

In general, leave bifocal style and position up to the optician; however it is often wise to specify "same bifocal style as old glasses."

Base prescription on as complete data as necessary and/or possible:
- Uncorrected visual acuity
- Present correction and visual acuity obtained
- Manifest refraction and visual acuity obtained
- Cyclopleglic refraction and visual acuity obtained
  - **Over**-refract if correction is more than ± 5.00 D, and read resultant through lensmeter.

If **myopia**

Threshold for prescribing in a child: when binocular distance visual acuity is worse than 20/30 (usually occurs at about -1.50 D OU).

Try to limit progression of the myopia (linked to prolonged near work inside the far point, with the images tending to fall behind the retinas):
- Do not **over**correct! (Never prescribe more minus than the cycloplegic refraction.)
- Consider undercorrecting by 0.50 to 0.75 D up to age 30 if the patient is agreeable (but adults usually demand full correction, at least to the end of the room).
- Encourage removing glasses for prolonged close work.
- Encourage looking up frequently from close work.

If myopia is rapidly progressing:
- Consider bifocals ± chronic atropinization (controversial). (If use atropine, prescribe UV filter in glasses.)
- In the middle- to older-age adult, cause is almost always nuclear sclerosis. If increase minus for distance vision, add plus power to add to keep reading distance the same.

Prescribing, cont.

If **hyperopia**

Threshold for prescribing in a child: when visual acuity is not developing properly (usually occurs with refraction of +5.00 D or more). Can confirm by noting absent or insufficient accommodation on a near target held just beneath the retinoscope peephole (dynamic retinoscopy). In that case, prescribe close to the full plus correction (perhaps subtract 0.50 D).

If symptomatic (asthenopia, intermittent blurring, trouble reading): Give full **manifest** refraction, if sufficiently different from what patient is wearing that symptoms are likely to be relieved. If only have cycloplegic refraction, give 1/2 to 2/3 of the full correction in children; more in adults.

Do not overcorrect hyperopes; adjust for difference between end of room and infinity.

If **anisometropia**

Threshold for prescribing in a child: when visual acuity is not developing properly in the eye with the higher refractive error (most commonly with 1.00 D or more of **hyperopic** anisometropia).

If prescribing, generally give the full anisometropic **difference** to promote binocularity. For example, if refraction is RE plano, LE +2.00, might prescribe plano, +2.00; or -1.00, +1.00; but **not** plano, +1.00.

Exception #1: If patient has natural "monovision" (one eye focused for distance and the other eye for near), do not correct unless patient insists.

Exception #2: If **amblyopia** is present and occlusion is not convenient or tolerated, consider over-plussing the sound eye to cause distance fixation to switch to the amblyopic eye as confirmed by cover testing or distance vectographic chart. This "optical penalization" usually requires +0.75 to +2.00 D of over-plus, works with amblyopia as bad as 20/40 or so, and is an excellent method of long-term treatment of mild amblyopia in the school-age years. Can use **atropine** penalization of sound eye if amblyopia is worse, in which case the full cycloplegic correction is necessary for the sound eye (with UV filter) unless penalization is only part-time (1 to 3 consecutive days per week).

Prescribing, cont.

If **strabismus** with possible refractive or accommodative component

Give **full** cycloplegic refraction, adding bifocals if still have more than 8^{Δ} of esotropia at near.

If alignment is not obtained with glasses, consider surgery.

Try to wean off bifocals (and hyperopic correction also if possible) by age 8 to 10 years without losing fusion/stereopsis. If cannot wean off bifocals, consider surgery.

If **astigmatism**

Threshold for prescribing in a child: when visual acuity is not developing properly (usually with 1.50 D or more of astigmatism.

Generally give the full cylinder at the correct axis.

Children always tolerate and adapt to the full correction.

Adults may not. In adults when the change in astigmatic correction is significant:

- Be sure your refraction is correct.
- Give patient a walking-around trial with new correction in a trial frame.
- Give warning and encouragement.
- Be willing, if patient is sufficiently uncomfortable, to reduce distortion by:
  - If a new cylinder:
    - Reduce the cylinder power.
    - Consider rotating the axis toward 90° or 180°.
  - If a new axis for a significant cylinder previously worn:
    - Rotate toward the old axis.
- Balance the reduced distortion against the resulting increase in blur by careful adjustment of cylinder power and sphere. Do not blindly prescribe the spherical equivalent. Minimize residual astigmatism at **any** axis setting by using the cross cylinder test for cylinder power.

