

# Optics Review

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line drawings by Angie England



**UNIVERSITY OF IOWA**  
CARVER COLLEGE  
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University of Iowa Health Care

*Department of Ophthalmology and Visual Sciences*

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## 1. Light

### *a. Nature of Light*

Light resembles sound in that it passes through a media; but unlike sound, it can also travel across a vacuum. This dual behavior of light, i.e. the ability to travel through a media as well as across a vacuum, has led to separate theories of its nature: wave theory and quantum theory.

Classically, light has been considered as a “stream of particles”, a “stream of waves” or a “stream of quanta”.

*Physical Optics* examines light as energy particles that are emitted by light sources and absorbed by other substances (*Wave or Quanta Theory of Light*).

- *Wave Theory* helps to understand how light interacts with itself, different media and various surfaces. Wave theory allows us to understand the naturally occurring phenomena of interference, diffraction and polarization.
- Diffraction causes a decrease in normal visual acuity for apertures less than 2 mm (such as a very small pupil of the eye).

*Geometric Optics* deals with the formation of images by rays of light acted on by lenses, prisms and mirrors (*Particle Theory of Light*).

- The concept of vergence is the unifying concept between wave theory and geometric optics.

*Quantum Optics* deals with the interaction of light and matter. It considers light as having both wave and particle (photon) characteristics. When light interacts with matter, photons are emitted or absorbed.

- Visible light is in the very narrow portion of the electromagnetic spectrum with wavelengths roughly between 400 and 800 nanometers (380 – 760nm or  $4 \times 10^{-6}$  m to  $8 \times 10^{-6}$  m). This portion of the electromagnetic spectrum represents approximately 1% of the sun’s electromagnetic spectrum that ranges from  $1 \times 10^{-16}$  m to  $1 \times 10^6$  m.
- Yellow light is the standard wavelength for calibration. It holds mid position in the chromatic interval of the emmetropic eye and so is in best focus.
- A photon of wavelength 100 nm has 12.50 eV per photon. A photon of wavelength 193 nm has 6.4 eV per photon. This shows why shorter wavelengths of light (e.g.

ultraviolet) have greater potential for photic damage, due to their higher energy level.

### *b. History of Light*

- Newton, in 1665 stated that light was made of particles that moved in straight lines.
- One hundred years later, Kristian Huygens, a Dutch mathematician, suggested that the light was a wave form, after observing that a small amount of light was always bent onto the shadow behind an opaque object.
- Thomas Young proved the wave nature of light with a double slit defraction experiment.
- Einstein taught that the speed of light in a vacuum is always 186,000 miles per second regardless of the speed of the observer or the source. This was proven by the Michelson-Morely experiment. Einstein's work on light concluded that light really does act as a particle, but a particle that has wave properties.
- The Heisenberg principle rationalizes that when you try to measure something too precisely, the act of measurement itself, changes the thing being measured. This has led to light particles being called photons or quanta. Heisenberg suggested that quanta have wave properties.
  - o When light is considered as being composed of quanta, the results of all experiments and physical phenomenon can be predicted.
  - o A quanta of light's energy (E) is described by the equation  $E = h\nu$ , where  $\nu$  is the frequency of the light wave and h is Planck's constant:  $6.626 \times 10^{-34}$  J/sec.
  - o Frequency and wavelength of light are related in the equation  $c = \nu w$  where  $c$  = speed of light,  $\nu$  = frequency and  $w$  = wavelength. Therefore, the constancy of the speed of light, c, guarantees a constant relationship between frequency and wavelength.

### *c. Movement of Light*

- Movement of light by convention is from left to right. Positive numbers measure in the direction of light, negative measure against the direction of light. Therefore, a positive lens or waveform is converging and a negative lens or waveform is diverging.
- All naturally occurring wave fronts are diverging as they emerge from a source.
- As light rays approach infinity, they become parallel.
  - o Optical infinity is considered 20 feet (6 m) or greater.

## 2. Vergence

Vergence is defined as the reciprocal of the distance from a reference point (in meters) to the point of focus.

- Vergence is measured in diopters. (1 diopter =  $1/1\text{m} = 100/100\text{cm}$ )
- The vergence of the light rays coming from an object is directly related to the distance from the object.

In Figure 1, the divergence of rays of light emanating from point O is,

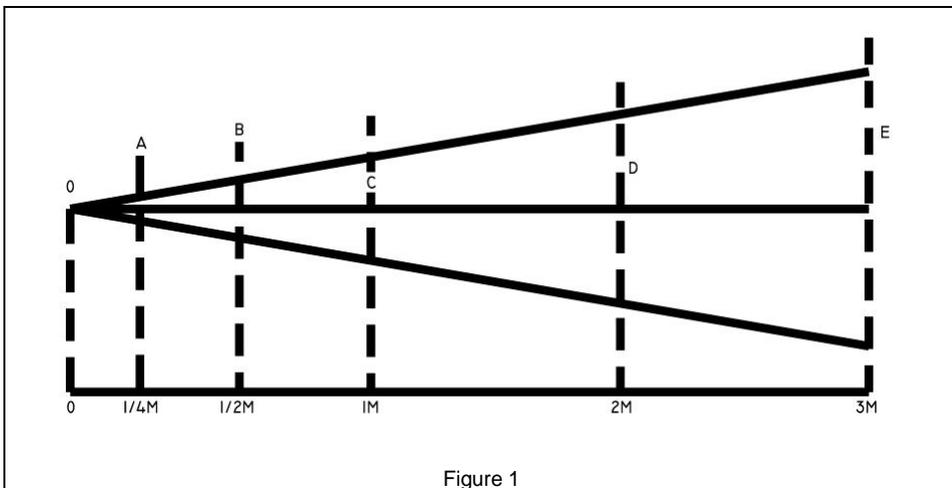
at A,  $1/-0.25 = -4.00\text{D}$ ;

at B,  $1/-0.50 = -2.00\text{D}$ ;

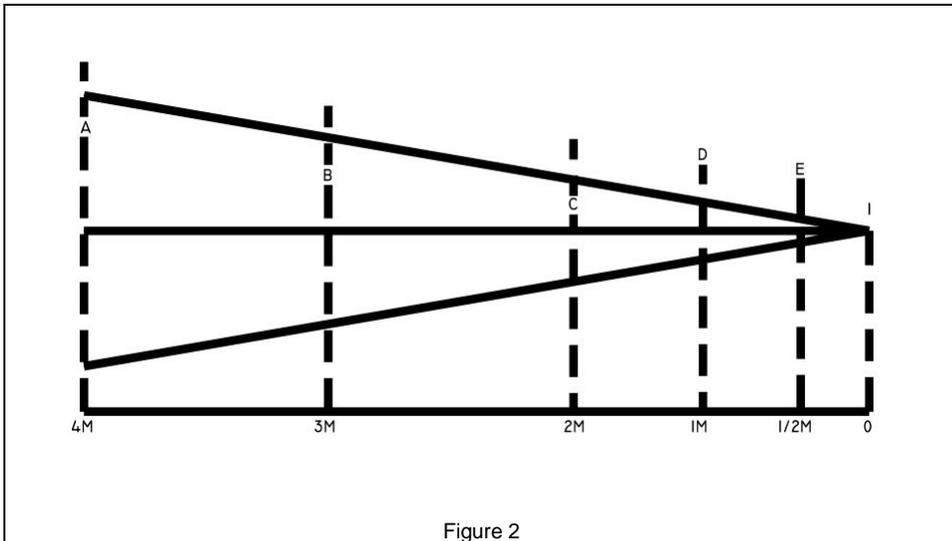
at C,  $1/-1 = -1.00\text{D}$ ;

at D,  $1/-2 = -0.50\text{D}$  and

at E,  $1/-3 = -0.33\text{D}$ .



In Figure 2, the convergence of the rays of light, converging to the point I is, at A,  $1/4 = +0.25D$ ; at B,  $1/3 = +0.33D$ ; at C,  $1/2 = +0.50D$ , at D,  $1/1 = +1.00D$  and at E,  $1/0.5 = +2.00D$



By convention, divergence is given in minus (–) vergence power and convergence is given in plus (+) vergence power.

- Convergent wave fronts are not found spontaneously in nature. They are the result of an alteration of a planar or divergent wave front by a refractive or reflective medium.
- An object (O) is defined as a point or extended source that the pencil/beam of light comes from.
- The object's distance from the object to the point of reference is designated as  $u$ .
- The object's vergence (U) is the distance from the object to the point of reference.  
 $U = 100/u$  (cm)
- The image (I) is defined as a point or extended source that the pencil/beam of rays go to.
- The image distance is measured from the point of reference to the image and is defined as  $v$ .
- The image's vergence (V) is the distance from the image to the point of reference.  
 $V = 100/v$  (cm)
- When defining an optical system, it is conventional to set the incoming rays as object rays, the outgoing rays as image rays, and light travels from left to right.

**Definition. Diopter:** a unit of accommodative amplitude; it describes the vergence of a waveform and describes the vergence at a specific distance from the source; and it is also defined as the power of the lens. A diopter is the reciprocal of the distance in meters.

### 3. Lens Systems

#### Objects and Images for Lens Systems (*Figure 3*)

- Real objects have diverging rays and are on the same side as the incoming object rays.
- Virtual objects are not naturally occurring and have converging rays.
- Real images have a focal point that can be focused on a screen and therefore are on the same side as the outgoing image rays.
- Virtual images cannot be focused on a screen and are always on the left side of the lens system.
- A virtual object may also have a virtual image.
- When light rays are about to cross, they are considered to have positive (+) vergence (convergence) and when they are receding from their crossing point, they are said to have negative (−) vergence (divergence).
- Rays that cross at the focal point of the lens are considered to have an infinite amount of vergence. Therefore, rays that are parallel (have no crossing point), have a vergence of zero.
- Converging lenses have real/inverted images that are on the opposite side of the lens from the object.
- Diverging lenses create virtual/erect images that are on the same side as the object.

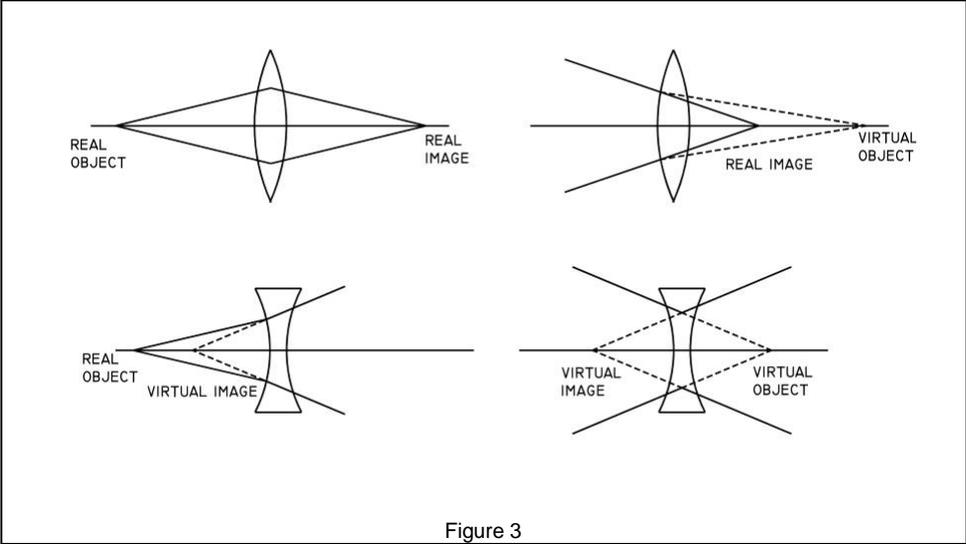


Figure 3

#### 4. Simple Lens Formula

$$U + D = V \text{ or } 100/u \text{ (cm)} + D = 100/v \text{ (cm)}$$

Where:  $U$  = vergence of object at the lens       $u$  = object position =  $100/U$  (cm)

$D$  = lens power

$V$  = vergence of image rays       $v$  = image position =  $100/V$  (cm)

Vergence: The reciprocal of the distance from a reference point.  $U = 100/u$ , where  $u$  is measured in centimeters or  $U = 40/u$  where  $u$  is measured in inches.

\*\*NOTE: Light travels from left to right unless otherwise stated.

\*\*NOTE: Light never comes out of the eyes.

**Question:** If parallel light rays strike a +4.00D lens, where will the image be? (Figure 4)

**Answer:** Parallel light has no vergence. Therefore, using the equation  $U + D = V$

$U$  = vergence of object at the lens = 0.00D

$D$  = lens power = +4.00D

Vergence of image rays =  $V = 0.00D + (+4.00D) = +4.00D$ .

Converting to centimeters,  $100\text{cm}/+4.00D = +25 \text{ cm}$  to the right of the lens.

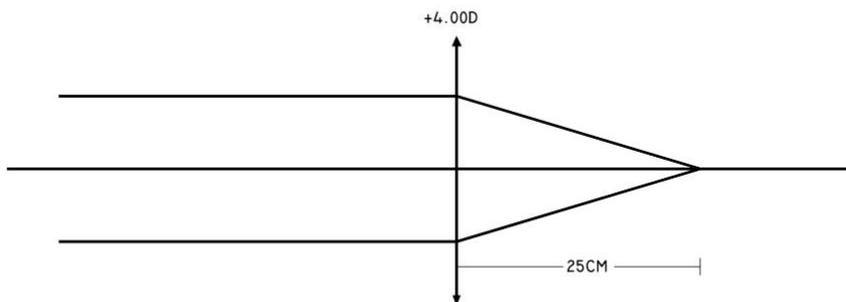


Figure 4

**Question:** An object is placed 25 cm in front of a refracting surface of power +10.0D. (Figure 5)

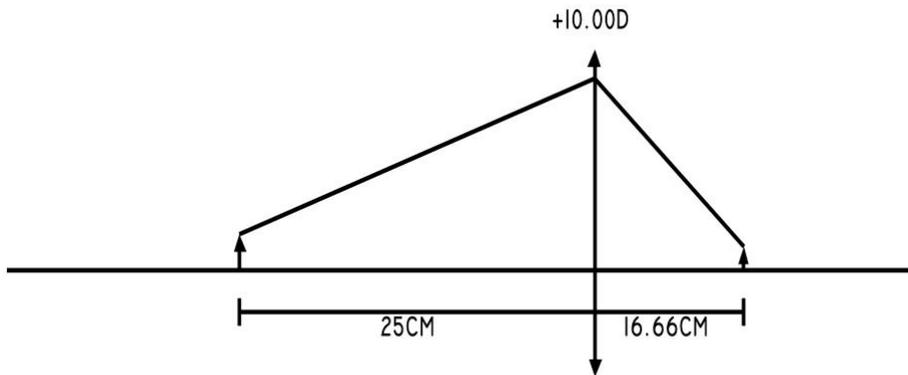


Figure 5

1. What is the image vergence?

Use the equation  $U + D = V$

$U = \text{object vergence} = -4.00\text{D}$

$D = \text{lens power} = +10.00\text{D}$

$V = \text{image vergence} = -4.00\text{D} + (+10.00\text{D}) = +6.00\text{D}$

2. Where is the image placed?

To find the location of the image, the image vergence ( $V$ ) is converted into cm.

Use the equation,  $v = \text{image position} = 100/V$  where  $V = +6.00\text{D}$

$v = \text{image position} = 100/6 = +16.66 \text{ cm}$  to the right of the lens.

3. Is the image real?

Yes, because its position is positive and to the right of the lens.

**Question:** An object is located 25 cm in front of a +5.00D lens.

1. What is the vergence of the incident rays?

Use the following equation to calculate the object vergence:  $U = 100/u$

Where  $u$  = object location in cm

$$U = \text{object vergence} = 100/-25 = -4.00D$$

2. What is the refracting vergence?

Use the equation  $U + D = V$  where

$$U = \text{object vergence} = -4.00D$$

$$D = \text{lens power} = +5.00D$$

$$V = \text{refracting vergence of the image} = -4.00D + (+5.00D) = +1.00D$$

3. Where is the image located?

Use the equation,  $v = \text{image position} = 100/V$  where  $V = +1.00D$

$$v = \text{image position} = 100/+1 = +100 \text{ cm to the right of the lens.}$$

4. Is the image real or virtual?

Real

**Question:** Define a plus lens

**Answer:** A plus lens always adds vergence; defines a focal point; and converges image rays to produce a real image of an object at infinity to the right of a plus lens.

**Question:** Define a minus lens

**Answer:** A minus lens always reduces vergence; defines a focal point; and diverges image rays to produce a virtual image of an object at infinity to the left of a minus lens.

**Question:** What is the focal length of a plus lens whose image is 20 cm behind the lens for an object that is 50 cm in front of the lens? (Figure 6)

**Answer:** First, determine the lens power by using the equation  $U + D = V$  where

$$u = \text{object distance} = -50\text{cm}$$

$$v = \text{image distance} = +20\text{cm}$$

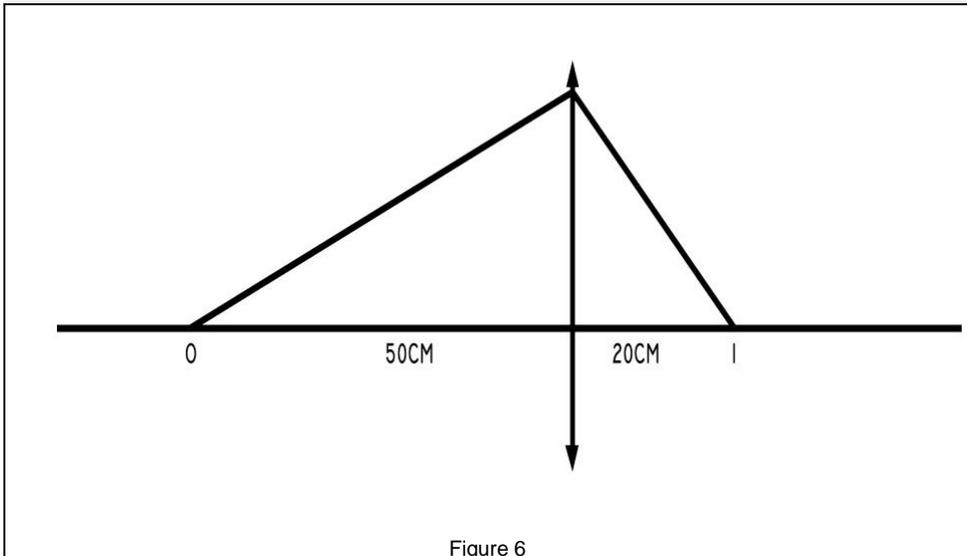
$$U = \text{object vergence} = 100/u = 100/-50 = -2.00\text{D}$$

$$D = \text{lens power}$$

$$V = \text{image vergence} = 100/v = 100/20 = +5.00\text{D}$$

$$\text{Lens power} = D = V - U = +5.00\text{D} - (-2.00\text{D}) = +7.00\text{D}$$

Therefore, the focal length ( $f$ ) of the lens, in cm, is  $100/D$ ,  $f = 100/+7.00\text{D} = +14.29\text{cm}$ .



**Question:** An object is imaged 20cm behind a  $-15.00\text{D}$  lens. (Figure 7)

1. Is the object real or virtual?

Virtual, because it is behind the lens.

2. Where will the image be focused?

Use the equation  $U + D = V$  where  $u = \text{object distance} = +20\text{cm}$

$U = \text{object vergence} = 100/u = 100/+20 = +5.00\text{D}$

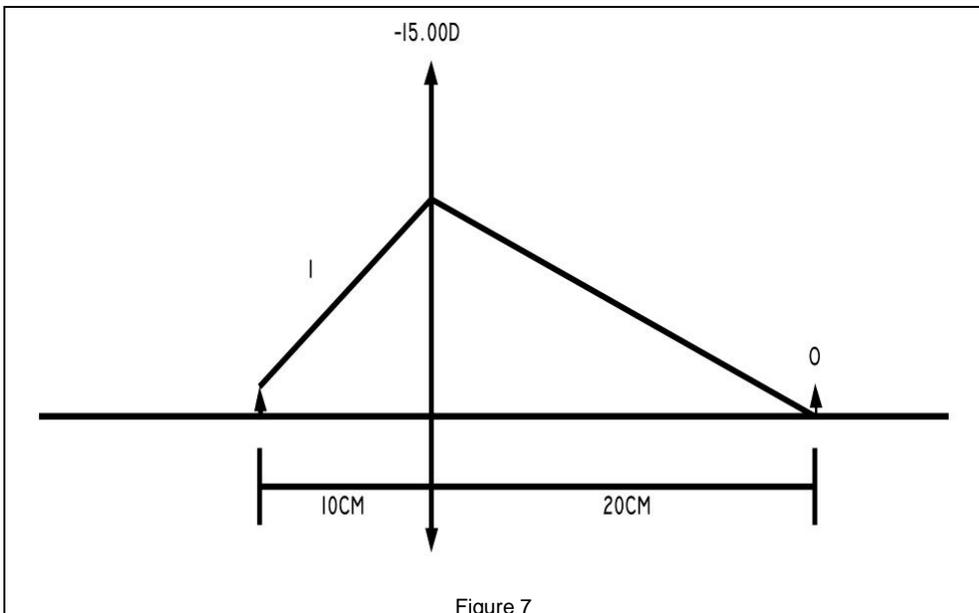
$D = \text{lens power} = -15.00\text{D}$

$V = \text{image vergence} = +5.00\text{D} + (-15.00\text{D}) = -10.00\text{D}$

$\text{image distance} = v = 100/-10.00\text{D} = -10\text{cm}$  in front of the lens.

3. Is the image real or virtual?

Virtual, because it is in front of the lens.



## 5. Depth of Focus

Depth of focus describes the image location range where the image is clear when focused by an optical system. Outside this range, the image will be significantly blurry. However, within this few millimeter range, the image appears quite sharp.

## 6. Depth of Field

Depth of field is the same principle for objects as the depth of focus is for images. When an optical system such as the camera is focused on an object, nearby objects are also in focus, inside the camera's depth of field. Objects outside of the depth of field will be out of focus.

## 7. Multiple Lens Systems

When working with a multiple lens system, it is essential to first calculate the position of the image formed by the first lens. Only after locating the first image is it possible to calculate the vergence of light as it reaches the second lens. This is the method by which any number of lenses can be analyzed. Always remember to locate the image formed by the first lens and use it as the object for the second lens to calculate the vergence of light as it reaches the second lens. Repeat the process for each subsequent lens.

**Question:** Where will the image be formed for an object placed 50cm in front of a +4.00D lens that is separated from a -2.00D lens by 25cm. (Figure 8)

**Answer:** First, determine the vergence of the image of the object after it passes through the first lens (+4.00D).

Use the equation  $U_1 + D_1 = V_1$  for the first image, where

$u_1 =$  object distance = -50cm

$U_1 =$  object vergence =  $100/u_1 = 100/-50 = -2.00D$

$D_1 =$  Lens 1 power = +4.00D

$V_1 =$  image vergence =  $U_1 + D_1 = -2.00D + (+4.00D) = +2.00D$

Therefore, Image 1 focuses at  $v_1 = 100/V_1 = 100/+2.00D = +50cm$  behind Lens 1.

Now, Image 1 becomes Object 2 ( $I_1 = O_2$ ).

At Lens 2 (-2.00D), Object 2 is located +50cm behind Lens 1 and +25cm behind Lens 2 because Lens 2 is 25cm from Lens 1.

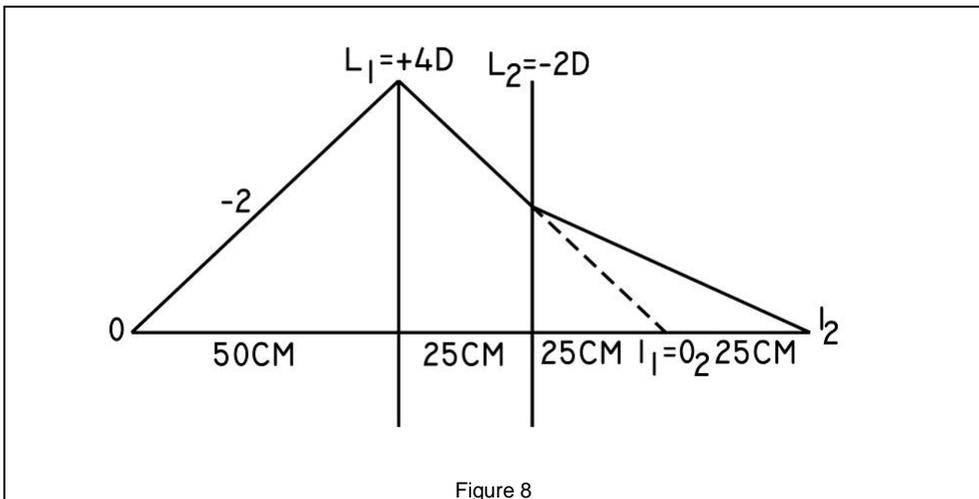
Object 2 has a vergence of  $U_2 = 100/u_2 = 100/+25 = +4.00D$

Using the formula  $U_2 + D_2 = V_2$  where

$U_2 =$  Object 2 vergence  $= +4.00D$

$D_2 =$  Lens 2 power  $= -2.00D$

$V_2 =$  Image 2 vergence  $= U_2 + D_2 = +4.00 + (-2.00) = +2.00D$ . Therefore, Image 2 focuses at  $v_2 = 100/V_2 = 100/+2.00D = +50cm$  behind Lens 2.



**Question:** Consider an object 10cm in front of a +5.00D lens in air. Light strikes the lens with a vergence of  $100/u = 100/-10 = -10.00D$ . (Figure 9)

The image has a vergence of  $V = U + D = -10.00D + (+5.00D) = -5.00D$ . In this case, light emerges with a negative vergence, which means the light is still diverging after crossing the lens. No real image is produced. In this case, we have a real object and a virtual image. Now suppose that a +6.00D thin lens is placed 5 cm behind the first lens.

1. Will an object be formed?
2. If so, what are its characteristics?

Image 1 becomes Object 2 and has a vergence of  $-5.00\text{D}$ . As the light crosses the 5cm to the second lens, its vergence changes. In order to determine the vergence at the second lens, it is necessary to find the location of the image formed by the first lens. If the first lens does not form a real image, it has a virtual image. As light leaves the first lens, it has a vergence of  $-5.00\text{D}$ . The same vergence would be produced by an object 20cm away if the first lens were not present. So, as light leaves the second lens, it appears to be coming from an object 20cm to the left of the first lens and 25cm away from the second lens. Therefore, the vergence at the second lens is  $U_2 = 100/u_2 = 100/-25\text{cm} = -4.00\text{D}$ . When light leaves the second lens, it has a vergence of  $V_2 = U_2 + D_2 = -4.00\text{D} + (+6.00\text{D}) = +2.00\text{D}$  forming a real image 50cm ( $v = 100/V = 100/+2.00\text{D}$ ) to the right of the second lens.

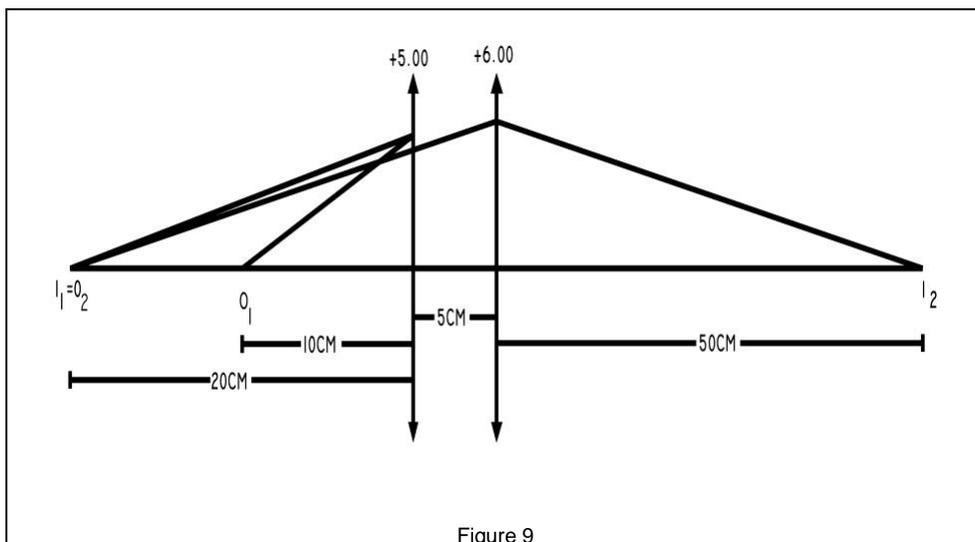


Figure 9

**Question:** A +2.00D and a -3.00D lens are separated by 30cm. The final image is 20cm behind the second lens (-3.00D). (Figure 10) Where is the object located?

**Answer:** In this case we need to work backwards. Using the formula  $U_2 + D_2 = V_2$  where

$$v_2 = \text{Image 2 distance} = +20\text{cm}$$

$$U_2 = \text{Object 2 vergence}$$

$$D_2 = \text{Lens 2 power} = -3.00\text{D}$$

$$V_2 = \text{Image 2 vergence} = 100/v_2 = 100/+20\text{cm} = +5.00\text{D}$$

$$U_2 = V_2 - D_2 = +5.00\text{D} - (-3.00\text{D}) = +8.00\text{D}$$

Therefore, the location of Image 1/Object 2 is  $v_1 = 100/V_1 = 100/+8.00 = +12.5\text{cm}$  right of lens 2. Next, use the formula  $U_1 + D_1 = V_1$  where

$$v_1 = \text{Image 1 distance from Lens 1} = +30\text{ cm} + 12.5\text{cm} = +42.5\text{cm}$$

$$U_1 = \text{Object 1 vergence}$$

$$D_1 = \text{Lens 1 power} = +2.00\text{D}$$

$$V_1 = \text{Image 1 vergence} = 100/v_1 = 100/+42.5 = +2.35$$

$U_1 = V_1 - D_1 = +2.35 - (+2.00\text{D}) = +0.35\text{D}$ . Therefore, object 1 is located at  $u_1 = 100/U_1 = 100/+0.35\text{D} = +285.71\text{cm}$  to the right of the first lens.

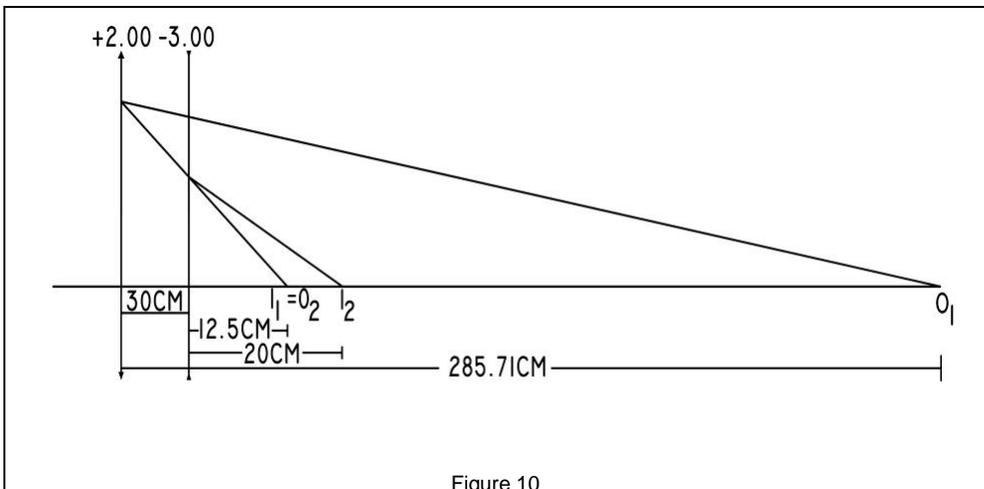


Figure 10

## 8. Lens Effectivity

Lens effectivity is the change in vergence of light that occurs at different points along its path. This is related to vertex distance.

Formula:  $F_{\text{new}} = F_{\text{current}} / (1 - dF_{\text{current}})$  where F is in Diopters and d is in meters.

When providing a “distance correction”, the principle focal point  $F_2$  of the correcting lens must coincide with the far point of the eye. The lens power depends on its location in front of the eye. The closer to the eye the lens is mounted, the shorter is its focal length in the case of hyperopia, and the longer its focal length in the case of myopia. Because of this, plus power has to be added in both cases. Therefore, myopes need less minus and hyperopes need more plus when going from spectacles to contact lenses.

*Remember CAP – Closer Add Plus.*

For spectacles, pushing a minus lens closer to the eyes increases the effective power of the lens (more –). Moving a plus lens away from the eyes increases the effective power of the lens (more +).

**Question:** A +12.00 diopter lens mounted 12mm in front of the cornea would require what contact lens power?

**Answer:**  $F_{\text{new}} = F_{\text{current}} / (1 - dF_{\text{current}}) = +12.00 / (1 - 0.012(+12.00)) = +14.02\text{D}$

**Question:** For a myopic eye that can be corrected with a –12.00 diopter lens mounted 12 mm in front of the cornea would require what contact lens power?

**Answer:**  $F_{\text{new}} = F_{\text{current}} / (1 - dF_{\text{current}}) = -12.00 / (1 - 0.012(-12.00)) = -10.49\text{D}$

**Question:** An object is placed 0.3m in front of a +5.00D lens. (Figure 11) **What** lens power could be used 0.2m from the image to achieve the same effectivity?

**Answer:** First, we need to know where the image will be focused.

Using the equation  $U + D = V$  where

$u$  = object distance =  $-30\text{cm}$

$U$  = object vergence =  $100/u = 100/-30\text{cm} = -3.33\text{D}$

$D$  = lens power =  $+5.00\text{D}$

$V$  = image vergence =  $U + D = -3.33\text{D} + (+5.00\text{D}) = +1.66\text{D}$

$v$  = image distance =  $100/V = 100/+1.66\text{D} = 60\text{cm}$  to the right of the lens. Therefore, the image is  $30\text{cm} + 60\text{cm} = 90\text{cm}$  from the object and the new lens will be  $90\text{cm} - 20\text{cm} = 70\text{cm}$  from the object.

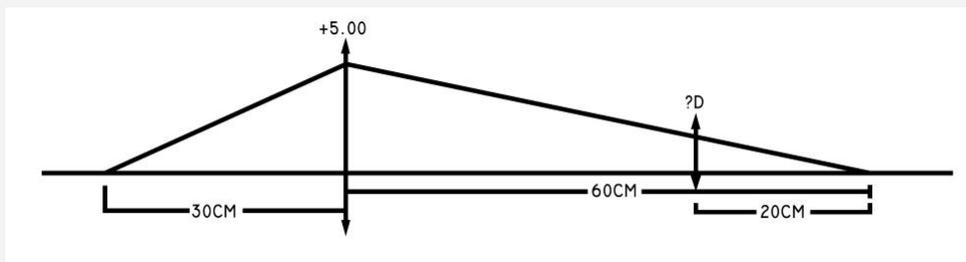


Figure 11

For the new lens, use the equation  $U + D = V$  where

$u = -70\text{cm}$

$U$  = object vergence =  $100/-70 = -1.43\text{D}$

$v$  = image distance =  $+20\text{cm}$

$V$  = image vergence =  $100/+20\text{cm} = +5.00\text{D}$

$D$  = new lens power =  $V - U = +5.00\text{D} - (-1.43\text{D}) = +6.43\text{D}$  (the lens power needed to achieve the same effectivity).

## 9. Focal Points

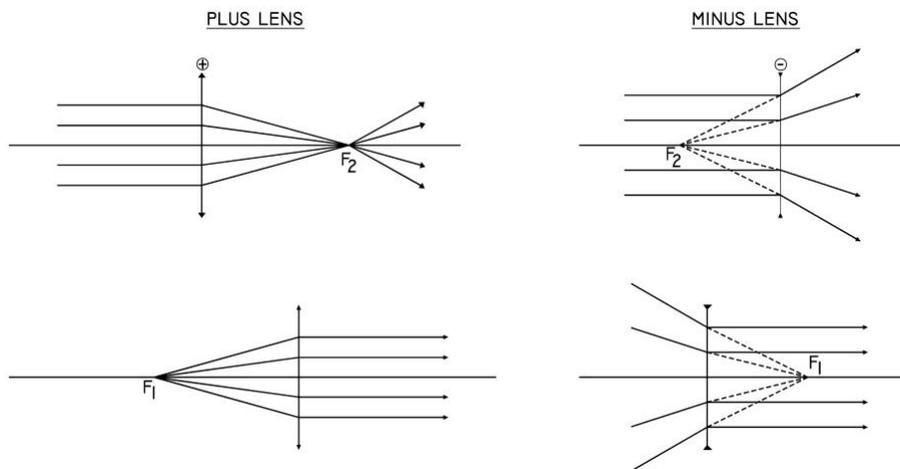


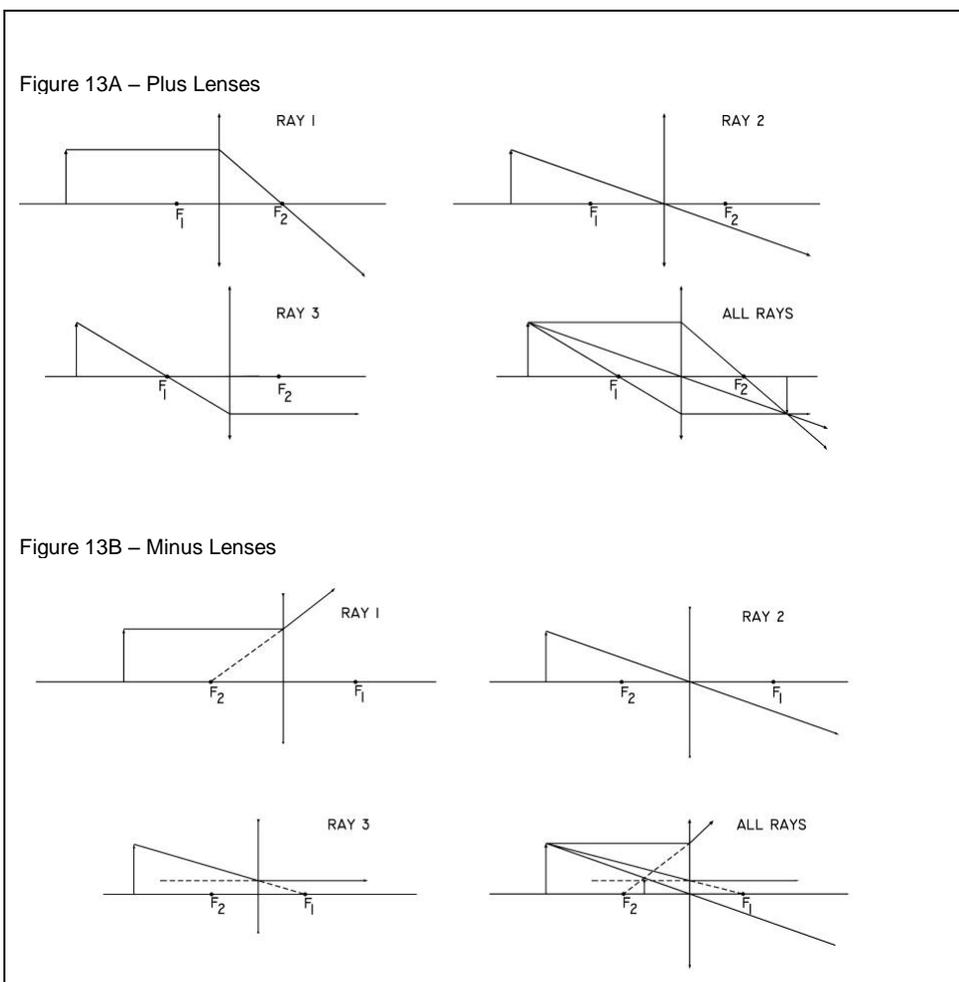
Figure 12

- The primary focal point ( $F_1$ ) of a lens is also called the Object-Space Focus.
  - For a plus lens, this is the point from which light must originate to emerge parallel from the lens. Thus, the image is at infinity.
  - For a minus lens, this is the point towards which the incident light must be directed in order for the image rays to emerge parallel.
- The primary focal length, ( $f_1$ ), is the distance from the optical surface to the primary focal point ( $F_1$ ).
- Secondary focal point ( $F_2$ ) of a lens is also called the Image-Space Focus.
  - For a plus lens, this is the point where parallel rays from a distant point object are rejoined to form an image at that point. When parallel rays enter the optical surface, they will focus at the secondary focal point.
  - For a minus lens, this is the point from which diverging rays seem to come from, after a parallel bundle of rays are refracted by a negative lens.
- The secondary focal length, ( $f_2$ ), is the distance from the optical surface to the secondary focal point ( $F_2$ ).
- For a plus (+)/convergent lens, the secondary focal point is to the right of the lens.
- For a minus (-)/divergent lens, the secondary focal point is to the left of the lens.

## 10. Ray Tracing – Lenses

When performing ray tracing, there are three rays that follow simple known paths before and after their refraction by the lens. Use two of the three construction rays to find the image. (figures 13 A & B)

1. Draw a line from the object to the lens, parallel with the direction of light. At the lens, draw the line through the secondary focal point of the lens.
2. Draw a line from the object, through the center of the lens (no deviation at the lens).
3. Draw a line from the object to  $F_1$  and then to the lens. At the lens, draw the line parallel with the direction of light.



Where the lines cross is where the image will be. By doing this, you can estimate the approximate location of the image, tell whether the image is erect or inverted as well as real or virtual.

Figures 14 show the construction of images produced by a plus lens:

- Object farther from the lens than  $F_1$ , image is real
- Object lies in  $F_1$  plane, the image therefore is at infinity
- Object closer to lens than  $F_1$ , image is virtual
- Object at infinity, image at  $F_2$ .
- Object lies to the right of the lens, (a virtual image projected by another optical system), image is real.

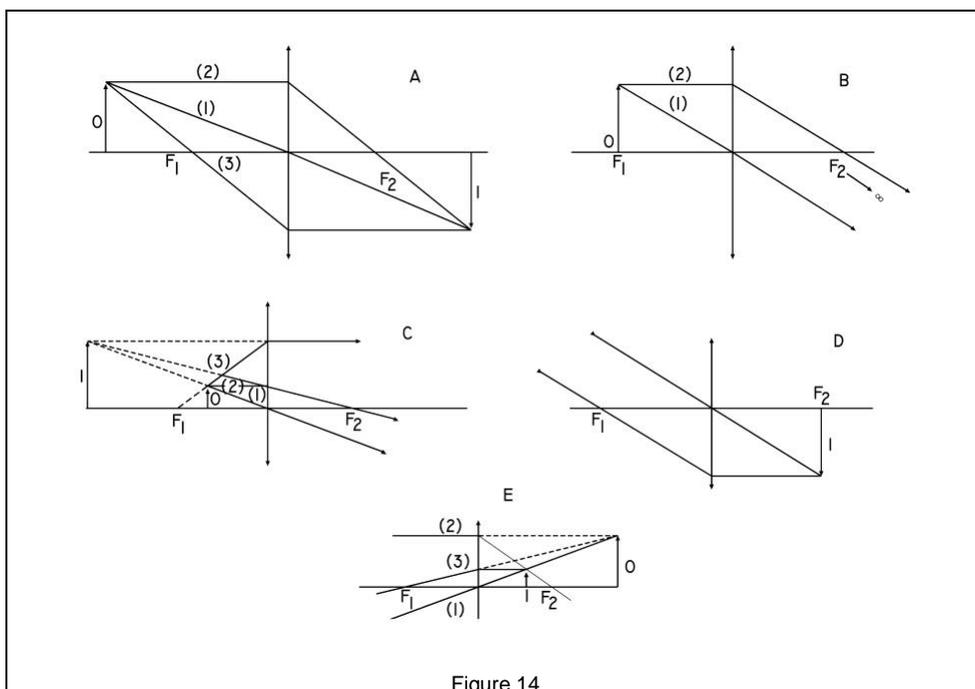


Figure 14

Figure 15 shows the construction of images produced by a minus lens:

- Object real, image virtual
- Object at infinity, image at  $F_2$  plane
- Virtual object in  $F_1$  plane, image at infinity
- Virtual object closer to lens than  $F_1$ , image real
- Virtual object farther than  $F_1$ , image virtual

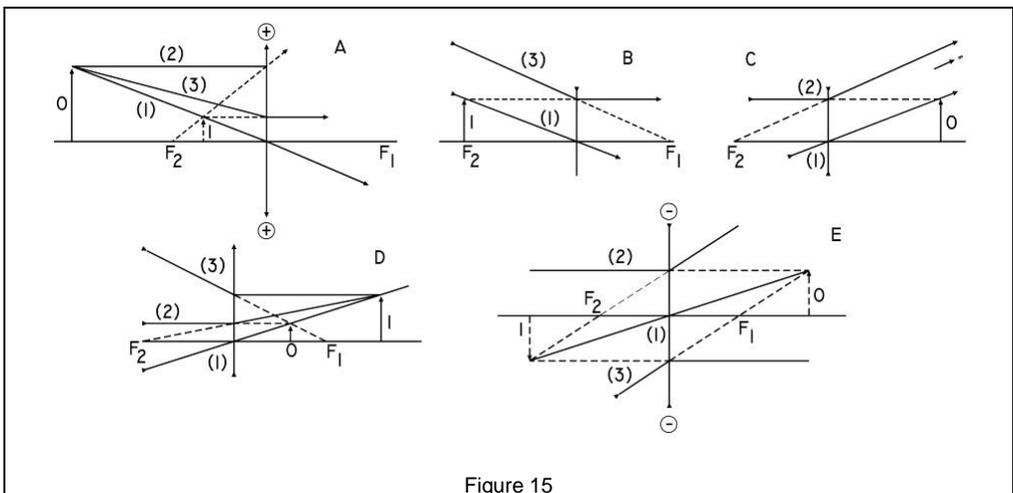


Figure 15

## 11. Optical Media and Indices of Refraction

A medium is any material that transmits light. Light travels at different speeds in different media. Light travels faster in a vacuum and slower through any material. A medium's refractive index ( $n$ ) = speed of light in a vacuum ( $c$ )/speed of light in a particular medium ( $v$ ). Refractive indices are always equal to or greater than 1.0. The index tells us how much light has slowed down when entering a refractive media. Denser media have higher  $n$  values; rarer media have smaller  $n$  values.

- Vacuum = 1.00
- Air is assumed to be 1.00
- Water, aqueous, vitreous = 1.33
  
- Averaged corneal refractive index used for keratometry = 1.3375
- Cornea = 1.37
- Crystalline lens = 1.42
- Plastic (CR-39) = 1.49
- Crown glass = 1.52
- Polycarbonate (higher index than glass or plastic) = 1.58
- Trivex = 1.53
- High index glasses = 1.6/1.7/1.8
- Titanium glass is now available with an index of 1.806. However, it is 2 ½ times heavier than CR-39.

With higher index lenses, chromatic aberration becomes a factor (chromatic aberration is discussed in Section 20). Although higher index glass lenses are thinner, they have a higher specific gravity and so are considerably heavier than plastic, polycarbonate, Trivex or crown glass. Because Polycarbonate lenses have a higher index of refraction than Trivex lenses, they are about 10% thinner than Trivex lenses. However, Trivex has a lower specific gravity than polycarbonate, making Trivex lenses about 10% lighter than polycarbonate lenses. Trivex lenses are now considered to be the lens of choice, because of its greater safety and lighter weight.

As light goes from a vacuum to a medium, the light waves slow down slightly. The denser the medium, the slower they move.

Object vergence  $V = n/u$

Image vergence  $V' = n'/u'$

Where:  $n$  = index of refraction for where the light is coming from

$n'$  = index of refraction for where the light is going to

$u$  = object distance

$u'$  = image distance

**Question:** If light of wavelength 460nm encounters the interface of a new medium with an index refraction of 1.24, find the reduced wavelength of the new medium.

**Answer:** When light encounters a denser medium, the frequency remains constant. Therefore, the speed of light is reduced compared to that inside a vacuum, and thus, the wavelength must be reduced to maintain  $c = wv$ . Vergence is inversely related to wavelength and is thus, increased. The light rays may emerge with the same frequency, wavelength, or be reflected or refracted.

To calculate the wavelength in the new medium:  $w_m = w/n = 460/1.24 = 371 \text{ nm}$

## 12. Snell's Law of Refraction

If light hits the surface of a media at less than a  $90^\circ$  angle, the angle formed between the line representing the path of light and a line that is perpendicular to the surface (the so called normal line), is called the angle of incidence. The line representing the light that emerges on the other side of the interface, measured from the normal line, is called the angle of refraction. (Figure 16)

$n \sin i = n' \sin r$  where:

$i$  = angle of incidence as measured from the normal

$r$  = angle refracted as measured from the normal

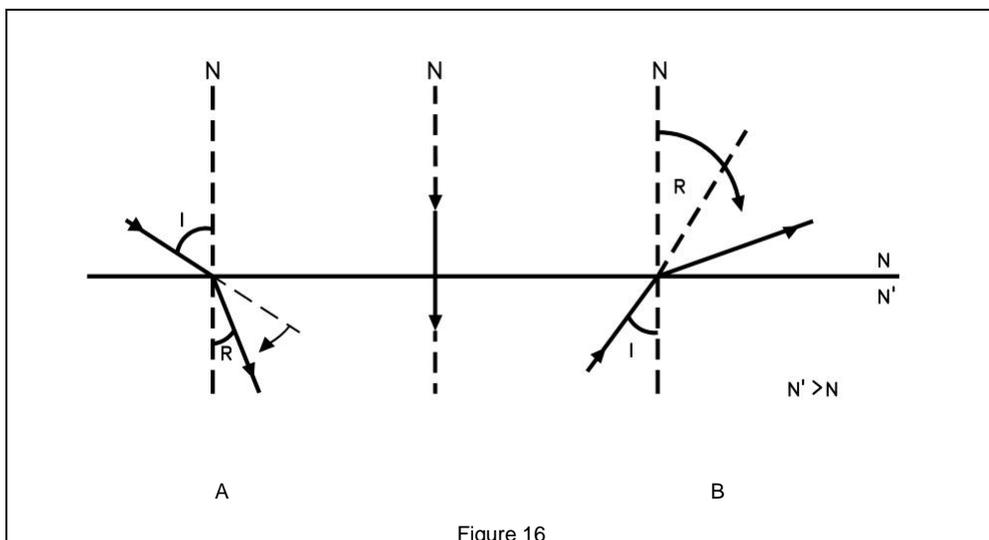


Figure 16

When light enters a denser media at an angle, it slows down so that the path becomes a bit more perpendicular. Therefore, light assumes a more nearly perpendicular path when passing from a less dense, into a denser medium, but assumes a less perpendicular path when passing from a denser medium into a less dense one.

- When moving from rarer to denser medium, light is bent towards the normal. (Figure 16 A)
- When moving from a denser to a rarer medium, light is bent away from normal. (Figure 16 B)

**Question:** Light leaves a medium of  $n = 1.55$  at an angle of  $30^\circ$  to the normal, how much does the angle change in air?

**Answer:** Using  $n \sin i = n' \sin r$  where

$n$  = index of refraction of the medium where light is coming from = 1.55

$i$  = angle of incidence =  $30^\circ$

$n'$  = index of refraction of air = 1

$r$  = angle of refraction =  $(n \sin i)/n' = (1.55 \sin 30^\circ)/1 = 50.81^\circ$ . Therefore, the angle would change  $50.81^\circ - 30^\circ = 20.81^\circ$ .

**Question:** Define refraction of light.

**Answer:** Refraction is the bending of light between media and is a function of the incident angle. This is based on Snell's Law and is not dependent on the speed of light. Snell's Law is the relationship between the incident and refracted angles of the light ray. It has no bearing on the Law of Reflection.

**Question:** What happens to light as it travels from a less dense to a denser medium?

**Answer:** It is refracted towards the normal. If it travels from a denser to a less dense medium, it is refracted away from the normal.

**Question:** What happens to a beam of light, perpendicular to the interface between two media, as it emerges from the more a dense medium?

**Answer:** It is transmitted at a higher speed.

### 13. Apparent Thickness Formula

Apparent Thickness Formula:  $n/u = n'/u'$

Where:  $n$  = index of refraction for where the light is coming from

$n'$  = index of refraction for where the light is going to

$u$  = object distance

$u'$  = image distance

**Question:** A butterfly is embedded 10cm deep in a piece of CR-39 ( $n = 1.498$ ) lens material. How far into the lens material does the butterfly appear to be?

**Answer:** Using the formula  $n/u = n'/u'$ ,  $1.498/10\text{cm} = 1/u'$ ,  $u' = 10\text{cm}/1.498 = 6.68\text{cm}$ .

**\*\*NOTE:** Light leaves the object of regard, not the eye. In this case, although we are looking into the block of plastic at the butterfly, light is coming from the butterfly. For this reason,  $n = 1.498$ .