Contact lenses, which produce little or no distortion, will often provide the solution when all else fails.

Prescribing, cont.

If **post-op anisometropia** (or loss of pre-op anisometropia)

- If diplopia or asthenopia in reading position from induced vertical prism:
  - Consider contact lenses, single vision reading glasses, or raising the reading segments to lessen the induced vertical prism.
  - Consider slab-off prism on the more minus or less plus lens (or reverse slab on the less minus or more plus lens), **measuring** the vertical deviation in reading position rather than calculating (because of unknown amount of previous adaptation).

- If symptomatic from overall size difference (aniseikonia):
  - Consider contact lens/ spectacle Galilean telescope arrangement **added** to present correction.
    - Example: Over-plussing an aphakic contact lens by 4.00 D and wearing a -4.25 D spectacle lens yields 6% minification.

- Consider converting patient to monovision (one eye for distance and the other for near), if the vision is good in both eyes and ocular dominance is not too strong. Can use **either** contact lenses or glasses. The dominant eye is usually preferred for distance.

Prescribing Cylinders: The Problem of Distortion

Why can some patients not tolerate the full astigmatic correction? The reason is distortion of the **binocular** spatial sense caused by meridional magnification in one or both eyes. If a retinal image is magnified more in one direction than the other, vertical lines may become slanted, horizontal lines may become tilted, objects may appear taller, or shorter, and these effects are **greatly** magnified under binocular conditions. (Perceived distortion should essentially disappear when covering one eye!)

Uncorrected astigmatism causes only a very small amount of distortion, and in the opposite direction to that caused by the correcting cylindrical spectacle lens. The cylindrical spectacle lens itself, located relatively far from the entrance pupil of the eye, primarily determines the magnitude and orientation of the distortion produced. Magnitude is determined by the power of the lens, and orientation by the axis position. In addition, the plus cylinder form of spectacle lens (cylinder ground on the front surface) introduces a small amount of additional distortion, but this form has been dispensed only rarely in recent years (not to be confused with the **prescription** being written in plus cylinder form).

To minimize distortion, minus cylinder spectacle lenses should be used (as they usually are), and vertex distances should be kept to a minimum (there is no significant distortion with contact lenses).

Distortion may be reduced further, if necessary, at the expense of visual acuity, by decreasing the cylinder power from the correct value, or by rotating the cylinder axis toward 90°, toward 180°, or toward the old axis. Although reducing the cylinder power often gives good results, many prefer to rotate the cylinder axis toward 90° or 180°, producing a vertical or horizontal distortion which is better tolerated. **If** the cylinder axis is rotated away from the correct orientation, cylinder power should definitely be reduced. The optimal value for cylinder power, under these conditions, to result in the least residual astigmatism, may be simply and easily found by applying the Jackson cross cylinder test for cylinder power, aligning the axes of the cross cylinder parallel and perpendicular to the new axis of the correcting cylinder.

When reducing the cylinder power by any method, the sphere should be adjusted appropriately, using the spherical equivalent concept as a guide, but relying on a final subjective check for best accuracy.

Prescribing Cylinders: The Problem of Distortion, cont.

In summary, generally prescribe the full cylinder at the correct axis. **Children** always tolerate and adjust to the full correction. **Adults** may not. In adults, when the change in astigmatic correction is significant:

1. Be sure your refraction is correct.
2. Give the patient a walking-around trail with the new correction in a trial frame.
3. Give warning and encouragement.
4. Be willing, if the patient is sufficiently uncomfortable, to reduce the distortion by:
    a. Rotating the cylinder axis toward 90°, toward 180°, or, in older patients, toward the previous axis position; and/or by
    b. Reducing cylinder power (first choice in young adults).
5. Balance the reduced distortion against the resulting increase in blur by careful adjustment of cylinder power and sphere. Do not blindly prescribe the spherical equivalent. Minimize residual astigmatism at **any** axis setting by using the cross cylinder test for cylinder power.

Contact lenses, which produce little or no distortion, will often provide the solution when all else fails.