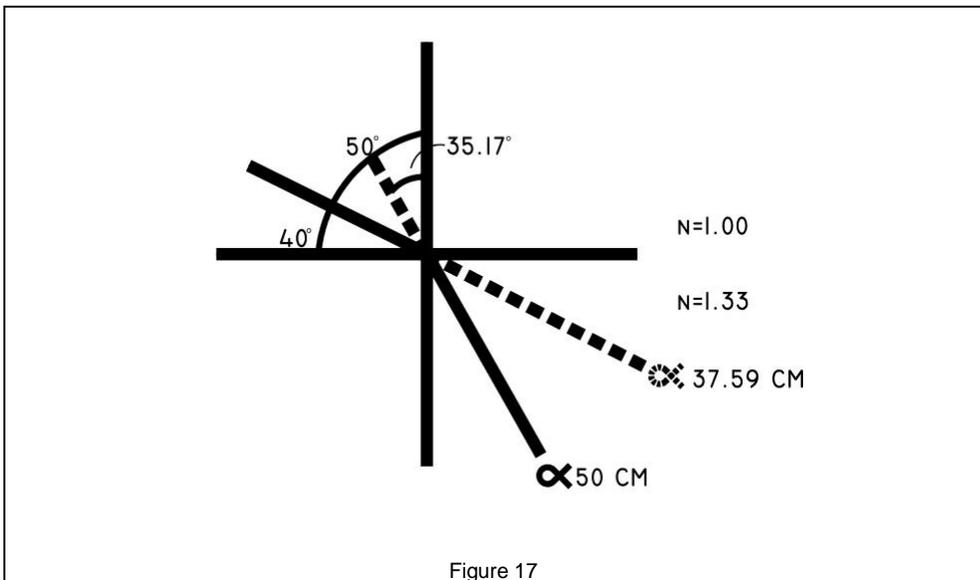
**Question:** If a fisherman is going to spear a fish that is 50cm below the surface of the water, which he sees at an angle of  $40^\circ$  from the surface of the water, where should he aim to spear the fish? (Figure 17)

**Answer:** The image that is viewed, as  $40^\circ$  from the surface of the water will be  $50^\circ$  from the normal (a line perpendicular with the surface of the water).

Using the formula  $n \sin i = n' \sin r$ ;  $1.33 \sin i = 1 \sin 50^\circ$ ;  $i = 35.17^\circ$

Using the formula  $n/u = n'/u'$ ;  $1.33/50 \text{ cm} = 1/u'$ ;  $u' = 50\text{cm}/1.33 = 37.59\text{cm}$

Therefore, the fisherman should aim behind and below the fish because light from the fish is passing from a denser to a less dense medium and will be refracted away from the normal. The fisherman sees a virtual image ahead of and above the actual fish.



### Reflection and refraction of smooth surfaces

When light enters a medium, it may be: reflected off the surface, refracted (bending of light due to a change in velocity when it hits the medium) or absorbed (where it is changed into a different type of energy).

## 14. Law of Reflection and Critical Angle

The *Law of Reflection*  $A = a'$  where  $A$  = angle of incidence and  $a'$  equals the angle of reflection. The angle of incidence and the angle of reflection are both measured from a normal to the surface. The normal is at  $90^\circ$  to the surface the light is hitting. (figure 18)

The *Critical Angle* occurs when going from a *denser to a rarer* medium. There is a point where  $a' = 90^\circ$  and all light is therefore internally reflected. The angle of incidence ( $a$ ) that produces this condition is termed the Critical Angle (CA). Total internal reflection occurs when the angle exceeds CA. As  $n$  increases, CA decreases. The angle can be determined using Snell's law as follows:

$$n \sin i_c = n' \sin 90^\circ \quad \text{where: } i_c = \text{the critical angle and the refracted angle is } 90^\circ,$$

$$\sin i_c = n'/n \times 1$$

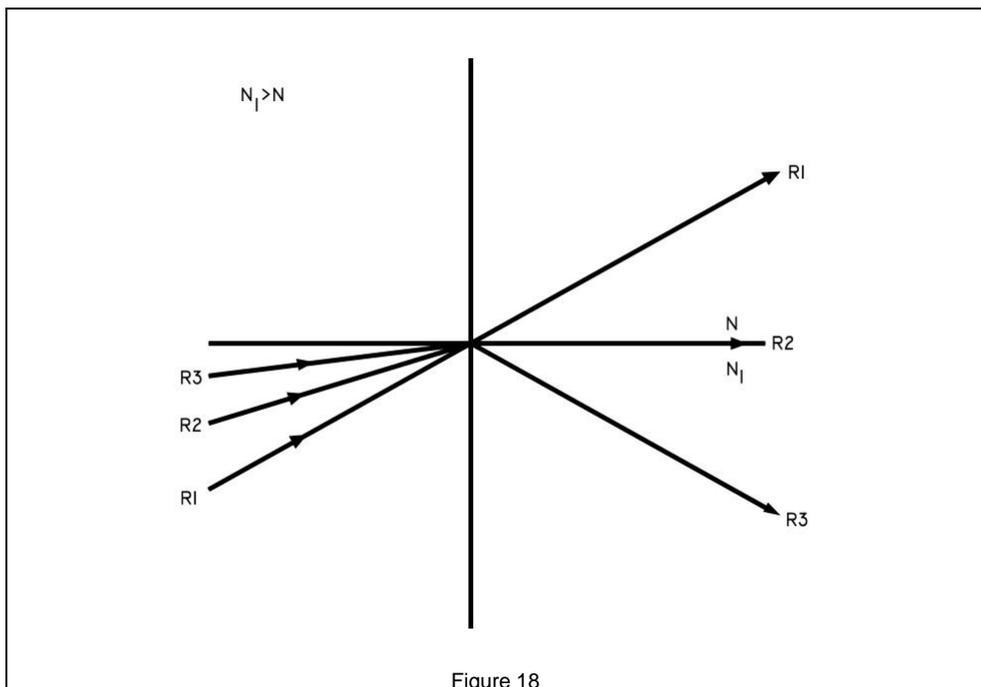


Figure 18

As the refractive index increases, the critical angle decreases. The refractive index of blue light is greater than the refractive index of red light. For this reason, blue light has a smaller critical angle than red light.

**Question:** If light is passing through a prism and hits the second surface at the critical angle for the blue wavelength, red light will be:

- a) totally internally reflected
- b) will be refracted
- c) this system is not subject to chromatic dispersion

**Answer:** b, because the critical angle of red light is greater than that for blue light

**Question:** What is the critical angle when going from water to air?

**Answer:** Using Snell's law:  $n (\sin i_c) = n' (\sin 90^\circ)$

$i_c$  = the critical angle

refracted angle is  $90^\circ$

$n$  = index of refraction for water = 1.33

$n'$  = index of refraction for air = 1.00

$(\sin i_c) = n'/n \times 1 = 1/1.33 = 48.75^\circ$

**Question:** What is the critical angle when going from a CR-39 ( $n = 1.4988$ ) lens to air.

**Answer:** Using Snell's law:  $n (\sin i_c) = n' (\sin r)$

$i_c$  = the critical angle

$n$  = index of refraction of CR-39 = 1.4988

$n'$  = index of refraction of air = 1.00

$r = 90^\circ$

$\sin i_c = n'/n \times \sin 90^\circ = 1/1.498 \times 1 = 41.88^\circ$

**Question:** What types of ophthalmic instruments are the applications of the critical angle the basis for?

**Answer:** Fiberoptics, gonioscopy, reflecting prisms, and Goldmann lens funduscopy. Critical angle has no relationship to retinoscopy.

## 15. Mirrors

- The focal length of a curved mirror is always  $\frac{1}{2}$  its radius of curvature ( $f = r/2$ )
  - o  $f$  = focal length of the mirror in meters
  - o The reflecting power of a mirror in diopters  $D_M = 1/f$  (m)
  - o  $r$  = radius of curvature of the mirror in meters.
  - o For mirrors or reflecting surfaces:  $U + 2/r_m = V$ , ( $r_m$  is in meters) or  $U + 1/f = V$
- If the mirror is convergent or plus, the focal point is to the left of the mirror.
- If the focal point is to the right of the mirror, the mirror is divergent or minus.
- Convex mirrors form virtual images on the opposite side from the object.
- Concave mirrors form real images on the same side as the object.
- A plus (concave) mirror adds positive vergence, while a minus (convex) mirror adds minus vergence.
- Convex mirrors add negative vergence like minus lenses.
- Concave mirrors add positive vergence like plus lenses.
- Plane mirrors add no vergence.
- The field of view of a plane mirror is 2 times its size.
  - o Holding a hand mirror farther away from the face does not enlarge the field of view.
  - o You need approximately a  $1/2$  length mirror to see your entire self.

When the object is located closer to a converging lens or a converging mirror than its focal distance, the image will be virtual and erect, not real and inverted. These are the principles applied to magnifying glasses used to read small print and a concave mirror, used as a shaving mirror.

**Question:** (Figure 19) Consider a concave mirror whose radius of curvature is 50cm. Therefore, the focal length of the mirror is  $f = r/2 = 0.5/2 = 0.25\text{m}$ , and the reflecting power of the mirror is  $1/f = 1/0.25 = +4.00\text{D}$ .

a) If an object lies 1m in front of the mirror, where is the image vergence?

**Answer:**

Use the equation  $U + D = V$  where

$$u = -1\text{m} = -100\text{ cm}$$

$$U = \text{object vergence} = 100/u = 100/(-100) = -1.00\text{D}$$

$$D = \text{reflecting power of the mirror} = +4.00\text{D}$$

$$V = \text{image vergence} = U + D = -1.00\text{D} + (+4.00\text{D}) = +3.00\text{D}$$

Therefore, the image is real and lies 33cm in front of the mirror.

b) If an object point is 50cm in front of the mirror, which coincides with C – the center of curvature, the image vergence ( $-2 + 4 = +2$ ) also coincides with C.

c) If an object point coincides with F, the focal point of the mirror, the image vergence ( $-4 + 4 = 0$ ) is at infinity.

d) If an object point lies 20cm in front of the mirror, the image point ( $-5 + 4 = -1$ ) is virtual (reflected rays are divergent) and lies 1m in back of the mirror.

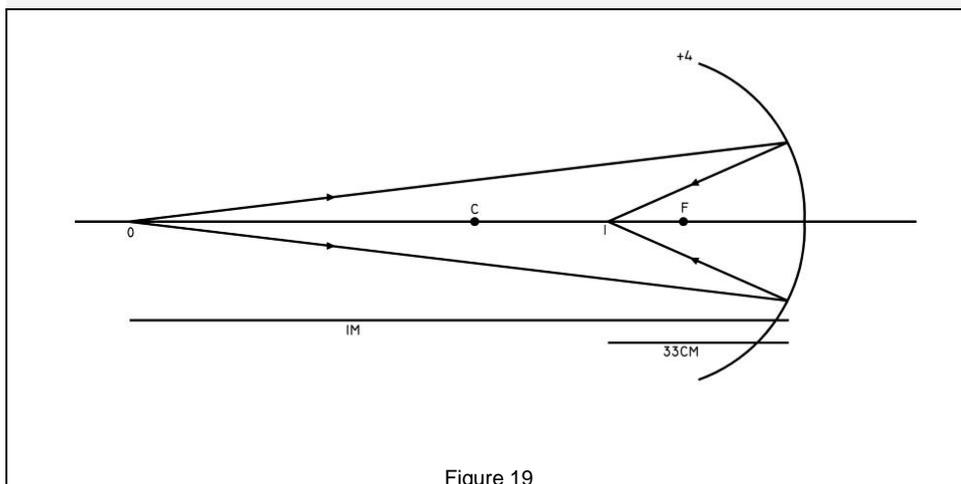


Figure 19

**Question:** (Figure 20) Consider a convex mirror whose radius of curvature is 40cm. Therefore, the focal length of the mirror is  $f = -(r/2) = -0.4/2 = -0.20\text{m}$ , and the reflecting power of the mirror is  $1/f = 1/-0.20 = -5.00\text{D}$ .

If an object lies 1m in front of the mirror, what is the image vergence?

**Answer:**

Use the equation  $U + D = V$  where

$$u = -1\text{m} = -100\text{ cm}$$

$$U = \text{object vergence} = 100/u = 100/(-100) = -1.00\text{D}$$

$$D = \text{reflecting power of the mirror} = -5.00\text{D}$$

$$V = \text{image vergence} = U + D = -1.00\text{D} + (-5.00\text{D}) = -6.00\text{D}$$

Therefore, the image is virtual and lies 16.67cm behind the mirror.

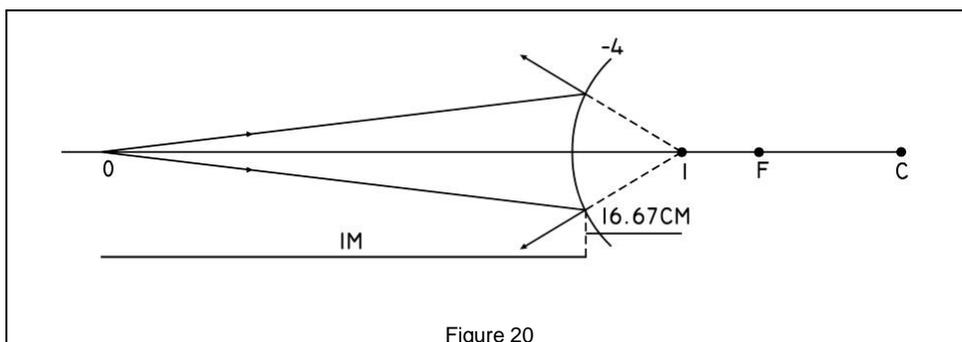


Figure 20

**Question:** For a cornea with a radius of curvature of 8mm, what is the reflective power of the cornea?

**Answer:**

The cornea is a convex mirror, and its reflective power is negative. The focal length of the cornea is  $f = -(r/2) = -(0.008/2) = -0.004\text{m}$ , and the reflecting power of the cornea is  $1/f = 1/-0.004 = -250\text{D}$ .

## 16. Ray Tracings – Mirrors

(Figures 21 & 22)

When doing ray tracings, there are three rays that follow simple known paths before and after their reflection by the mirror, just as there were with lenses. Use two of the three construction rays to find the image.

1. Draw a line from the object to the mirror, parallel with the direction of light. At the mirror, draw the line through the primary focal point of the mirror.
2. Draw a line from the object, through the center of curvature of the mirror, then to the mirror.
3. Draw a line from the object to F and then to the mirror. At the mirror, draw the line back parallel to the axis of the mirror.

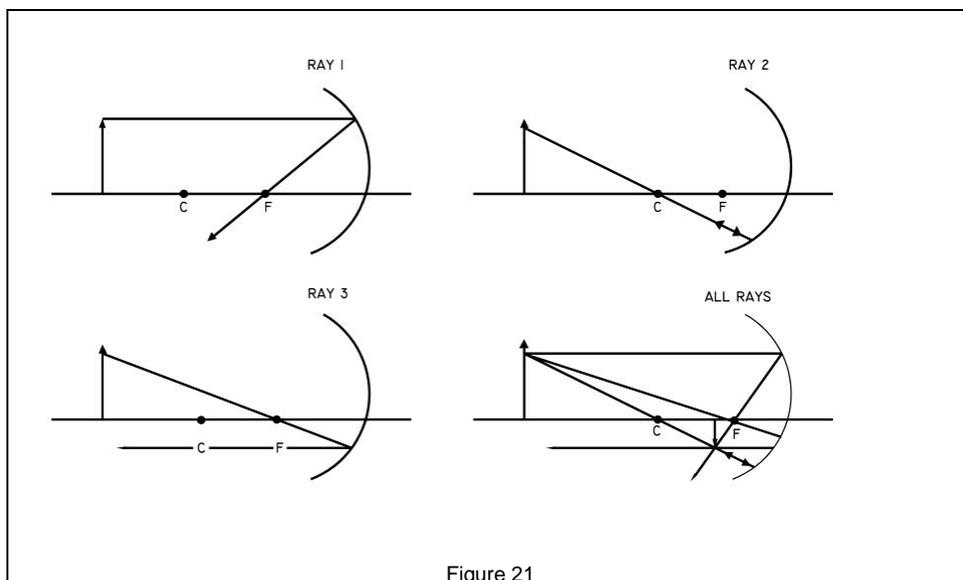


Figure 21

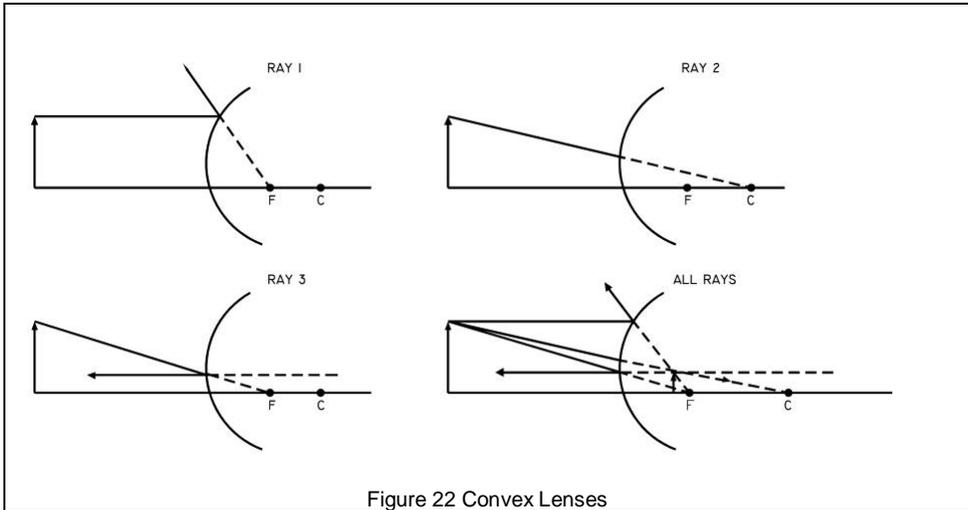


Figure 22 Convex Lenses

Where the lines cross is where the image will be formed. By doing this, you can estimate the approximate location of the image, tell whether the image is erect or inverted as well as real or virtual.

Figure 23 shows the construction of mirror images produced by a concave mirror:

- a) Object farther from mirror than C, image real and inverted
- b) Object at C, image also at C, real and inverted
- c) Object at F, image at infinity
- d) Object closer to mirror than F, image virtual and erect

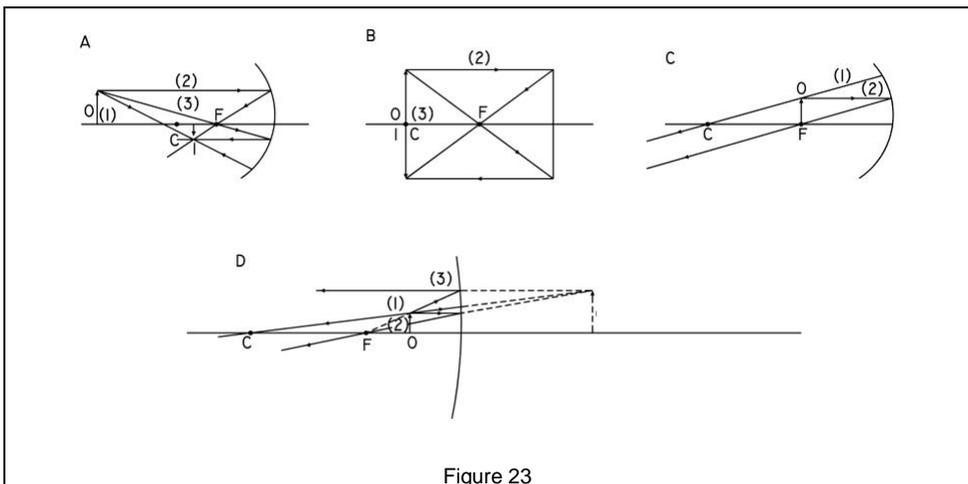


Figure 23

Figure 24 shows the construction of mirror images produced by a convex mirror:

- The object is real, the image is virtual, erect and minified.

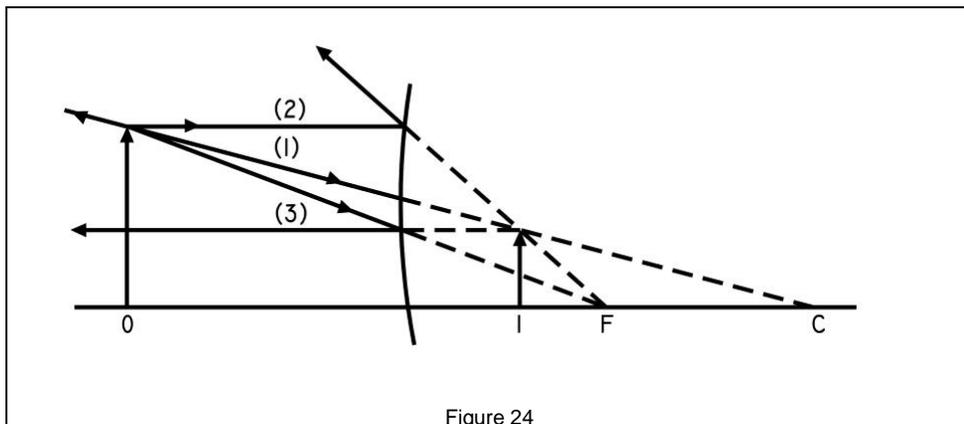


Figure 24

**Plane Mirror: (Figure 25)**

This mirror has a power of zero. Therefore,  $U = V$  and  $m = +1$ . This indicates that any real object has a virtual erect image of the same size and any virtual object has a real, erect image of the same size. The virtual image of a real object will be located as far behind the mirror as the real image is in front of the mirror.

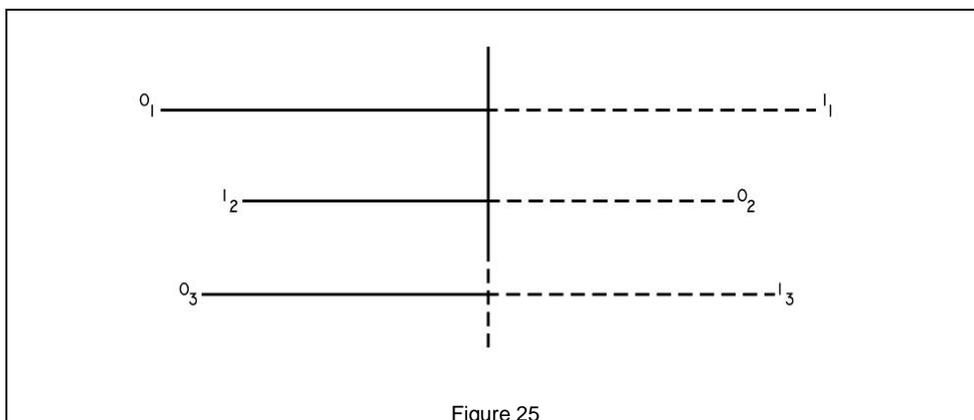


Figure 25

**Question:** An object is placed 1m to the left of a concave mirror with a radius of curvature of 20cm. Where will the image be focused? Will the image be real or virtual; magnified or minified; erect or inverted? Additionally, do a line drawing to show these results. (Figure 26)

**Answer:**

The focal length of the mirror ( $f$ ) =  $r/2 = 0.2/2 = 0.10\text{m}$ .

The power of the mirror ( $D_m$ ) =  $1/f = 1/0.10 = +10.00\text{D}$ .

The position of the image is:

$u$  = object distance =  $-1\text{m}$

$U$  = object vergence =  $1/u = 1/(-1) = -1.00\text{D}$

$D_m$  = reflecting power of the mirror =  $+10.00\text{D}$

$V$  = image vergence =  $U + D_m = -1.00\text{D} + (+10.00\text{D}) = +9.00\text{D}$

Image position is  $v = 100/V = 100/+9.00 = +11.11\text{cm}$ .

Magnification =  $U/V = -1.00\text{D}/+9.00\text{D} = -0.11$ .

Therefore, the image will be real, inverted and minified.

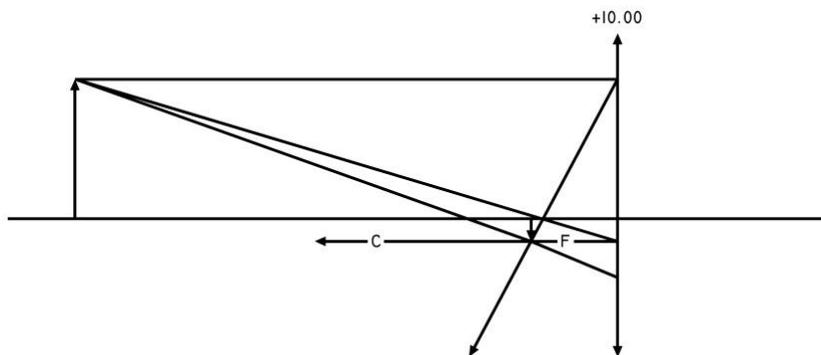


Figure 26

**Question:** (Figure 27) An object is placed 0.5m to the left of a cornea with a radius of curvature of 10mm. Where will the image be focused? Will the image be real or virtual; magnified or minified; erect or inverted? Additionally, do a line drawing to show these results.

**Answer:**

The focal length of the cornea ( $f$ ) =  $-(r/2) = -0.01/2 = -0.005\text{m}$ .

The reflective power of this cornea is ( $D_m$ ) =  $1/f = 1/-0.005 = -200.00\text{D}$ .

$U$  = object vergence =  $1/u = 1/(-0.5) = -2.00$

$V$  = image vergence =  $U + D_m = -2.00\text{D} + (-200.00\text{D}) = -202\text{D}$

Image position =  $v = 1000/V = 1000/-202 = -4.95\text{mm}$ .

Magnification =  $M = U/V = -2/-202 = 0.0099$ .

Therefore, the image will be virtual, erect and minified.

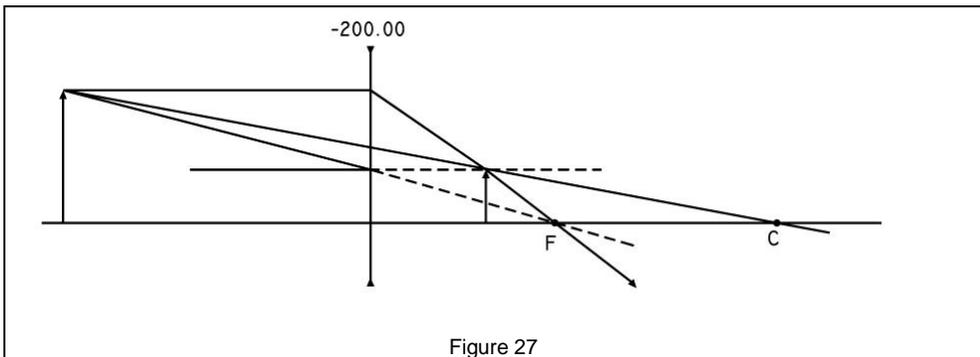


Figure 27

## 17. Prisms

Prisms are defined as a transparent medium that is bound by two plane sides that are inclined at an angle to each other. Prisms are used to deviate light, but do not change the vergence and for this reason, they do not focus light. With prisms, light is bent towards the base. The image of an object formed by a prism is a virtual image. The image will appear displaced towards the apex of the prism.

A *Prism Diopter* ( $\Delta$ ) (See Figure 28) is defined as a deviation of 1 cm at 1 meter. For angles under  $45^\circ$  (or  $100^\Delta$ ), each degree ( $^\circ$ ) of angular deviation equals approximately  $2^\Delta$  (*Approximation Formula*).

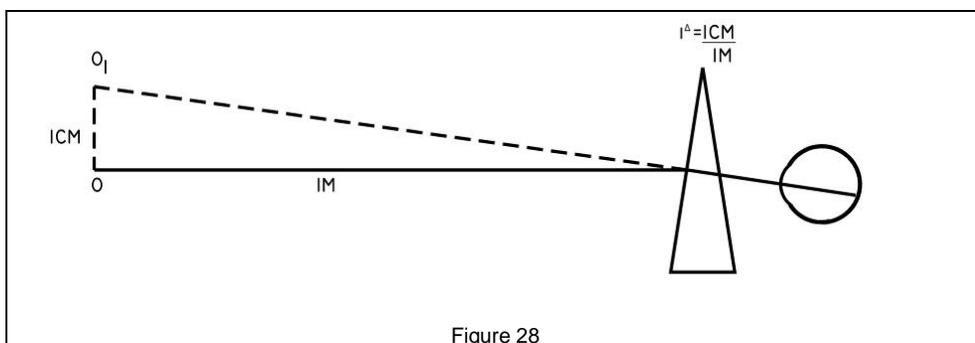


Figure 28

**Question:** A 6 PD prism will displace a ray of light how far at 1/3m?

**Answer:** A 6PD prism will deviate light 6cm at 1m. Therefore, at  $1/3\text{m} \times 6\text{PD} = 2\text{cm}$ .

**Question:** What is the power of a prism that displaces an object 10cm at a distance of 50cm?

**Answer:**  $10/50 = x/100 = 20\text{PD}$ .

## 18. Prentice's Rule

Prentice's Rule determines how much deviation you get by looking off center of a lens. There is no prismatic power at the optical center of the lens. Deviation in prism diopters (PD) =  $h$  (cm) x  $F$  where  $F$  = power of the lens and  $h$  = distance from the optical center of the lens.

\*\*NOTE: a plus lens is really 2 prisms stacked base to base and a minus lens is 2 prisms stacked apex to apex.

+ LENS



VERTICAL



HORIZONTAL



COMBINED

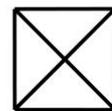
- LENS



VERTICAL



HORIZONTAL



COMBINED

**Question:** A patient wearing glasses with these lenses, OD: +3.00, OS: -1.00, complains of vertical diplopia when reading. Both eyes are reading 5 mm down from the optical center. How much total prism is induced in this reading position?

**Answer:** Use Prentice's rule:  $PD = hF$ , where  $h$  = distance from optical center in centimeters and  $F$  = power of the lens.

Therefore, in the right eye,  $0.5\text{cm} \times 3.00\text{D} = 1.5$  prism diopters base up (inferior segment of a plus lens), and in the left eye,  $0.5\text{cm} \times 1.00\text{D} = 0.5$  prism diopters base down (inferior segment of a minus lens). Total induced vertical prism is 2.0 prism diopters.

**Question:** What is the induced prism for an individual wearing +5.00D OU, when reading at the usual reading position of 2mm in and 8mm down from the optical center of his lenses?

**Answer:** Use Prentice's rule:  $PD = hF$

Therefore, vertically  $5.00D \times 0.8 = 4PD$  BU per eye (inferior segment of a plus lens) and horizontally  $5.00D \times 0.2 = 1PD$  BO per eye (nasal segment of a plus lens)

Spectacles provide a prismatic effect in viewing strabismic deviations. A plus lens will decrease the measured deviation, whether it is esotropia, exotropia or hyper/hypotropia. A minus lens increases the measured deviation, whether it is esotropia, exotropia or hyper/hypotropia. The true deviation is changed by approximately 2.5% per diopter.

For example, an exotrope of  $40^\Delta$  wearing  $-10.00D$  spherical glasses will measure 2.5 (10) = 25% more exotropia, for a total measured deviation of  $50^\Delta$  XT.

**\*\*NOTE:** the 3M mnemonic - **Minus Measures More**

*Convergence* (in prism diopters) required for an ametropes to bi-fixate a near object is equal to the dioptric distance from the object to the center of rotation of the eyes, multiplied by the subject's intra-pupillary distance in centimeters.

$Convergence (\Delta) = 100 / \text{working distance (cm)} \times \text{Pupillary Distance (cm)}$

**Question:** What is the convergence required by an individual with a 60mm intra-pupillary distance when viewing an object at 40cm?

**Answer:**

$Convergence (\Delta) = 100 / \text{working distance (cm)} \times \text{Pupillary Distance (cm)}$

$100 / \text{working distance (cm)} = 100 / 40\text{cm} = 2.50D$

$\text{Pupillary Distance (cm)} = 6\text{cm}$

$Convergence (\Delta) = 2.50D \times 6 = 15$  prism diopters of convergence

## 19. Lenses

### a. Surface type

- Spherical - power and radius is the same in all meridians
- Aspheric - radius changes from the center to the outside (becomes less curved usually)
- Cylindrical- different powers in different meridians

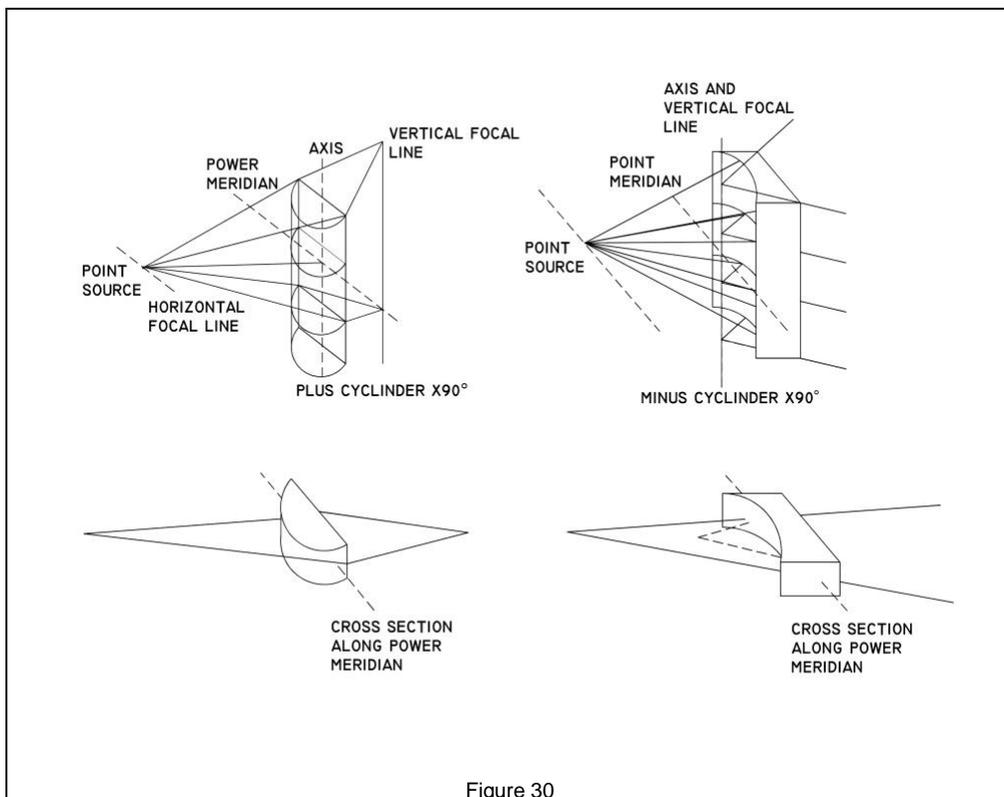


Figure 30

### b. Cylinder Optics

The power meridian is always 90 degrees away from the axis. Therefore, if the axis is 45 degrees, the power meridian is at 135 degrees. (Figure 30)

Example: Plano + 5.00 x 45 = +5.00 @ 135 and Plano @ 45

- A cylinder is specified by its axis
- The power of a cylinder in its axis meridian is zero.
- Maximum power is 90 degrees away from the axis. This is known as the power meridian.

- The image formed by the power meridian is a focal line parallel to the axis.
- Example: Plano + 5.00 x 045 will have a focal line at 45 degrees.
- There is no line focus image formed by the axis meridian, because the axis meridian has no power.

### *c. Astigmatism Types*

**With the rule astigmatism** occurs when the cornea is steepest in the vertical meridian. It is corrected with a plus cylinder lens at 90 degrees (plus or minus 30 degrees).

**Against the rule astigmatism** occurs when the cornea is steepest in the horizontal meridian. It is corrected with a plus cylinder lens at 180 degrees (plus or minus 30 degrees).

Therefore, **oblique astigmatism** is from 31 to 59 and 121 to 149 degrees.

**Irregular astigmatism** occurs when by retinoscopy or keratometry, the principal meridians of the cornea, as a whole, are not perpendicular to one another. Although all eyes have at least a small amount of irregular astigmatism, this term is clinically used only for grossly irregular corneas such as those occurring with keratoconus or corneal scars. Cylindrical spectacle lenses can do little to improve vision in these cases, and so for best optical correction, rigid contact lenses are needed.

### *d. Astigmatism of Oblique Incidence*

Tilting a spherical lens produces astigmatism. Tilting a plus lens induces plus cylinder with its axis in the axis of tilt. Tilting a minus lens induces minus cylinder with its axis in the axis of tilt. Therefore, if a lens is tilted along its horizontal axis, the increased plus or minus astigmatism will occur along axis 180. A small amount of additional sphere of the same sign is induced as well.

### *e. The Interval or Conoid of Sturm*

The interval is a conical image space bound by the two focal lines of a spherocylinder lens. At the center of the Conoid of Sturm is the *Circle of Least Confusion*. (Figure 31) The Circle of Least Confusion is the dioptric midpoint of a cylindrical lens and is defined as the *spherical equivalent* of the cylindrical lens. This is where the horizontal and vertical dimensions of the blurred image are approximately equal. The goal of a

spherical refractive correction is to choose a lens that places the Circle of Least Confusion on the retina. The smaller the Interval of Sturm, the smaller is the blur circle (Circle of Least Confusion).

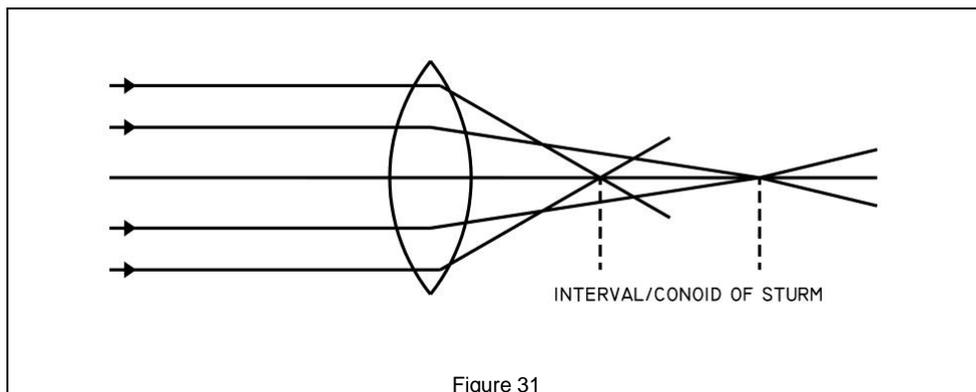


Figure 31

#### *f. Spherical Equivalent*

Dioptric midpoint of a sphero-cylindrical lens.  $\frac{1}{2}$  cylinder power + sphere power. This is also known as the Circle of Least Confusion.

When one wishes to utilize only partial correction of the astigmatism, it is still desirable to keep the circle of least confusion on the retina. This is why we use the spherical equivalent formula to maintain the circle of least confusion on the retina.

#### *g. Power Transposition: converting plus to minus cylinder and vice versa*

To convert plus to minus cylinder and vice versa, add sphere power to cylinder power = new sphere power, change sign of cylinder power, change axis by 90 degrees.

**Examples:**

$$+2.50 + 3.50 \times 95 = +6.00 - 3.50 \times 005$$

$$-2.75 - 2.00 \times 010 = -4.75 + 2.00 \times 100$$

#### *h. Base Curves of Lenses*

- The base curve is used to designate the lens form.
- The base curve varies not only for different ranges of power but also for the same ranges of powers among different lens manufacturers.
- The following definitions are standard for lenses (exceptions can be found):

- For single vision spherical lenses, it is the weaker of the two curves. The base curve will be the back or concave side of a plus lens and the front or convex side of a minus lens.
- For astigmatic single vision lenses, it is the lesser (weaker/flatter) of the two curves on the side in which the cylinder is ground. For plus cylinder form lenses, the cylinder is ground on the front surface of the lens while for minus cylinder form lenses, the cylinder is ground on the back surface of the lens.
- Because almost all lenses are designed in a minus cylinder form, manufacturers identify their lenses in terms of the front curve.
- For multifocal lenses, the base curve is on the spherical side containing the reading segment.

## 20. Aberrations

### *a. Chromatic (color) Aberrations*

is the change in light direction in materials with different refractive index due to the different wavelengths of light. A simple plus lens will bend blue light 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 3.00D difference in the focus of the far ends the visible spectrum. This is the basis of the red-green test used for refinement of the sphere power in clinical refraction.

### *b. Chromatic dispersion*

is caused because each wavelength of light has its own index of refraction. Shorter wavelengths (blue) deviate the most in materials with higher index of refraction.

Aberration can be modified by

- Changing the shape of the lens
- Changing the refractive index of the lens
- Changing the aperture size (results in fewer marginal rays)
- Changing the position of the aperture

In general, it is not possible to eliminate all aberration at once. Minimize one may worsen the other; therefore, we need to prioritize and minimize the most irritating aberrations.

- Aberrations are all object/image distance dependent.

### *c. Monochromatic Aberration*

is caused by non-paraxial rays of light. Monochromatic aberrations include spherical aberration, coma, oblique astigmatism, curvature of field and distortion.

#### *i. Spherical aberration*

is shape dependent. Spherical aberration normally increases as you move towards the peripheral portion of the lens. This is because the deviating power of the lens increases towards the periphery of the lens (Prentice Rule). To minimize spherical aberration, a biconvex lens is used. Aspheric lenses, lenses where the radius of curvature gets flatter in the periphery (have less power at the edge of the lens) also help minimize

aberrations. The cornea is an aspheric surface that gradually flattens towards the periphery.

*ii. Aperture size:*

The larger the aperture, the more spherical aberration from marginal rays occurs. Increasing pupil diameter causes greater spherical aberration. This is due to off axis points or extended objects that result in light rays passing through the marginal surface of the lens. This results in the lens not focusing the image at the same point due to para-axial rays. The difference in angles causes the aberration. The pupil of the eye corrects spherical aberration and coma.

*iii. Coma*

is an off axis spherical aberration. Peripheral rays produce coma. The image is a series of circles that form a comet shape. This is primarily a problem for large aperture optical systems and can be ignored in spectacles because of the limited affect of the pupil. If we increase the aperture size, we have more coma. Shorter objects have less coma. Objects off axis have more coma. Lens shape will minimize spherical aberration, but not totally eliminate coma. When the aperture is closer to the lens, greater coma occurs.

*iv. Aplanatic system*

is free of spherical aberration and coma.

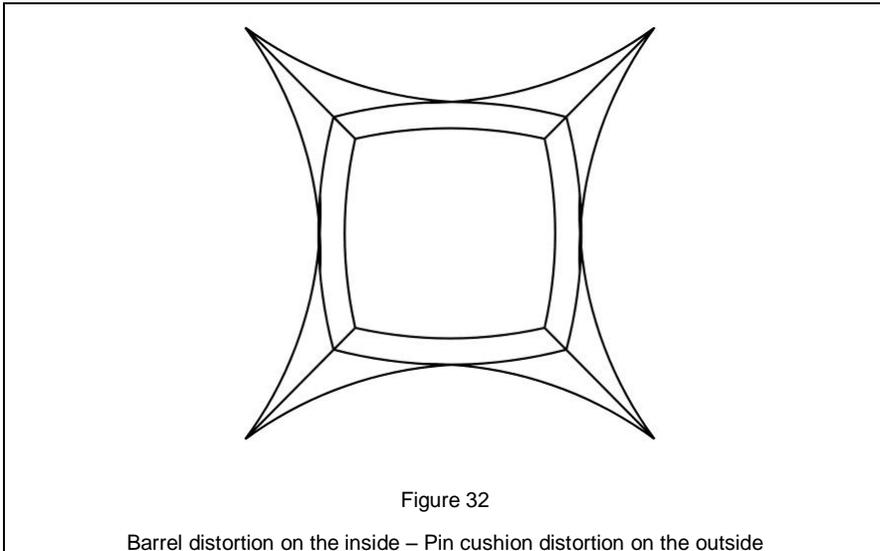
*v. Curvature of field*

is corrected by the curvature of the retina. Curvature of field is an advantageous aberration in the human eye because it produces a curved image on the retina, as opposed to a flat image.

*vi. Distortion*

Distortion (Figure 32) is another aberration of thick lenses. It concerns the distortion of straight edges of square objects. There are two types of distortion resulting from lateral magnification of the image that results in a lateral displacement of the image.

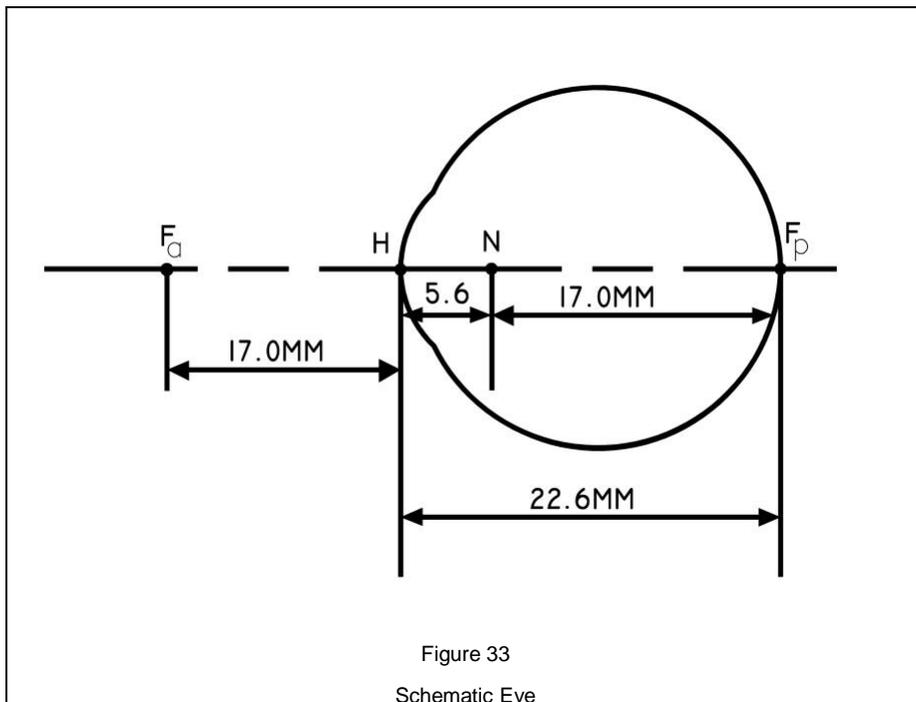
- *Barrel distortion* - where the rays in the center are more magnified than the rays further off axis. This is due to minification of the corners of a square object, more than the sides, from minus lenses.
- *Pincushion* - where the central rays are less magnified than the rays off axis. This is due to magnification of the corners of a square object, more than the sides, from plus lenses.



## 21. Schematic Eye

A schematic eye (Figure 33) helps to conceptualize the optical properties of the human eye. The reduced schematic eye treats the eye as if it were a single refracting element consisting of an ideal spherical surface separating two media of refractive indices of 1.00 and 1.33. The reduced schematic eye assumes an eye power at the corneal surface of +60.00D (actual power of the Gullstrand's schematic eye is +58.60D). The anterior focal point is approximately 17mm ( $1/-60 = -16.67\text{mm}$  in front of the cornea) and the eye is 22.6mm in length with the nodal point 5.6mm behind the cornea.

The nodal point is the point in the eye where light entering or leaving the eye and passing through the nodal point, is undeviated. This allows similar triangles to be used to determine the retinal image size of an object in space. For example, to determine the retinal image size of a Snellen letter (viewed at 6 meters), the following formula would be used: Retinal image height/Snellen letter height = 17mm/6000mm



**Question:** Assume a disc diameter of 1.7 mm. What is the diameter of the blind spot when plotted on a tangent screen, 2 meters from the eye?

**Answer:** Using similar triangles,  $1.7/17 = X / 2,000$ . Rearranging  $X = 1.7/17 \times 2,000 = 200$  mm or 20 cm. In general, you can use the formula: object height/retinal image height = distance from the point of reference/17 mm. 17mm is the distance from the internal focal point of the eye to the retina.

## 22. Refractive/Axial Myopia and Hyperopia

**Refractive Myopia:** occurs when the power of the eye exceeds 60D and the length of the eye is 22.6mm. This is due to steeper corneal curvatures or higher lenticular powers.

**Axial Myopia:** occurs when the power of the eye is 60D but the eye is longer than 22.6mm. Every millimeter of axial elongation causes approximately 3D of myopia.

**Refractive Hyperopia:** occurs when the power of the eye is less than 60D and the length of the eye is 22.6mm.

**Axial Hyperopia:** occurs when the power of the eye is 60D but the eye is shorter than 22.6mm.

### **23. Knapp's Law**

One problem in treating refractive errors is that the corrective lens usually changes the size of the retinal image. Many individuals can tolerate this change in image size. Problems can arise with differences in image size between the two eyes, because of asymmetric refractive errors. According to Knapp's Law, the retinal image size will not be different between the two eyes, no matter what amount of axial ametropia exist, when the spectacle lens is placed at the eye's anterior focal point. The front focal point of the eye is about 17 mm in front of the cornea (see schematic eye information). Preventing this from being strictly applied in clinical practice is the fact that ametropia is almost never purely axial, and a vertex distance of 16-17 mm for a spectacle correction is impractical. Most people prefer to wear their spectacles 10-14 mm in front of the cornea. Additionally, the retina in the myopic eye of a unilaterally high myope is stretched, which increases the separation of photoreceptors. This results in the effective magnification not being exactly what would be expected.

### **24. Far Point of the Eye**

The far point of the eye is the object point imaged by the eye onto the retina in an unaccommodated eye. If a corrective lens is used to correct for myopia, the lens has its secondary focal point coincident with the far point of the eye.

- The far point of the emmetropic eye is at infinity.
- Myopia exists if, without accommodation, a point at infinity is imaged in front of the retina (in the vitreous). The stimulus on the retina is therefore not a point, but a blur circle. Moving the object closer to the myopic eye, until the image is a point focus on the retina, establishes the far point of the eye.
- Hyperopia exists, if without accommodation, an object point at infinity is imaged neither in the vitreous nor on the retina, but theoretically, behind it.

## 25. Accommodation

Accommodation is the mechanism by which the eye changes its refractive power by altering the shape of its crystalline lens. During accommodation, the ciliary muscle contracts allowing the zonular fibers to relax. This relaxation causes the equatorial edge of the lens to move away from the sclera during accommodation resulting in increased lens convexity (roundness). This increase in roundness primarily occurs on the front surface of the lens.

### *a. The Amplitude of Accommodation,*

also known as the accommodative response, is the maximum increase in diopter power obtainable by an eye. The amplitude of accommodation is measured monocularly.

### *b. The Range of Accommodation*

denotes the linear distance (expressed in centimeters or meters) over which the accommodative power allows an individual to maintain clear vision. The range lies between the near point of accommodation and the far point of accommodation. This is considered the most useful clinical measurement of accommodation. It helps answer the question as to whether an individual's accommodative range comfortably encompasses his visual needs.

Clinically, accommodative ranges are measured from the anterior corneal surface (reference position). Optically, for the purist, that reference should be the primary principle plane of the eye, 1.4 mm behind the anterior corneal surface.

### *c. Resting Level of Accommodation:*

In the absence of visual stimuli, the eye assumes an accommodative posture approximately 1D 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.

*d. Measuring Accommodation:*

Tests of accommodation are performed monocularly.

When measuring the accommodative amplitude, it is assumed that you are testing an emmetropia, or someone who is corrected with spectacles, so that their far point is at infinity.

Target size, target illumination, and speed of target approach will affect the measurement of the amplitude of accommodation. The push up method works well for emmetropes, or fully corrected ametropes.

*i. Near point of accommodation “Push Up Test”*

For this test, use relatively small letters (0.4M or 0.5M) to help better control accommodation. Slowly move these letters closer to the eye until they become blurry. Measure the distance the letters became blurry. This is the near point of accommodation.

*ii. Prince Rule*

A scaled accommodative ruler is used. Normally it is done with +3.00D sphere over the distance correction. A standard reading card is used and moved slowly towards and away from the individual to locate both the near and far points as in the push up method.

**Question:** An emmetrope views the reading card through a +3.00-diopter lens. She finds that as the card is moved towards her, the print that was blurred when held at the far end of the prince scale (50 cm) becomes clear at 33 cm (3.00D) and remains clear until it reaches 10 cm (10D). What is her accommodative amplitude?

**Answer:** Accommodative amplitude then is 7 diopters,  $10D - 3D$ .

*iii. Spherical Lens Test*

Spherical lenses are used in this test. The individual focuses on a stationary target while plus or minus lenses are used to measure the accommodative amplitude. A reading card is put at a convenient distance, say 40 cm, and the individual fixates on threshold size type (0.5M). Plus lenses are added until the print is blurred and then minus spheres are gradually added until the print blurs again. The difference is the accommodative amplitude.

Always test for accommodate relaxation with plus lenses before performing accommodative stimulation with minus lenses. This is because some individuals cannot adequately relax accommodation after exerting a maximum accommodative effort.

During the act of accommodation, there is a thickening of the lens and a decrease in its diameter (vertically and horizontally), with at the same time, a protrusion forward of the center and a relative flattening of the periphery, the whole process being accomplished by an axial movement of the lens substance which is evident, particularly in the central regions (Duke-Elder, 1938)

**Question:** What is the interval of clear vision for an uncorrected 5.00D myope with 10D of accommodative amplitude?

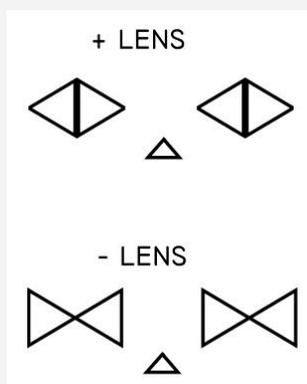
**Answer:** Far point =  $100/5 = 20\text{cm}$   
Near point =  $100/(5 + 10) = 6.67\text{cm}$   
Interval of clear vision = 6.67cm to 20cm

**Question:** What is the interval of clear vision for an uncorrected 2.00D hyperope with 4.00D of accommodative amplitude?