People **adapt** to distortion: children quickly and physiologically, adults slowly and "psychologically." Removing cylindrical correction after adaptation can result in **perceived** distortion until readaptation occurs. This is seen in adults when switching from glasses to contact lenses, and after anterior segment surgery with purposeful or inadvertent correction of preoperative astigmatism. Again, only if the patient is fusing will symptoms occur. Such symptoms are usually attributed to the "breaking in period" for the new contact lenses, or to the recovery period after surgery, and complaints are rare. However, surgical techniques have changed so much that patients expect almost immediate visual recovery (i.e. "no stitch" surgery and topical anesthesia). If we alter the astigmatism surgically without discomfort or accompanying morbidity, the resulting spatial distortion may be so obvious and bothersome that we will find it best to leave the astigmatism alone when performing such surgery — for exactly the same reason that many seasoned ophthalmologists are wary about changing the cylinder axis in an older person's glasses.

References:

Guyton DL. Prescribing cylinders: the problem of distortion. Surv Ophthalmol 1977; 22:177-188.

Guyton DL. Prescribing Cylinders Postoperatively. In Ernest JT (ed): Year Book of Ophthalmology 1985, Chicago, Year Book Medical Publishers 1985, pages 63-66.

Irregular Astigmatism and Monocular Diplopia

Monocular diplopia is a frequent and confusing complaint in general ophthalmic practice. Under certain conditions, up to 80% of normal eyes can experience monocular diplopia. White letters or lines on a dark background, such as chalk marks on a blackboard, or neon signs at night, are most likely to elicit monocular diplopia.

The usual cause of monocular diplopia is optical irregularity in the eye, arising either in the cornea or in the crystalline lens. Such irregularities may be lumped together under the term "irregular astigmatism," with this term indicating any irregular refractive property of the eye (i.e. scissors movement noted on retinoscopy).

Other causes of monocular diplopia, usually obvious, are a decentered contact lens, double reflection in spectacle lenses, transient sensory adaptation after strabismus surgery, and distortion from retinal lesions occasionally interpreted by the patient as diplopia.

The fact that most eyes can achieve 20/20 acuity even with moderate degrees of irregular astigmatism indicates that only a portion of the rays passing through the eye's pupil are sufficient to form a satisfactory image. This fact has been used in the design of several types of bi- and multifocal contact lenses and intraocular lenses.

Irregular astigmatism causes confusion with retinoscopy and with astigmatic dial methods of refracting. The Jackson cross cylinder technique is probably the best method of refraction in cases of irregular astigmatism.

Monocular diplopia from optical irregularities may be **confirmed** by observation of these irregularities by scissors movement on retinoscopy, by eliminating the diplopia with a pinhole, by passing the edge of a card over half of the pupil, or by eliminating the diplopia with a trial contact lens (in those 30% of cases where the irregularity arises in the cornea).

A few patients will complain of monocular diplopia that occurs only after reading. In some such cases keratoscopic photographs have confirmed deformation of the cornea from the upper lid's resting in a lowered reading position for long periods. Prescription of single vision reading glasses may be necessary for these patients to allow variation in direction of gaze during reading.

Irregular Astigmatism and Monocular Diplopia, cont.

Treatment of monocular diplopia includes trying a different refractive correction, contact lenses, or miotics such as pilocarpine or simply **more light.** The best treatment of monocular diplopia is explanation, demonstration that it can be eliminated by optical techniques, and reassurance that the patient does not have a brain tumor. Once reassured, most patients can easily learn to live with monocular diplopia and can often learn to ignore it entirely.

References:

Bowman KJ, Smith G, Carney L. Corneal topography and monocular diplopia following near work. Am J Optom Physiol Optics 1978; 55:818-823.
Coffeen P, Guyton DL. Monocular diplopia accompanying ordinary refractive errors. Am J Ophthalmol 1988; 105:451-459.
Guyton DL. Diagnosis and treatment of monocular diplopia. Focal Points: Clinical Modules for Ophthalmologists. Vol II, Module 2. 1984.
Records, RE. Monocular Diplopia. Surv Ophthalmol 1980; 24:303-306.

The Bag of Glasses Syndrome

Various symptoms:

- "Glasses not right"
- Blurred, distorted, or double vision
- Asthenopia, headaches
- etc., etc., etc.

Signs:

- Detailed written documentation of ophthalmic history, often with underlining in red.
- Paper bag (men) or large purse (women) containing multiple pairs of glasses.
- Glasses numbered, all close to the same prescription.
- Presentation during busiest hours, with angry patients waiting to be seen.

Common causes:

- Bifocal segments too low
  — should be level with lower lid.
- Dry eyes
  — Schirmer test, rose bengal, etc.
- Decreased blinking when reading or using the computer screen
  — blink rate <3/min; must learn to blink more often
- Surgically-induced anisometropia
  — with diplopia in downgaze; consider slab-off, reverse slab, or contact lenses.
- Plus cylinder on old glasses
  — check with Geneva lens clock.
- Change in base curve
  — check with Geneva lens clock.