**Answer:** Far point is 50 cm behind the eye  
With +2.00D of accommodation, the far point is at infinity  
Near point =  $100/(4-2) = 50\text{cm}$   
Interval of clear vision is 50cm to infinity

**Question:** What is the relative effect of spectacles versus contact lenses on convergence for a myope? For a hyperope?

**Answer:** When wearing contact lenses, the convergence requirement is the same as that of an emmetrope, because the lenses rotate with the eye and the line of sight remains relatively well directed through the center of the lenses. When an ametropes wearing spectacle lenses centered for his distance pupillary distance fixates a near object, the amount of convergence required is not only a function of his intrapupillary distance and the distance of the object, but will also be a function of the refracting power of the spectacle lenses. As a myope converges to bi-fixate a near object, his line of sight departs from the center of his spectacle lenses and encounters increasing amounts of base in prismatic effect. The spectacle wearing hyperope encounters base out prismatic effect, as he converges to bi-fixate a near object. Thus, to bi-fixate a given object at a distance less than infinity, the bespectacled myope converges less than the emmetrope or the contact lens wearer, while the hyperope wearing spectacles converges more than the emmetrope or the contact lens wearer. Therefore, the myope who discards his spectacle lenses in favor of contact lenses, must converge more to bi-fixate a given near object, while the hyperope will converge less under the same conditions.



## 26. Near Point of the Eye

The near point of the eye is found when the uncorrected refractive error of the eye is added to the accommodative ability of the eye. If the amplitude of accommodation is 10D, the near point is 10cm in front of the eye (specifically, 10cm in front of the vertex of the cornea which is used as a convenient reference point).

When a myope is fit with contact lenses, they may experience asthenopia, or “focusing” difficulties when doing close work. The symptoms generally subside as the individual adapts to the greater accommodative stimulus. However, this can be a more of a problem for the myope who is approaching presbyopia. This is because the myope, when viewing a near object, will accommodate more when his ametropia is corrected with contact lenses than when it is corrected with spectacle lenses.

For the hyperope who is approaching presbyopia, they will experience less difficulty when reading with a full contact lens correction than with the equivalent spectacle lens correction. This is because the hyperope, under the same conditions, will accommodate less with contact lenses than with spectacle lenses.

The effect is greatest with high refractive errors. For example, a spectacle-corrected myope may be able to read without bifocal glasses, but require reading glasses with contact lenses. Conversely, a hyperope may be able to forego reading glasses with contact lenses, but need bifocal glasses when wearing spectacles.

The change in lens position from the spectacle plane to the corneal plane is primarily responsible for the change in the stimulus to accommodation.

**Question:** In general, when using the direct ophthalmoscope, which patient provides the larger image of the retina, the hyperope or myope?

**Answer:** Myopes will have a larger image, hyperopes smaller. This is related to the total power of the eye.

**Question:** Where is the secondary focal point for an uncorrected myope found?

**Answer:** The secondary focal point for a myopic eye is anterior to the retina.

**Question:** Where is the secondary focal point for an uncorrected hyperope found?

**Answer:** The secondary focal point for a hyperopic eye is behind the retina.

**Question:** Where is the far point for an uncorrected myopic eye found?

**Answer:** The far point is between the cornea and infinity.

**Question:** Where is the far point for an uncorrected hyperopic eye found?

**Answer:** The far point is beyond infinity or behind the eye.

## 27. Magnification

Traditionally, three types of magnification are discussed: relative distance magnification, relative size magnification, and angular magnification.

### *a. Relative Distance Magnification*

The easiest way to magnify an object is to bring the object closer to the eye. By moving the object of regard closer to the eye, the size of the image on the retina is enlarged. Children with visual impairments do this naturally. Adults will require reading glasses to have the object in focus.

- Relative Distance Magnification =  $r/d$  where  $r$  = reference or original working distance and  $d$  = new working distance
- Example
  - Original working distance = 40cm
  - New working distance = 10cm
  - Relative Distance Magnification (RDM) =  $40/10 = 4x$

With reading glasses, as the lens power increases, the working distance decreases. The reading glasses do not magnify by their power alone when worn in the spectacle plane. Magnification occurs because the lens strength requires the individual using them to hold things closer to have the object in focus.

### *b. Relative Size Magnification*

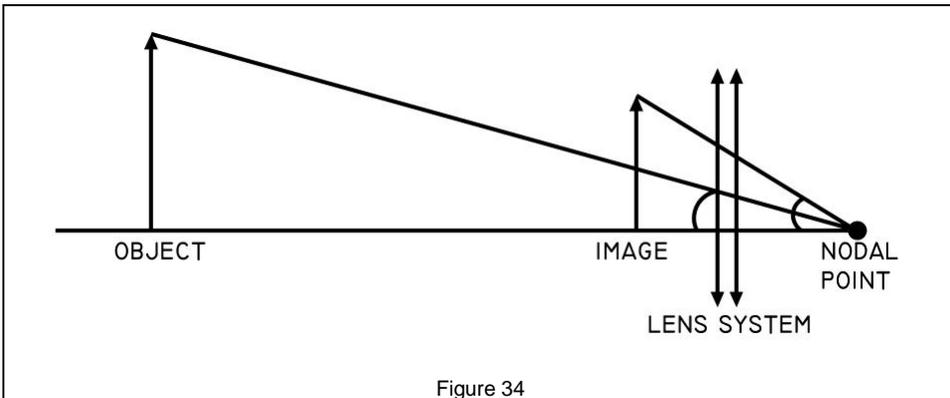
Relative size magnification enlarges the object while maintaining the same working distance, for instance, as observed with large print.

- Relative Size Magnification =  $S2/S1$  where  $S1$  = original size and  $S2$  = the new size
- Example
  - Original size = 1M
  - New size = 2M
  - Relative Size Magnification (RSM) =  $2/1 = 2x$

### c. Angular Magnification

Angular magnification (Figure 34) occurs when the object is not changed in position or size, but has an optical system interposed between the object and the eye to make the object appear larger.

Examples: Telescopes and hand magnifiers



This optical system produces a virtual image smaller than the original object but much closer to the eye. The image has a larger angular subtense than the original object; therefore, the objects appear larger when seen through this optical system even though the virtual image is smaller than the object.

Angular magnification is the ratio of the angular subtense of the image produced by a device divided by the angular subtense of the original object. Angular magnification takes into account not only the size of an image, but also its distance from the observer.

### d. Magnification Basics

- Perceived size is proportional to the size of the object's image on the retina.
- Retinal image size is proportional to the object's angular subtense.
- Angular subtense is directly proportional to the object size and inversely proportional to the object's distance from the observer.

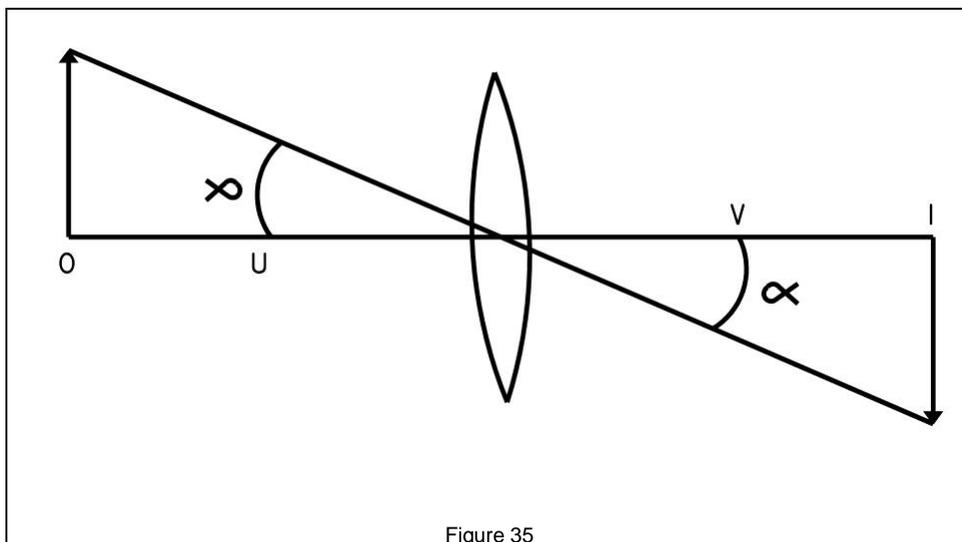
Magnification looks at the ratio of object size ( $Y$ ) to the image size ( $Y'$ ) or the ratio of the angular subtense of the image viewed with the optical system to the angular subtense of the object viewed without the optical system.

- Plus (+) indicates the image is upright
- Minus (-) indicates the image is inverted.

- When the image is smaller than the object, magnification is numerically between 0-1.
- If the absolute number is greater than 1, the image is larger.
- If the absolute number is equal to 1, it is the same size.
  - o A magnification of  $-4$  implies that the image is inverted and 4x larger than the object
  - o A magnification of 0.2 implies that the image is erect and 1/5 the size of the object.
- If the object and image are on the same side of the lens, the image is erect, if not, the image is inverted.
- Generally, if the image is located farther from the lens than the object is, the image is larger than the object, if the image is closer to the lens than the object; the image is smaller than the object.

*e. Transverse/Linear Magnification*

The ratio of the image size to the object size or image vergence to object vergence is called transverse or linear magnification. (Figure 35)  $M_T = I/O = U/V = v/u$



**Question:** An object is placed 20cm in front of a +10.00-diopter lens. What will the resultant linear magnification be?

**Answer:**  $-1$

**Explanation:** In order to calculate linear magnification for a single lens system, one must know only the object distance and the image distance and/or the object vergence and the image vergence.

The formula is *Magnification = image distance (v)/object distance (u) = U/V*.

If the object distance is 20cm, the rays incident on the lens have a vergence of  $100/-20 = -5.00\text{D}$ . After refraction, through the  $+10.00$ -diopter lens, the rays have a vergence of  $-5.00 + (+10.00\text{D}) = +5.00\text{D}$ . Therefore, a real image is formed  $100/+5.00\text{D} = +20\text{cm}$  behind the lens.

As it turns out, the object distance of 20cm and the image distance of 20cm, are equal, so the magnification is  $-1$ . Also, the object vergence is  $-5.00\text{D}$  and the image vergence is  $+5.00\text{D}$  giving a magnification of  $-5.00/+5.00$  of  $-1$ , indicating the image is inverted.

**Question:** Consider an optical system consisting of two lenses in air. (Figure 36) The first lens is  $+5.00\text{D}$ , the second lens is  $+8.00\text{D}$  and they are separated by 45 cm. If an object is 1 meter in front of the first lens, where is the final image and what is the transverse magnification?

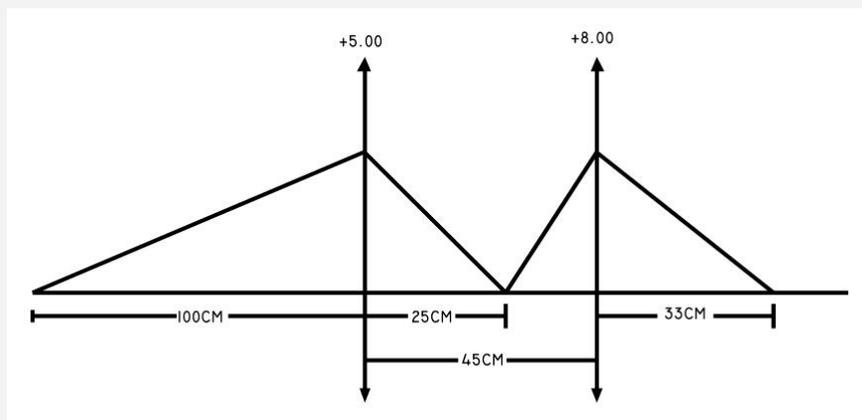


Figure 36

**Answer:** To analyze a combination of lenses, we must look at each lens individually. The thin lens equation ( $U + D = V = 1/-1 + (+5.00) = -1 + 5 = +4.00\text{D}$  and  $100/+4.00 = +25\text{cm}$ ) shows that the first lens produces an image 25cm behind itself, with the magnification ( $M = U/V = -1/+4 = -0.25$ ). Light converges to the image and then

diverges again. The image formed by the first lens becomes an object for the second lens. The image is 20 cm in front of the second lens, thus light strikes the second lens with a vergence of  $(1/-0.20) = -5.00\text{D}$  and forms an image 33cm behind the second lens  $(-5 + (+8) = +3.00, 100/+3.00 = +33\text{cm})$ . Transverse magnification for the second lens alone is  $-5.00\text{D}/3.00\text{D}$  or  $-1.66$ . The total magnification is the product of the individual magnification  $-1.66 \times -0.25 = 0.42$ .

*f. Axial Magnification =  $M_1 \times M_2$*

Axial magnification (Figure 37) is used when talking about objects that do not occupy a single plane (3D objects). Axial magnification is the distance, along the optical axis, between the two image planes divided by the distance between the two object planes (extreme anterior and posterior points on the object with their conjugate image points). Axial magnification is proportional to the product of the transverse magnifications for the pair of conjugate planes at the front and back of the object.

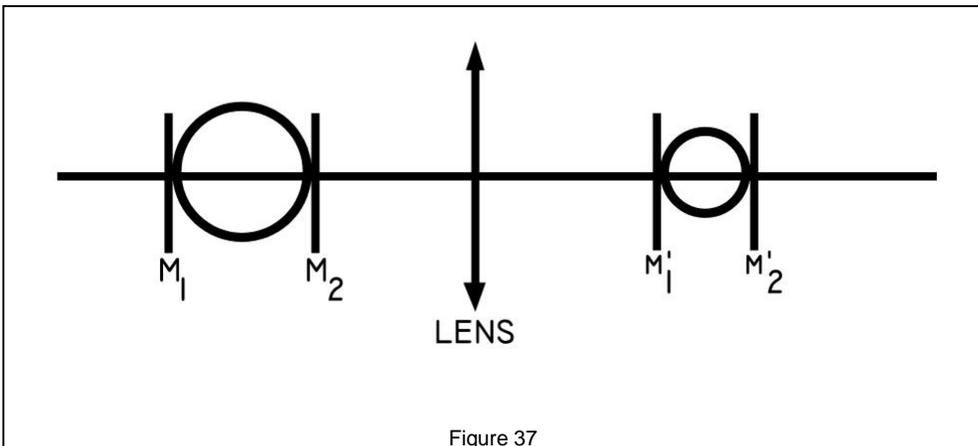


Figure 37

For objects with axial dimensions that are relatively small,  $M_1$  and  $M_2$  are usually very close in numerical value, which leads to the approximate formula of:

$$\text{Axial Magnification} = M^2$$

Where  $M$  is the transverse magnification for any pair of the object's conjugates.

**Question:** The front of a 5cm thick object is 20cm in front of a +9.00D lens. Calculate the axial magnification using both formulas.

**Answer:** The two faces of the object are positioned 20 and 25cm in front of the lens. From the vergence equation, the face located 20cm ( $U = 100/-20 = -5.00D$ ) in front of the lens is imaged 25 cm behind the lens ( $U + D = V = -5 + (+9) = +4D$ ,  $v = 100/+4 = +25cm$ ). The magnification = image distance/object distance =  $+25/-20 = -1.25X$ .

The other side of the object located 25cm ( $100/-25 = -4.00D$ ) from the lens is imaged at 20cm ( $U + D = V = -4 + (+9) = +5D$ ,  $v = 100/+5 = +20cm$ ) behind the lens with a magnification of  $20/-25 = -0.8$

Using the approximation formula, the axial magnification is either  $(-1.25)^2 = 1.56$  or  $(-0.8)^2 = 0.64$ , depending on which plane we choose.

Using the exact formula, the axial magnification is  $-0.8 \times -1.25 = 1.00$

**Question:** An example of the importance of axial magnification is the evaluation of optic nerve cupping using indirect ophthalmoscopy. The cup can be evaluated using a +20.00D lens, but a +14.00D lens markedly improves the evaluation. What is the axial magnification of a 20D versus a 14D-condensing lens?

**Answer:** Lateral magnification produced through the indirect ophthalmoscope is the ratio of the total refracting power of the eye (60D) to the power of the condensing lens. The 14.00 diopter lens gives a slightly larger transverse magnification ( $60/20 = 3X$  versus  $60/14 = 4.286X$ ), but a significantly larger axial magnification because axial magnification increases as the square of transverse magnification ( $3X^2 = 9X$  versus  $4.286X^2 = 18.37X$ ). Larger axial magnification increases the distance between the optic nerve rim and the base of the cup in the aerial image, improving assessment of the cup.

*g. Effective Magnification =  $M_e = dF$*

Where  $d$  = reference distance in meters to the object (image is formed at infinity)

If  $d = 25\text{cm}$  than  $M_e = F/4$

If  $d = 40\text{cm}$  than  $M_e = F/2.5$

**Question:** A +24.00D lens is used as a hand-held magnifier with the patient viewing an object that is 50cm from the eye and at the focal point of the lens. How much larger do things appear to the patient?

**Answer:**  $d = 0.50\text{m}$ ,  $F = +24.00\text{D}$ ,  $M_e = dF = 0.50(24) = 12\text{X}$

This indicates that closer working distances result in less effective magnification.

*h. Rated Magnification =  $M_r = F/4$*

Assumes that the individual can accommodate up to 4.00 diopters when doing close work which gives  $d = 25\text{cm}$  (25cm is the standard reference distance used when talking about magnification).

**Question:** A simple lens magnifier to be used as a low vision device is marked 5X (reference plane at 25cm). What would you expect to find when you measure the lens on a lensometer?

**Answer:**  $M = F/4 = 5 = F/4$ ,  $F = 20\text{D}$

**Question:** A view of the retina is obtained through an indirect ophthalmoscope, using a 30-diopter lens. The observer is 40cm from the arial image. What is the perceived lateral magnification?

**Answer:** 1.25x

**Explanation:** Lateral magnification produced through the indirect ophthalmoscope is the ratio of the total refracting power of the eye (60D) to the power of the condensing lens (30D), assuming the standard reference distance for magnification of 25cm from the observer to the arial image. If the distance is greater than 25cm, the lateral magnification is multiplied by the ratio of the standard reference distance, 25cm, to the distance in question, 40cm.

$60/30\text{D} = 2\text{x}$  magnification at 25cm ( $2 \times 25\text{cm}/40\text{cm}$ ) = 1.25x magnification

*i. Conventional Magnification =  $M_c = dF + 1$*

The underlying assumption in this equation is that the patient is “supplying” one unit (1X) of magnification

**Question:** Which patient needs more magnification and which patient needs the stronger lens? Patient A wants to read 1M print and has a near acuity of 2M using a +5.00 diopter add at 20cm. Patient B also wants to read 1M and has an acuity of 3M with a +2.50 diopter add at 40cm.

**Answer:** Patient A reads 2M print and wants to read 1M print, therefore,  $2M/1M = 2x$  magnification.  $F_s$  needed is  $+5D \times 2 = +10.00$  diopters.

Patients B needs  $3M/1M$  or  $3x$  magnification and has  $F_s$  of  $+2.5 \times 3 = +7.5D$ . Even though Patient B needs  $1 \frac{1}{2}$  times the amount of magnification Patient A does, ( $3M$  versus  $2M$  to start) he actually requires a weaker lens than Patient A does.

This apparent paradox in magnification is because we are comparing apples to oranges when we use different distances. To compensate for different viewing distances, change patient B’s working distance to 20cm, the same as patient A. He would then see 1.5M print using a 5.00 diopter add for the 20cm working distance.  $1.5M/1M = 1.5x$  times 5 diopters which = 7.5 diopters of magnification needed.

*j. Magnification Ratings*

Some companies use  $F/4$  (Rated Magnification) while others use  $(F/4) + 1$  (Conventional Magnification) to determine magnification strength for their magnifiers. This is why dioptic power, which is an absolute value and is the same under all conditions, is a better way to discuss the magnification needs of an individual.

*k. Determining Needed Magnification*

- Magnification needs are based on the initial reference value and the desired final value. Clinically, it is the entrance acuity divided by the goal acuity ( $VA/VA'$ ).

## 28. Telescopes

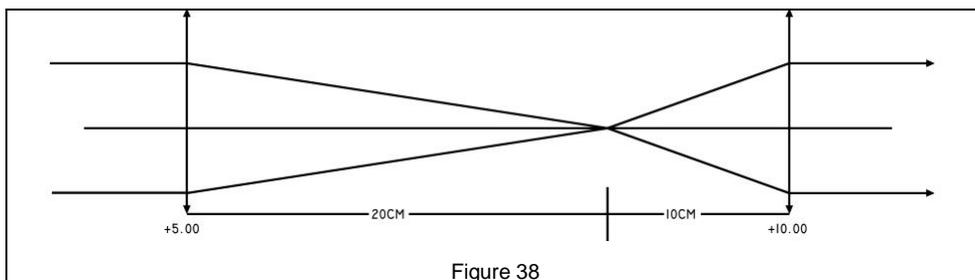
Telescopes are afocal optical systems consisting of two lenses, separated in space, in air.

There are two types of telescopic systems, Keplerian and Galilean.

### a. Keplerian telescopes

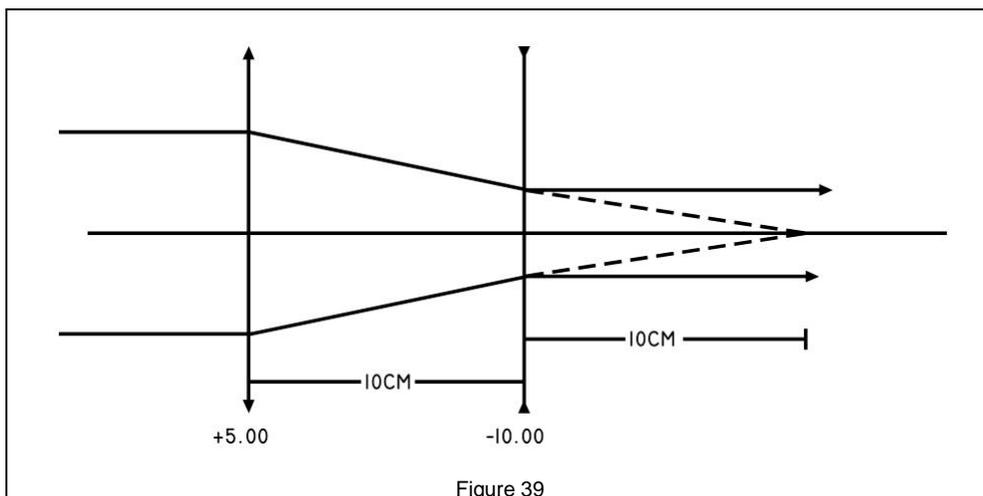
Keplerian telescopes have a weak (+) objective lens and a strong (+) eyepiece lens. (Figure 38)

The lenses are separated by the sum of their focal lengths. Keplerian (astronomical) telescopes form an inverted image so they require an erecting lens or prisms to make it a Terrestrial telescope.



### b. Galilean telescopes

Galilean telescopes (Figure 39) have a weak (+) objective lens and a strong (–) eyepiece lens. The lenses are separated by the difference of their focal lengths. Galilean telescopes form an erect/upright image.



The *angular magnification* of a telescope is equal to the power of the eyepiece divided by the power of the objective.

$$M_{A \text{ Telescope}} = (-) F_E/F_O$$

- The eyepiece in the Galilean telescope has a negative power. Therefore, the magnification given by the equation above is positive, indicating an upright image.
- Keplerian telescopes have both positive objective and eyepiece lenses; the magnification is negative, indicating an inverted image.
- With any telescope, the secondary focal point of the first lens must coincide with the primary focal point of the second lens. With Galilean telescopes, the second lens is minus and so the primary focal point is virtual.
- Galilean telescopes have several practical advantages for low vision work. The image is upright, without the need for image erecting prisms and the device is shorter. Galilean telescopes typically are 2, 3 or 4x in strength, inexpensive, light, and have a large exit pupil, which makes centering less difficult.
- 4x telescopes and stronger are usually Keplerian in design which gives an optically superior image, but are more expensive with a smaller exit pupil requiring better centering and aiming. Keplerian binoculars, contain prisms to erect the otherwise inverted image.
- Galilean telescopes used as surgical loupes, require an add to be combined with the objective lens. The field size is far smaller than that obtained with bifocal spectacles.
- Telescopic loupes can produce asthenopia with any type of refractive error. If binocular loupes are not aligned properly, vertical or horizontal phorias can be induced. Adopting a working distance too far inside the focal distance of the “add” can require excessive accommodation, even for a myope.
- When viewing a near object through an afocal telescope, the telescope acts as a vergence multiplier. The approximate accommodation required is given by  $A_{oc} = M^2U$ , where  $A_{oc}$  = vergence at the eyepiece = accommodation,  $U$  = object vergence at the objective =  $1/u$ ,  $M$  = the magnification of the telescope.

**Question:** How far apart must a +5D lens and a -10D lens be placed to form a Galilean (afocal) telescope?

**Answer:** With any telescope, the secondary focal point of the first lens must coincide with the primary focal point of the second lens. With Galilean telescopes, the second lens is minus and so the primary focal point is virtual. To make the secondary focal point (20cm) of the plus lens coincide with the virtual primary focal point of the minus lens (10cm), the lenses must be separated by  $20 - 10 = 10\text{cm}$ .

**Question:** You are a -5D spectacle corrected myope stranded on a small island with your significant other. Unfortunately, your companion has broken your glasses (which had an 11mm vertex distance). The only lens available to you is a -55D Hruby lens, which your companion had.

- a) How many cm from the eye should you hold the lens to fully correct your refractive error?

**Answer:** a) first, locate the far point of your eye. The far point of the lens is 0.211m in front of the eye ( $F = 1/-5$  which equals  $0.20\text{m} + 0.011\text{m}$  vertex distance =  $0.211\text{m} = 211\text{mm}$ ). The Hruby lens has a power of -55D which means, its focal point is  $1/55$  which equals 0.018m or 18mm away from the lens. To correct the refractive error, the focal point of the lens should coincide with the far point of the eye. Therefore, it should be 18mm away from the far point or  $211 - 18 = 193\text{mm}$  in front of the eye.

**Question:** Why would you not be able to read the 20/20 line with this correction?

**Answer:** b) The problem is magnification. This configuration turns the combination of the eye and its corrective lens into a reverse Galilean telescope, where the eyepiece is approximately +5D (the extra power of the myopic eye) and the objective lens is

-55D. The resulting magnification is  $(-)/5/-55$ , which equals 0.1x. Thus, the 20/20 line, while in focus, subtends 1/10 of the angle it would in the eye of an emmetrope. Therefore, the best distance acuity obtainable is only about 20/200, assuming an otherwise normal eye.

It should be noted that properly corrected patients with high myopia might not be able to read 20/20 through their spectacle lenses even in the absence of other pathology. This is because the longer axial length commonly found in higher amounts of myopia, results in greater separation of the photoreceptors, which decrease the visual potential of the eye.

**Question:** You and a stowaway are ship wrecked on a lost island with your trial lens set, but only a few lenses survive the shipwreck. you are left with a -20D, +4D, +5D, and a +20D. You build a viewing device to search the horizon for ships using the -20D and the +4D lens. The stowaway, Dr. Smith, uses the +20D and the +5D lens. Dr. Smith complains that his viewing device is inferior.

- a) What did each of you build?
- b) How did you position the lenses?
- c) Why is Dr. Smith plotting to steal your telescope?

**Answer:** You use the -20D lens as the eyepiece and the +4D lens as the objective lens of a Galilean telescope. The secondary focal point of the plus lens should coincide with the primary focal point of the minus lens; thus, the lenses are  $25\text{cm} - 5\text{cm} = 20\text{cm}$  apart. Dr. Smith built a second telescope (astronomical) using the +20-diopter lens as the eyepiece and the +5D lens as the objective. The secondary focal point of the objective lens needs to coincide with the primary focal point of the eye piece lens, so he positions them  $5\text{ cm} + 20\text{ cm} = 25\text{ cm}$  apart.

Dr. Smith does not like having to stretch his arms the additional 5cm.

**Question:** Which telescope above will provide more magnification?

**Answer:** The angular magnification of a telescope is equal to the power of the eyepiece divided by the power of the objective. Magnification of the Galilean telescope is  $(-)\frac{20}{4} = 5x$ . The magnification of the astronomical telescope is  $(-)\frac{20}{5} = -4x$ . Therefore, Dr. Smith's telescope will provide less magnification.

**Question:** Will the telescopes have an erect or inverted image?

**Answer:** The Galilean telescope will produce an upright image of the, hopefully approaching ships, while Dr. Smith's astronomical telescope will produce an inverted image.

**Question:** How is the Galilean telescope modified when used as a surgical loupe?

**Answer:** The binocular surgical loupe is just a short Galilean telescope with an add to bring the working distance in from infinity. Powerful lenses are used so that the tube length of the telescope is kept to a minimum. A +25D object, combined with a -50D eyepiece, would provide 2x magnification. The additional add needed to focus the telescope at near is the reciprocal of the working distance in meters. Example: for a 25cm working distance, the add would be  $100/25 = 4D$ .

**Question:**

- How long is the 2x Galilean telescope described above?
- What if it were made using a +5.00D objective lens and a -10D eyepiece lens?

**Answer:**

- The focal length of the -50D lens is  $1/50 = 2\text{cm}$ . The +25D lens has a  $100/25 = 4\text{cm}$  focal length. Thus, the telescope is  $4 - 2 = 2\text{cm}$  long.
- The +5/-10 telescope is  $20 - 10 = 10\text{cm}$  long.

**Question:** You are working with a 2x afocal Galilean telescope that is fabricated with a +8D objective lens. We know that the ocular lens must be -16D and the 2 lenses are separated by 6.25cm (objective lens  $1/8 = 12.5\text{cm}$ , ocular lens  $1/16 = 6.25\text{cm}$ , tube length =  $12.5 - 6.25 = 6.25\text{cm}$ ).

When viewing at infinity by an uncorrected 4D hyperope, the ocular has an effective power of?

**Answer:** +4D is needed to correct for the hyperopic refractive error. This power must be taken from the ocular lens of the telescope and so the effective power of the ocular lens becomes  $-16 - 4 = -20\text{D}$ . (The -20D effective ocular lens combined with the +4D correction lens gives us the -16D the ocular lens of the telescope actually has).

**Question:** For the telescope to remain afocal, the tube length must be?

**Answer:** The objective lens focal length is still 12.5cm, ocular lens is now  $1/20 = 5\text{cm}$ . Therefore  $12.5 - 5 = 7.5\text{cm}$

**Question:** What is the telescopic power now?

**Answer:**  $M_{\text{A Telescope}} = (-)F_E/F_O = (-)20/8 = 2.5\times$

**Question:** When viewed by an uncorrected 4D myope, the ocular has an effective power of?

**Answer:** The uncorrected -4D of the eye must act as a correcting lens so the ocular now has an effective power of  $-16 + 4 = -12\text{D}$ . (The -12D effective ocular lens combined with the -4D correction lens gives us the -16D the ocular lens of the telescope actually has).

**Question:** To make the telescope afocal, the tube length must be?

**Answer:** The objective lens focal length is still 12.5cm, ocular lens is now  $1/12 = 8.33\text{cm}$ . Therefore  $12.5 - 8.33 = 4.17\text{cm}$ .

**Question:** What is the telescopic power now?

**Answer:**  $M_{A \text{ Telescope}} = -F_E/F_O = (-)12/8 = 1.5x$ .

**Question:** An afocal Keplerian telescope has an objective lens that is +7D and an eyepiece lens that is +17.50D. What is the separation between the lenses?

**Answer:** The focal length of the objective lens is  $1/7 = 14.3\text{cm}$ . The focal length of the eyepiece lens is  $1/17.5 = 5.7\text{cm}$ . Therefore, the lens separation is  $14.3 + 5.7 = 20\text{cm}$

**Question:** What is the power of the telescope now?

**Answer:**  $M_{A \text{ Telescope}} = (-)F_E/F_O = (-)17.5/7 = -2.5x$

**Question:** A patient uses a focusable 2x Keplerian telescope that has a +8D objective lens. What is the power and tube length of the afocal telescope when used by an emmetropic patient and focused for distance viewing?

**Answer:** The power is 2x because it is being used by an emmetrope.

The eyepiece lens power would be +16.00D

$(M_{A \text{ Telescope}} = (-)F_E/F_O = (-)X/8 = -2x)$

To find the tube length, the focal length of would be  $1/8 = 12.5\text{mm}$  for the objective lens and  $1/16 = 6.25\text{mm}$  for the eyepiece lens. Therefore, the tube length would be  $12.5 + 6.25 = 18.75\text{mm}$ .

**Question:** When used by a 4D hyperope in a similar fashion?

**Answer:** For the uncorrected 4D hyperope, the eyepiece lens now has an effective power of  $16 - 4 = 12\text{D}$ . (The +12.00D effective ocular lens combined with the +4D correction lens gives us the +16D the ocular lens of the telescope actually has). The power of the telescope would become  $(-) 12/8 = -1.5x$ . The tube length would be 20.83mm. ( $1/12 = 8.33\text{mm} + 12.5 = 20.83\text{mm}$ )

**Question:** When used by a 4D myope in a similar fashion?

**Answer:** For the uncorrected 4D myope, the eyepiece lens now has an effective power of  $16 + 4 = 20\text{D}$ . (The  $+20\text{D}$  effective ocular lens combined with the  $-4\text{D}$  correction lens gives us the  $+16\text{D}$  the ocular lens of the telescope actually has). The power of the telescope would be  $(-)/20/8 = -2.5x$ . The tube length would be  $17.5\text{mm}$  ( $1/20 = 5\text{mm} + 12.5\text{mm} = 17.5$ )

**Question:** A focusable Galilean telescope with a  $+20\text{D}$  objective lens with a  $-40\text{D}$  ocular lens is dispensed to a patient for a variety of tasks.

a) What is the magnification of the telescope at distance?

**Answer:**  $M = (-) -40/20 = 2x$

b) What tube length is required for viewing distance objects?

**Answer:**  $1/20 = 5\text{cm}$ ,  $1/40 = 2.5\text{cm}$ ,  $5 - 2.5 = 2.5\text{cm}$

c) What is the tube length required for viewing numbers that are 50cm away in an elevator?

**Answer:** The objective power would now be  $+20 + (-2) = +18\text{D}$ .  $100/+18 = +5.55$ ,  $+5.55 - 2.5 = 3.05\text{cm}$ .

**Important to remember** – 20 inches = 50 cm. To find the vergences when working in inches, use the formula  $V = 40/\text{distance (inches)} = 100/\text{distance (cm)}$

**Question:** A 3x afocal Galilean telescope has a separation between the objective and ocular lens of 2cm. When viewing an object 25cm in front of the objective lens, what power reading cap would eliminate the need to accommodate for this target distance?

**Answer:**  $100/25 = +4\text{D}$

**Question:** A patient with vision loss needs a 10D add to read the text on a computer monitor but the 10cm working distance is too close. He wants to work at a 25cm distance. What theoretical telescope and reading cap combination would be needed?

**Answer:**  $25/10 = 2.5x$ ,  $100/25 = +4D$ , therefore you would need a 2.5x telescope with a +4D reading cap.

**Question:** What is the equivalent lens that should be prescribed to replace a 4x telescope with a +2.50D reading cap ( $F_{RC}$ ) so the patient has the same resolution ability through the lens that he has through the telemicroscopic system?

**Answer:**  $F_e = (F_{RC}) (\text{power of telescope}) = 2.5D (4) = 10D$

**Question:** If a patient is able to read enlarged sheet music with a 3x telescope and a cap focus for 16 inches, what telescope and cap are needed to read the same sheet music set at 32 inches?

**Answer:**  $32/16 = 2x$  additional magnification,  $40/32 = 1.25D$ , Therefore, you would need a 6x telescope with 1.25D cap

## 29. Aniseikonia

Aniseikonia... “may be due to differences in the size of the optical images on the retina or may be anatomically determined by a different distribution in spacing of the retinal elements”. (Duke-Elder, 1963)

Aniseikonia is a term coined by Dr. Walter Lancaster in 1932. It means literally “not equal images (either size, shape, or both)” from the two eyes, as perceived by the patient and is one of the problems most frequently associated with the correction of anisometropia with spectacles. It is an anomaly of the binocular visual process that affects the patient’s perceptual judgment. The most common cause is the differential magnification inherent in the spectacle correction of Anisometropia. This difference in magnification produces different sized retinal images. Approximately 1/3 of the cases of aniseikonia are predicted from anisometropia. Aniseikonia is more commonly caused by unequal refractive errors common in conditions such as monocular aphakia or pseudophakic surprises. However, it is also found with retinal problems and occipital lobe lesions. Aniseikonia occurs in 5-10% of the population with only 1-3% having symptoms.

The perception of an image size disparity between the two eyes is due to the image on the retina not falling on corresponding retinal points. The ocular image is the final impression received in the higher cortical centers, involving the retinal image with modifications imposed by anatomical, physiologic, and perhaps psychological properties of the entire binocular visual apparatus. This is why there are cases of aniseikonia in individuals with emmetropia and isometropia (equal refractive errors).

In general, aniseikonia is associated with a false stereoscopic localization and an apparent distortion of objects in space. Aniseikonia can be the cause of asthenopia, diplopia, suppression, poor fusion, headaches, vertigo, photophobia, amblyopia, and strabismus. The differences in size may be overall, that is, the same in all meridians, or meridional, in which the difference is greatest in one meridian and least in the meridian 90° away.

Clinically, aniseikonia usually occurs when the difference in image size between the two eyes approaches 0.75%. Individuals with greater than 4-5% image size difference, have such a large disparity in image size, that they generally do not have binocularity. It

is usually assumed that patients can comfortably tolerate up to 1% of aniseikonia in non-astigmatic cases.

A change in refractive correction is always accompanied by some change in the retinal image size and in the conditions under which the patient sees. The magnitude of these changes and the patient's tolerance determines whether these changes will produce symptoms of discomfort or inefficiency. Persons with normal binocular vision can readily discriminate differences in image size as low as 0.25 to 0.5 percent. For persons with normal binocular vision, a deviation of 4-5x the threshold of discrimination is usually considered significant.

Aniseikonia can be noted when a patient, for the sake of comfort, prefers to use one eye for reading or watching moving objects. If an individual can learn to rely on non-stereoscopic, rather than stereoscopic clues, they may be able to avoid irritation from aniseikonia, even when it is present.

Aniseikonic patients may see an apparent slant of level surfaces, such as tabletops and floors. The effect is more pronounced with objects on the surfaces, for instance, with an irregular pattern carpet on the floor. For high levels of cylinder correction, spherical equivalents may help reduce the aniseikonia.

- The magnification for flat trial lens case cylinders is approximately 1.5% per diopter.
- The uncorrected refractive myopic eye will have a larger image by 1.5% per diopter and the uncorrected refractive hyperopic eye will have a smaller image by 1.5% per diopter. This holds for anisometropia primarily of refractive origin.
- The corrected refractive myopic eye will have a smaller image by 1.5% per diopter and the corrected refractive hyperopic eye will have a larger image by 1.5% per diopter. This holds for anisometropia primarily of refractive origin.
- However, since anisometropia may be partially axial, an estimate of 1% per diopter is more clinically useful.

When considering axial versus refractive anisometropia:

If the amount of anisometropia is  $> 2D$  – assume it to be axial.

If the amount of anisometropia is  $< 2D$  or is in cylinder only – assume it to be refractive.

Spectacle correction of astigmatism produces meridional aniseikonia with accompanying distortion of the binocular spatial sense. Anisometropia is commonly stated to be present if the difference in the refractive correction is 2.00D or more either spherical or astigmatic. However, smaller differences than 2.00D may be significant.

When prescribing aniseikonic lenses, it is important to realize that the size and shape of the final image does not matter, it is only important that the images of each eye match each other. For this reason, instead of magnifying the image of one eye, it may be easier to minify the image of another. This may allow for more cosmetically acceptable spectacles, or at least lenses that are easier to manufacture, and therefore, less costly.

#### *a. Cylindrical Corrections*

Cylindrical corrections in spectacle lenses produce distortion. This is a problem of aniseikonia, which may be solved by prescribing iseikonic spectacle corrections. *Iseikonia* is when perceived images are the same size. Iseikonic spectacle corrections may be complicated and expensive and the vast majority of practitioners prefer to prescribe cylinders according to cylinder judgment using guidelines that have evolved over the years. Remember the reason for intolerance of an astigmatic spectacle correction is distortion caused by meridional magnification which is more poorly tolerated. Unequal magnification of the retinal image in the various meridians produced monocular distortion manifested by tilted lines or altered shapes of objects. The monocular distortion by itself is rarely a problem. The effect is too small.

Oblique meridional aniseikonia causes a rotary deviation between fused images of vertical lines in the two eyes. The maximum tilting of vertical lines is called the *Declination Error*. The maximum declination error occurs when the corrected cylinder axis is at  $45$  or  $135^\circ$ , but even under these conditions, each diopter of correcting cylinder power produces only about  $0.4^\circ$  of tilt. This problem occurs more often with plus cylinder lenses which is why most spectacle lenses are now made in the minus cylinder form. Clinically significant problems begin to occur when the declination approaches 0.3%. Minor degrees of monocular distortion can produce major alterations in binocular spatial perception.

The *Total Magnification of a Lens* ( $M_T$ ) is found by adding the magnification from its power ( $M_P$ ) and the magnification from its shape ( $M_S$ ). Therefore, total magnification  $M_T = M_P + M_S$ .

*Magnification from Power* ( $M_P$ ) is dependent on the dioptric power of the lens ( $D_V$ ) and its vertex distance ( $H$ ). If  $H$  is measured in cm, the relationship is  $M_P = D_V H$ . From this formula, we see that moving a lens away from the eye increases the magnification of a plus lens and the minification of a minus lens. Moving a lens toward the eye (decreasing the vertex distance) decreases the magnification of a plus lens and the minification of a minus lens. These effects are especially notable with higher powered lenses.

### Examples

+10.00D lens @ 10mm and 15mm vertex distance

$$\text{@ 10mm, } M_P = D_V H = +10.00 \times 1.0 = +10$$

$$\text{@ 15mm, } M_P = D_V H = +10.00 \times 1.5 = +15$$

-10.00D lens @ 10 and 15 mm vertex distance

$$\text{@ 10mm, } M_P = D_V H = -10.00 \times 1.0 = -10$$

$$\text{@ 15mm, } M_P = D_V H = -10.00 \times 1.5 = -15$$

For spectacle lenses remember, as you move a lens closer to the eye, you must add plus power to the lens. Therefore, remember *CAP = Closer Add Plus*.

*Magnification from Shape* ( $M_S$ ) is dependent on the curvature of the front surface of the lens  $D_1$  and the center thickness of the lens  $t$ . The 1.5 in the following equation is the index of refraction (approximately) of glass or plastic.  $M_S = D_1 (t_{cm}/1.5)$ . Therefore, the more curved the lens, the larger the  $D_1$  and the more magnification from shape the lens have. Also, the thicker the lens ( $t$ ), the more magnification from shape.

### Examples

Front curve of a +2.00D lens is +2.00D and +6.00D, Thickness is 2mm.

$$M_S = D_1 (t_{cm}/1.5) = +2.00(0.2/1.5) = +0.27$$

$$M_S = D_1 (t_{cm}/1.5) = +6.00(0.2/1.5) = +0.80$$

Front curve of a +2.00D lens is +2.00D and +6.00D, Thickness is 4mm.

$$M_S = D_1 (t_{cm}/1.5) = +2.00(0.4/1.5) = +0.53$$

$$M_S = D_1 (t_{cm}/1.5) = +6.00(0.4/1.5) = +1.60$$

Magnification may be reduced by making the front surface power of a lens less positive.

Decreasing center thickness also decreases magnification.

However, a change in either the front curve or the thickness of the lens will also cause the vertex distance ( $h$ ) to be changed so that the magnification from the power factor ( $M_p$ ) is also affected. If the front curve is changed to give the magnification or minification needed, the back curve must also be changed to maintain the same power of the lens.

If, for example, the front curve is increased, the back curve must also be increased, which increases the vertex distance. If the front curve is flattened, the back curve must be flattened, which causes the vertex distance to decrease. If center thickness is increased to increase the magnification of the lens, but the front curve is left the same, the increase moves the back-surface closer to the eye by the amount of the increase, therefore decreasing the vertex distance. On the other hand, if the center thickness is decreased, but the front curve is left the same, the decrease causes the vertex distance to be increased by that amount.

For further review on this subject, go to the *THILL Aniseikonia Worksheet* in Duane's Clinical Ophthalmology (Lippincott Williams & Wilkins).

Contact lenses may provide a better solution than spectacles in most patients with anisometropia, particularly children, where fusion may be possible, because it gives the least change in image size from the uncorrected state in refractive ametropia.

### **30. Multifocal Design**

Bifocals are made in two different ways. (Figure 40) One piece and fused lenses.

The one-piece type is made from one piece of glass or plastic. The lens surface is ground with two different curvatures. The shorter radius of curvature in the bifocal area creates the additional power. Fusing two different types of glass together makes fused bifocals. Each type of glass has a different index of refraction, which is not possible with plastic lenses. The segment button has a higher refractive index (flint  $n = 1.7$ ) than the basic lens (crown  $n = 1.523$ ).

Most flat top fused segments are designed with the optical center 4 mm below the segment top and produce only a very small amount of image jump (see below). Larger,

flat top segments are similar to an executive bifocal, in that they will have little to no image jump.

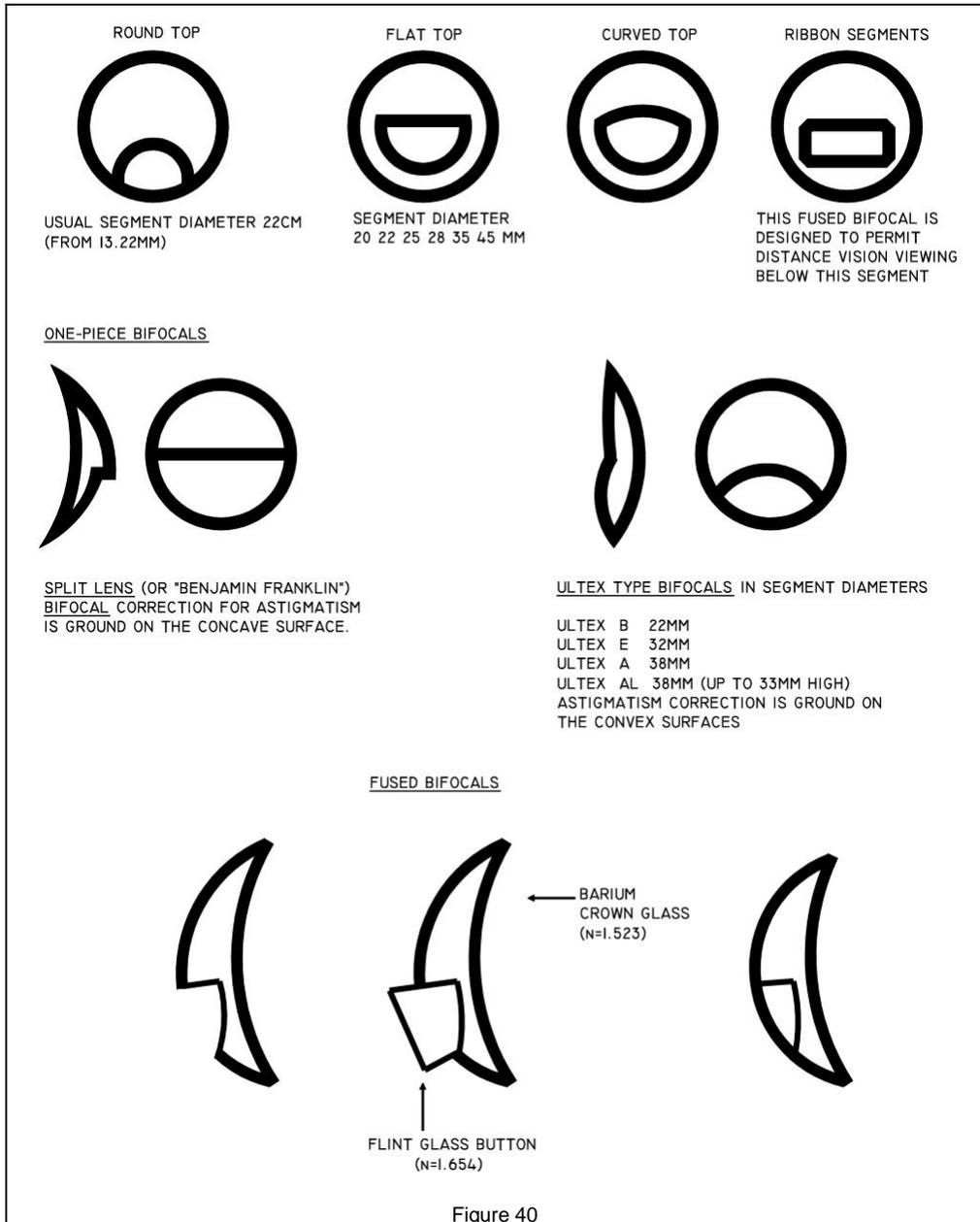


Figure 40

a. *Image Jump* is produced by the sudden introduction of the prismatic power at the top of a bifocal segment. The object the individual sees in the inferior field 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. Image jump is worse in glasses with a round top bifocal, because the optical center of the bifocal is farther from the distance lens optical center. A flat top bifocal is better because the optical center of the bifocal is close to the distance optical center.

b. *Image Displacement* is the prismatic effect induced by the combination of the bifocal type and the power of the distance lens prescription in the reading position. Image displacement is more bothersome than image jump for most people. Most bifocal corrected presbyopes read through a point about 10 mm below the optical center of their distance lenses. If that position is also at the bifocal segment's optical center, as in most fused flat top bifocals, the bifocal segment produces no prismatic effect at all. The prismatic effect that is there is induced by the distance lens correction, not the segment. However, if the optical center of the bifocal segment is located below or above the reading position, the bifocal will contribute to image displacement at the reading position. The total prismatic displacement will be the sum of that produced by the bifocal and that induced by the distance lens.

A flat top lens is essentially a base up prism, whereas a round top lens is a base down prism at the normal reading spot, 10 mm below the optical center of the lens. A myopic distance lens has base down prismatic power in the reading position; thus, *image displacement* is worsened with a round top lenses. The prism effects are additive. Similarly, a hyperopic spectacle lens is a base up prism in the reading position; thus, a flat top lens makes image displacement an issue.

Most individuals will physiologically adapt, or learn to fuse small vertical deviations. If they cannot, there are several ways to compensate for the problem including, using contact lenses instead of spectacles, prescribing dissimilar segments, or providing "slab-off" prism.

In the past, slab-off prism (base up) was added to the spectacle lens that had the most minus or least plus correction for distance. Now, with modern plastic lenses, slab-off prism is taken off the mold, effectively adding base down prism to the most plus or less minus lens. This is called "reverse slab". Slab off is fabricated by way of bicentric grinding which creates two optical centers in the lens. One optical center is for the distance correction and the other is for the reading correction of the lens.

**Question:** If a patient comes in wearing glasses: OD +2.00, OS -2.00, and complains of vertical diplopia when reading. Both eyes are reading 5 mm down from the optical center. How much slab-off do you prescribe?

**Answer:** 2.00 prism diopters base up OS. A slab-off prism is always put in front of the more minus eye because slab off provides base up prism. In this example, the right eye will have induced 1.00 prism diopter base up and the left eye will have induced 1.00 prism diopter base down.

**Question:** Should a hyperope use a round top or a flat top bifocal?

**Answer:** A plus lens will have significant image displacement with a flat top lens. Image displacement is lessened with a round top lens. Although image jump will be present, it is less disturbing than image displacement.

**Question:** Should a myope use a flat top or a round top bifocal?

**Answer:** A round top lens has significant image displacement with a minus lens. A flat top lens minimizes image displacement and image jump for a myope.

**Question:** What is the induced prism for an individual wearing +5.00D OU, when reading at the usual reading position of 2mm in and 8mm down from the optical center of his lenses?

**Answer:**  $PD = hF$ , therefore, vertically  $+5.00D \times 0.8 = 4PD$  BU per eye

horizontally  $+5.00D \times 0.2 = 1PD$  BO per eye

**Question:** What vertically compensating prism is needed for an individual wearing +5.00D OD and +2.00D OS when they are viewed in the normal reading position of 8mm down from the optical center of the lens?

**Answer:**  $+5.00D \times 0.8 = 4PD$  BU and  $+2.00 \times 0.8 = 1.6PD$  BU,  $4 - 1.6 = 2.4PD$  BU needed for the left eye.

### 31. Visual Acuity Assessment

- Measures spatial resolving capacity (ability to see fine detail) of the visual system.
- Allows for quantification of degree of high contrast vision loss.
- Monitors stability or progression of disease and visual abilities as rehabilitation progresses.
- Allows assessment of eccentric viewing postures and skills, patient motivation and scanning ability (for field loss).
- Allows teaching of basic concepts and skills (i.e., eccentric viewing).
- Is the basis for determining initial magnification requirements.
- Verify eligibility for tasks such as driving.
- Verify eligibility as "legally blind".
- Inaccurate acuity testing underestimates ability.

Factors to consider when measuring VA include; contrast of chart, lighting, number of optotypes at each acuity level, spacing of targets, difficulty of targets used (letters, numbers, pictures), single targets versus words (or multiple digits) versus continuous text, eccentric viewing postures, expressive as well as receptive language skills and cognitive level. The best quantification of visual acuity is obtained when using appropriate charts.