If all else fails:

DO NOT REFER TO THE AUTHORS!

General References

(*recommended, **highly recommended)

General study and review

** American Academy of Ophthalmology, Basic and Clinical Science Course. Section 3: Optics, Refraction and Contact Lenses. Revised every three years. Excellent.

* Hunter and West, Last Minute Optics. Slack, 1996, 128 pp. Question-and-answer format for review.

MacInnis, Ophthalmology Board Review: Optics and Refraction. Mosby, 1994, 340 pp. Wealth of material including multiple-choice problems and solutions.

Visual optics

* Michaels, Visual Optics and Refraction, a Clinical Approach, 3rd ed., Mosby, 1985, 654 pp. Out of print. Complete textbook, excellent references, wealth of material.

** Rubin, Optics for Clinicians, 2nd ed., Triad, 1974, 367 pp. Readable, common sense optics - little math - good teaching book.

** Bennett and Rabbetts, Clinical Visual Optics, 2nd ed., Butterworths, 1992, 424+ pp. Superb up-to-date British text. Exact and complete. Problems and answers.

* Elkington and Frank, Clinical Optics, Blackwell, 1984, 164 pp. Excellent, concise, practical. Many diagrams. British terminology.

Campbell, et al., Physiological Optics, Harper and Row, 1974, 269 pp. Out of print. Numerous illustrations - more technical than others but simply presented.

Ogle, Optics. An Introduction for Ophthalmologists, 2nd photocopy ed., Thomas 1979, 288 pp. Good - more math than others - simplified physicist's approach.

Geometric optics

Fry, Geometrical Optics, Chilton, 1969, 290 pp. Out of print. Thorough - pure geometric optics - reference only.

Southall, Mirrors. Prisms and Lenses, 3rd ed., 1933 (1964 - Dover), 806 pp. Out of print. Classic textbook - reference only.

General Refernces, cont'd.

Ophthalmic instruments

Henson, Optometric Instrumentation, 2nd ed., 1996, 254 pp. Excellent text with numerous diagrams and references.

Refraction

** Michaels, Basic Refraction Techniques, Raven 1988, 188 pp. Excellent practical text. Light on theory; heavy on essentials. Best buy.

* Michaels, Visual Optics and Refraction, a Clinical Approach, 3rd ed., Mosby, 1985, 654 pp. Out of print. Complete textbook, excellent references, wealth of material.

** Bennett and Rabbetts, Clinical Visual Optics, 2nd ed., Butterworths, 1992, 424+ pp. Superb up-to-date British text. Exact and complete. Problems and answers.

Reinecke and Herm, Refraction: A Programmed Text, 3rd ed., Appleton-Century-Crofts, 1983, 373 pp. Good programmed text but difficult reference - leans toward minus cylinders.

* Corboy, The Retinoscopy Book, an Introductory Manual for Eye Care Professionals, 3rd ed., Slack 1989, 123 pp. Spiral bound clinical treatise on the Copeland method of streak retinoscopy.

** Copeland, Streak Retinoscopy, current, 32 pp. Instruction manual for Copeland-Optec 360 Streak Retinoscope; available from Stereo Optical Co., Inc., 3539 N. Kenton Ave., Chicago, IL 60641.

Garcia, Handbook of Refraction, 4th ed., Little, Brown, 1989, 244 pp. Good general text; entirely clinical; leans toward minus cylinders and dial methods; heavy clinical impressions.

Borish, Clinical Refraction, 3rd ed., Professional Press, 1970, 1400 pp. Optometrists' equivalent to Duke-Elder; good reference source heavy on the optometric literature.

* Milder and Rubin, The Fine Art of Prescribing Glasses, 2nd ed., Triad, 1991, 544 pp. Excellent and detailed; wordy but enjoyable.

Granddaddy reference

Duke-Elder, System of Ophthalmology, Vol. 5, Ophthalmic Optics and Refraction, Mosby 1970, 879 pp. Excellent guide to older literature, reference only.

General Refernces, cont'd.

Newer reference text

Duane, Clinical Ophthalmology, Vol. 1, chapters 31-70, Refraction and Clinical Optics, Harper and Row, 1993. Looseleaf text. Multi-author; many excellent sections but with varying breadth and depth of coverage at the present time; updated yearly. Primarily a reference text, not a teaching text.

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