It is important to accurately measure visual acuity to determine if your refraction/plan of care is helping. For this reason, do not use “counts fingers” if at all possible. If the patient can see fingers, they can read the larger figures on the chart, if the chart is brought closer.

If you must use “counts fingers”, note the distance at which the patient can count your fingers. Most fingers are equivalent in size to a 200 (60) size letter. Therefore, CF at 3 feet (1 meter) is equivalent to  $\frac{3}{200}$  ( $\frac{1}{60}$ ) =  $\frac{20}{1300}$  ( $\frac{6}{360}$ ).

If the patient’s visual acuity is reduced to the point where they can only see “hand motions”, note which quadrant(s) and at what distance? If the patient can only see light, do they have “light perception with projection” versus just “light perception”? If yes, in which quadrant(s) and at what distance?

Shorter test distances allow for greater accuracy when measuring lower levels of acuity

Typical starting test distances are 5 or 10 feet or 2 to 4 meters, depending on the chart used. Remember to account for accommodative demands at closer distances.

Record the visual acuity as actual test distance over size of character read.

For a Snellen or Feinbloom chart, the test distance in feet becomes the numerator, and the size of the number read (noted in foot size) is the denominator

Example: 400 size optotype @ 10 feet = 10/400, 80 size optotype @ 5 feet = 5/80

For the ETDRS chart, measure at 1, 2 or 4 meters

Use the testing distance as the numerator, and the M size of the letters read as the denominator. M size is given in the far-left column. The next column gives the conversion to Snellen equivalent (not the letter size). For example, when testing at 2 meters and the patient reads the 32M line (160 Snellen equivalent), the acuity is recorded as  $2/32 = 20/320$ .

During measurement of visual acuity, the clinician should evaluate eccentric viewing techniques demonstrated by the patient.

### **Near Acuity Measurement & Charts**

- The M unit chart was developed by Bailey in 1978. The International Council of Ophthalmology as well as the International Society for Low Vision Research and Rehabilitation recommends metric acuity testing, because it is the most accurate and reproducible test available.
- Testing distance must be measured and recorded
- The designation of letters signs (e.g., 1M, 2M) indicates the distance in which the print is equivalent in angular size to a 20/20 optotype. Example: 1M print subtends 5 minutes of arc at 1 meter

### **Near Acuity Charts**

ETDRS near charts

- Like distance version, has a logarithmic progression in sizes, with proportional spacing of letters and rows which allows the task to remain constant at different distances

Lighthouse “Game” & “Number” cards

- Words and triple digit numbers
- Allows assessment of “crowding” as well as cognitive influences in reading difficulties

Sloan continuous text reading cards

- Continuous text cards of appropriate reading level will provide a more accurate measure of reading ability than single optotype acuities

Jaeger Acuity

- Least desirable letter-size designation (Source: International Council of Ophthalmology and the American Academy of Ophthalmology)
- Jaeger numbers are a printer’s designation that refer to the boxes in the print shop in Vienna where Jaeger selected his print samples in 1854
- The print boxes are not proportional to the letter size
- System has never been standardized
- Print size is not the same from one test card or chart to another

### **Recording near acuity**

Near visual acuity is recorded as testing distance in meters over M-size letter read. Can also be recorded as M-sized read at what testing distance. For example, if a 4M letter is read at 40 cm, the acuity is recorded as 0.40/4M or 4M @ 40cm.

Use of the M system also facilitates calculation of addition power (i.e., the dioptric power required to focus at a specific metric distance). For example, if a patient reads 0.40/4M and wants to read 1M print, they must hold the material 4x closer. Therefore,  $.40/4M = X/1M$ .  $X = .10M$  or 10cm. The lens that focuses at this distance is  $100/10 = +10D$

### **Types of Visual Acuity Testing**

*a. Minimum Visible Acuity:* measures brightness discrimination; the person's ability to detect small differences in the brightness of two light sources. Minimum visible acuity is determined by the brightness of the object relative to its background illumination as opposed to the visual angle subtend by the object.

*b. Minimum Perceptible Acuity:* measures **detection** discrimination. Minimum perceptible acuity is concerned with simple detection of objects, not their identification or naming. An example of this type of acuity testing is determining if a child can see and grasp a small candy bead held in the examiner's hand.

c. *Minimum Separable Acuity*: measures the **resolution** threshold, or smallest visual angle at which two separate objects can be discriminated. Landolt C, and grating acuity are examples of minimum separable tasks.

d. *Vernier Acuity (hyper acuity)*: a precise form of visual discrimination still under study. Hyper acuity has been coined to classify the high precision (within a few seconds of arc) with which Vernier alignment task can be performed. This level of precision is well above resolution or recognition acuity thresholds.

e. *Minimum Legible Acuity*: measures the individual's ability to **recognize** progressively smaller objects (letters, numbers or objects) called optotypes. The angle that the smallest recognized letter or symbol subtends on the retina is a measure of visual acuity. This type of acuity testing is used most often clinically.

f. *Snellen Acuity* uses a notation in which the numerator is the testing distance (in feet or meters) and the denominator is the distance at which a letter subtends the standard visual angle of 5 minutes. A 20/20 letter (6/6 in meters) subtends an angle of 5 minutes when viewed at 20 feet (6 meters). Each leg and space of the “E” is 1 minute ( $1/60$  degrees) = 0.017 degrees of visual angle. The 20/20 “E” viewed on a chart meant to be viewed at 20 feet is about 9 mm tall. Each leg and space between the legs is about 1.7 mm tall. For the Landolt “C”, the opening in the “C” is about 1.75 mm (1 minute of arc).

**Question:** How many minutes does the “E” on the 20/20 line of the Snellen eye chart subtend?

**Answer:** 5 minutes at 20 feet. Snellen eye chart measures the minimum legible acuity.

**Question:** What is the optimum size of pinhole used to measure “pinhole acuity”?

**Answer:** The optimum size is 1.2 mm. Larger pinholes do not effectively neutralize refractive error and smaller pinholes markedly increase diffraction and decrease the amount of light entering the eye.

### 32. Contrast Sensitivity

Contrast indicates the variation in brightness of an object. When an eye chart uses perfectly black ink on perfectly white paper, 100% contrast is achieved. Acuity charts approximate 100% contrast. Acuity charts are helpful for characterizing central visual acuity. However, they are less helpful for examining visual function away from fixation.

Contrast sensitivity is tested using alternating light and dark bars at varying intensity. The number of light bands per-unit length or per-unit angle is called the spatial frequency. During clinical testing of contrast sensitivity, patients are presented with targets of various spatial frequencies and peak contrasts. The minimum resolvable contrast is the contrast threshold. The reciprocal of the contrast threshold is defined as the contrast sensitivity, and the manner in which contrast sensitivity changes as a function of the spatial frequencies of the target is called the contrast sensitivity function.

Contrast sensitivity can be tested with sine wave gratings presented using either charts or video gratings. Because standard Snellen acuity charts test only the higher spatial frequency (30 cycles per degree), they do not provide an accurate picture of an individual's visual functioning, particularly when the individual has an ocular disease.

Acuity charts provide us with a quantitative assessment of visual functioning while contrast sensitivity charts provide us with a qualitative assessment of visual functioning. Contrast sensitivity testing is similar to current audiological testing which assesses an individual's ability to hear various tones and frequencies.

Contrast sensitivity testing can detect changes in visual function at times when Snellen visual acuity is normal. This can occur when corneal pathology, cataracts, glaucoma and various other ocular diseases are present.

### 33. Jackson Cross Cylinder (JCC)

Cross cylinders are combinations of two cylinders whose powers are numerically equal and of opposite sign and whose axes are perpendicular to each other. The Jackson Cross Cylinder is usually mounted in a ring with a handle at 45 degrees from the axis so that a twirl of the handle changes the cross cylinder to a second position.

Example:  $+0.25 \times 90 / -0.25 \times 180$  to  $-0.25 \times 90 / +0.25 \times 180$

When the JCC is placed in contact with a spherocylinder, it displaces both focal lines simultaneously in opposite directions, expanding the initial Interval of Sturm in the first position and contracting it in the second. However, there will be no displacement of the Circle of Least Confusion, only the diameter of the circle will increase in the first and decrease in the second position of the JCC.

When a  $\pm 0.50$  JCC is placed on a lensometer, with the red axis at 0 and 180 degrees, the lensometer will read the power as  $-0.50 + 1.00 \times 090$ . But, remembering that the JCC has no spherical power, only cylindrical power. For this reason, we can more accurately write the power of the JCC as  $-0.50 \times 180$  combined with  $+0.50 \times 90$

**Question:** When the Jackson cross cylinder is used to define the astigmatic axis, is the handle of the lens parallel to the axis or 45 degrees from it?

**Answer:** Parallel. To define the astigmatic power, the handle is rotated 45 degrees to the axis. Normally, you should define the axis before the power.

### 34. Duochrome Test

Chromatic aberration of the eye results in green light being focused in front of the retina, yellow light at the retinal plane, and red light behind the retina. Therefore, when red is brighter, it indicates that more minus is needed to move the focus of red light further behind the retina? When green is brighter, more plus is needed to move the green light to focus further into the posterior chamber.

### 35. Night Myopia

Light rays at the edge of the human lens are refracted more than those at the center of the lens. Because our pupils are larger at night, more spherical aberration is present under lower light conditions. A refractive shift towards more myopia is needed to compensate for this increase in spherical aberration. Additionally, accommodation does not go to a neutral state under low light conditions. The visual system actually accommodates approximately 0.75D under low light conditions. These changes result in a need for more minus or less plus correction for those individuals, such as over the road truck drivers, who need to function with their highest visual clarity at night.

### 36. Ring Scotoma

Produced by the aphakic or high plus spectacle lens resulting from the prism effect induced by the peripheral edge of the lens which possesses the maximum prismatic power and creates the greatest deviation of rays.

### 37. Lensmaker equation

The surface power of a lens =  $D_s = (n' - n)/r$ , where  $r$  is in meters,  $n$  = the index of the object space (air or fluid the lens is in) and  $n'$  = the index of the lens. This is also called the refractive power or simply the power of a spherical refracting surface.

The power of a thin lens (IOL) immersed in fluid

$$D_{\text{air}}/D_{\text{fluid}} = (n_{\text{IOL}} - n_{\text{air}})/(n_{\text{IOL}} - n_{\text{fluid}})$$

### 38. IOL Power (SRK Formula)

$D_{\text{IOL}} = A - 2.5L - 0.9K$ . Where  $D_{\text{IOL}}$  = recommended power for emmetropia,  $A$  = a constant (provided by manufacturers for their lenses),  $L$  = axial length in mm,  $K$  = average keratometry reading in diopters for desired ametropia. Change IOL power by 1.25 to 1.5D for each diopter of desired ametropia. Alternate formulas are needed for shorter or longer eyes.

### 39. Instruments

#### a. Lens Clock = Lens Gauge = Geneva Lens Measure

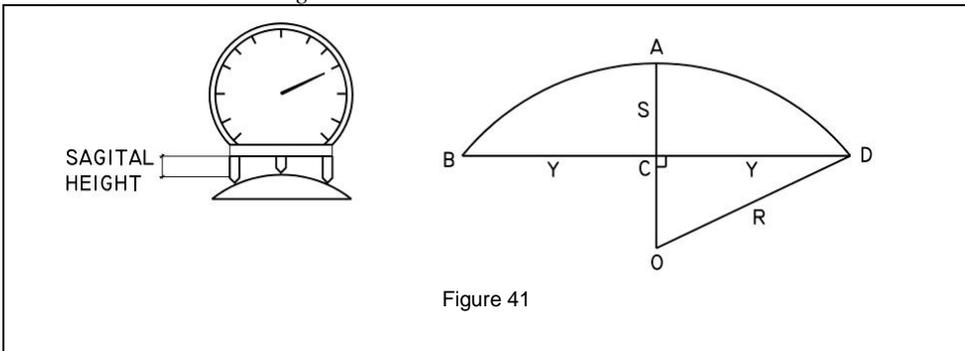


Figure 41

The lens measure, lens clock, or lens gauge has two fixed pins on the outside and in the center, a spring-loaded, movable pin. This device physically measures the sagittal depth of a refracting surface and calculates the refracting power of the surface. A pointer that is activated by a system of gears indicates the position of the movable pin in relation to the fixed pins. If the instrument is placed on a flat surface, the protrusion of the central pin is equal to that of the fixed pins, with the result that the scale reading is zero. If placed on a convex surface, the protrusion of the central pin is less than that of the fixed pins, but if placed on a concave surface, the protrusion of the central pin is greater. Because the chord length (the distance between the two outer pins) has a constant value for the instrument, the position of the central pin, indicates the sagitta of the surface, which provides a direct reading of diopters of refracting power of a surface of the lens.

- The lens clock physically measures the sagittal height/depth.
- The reading is in power (diopters)
- The lens clock assumes that  $n$  is in air and  $n' = 1.53$  (crown glass)

To calculate for the lens radius (assumes that  $s$  is very small)  $r = y^2/2s$  (see diagram)

To calculate true power of a single refracting surface (SRS)

$$F_{\text{true}} = F_{\text{lens clock}} (n'_{\text{true}} - n) / (n'_{\text{lens clock}} - n)$$

**Question:** What is a Geneva lens clock?

**Answer:** A device used to determine the base curve of the back surface of a spectacle lens. It is often used clinically to detect plus cylinder spectacle lenses in an individual who is use to minus cylinder lenses. It is specifically calibrated for the refractive index of crown glass ( $n = 1.53$ ). Special lens clocks are available for plastic lenses.

**Question:** A lens clock measures the power of a high index plastic lens ( $n = 1.66$ ) to be  $-5.00$  diopters. Has the lens clock overestimated, underestimated or accurately determined the power of the lens?

**Answer:** The lens clock has underestimated the power of the surface.

**Question:** A lens clock is used to measure the power of a SRS where  $n = 1.00$  and  $n' = 1.60$ .

1. What is the true power of the SRS if the lens clock reads  $-10.00\text{D}$ ?

$$F_{\text{true}} = F_{\text{lens clock}} (n'_{\text{true}} - n) / (n'_{\text{lens clock}} - n) = -10.00\text{D} (1.6 - 1) / (1.53 - 1) = -10.00 (.6 / .53) = -10.00\text{D} (1.132) = -11.32\text{D}$$

2. How much error was induced by the lens clock?  $-11.32 - (-10.00) = -1.32\text{D}$

**Question:** A lens clock is used to measure the power of a SRS where  $n = 1.00$  and  $n' = 1.498$ .

1. What is the true power of the SRS if the lens clock reads  $-10.00\text{D}$ ?

$$F_{\text{true}} = F_{\text{lens clock}} (n'_{\text{true}} - n) / (n'_{\text{lens clock}} - n) = -10.00\text{D} (1.498 - 1) / (1.53 - 1) = -10.00 (.498 / .53) = -10.00\text{D} (0.939) = -9.39\text{D}$$

2. How much error was induced by the lens clock?  $-9.39 - (-10.00) = +0.61\text{D}$

From these examples, you see that for lenses made with indexes of refraction greater than crown glass, the lens clock will underestimate the true lens power and for those lenses with indexes of refraction less than crown glass, the lens clock will overestimate the true lens power.

*b. Manual lensometer*

The lensometer measures the vertex power of the lens. The vertex power is the reciprocal of the distance between the back surface of the lens and its secondary focal point. This is also known as the back focal length. For this reason, a lensometer does not really measure the focal length of a lens. The true focal lengths are measured from the principal planes, not from the lens surface. The lensometer works on the Badel principle with the addition of an astronomical telescope for precise detection of parallel rays at neutralization. The Badel principle is Knapp's law applied to lensometers.

A lensometer is really an optical bench consisting of an illuminated moveable target, a powerful fixed lens, and a telescopic eyepiece focused at infinity. The key element is the field lens that is fixed in place so that its focal point is on the back surface of the lens being analyzed. A lensometer measures the back-vertex power of the spectacle lens. However, when measuring a bifocal addition, the spectacles must be turned around in the lensometer so that the front vertex power is measured. This is because the distance portion of the spectacle lenses is designed to deal with essentially parallel light. However, the bifocal addition is designed to work on diverging light, originating from a standard working distance of 40 centimeters. This diverging light from the near object is made parallel by the bifocal lens. The parallel light then enters the distance lens where it is refracted with the expected optical affect to give the patient clear vision. In this way, the bifocal exerts its effect on the light from the object before it passes through the rest of the lens. For strong bifocal corrections, there would be a significant difference in the bifocal strength measurement when using the front versus back vertex measurement. Higher bifocal powers will measure more powerful than they actually are when using the back-vertex measurement instead of the front vertex measurement.

*c. Direct ophthalmoscope*

The direct ophthalmoscope works by illuminating the patient's fundus. In doing this, light reflecting off the patient's retina is refracted by their lens and cornea, causing the light rays to leave the patient's eye parallel, if the patient is emmetropic. If the patient is myopic, the light rays leaving the patient's eyes are converging, requiring the use of a minus lens in the ophthalmoscope for the observer to see the retina clearly. If the patient is hyperopic, the light rays leaving the patient's eyes are diverging, requiring the use of a plus lens in the ophthalmoscope for the observer to see the retina clearly. The

direct ophthalmoscope has auxiliary lenses built into it to correct for any refractive error the patient or the observer might have.

With the direct ophthalmoscope, the image of the retina is upright. Magnification is based on the total refractive power of the eye. Using the basic magnification formula of  $M = F/4$ , an emmetropic eye of +60.00D would provide  $+60/4 = +15X$ . An aphakic eye of +40.00D would provide  $+40/4 = +10X$ .

#### *d. Indirect Ophthalmoscopy*

Indirect ophthalmoscopy works on the principle of an astronomical telescope, where the patient's cornea and lens act as the telescopes objective lens and the condensing lens acts as the telescopes eyepiece lens. Because indirect ophthalmoscopy uses two plus lenses in a telescopic arrangement, the fundus is the object of the condensing lens. The image formed by this system is located above the condensing lens and is called an aerial image. This image of the fundus is larger and inverted.

The two plus lenses (the eye and the condensing lens) determine the magnification of the aerial image. For the emmetropic eye, using the formula  $M_A = (-)D_{\text{Eye}}/C_{\text{Condensing lens}} = (-)60/D$  (condensing lens), we find that a 20D condensing lens results in  $(-)60/20 = -3X$ .

As the power of the condensing lens decreases, the magnification increases. Axial magnification increases exponentially, based on the formula *Axial magnification*:

$$M_A = (M)^2$$

#### *e. Keratometer*

The keratometer is an instrument that uses the reflecting power of the cornea to measure its curvature/refractive power. This is accomplished by measuring the radius of curvature of the central 3mm of the cornea. The central cornea can be thought of as a high powered (~250D) convex spherical mirror. The formula used to determine the curvature/refractive power of the cornea is:  $D = (n-1)/r$ . Where D is the reflecting power of the cornea, n is the standardize refractive index of the cornea (1.3375) and r is the radius of curvature of the central cornea.

To determine the radius of curvature of the cornea (r), keratometers employ the relationship that exist between the object and image size of a convex mirror.

Keratometers determine r by either varying the image size to a get a known object size,

or by varying the object size to get a known image size. Keratometers use optical doubling (discussed below) prisms to allow for the measurement of the unknown size.

When computing the anticipated astigmatic correction based on the keratometry readings, the clinician takes the amount of with the rule astigmatism noted by the keratometry readings, multiply that by 1.25 and then subtract that number from 0.75 diopters (lenticular astigmatism). For example, if an individual has 1.00 diopter of with the rule corneal astigmatism, the expected refractive astigmatism is calculated as follows;  $1.00D \times 1.25 - 0.75D = 1.25D - 0.75D = 0.50D$

*f. Gonioscope*

Total Internal Reflection (TIR) makes it impossible to view the anterior chamber angle without the use of a gonioscopic contact lens. Normally light from the angle undergoes TIR at the air-tear film interface. As result of this, the light from the angle is not able to escape from the eye making the angle impossible to visualize. This problem is overcome by the gonioscopic contact lens which sits on the cornea. In this way, the air at the surface of the cornea is eliminated. Total internal reflection occurs when light is trapped in the incident medium. Because TIR never occurs when light travels from a lower to a higher index, light is able to enter the gonioscopic contact lens where it is reflected by the gonioscopic mirror. This allows the angle of the anterior chamber to be visualized by the examiner.

Gonioscopic tilt angle should be approximately 7.5 degrees to the visual axis. This minimizes reflections and image distortion.

*g: Optical Doubling*

Optical doubling is the technique used in pachymetry, keratometry and applanation tonometry to allow these instruments to make their respective measurements. Optical doubling uses two prisms placed base to base. This creates two images for the clinician to view that are separated by a fixed amount.

In **Goldman tonometry**, the applanation head is exactly 3.06 mm in size. The optical doubling prism incorporated into the applanation head creates two images that are offset by 3.06 mm when the proper amount of pressure is applied to the cornea.

#### *h. Handheld Lenses for Slit Lamp Microscopy*

Hand lenses used during slit lamp microscopy are designed to either nullify the high refractive power of the cornea, or use the power of the cornea as a component of an astronomical telescope, similar to what is done with indirect ophthalmoscopy. In all cases, the image formed by these lenses is formed within the focal range of the slit lamp microscope. Without these lenses, the clinician would not be able to visualize the retina with the slit lamp microscope.

Goldmann contact lenses and other lenses of similar design nullify the cornea refractive power. By placing these lenses on the cornea, a virtual and erect image of the retina is created near the pupillary plane.

A Hruby lens is a -58.6D plano-concave lens that is held just in front of the cornea. This lens creates a virtual and erect image of the retina near the pupillary plane.

High powered biconvex condensing lenses (60D, 78D and 90D) use the same optical principle as indirect ophthalmoscopy. These lenses create an inverted, real image in front of the lens.

#### *i. A-Scan*

A-scan biometry is a device that uses sound waves in the 8-15 MHz range to produce a display of reflectivity versus time for the single direction the A-scan probe is pointing. This tool is used to calculate intraocular lens power, measure extraocular muscle thickness as well as measure intraocular tumor heights.

#### *j. Bagolini Lenses*

Bagolini lenses are Plano lenses that have tiny striations (0.005 mm in width) inscribed into them. These lenses are used to test for normal retinal correspondence (NRC) versus anomalous retinal correspondence (ARC), versus absent binocular vision. To test with these lenses, the lenses are oriented before each eye of the patient with the axis of striations at an angle  $90^\circ$  apart. For example, the striations might be placed at  $45^\circ$  for the right eye and  $135^\circ$  for the left eye. The test is performed both at distance (20 feet or 6 meters) and at near (13 inches or 33 centimeters). With the lenses in place, a small fixation light is viewed through the lenses. This creates a weak luminance ray oriented perpendicular to the striations on the glass, similar to the effect produced by a Maddox lens. If suppression is present, only one oblique line corresponding to that seen by the

non-suppressing eye is visualized. The advantage of this test is that the patient views through a more normal visual environment, in contrast to the Worth 4-Dot test.

*k. Worth 4-Dot*

The Worth 4-Dot test is a simple test for fusion, suppression and anomalous retinal correspondence. Testing can be done at any distance. For this testing, the patient wears a red filter before one eye and a green filter before the other. They are then exposed to four lights: two green, one red and one white. Normal individuals will see the white light through both filters, the green lights are seen through only the green filter and the red light is seen only through the red filter. Patients with fusion report that there are four lights, but the white light is a fluctuating mixture of red and green due to color rivalry.

*l. Stereo Fly Test*

Stereopsis testing is performed with the Stereo Fly Test. The Stereo Fly test allows for the testing of both gross and fine stereo vision. Stereopsis is quantified into the seconds of arc of retinal image disparity required to produce the perception of 3 dimensions. Stereopsis testing is designed to determine the minimum disparity needed to elicit a response. For very minimal quantities of retinal image disparity to be appreciated, the images must simultaneously project onto the retinal area having maximum resolving power. Maximum resolving power occurs within the maculas. Extra macular single binocular vision provides gross stereopsis but fine stereopsis is a product of macular binocular vision.

Fine stereopsis is a product of macular binocular vision. Individuals without macular binocular vision have an average stereo acuity of 200 seconds of arc and never better than 67 seconds of arc. The average person with macular binocular vision has an average stereo acuity of 24 seconds of arc and possibly as good as 14 seconds of arc.

## 40. Miscellaneous Information

### *a. LensTilt*

The position of the optical center will vary with the tilt of the lens before the eyes. The ideal tilt of standard lenses is 8 degrees in on the bottom of the lens. Such a tilt places the optical center 4mm below the center of the pupil when the line of sight passes normally through the lens surface.

When the lens is tilted, the incident light strikes the lens obliquely, inducing marginal or radial astigmatism even though the light passes through the center of the lens.

The change in power of the sphere through tilting is determined by the formula:

$F(1 + \frac{1}{3} \sin^2 a)$ . The created cylinder power is determined by the formula:  $F(\tan^2 a)$ , where  $a$  = the angle of tilt.

If a cylinder lens is tilted on its axis, no actual sphere power is induced however the total new cylinder power is increased by the formula previously noted.

The effect of tilting a minus spherical lens is the production of minus cylinder at the axis of rotation – 180 degrees. The cylinder power increases with both the degree of the tilt and the power of the lens.

A simplified formula to determine the change in sphere power is to take  $(1/10 \text{ the amount of tilt})^2$  = the percentage of power added to the original sphere. The increase in the cylindrical correct is approximately equal to 3x the induced sphere increase.

Examples of simplified formula:

A +3.00D sphere tilted 20 degrees will result in what spherical power increase? –  $(20/10)^2 = 4\%$ ,  $.04 \times 3.00D = 0.12D$

A +3.00D sphere tilted 20 degrees will result in a compound effect of +3.12 combined with +0.40 cylinder. Simplified formula –  $(20/10)^2 = 4\%$ ,  $.04 \times 3.00D = 0.12D$

A +1.00D sphere tilted 45 degrees will result in a compound effect of +1.16, combined with +1.00 cylinder.

An under corrected myope will therefore be able to obtain better distance acuity by tilting his glasses. For example, the effect of tilting a –10.00 diopter lens 10 degrees along the horizontal axis results in an optical correction of –10.10 –0.31 x 180 which gives a spherical equivalent of –10.25D. If the same lens is tilted 30 degrees, the

resultant effective optical correction is  $-10.83 -3.33 \times 180$  with a spherical equivalent of  $-12.50$  diopters. This is why an under-corrected myope tilts their spectacles to attain better distance vision.

**Question:** A point source is placed 50 cm from a cylindrical lens of  $+5.00$  diopters, axis 90 degrees. Find the position and direction of the line foci formed by this lens.

**Answer:** Do this yourself to understand how this works.

### *b. Pinhole Visual Acuity*

For individuals who do not have any type of ocular disease, a pinhole aperture can be a useful tool in determining if a refractive error is present or if a refractive change is needed. The most useful pinhole diameter for clinical purposes is 1.2 millimeters. This size pinhole will be effective for refractive errors of  $\pm 5.00D$ . A pinhole improves visual acuity by decreasing the size of the blur circle on the retina resulting in an improvement of the individual's visual acuity. However, if the pinhole aperture is smaller than 1.2 millimeters, the blurring effects of diffraction around the edges of the aperture will actually increase the blur circle, causing the vision to be worse.

Individuals with macular disease, as well as other ocular diseases that affect central vision, may have similar or even reduced acuity when looking through a pinhole. This is because the reduced amount of light entering through the pinhole makes the chart less clear. Additionally, it can be difficult to use eccentric fixation through a pinhole. For this reason, individuals with ocular disease should not be told that a spectacle correction change will not improve their vision, based solely on their looking through a pinhole. Careful retinoscopy along with a trial frame refraction is needed to determine whether an individual with pathology induced vision loss will benefit from a spectacle correction change.



**Critical Angle**

$$\sin i_c = n'/n \times 1$$

Where:  $i_c$  = the critical angle and the refracted angle is  $90^\circ$

$n$  = index of refraction for where the light is coming from

$n'$  = index of refraction for where the light is going to

**Apparent Thickness Formula**

$$n/u = n'/u'$$

Where:  $n$  = index of refraction for where the light is coming from

$n'$  = index of refraction for where the light is going to

$u$  = object distance

$u'$  = image distance

**Mirrors**

The focal length of a curved mirror is always  $\frac{1}{2}$  its radius of curvature ( $f = r/2$ )

The reflecting power of a mirror in diopters  $D_M = 1/f$  (m)

For mirrors or reflecting surfaces:  $U + 2/r_m = V$ , ( $r_m$  is in meters) or  $U + 1/f = V$

Where:  $f$  = focal length of the mirror in meters

$r$  = radius of curvature of the mirror in meters

**Prism Diopters**

A Prism Diopter ( $^\Delta$ ) is defined as a deviation of 1 cm at 1 meter.

**Approximation Formula**

For angles under  $45^\circ$  (or  $100^\Delta$ ), each degree ( $^\circ$ ) of angular deviation equals approximately  $2^\Delta$

**Prentice's Rule**

Deviation in prism diopters (PD) =  $h$  (cm) x F

Where: F = power of the lens

$h$  = distance from the optical center of the lens

**Convergence**

Convergence ( $\Delta$ ) =  $100/\text{working distance (cm)} \times \text{Pupillary Distance (cm)}$

Convergence (in prism diopters) required for an ametrope to bi-fixate a near object is equal to the dioptric distance from the object to the center of rotation of the eyes, multiplied by the subject's intra-pupillary distance in centimeters.

**Spherical Equivalent**

Spherical equivalent =  $\frac{1}{2}$  cylinder power + sphere power

**Relative Distance Magnification**

Relative Distance Magnification =  $r/d$

Where:  $r$  = reference or original working distance

$d$  = new working distance

**Relative Size Magnification**

Relative Size Magnification =  $S2/S1$

Where:  $S1$  = original size

$S2$  = the new size

**Transverse/Linear Magnification**

$$M_T = I/O = U/V = v/u$$

Where: I = Image size

O = Object size

U = Object vergence

V = Image vergence

u = object distance

v = image distance

**Axial Magnification**

$$M_A = M_1 \times M_2$$

$M_A = (M)^2$  (Approximation formula for Axial Magnification of objects with relatively small axial dimensions)

**Rated Magnification**

$$M_r = F/4$$

Assumes that the individual can accommodate up to 4.00 diopters when doing close work which gives  $d = 25\text{cm}$  (25cm is the standard reference distance used when talking about magnification).

**Effective Magnification**

$$M_e = dF$$

Where:  $d$  = reference distance in meters to the object (image is formed at infinity)

$F$  = the lens power

**Conventional Magnification**

$$M_c = dF + 1$$

Where:  $d$  = reference distance in meters to the object (image is formed at infinity)

$F$  = the lens power

The underlying assumption in this equation is that the patient is “supplying” one unit (1X) of magnification

**Angular Magnification of a Telescope**

$$M_{A \text{ Telescope}} = (-) F_E/F_O$$

Where:  $F_E$  = eyepiece lens power

$F_O$  = objective lens power

**Accommodation through a Telescope Formula**

(for accommodation required to view a near object through an afocal telescope)

$$A_{oc} = M^2U$$

Where:  $A_{oc}$  = vergence at the eyepiece = accommodation

$U$  = object vergence at the objective =  $1/u$

$M$  = the magnification of the telescope

**Aniseikonia**

Total Magnification of a Lens:  $M_T = M_P + M_S$ .

Where:  $M_P$  is the magnification from the lens power

$M_S$  is the magnification from the lens shape

Magnification from Power ( $M_P$ ):  $M_P = D_V H$

Where:  $D_V$  is the dioptric power of the lens

$H$  is the vertex distance measured in cm

Magnification from Shape ( $M_S$ ):  $M_S = D_1 (t_{cm}/1.5)$

Where:  $D_1$  is the curvature of the front surface of the lens

$t$  = the center thickness of the lens

The 1.5 in the following equation is the index of refraction (approximately) of glass or plastic

**IOL Power (SRK Formula)**

$$D_{IOL} = A - 2.5L - 0.9K$$

Where:  $D_{IOL}$  = recommended power for emmetropia

$A$  = a constant (provided by manufacturers for their lenses)

$L$  = axial length in mm

$K$  = average keratometry reading in diopters for desired ametropia

**Lens Clock**

To calculate true power of a single refracting surface (SRS) using a lens clock

$$F_{true} = F_{lens\ clock} (n'_{true} - n) / (n'_{lens\ clock} - n)$$

Where:  $n'_{true}$  = the true index of refraction of the lens being measured

$$n'_{lens\ clock} = 1.53 \text{ (crown glass)}$$

$$n = 1.00 \text{ (air)}$$

### **Ophthalmoscopic Magnification**

Direct:  $M = F/4$

Where:  $F$  = the total refractive power of the eye. The image is upright.

Indirect:  $M_A = (-)D_{Eye}/C_{Condensing\ lens}$

The image of the fundus becomes the object of the condensing lens, which then forms an aerial image that is larger and inverted.

### **Astigmatism Estimation from Keratometry**

Take the amount of with the rule astigmatism noted by keratometry readings, multiply that by 1.25, and then subtract that number from 0.75 diopters (lenticular astigmatism) to arrive at the estimated amount of refractive astigmatism.

When against the rule astigmatism is noted by keratometry, add 0.75 diopters to the full amount of corneal astigmatism to arrive at the estimated amount of refractive astigmatism.

### **Reflecting Power of the cornea to determine corneal curvature**

$$D = (n-1)/r$$

Where:  $D$  is the reflecting power of the cornea

$n$  is the standardize refractive index of the cornea (1.3375)

### **Lens Tilt**

The change in power of the sphere through tilting is determined by the formula:

$$F(1 + 1/3 \sin^2 a)$$

The created cylinder power is determined by the formula:  $F(\tan^2 a)$

Where:  $a$  = the angle of tilt

A simplified formula to determine the change in sphere power is to take  $(1/10 \text{ the amount of tilt})^2 = \text{the percentage of power added to the original sphere}$ . The increase in the cylindrical correct is approximately equal to 3x the induced sphere increase.

## 42. Optics Review Problem Set

**Subject: Vergence – Formula  $U = 100/u$  where  $u$  is in centimeters**

- 1) Light is traveling from right to left in air. Light converges 10 cm to right of a reference point. What is the vergence?
- +5.00D
  - +10.00D
  - 5.00D
  - 10.00D
  - 1.00D
- 2) Light is traveling from left to right in air. Light diverges from a point 20 cm to right of a reference point. What is the vergence?
- +5.00D
  - +10.00D
  - 5.00D
  - 10.00D
  - +1.00D
- 3) A pencil of rays converges toward a point 50 cm to the right of a lens. What is the vergence of light rays 15 cm to the right of the lens?
- +2.00D
  - 2.00D
  - +2.86D
  - +6.67D
  - 6.67D
- 4) A pencil of rays converges toward a point 50 cm to the right of a lens. What is the vergence of light rays 40 cm to the right of the lens?
- +2.50D
  - +2.00D
  - 10.00D
  - +10.00D
  - 2.50D

5) A pencil of rays converges toward a point 50 cm to the right of a lens. What is the vergence of light rays 55 cm to the right of the lens?

- a.  $-1.82D$
- b.  $+1.82D$
- c.  $+20.00D$
- d.  $-20.00D$
- e.  $+2.00D$

6) Pencils of rays converge toward a point 50-cm to the right of a lens. What is the vergence of light rays 150 cm to the right of the lens?

- a.  $+2.00D$
- b.  $-1.00D$
- c.  $+1.00D$
- d.  $-2.00D$
- e.  $-2.50D$

**Subject: Effectivity - Formula:  $F(\text{new}) = F(\text{current})/(1-dF(\text{current}))$  where F is in diopters and d is in meters**

7) A pencil of rays emerges from a lens with a vergence of  $+6 D$ . What is the vergence after a travel of 10 mm in air?

- a.  $+15.00D$
- b.  $+6.38D$
- c.  $+5.66D$
- d.  $-6.38D$
- e.  $-5.66D$

8) A pencil of rays emerges from a lens with a vergence of  $-8 D$ . What is the vergence after a travel of 15 mm in air?

- a.  $+7.14D$
- b.  $-7.14D$
- c.  $-3.63D$
- d.  $+3.63D$
- e.  $-6.67D$

9) A patient's prescription is  $-13.00+2.00 \times 067$  at a vertex distance of 17 mm. If a frame were selected with a vertex distance of 22 mm, what lens power would have to be used?

- a.  $-10.42+1.79 \times 067$
- b.  $-12.90+2.48 \times 067$
- c.  $-10.51+1.98 \times 067$
- d.  $-13.90+2.26 \times 067$
- e.  $-12.21+1.67 \times 067$

10) An aphake is wearing +18 D glasses OU. He says that he sees better if he slides his glasses 2-mm down his nose. How is he changing his prescription?

- a. He is making his glasses stronger
- b. He is making his glasses weaker.
- c. He is adding base in prism to his glasses.
- d. He is adding base out prism to his glasses.
- e. He is creating a telescopic effect with his glasses.

11) A myope is wearing  $-10D$  glasses OU. She says that she sees better if she pushes her glasses closer to her eyes. How is she changing her prescription?

- a. She is making her glasses stronger
- b. She is making her glasses weaker.
- c. She is adding base in prism to her glasses.
- d. She is adding base out prism to her glasses.
- e. She is creating a telescopic effect with her glasses.

**Subject: Index of refraction - Formula:  $U=n/u$  where U is in diopters, n is the index of refraction, and u is in meters.**

12) Light is traveling from left to right in a liquid  $n=1.5$ . Light converges 10 cm to the right of a reference point. What is the vergence of light in the liquid?

- a. +5.00D
- b. +10.00D
- c. +15.00D
- d.  $-10.00D$
- e.  $-5.00D$

**Subject: Prentice's rule -  $PD = hF$  where  $h$  is in cm and  $F$  is in diopters**

13) A patient comes in wearing glasses +2D OD, -2D OS, complaining of vertical diplopia while reading. Both eyes are reading 5 mm down from the optical center. How much slab-off do you prescribe?

- a. 2 PD BU OD
- b. 4 PD BD OD
- c. 2 PD BU OS
- d. 4 PD BU OS
- e. No slab off prism is needed

14) A patient comes in wearing glasses +2D OD, +6D OS, complaining of vertical diplopia while reading. Both eyes are reading 8 mm down from the optical center. How much slab-off do you prescribe?

- a. 3.2 PD BU OD
- b. 3.2 PD BD OD
- c. 3.2 PD BU OS
- d. 3.2 PD BD OS
- e. No slab off prism is needed

15) A patient comes in wearing glasses -3D OD, -8 D OS, complaining of vertical diplopia while reading. Both eyes are reading 7 mm down from the optical center. How much slab-off do you prescribe?

- a. 3.5 PD BU OD
- b. 7.7 PD BD OD
- c. 3.5 PD BD OS
- d. 3.5 PD BU OS
- e. No slab off is needed

**Subject: Lens Clock - Formula:**  $F_{\text{true}} = F_{\text{lens clock}} \left( \frac{n'_{\text{true}} - n}{n'_{\text{lens clock}} - n} \right)$

16) Lens clock assumes that n is air and  $n' = 1.53$  (crown glass)

A lens clock measures the power of a high index plastic surface ( $n=1.66$ ) to be  $-5D$ .

The lens clock has:

- a. Overestimated the power of the surface
- b. Underestimated the power of the surface
- c. Measured the power of the lens surface correctly
- d. Cannot be used to measure the power of high index plastic lenses
- e. None of the above

17) A patient with an RX of  $-3.00+2.50 \times 180$  OU wants to buy a pair of over the counter swimming goggles and he wants to know what power to buy. What do you recommend?

- a.  $-3.00D$
- b. Plano sphere
- c.  $-1.75D$
- d.  $-0.50D$
- e. Power cannot be determined

18) A patient has never worn glasses before. You determine his prescription to be  $-4.00+6.00 \times 090$ . You decide to prescribe half of the actual cylinder in his prescription.

In order to keep the same spherical equivalent as his actual prescription, you should prescribe:

- a.  $-1.00+3.00 \times 090$
- b.  $-2.50+3.00 \times 090$
- c.  $-4.00+3.00 \times 090$
- d.  $-2.00+3.00 \times 090$
- e.  $-3.00+3.00 \times 090$

19) A patient brings in a prescription of  $+5.75-3.25 \times 063$ . Convert this to plus cylinder.

- a.  $+5.75+3.25 \times 063$
- b.  $+3.25+3.25 \times 153$
- c.  $+2.50+3.25 \times 153$
- d.  $+5.75+2.50 \times 063$
- e.  $+3.25+2.50 \times 153$

20) A patient brings in a prescription of  $-4.50+2.75 \times 077$ . Convert this to minus cylinder.

- a.  $-4.50-2.75 \times 077$
- b.  $-1.75-2.75 \times 077$
- c.  $-2.75-2.75 \times 167$
- d.  $-1.75-2.75 \times 167$
- e.  $-2.75-2.75 \times 077$

21) Three object points are located 33 cm, 25 cm, and 20 cm in front of a lens of +4.00 diopters; where are the three image points?

- a. +14.29cm, -12.5cm, +11.11cm
- b. +14.29cm, infinity, -11.11cm
- c. +100cm, infinity, -100cm
- d. -14.29cm, +12.5cm, +11.11cm
- e. -14.29cm, +12.5cm, -11.11cm

22) Three object points are located 100 cm, 50 cm, and 25 cm in front of a -2.00 diopter lens, where are the three image points?

- a. -33.33cm, -25cm, -16.67cm
- b. +33.33cm, +25cm, +16.67cm
- c. +100cm, infinity, -33.33cm
- d. +100cm, infinity, +33.33cm
- e. +100cm, infinity, +16.67cm

23) How much must an eye accommodate for a fixation point 10 cm in front of the eye?

- a. 10.00D
- b. 5.00D
- c. 2.50D
- d. 2.00D
- e. 3.00D

24) How much must a normal eye accommodate for a fixation point 20 cm in front of the eye?

- a. 10.00D
- b. 5.00D
- c. 2.50D
- d. 2.00D
- e. 3.00D

25) How much must a normal eye accommodate for a fixation point 33.3 cm in front of the eye?

- a. 10.00D
- b. 5.00D
- c. 2.50D
- d. 2.00D
- e. 3.00D

26) How much must a normal eye accommodate for a fixation point 50 cm in front of the eye?

- a. 10.00D
- b. 5.00D
- c. 2.50D
- d. 2.00D
- e. 3.00D

- 27) How much must an uncorrected 3.00D hyperope accommodate when viewing an object at 25cm?
- 1.00D
  - 7.00D
  - 4.00D
  - 3.00D
  - 9.25D
- 28) How much must an uncorrected 2.00D myope accommodate when viewing an object at 40cm?
- 2.00D
  - 4.50D
  - 0.50D
  - 2.50D
  - 1.00D
- 29) An object is located 33 cm in front of a +5.00 diopter lens; an eye located closely behind the lens can see the image distinctly without accommodation. What is the ametropia of this eye?
- +8.00D
  - 8.00D
  - +2.00D
  - 2.00D
  - +5.00D
- 30) Three emmetropic eyes have amplitudes of accommodation of 5, 8, and 10 diopters respectively, what are their near points?
- 20cm, 12.5cm, 10cm (all in front of the eye)
  - 20cm, 12.5cm, 10cm (all in back of the eye)
  - 8cm, 5cm, 4cm (all in front of the eye)
  - 8cm, 5cm, 4cm (all in back of the eye)
  - Cannot be calculated

31) The far point of an eye is found at 50 cm in front of the eye, the near point at 10 cm. What is the ametropia of this eye? What is its amplitude of accommodation?

- a.  $-2.00, 8.00\text{D}$
- b.  $-2.00, 10.00\text{D}$
- c.  $-2.00, 12.00\text{D}$
- d.  $-10.00, 8.00\text{D}$
- e.  $-10.00, 12.00\text{D}$

32) The far points of 4 eyes are found at 1 meter behind the cornea, 25 cm behind the cornea, 66.6 cm in front of the cornea, 20 cm in front of the cornea. What are the powers of the correcting lenses placed at the cornea?

- a.  $-1.00\text{D}, -4.00\text{D}, +1.50\text{D}, +5.00\text{D}$
- b.  $+1.00\text{D}, +6.25\text{D}, -1.66\text{D}, -2.00\text{D}$
- c.  $+1.00\text{D}, +4.00\text{D}, -1.50\text{D}, -5.00\text{D}$
- d.  $-1.00\text{D}, -6.25\text{D}, +1.66\text{D}, +2.00\text{D}$
- e.  $-1.00\text{D}, -4.00\text{D}, +1.66\text{D}, +5.00\text{D}$

33) Assume an amplitude of accommodation of 5.00 diopters in all cases noted on Problem 32, what are the respective near points?

- a. 16.67cm, 11.11cm, 28.75cm, infinity
- b. 25cm, 80cm, 15cm, 14.29cm
- c. 25cm, 100cm, 15.39cm, 10cm
- d. 16.67cm, 8.89cm, 29.94cm, 33cm
- e. 16.67cm, 11.11cm, 29.94, infinity

34) Calculate the magnification of a +28 D hand-held magnifier if the object is held at  $f$ :

- a. 11.2x
- b. 7.0x
- c. 4.2x
- d. 2.8x
- e. None of the above

- 35) When dealing with multiple lens systems, the total magnification is:
- The sum of each component magnifier
  - The average of all the component magnifiers
  - The product of each component magnifier
  - The product of each component magnifier divided by the number of component magnifiers used
  - None of the above
- 36) What is the accommodation required through a 3x Galilean telescope if the object is 25 cm away?
- 48D
  - 12D
  - 24D
  - 36D
  - None of the above
- 37) What power reading cap is needed for a Galilean telescope used to view an object at 10cm?
- 4.00D
  - 5.00D
  - 2.00D
  - 1.00D
  - None of the above
- 38) What power reading cap is needed for a Galilean telescope used to view an object at 25cm?
- 4.00D
  - 5.00D
  - 2.00D
  - 1.00D
  - None of the above

39) What power reading cap is needed for a Galilean telescope used to view an object at 50cm?

- a. 4.00D
- b. 5.00D
- c. 2.00D
- d. 1.00D
- e. None of the above

40) What power reading cap is needed for a Galilean telescope used to view an object at 100cm?

- a. 4.00D
- b. 5.00D
- c. 2.00D
- d. 1.00D
- e. None of the above

41) +6D and -15D lenses are used to make a Galilean telescope. Which of the following statements is true for an object at 5 cm?

- a. The image is real and to the right of the objective lens.
- b. Total magnification is 1%
- c. The image of a near object is coincident with that for far.
- d. The image is inside the telescope.
- e. None of the above.

42) +6D and -15D lenses are used to make a Galilean telescope. Which of the following statements is true for an object at infinity?

- a. The image is inverted and to the right of the objective lens.
- b. Total magnification is 2.5x.
- c. The image of a near object is coincident with that for far.
- d. The image is inside the telescope.
- e. None of the above.

- 43) +6 D and +15 D lenses are used to make a Keplerian telescope. Which of the following statements is true for an object at infinity?
- The image is erect and to the right of the objective lens.
  - Total magnification is 15%
  - The image of a near object is coincident with that for far.
  - The image is inside the telescope.
  - None of the above.
- 44) What is the tube length of a telescope fabricated with a +4D and a -20D lens, focused at infinity?
- 20cm
  - 25 cm
  - 15cm
  - 10cm
  - None of the above
- 45) What is the tube length of a telescope fabricated with a +5D and a +20D lens, focused at infinity?
- 20cm
  - 25cm
  - 15cm
  - 10cm
  - None of the above
- 46) What is the magnification of the telescope fabricated with a +5D and a +20D lens?
- 2x
  - 3x
  - 4x
  - 5x
  - 6x

- 47) If we increase the reference distance for simple magnifiers from 25 to 50 cm, what will happen to the effective image size?
- It appears 2x larger
  - No change would occur
  - It appears smaller by half
  - It appears 3x larger
  - It appears smaller by one third
- 48) Consider a concave lens of  $-15\text{ D}$ . If the object distance is 20 cm behind the lens, describe the image nature and position:
- The image is virtual and located 10 cm in front of the lens.
  - The image is virtual and located 5 cm in front of the lens.
  - The image is real and located 10 cm behind the lens.
  - The image is virtual and located 20 cm in front of the lens.
  - The image is real and located 5 cm behind the lens.
- 49) How far away from a plane mirror is the image of an object of vergence  $+5\text{ D}$ ?
- 2 m
  - 2 cm
  - 5 cm
  - 5 mm
  - None of the above
- 50) An object is 40 cm in front of a refracting surface of power  $+10\text{ D}$ . Which of the following is incorrect?
- The object vergence is  $-2.5\text{ D}$
  - The image is 13.3 cm to the right of the lens
  - The image is real
  - The image vergence is  $-7.5\text{ D}$
  - The image is inverted

**Answers:**

You can take practice exams online at:

<http://www.medrounds.org/ophthalmology-board-review/exam/>

1.....d

2.....a

3.....c

Light converges to 50cm to the right of the lens. This is the reference point for the vergence of light. At 15cm to the right of the lens, light is now 35cm from the convergent point. Vergence is  $= 100/u = 100/35 = +2.86D$ . This is positive because light is converging to the reference point.

4.....d

Light converges to 50cm to the right of the lens. This is the reference point for the vergence of light. At 40cm to the right of the lens, light is now 10cm from the convergent point. Vergence is  $= 100/u = 100/10 = +10D$ . This is positive because light is converging to the reference point.

5.....d

Light converges to 50cm to the right of the lens. This is the reference point for the vergence of light. At 55cm to the right of the lens, light is now 5cm from the convergent point and diverging. Divergence is  $= (-) 100/u = (-) 100/5 = -20D$ . This is negative because light is diverging from the reference point.

6.....b

Light converges to 50cm to the right of the lens. This is the reference point for the vergence of light. At 150cm to the right of the lens, light is now 100cm from the convergent point and diverging. Divergence is  $= (-) 100/u = (-) 100/100 = -1D$ . This is negative because light is diverging from the reference point.

7.....b

Light converges to 16.67cm to the right of the lens (vergence of +6D). This is the reference point for the vergence of light. After travel of 10mm in air, light has traveled 1cm or within 15.67cm of the convergent point. Vergence is =  $100/u = 100/15.67 = +6.38D$ . This is positive because light is converging to the reference point.

8.....b

Light diverges to 12.50cm to the right of the lens (divergence of -8D). This is the reference point for the divergence of light. After travel of 15mm in air, light has traveled 14cm from the lens. Divergence is =  $(-100/u = (-)100/14 = -7.14D$ . This is negative because light is diverging from the lens.

9.....d

To solve this problem, convert the prescription into a power cross consisting of -13.00D at 67 degrees and -11.00D at 157 degrees. Apply the lens effectivity formula. With increased vertex distance, the minus lenses need to be more minus; thus, the new power cross will be -13.90D at 67 degrees and -11.64D at 157 degrees. The prescription is -13.90+2.26x067.

10.....a

11.....a

12.....c

Use index of refraction formula:  $U=n/u$  where U is in diopters, n is the index of refraction, and u is in meters.

13.....c

2 Prism Diopters Base Up OS. Looking 5 mm down from the optical center produces 1 PD BU OD and 1 PD BD OS with an effective prism power of 2 PD BD OS. 2 PD BU OS will neutralize this. Slab-off is prescribed for the most minus or least plus lens.

14.....a

3.2 Prism Diopters Base Up OD. At 8 mm down from the optical center, there is 1.6 PD BU OD and 4.8 PD BU OS with a total 3.2 PD BU effect OS. Slab-off is prescribed in the most minus or least plus lens; thus, 3.2 PD BU OD is needed to neutralize the prismatic effect.

15.....d

3.5 Prism Diopters base up OS. At 7 mm down from the optical center, there is 2.1 PD BD OD and 5.6 PD BD OS with a total of 3.5 PD BD OS. Slab-off is prescribed for the most minus or least plus lens; thus, 3.5 PD BU OS is needed to neutralize the prismatic effect.

16.....b

17.....c

The spherical equivalent of  $-3.00+2.50 \times 180$  is  $-1.75D$ . To calculate the spherical equivalent, take  $1/2$  of the cylinder power and combine it with the sphere power. While wearing goggles, the patient will not need cylinder so an RX of  $-1.75D$  is needed.

18.....b

To calculate the spherical equivalent, take  $1/2$  of the cylinder power and combine it with the sphere power. In this case, a decrease in  $+3.00$  diopters of cylinder will result in a decrease of  $-1.50$  in the sphere power to maintain a spherical equivalence of  $-1.00$ .

19.....c

20.....d

21.....c

22.....a

23.....a

24.....b

25.....e

26.....d

27.....b

The hyperope needs 4.00D of accommodation and also an extra 3.00D to overcome his refractive error.

28.....c

The uncorrected myope can see well at 50cm, but needs 0.50D of accommodation to view an object at 40cm.

29.....c

An eye without refractive error needs a +3.00D lens to see an object at 33cm without accommodation. A +2.00D hyperope requires a +5.00D lens to see an image at 33cm without accommodation.

30.....a

31.....a

32.....c

33.....c

34.....b

35.....c

36.....d

36D where the approximate accommodation required is given by  $A_{oc} = M^2U$ , where  $A_{oc}$  = vergence at the eyepiece = accommodation,  $U$  = object vergence at the objective =  $1/u$ ,  $M$  = the magnification of the telescope.

37.....e

38.....a

39.....c

40.....d

41.....d

42.....b

43.....e

44.....a

45.....b

46.....c

47.....a

48.....a

49.....e

50.....d

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