The Direct Ophthalmoscope
How it Works and How to Use It

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Chapter 1

I. Introduction: Light, refraction, and lenses.

Light. Light is electromagnetic energy that propagates through space in a wave-like fashion. Other forms of electromagnetic energy are X-rays and radio waves. The distance between adjacent "crests" or "troughs" of a light wave is called the *wavelength*.[1] In a vacuum the speed of light is ~3×10^8 m/sec, but it is slower in other mediums such as water or glass. The speed of light depends on the *index of refraction, n,* of the medium in which it is traveling: the higher the n, the lower the speed. The index of refraction of air is 1.00, while for water $n \approx 1.33$. Most glasses and some plastics have $n \approx 1.50$.

Refraction. To understand how images are formed by lenses, it is convenient to think of a very thin beam of light called a "ray." A light ray continues moving in a perfectly straight line as long as the index of refraction of the medium is constant. When a light ray enters a new medium with a different n, not only does its speed change, but also its direction (Fig. 1). This is called <u>refraction</u>. The change in direction of the ray depends on the indices of refraction of the two media (n_1, n_2) and the angle at which the ray intersects the second medium. If the ray intersects the second medium with an angle of θ_1, its angle in the second medium will be θ_2.[2]
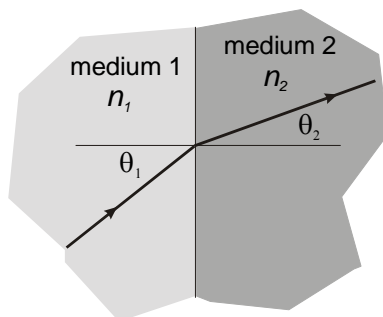

Fig. 1. Illustration of refraction of a light ray as it enters a new medium of higher index of refraction. Light ray indicated by dark line with arrows. $n_2 > n_1$

Notice that if the incoming light ray makes an angle, $\theta_1 = 0°$ (i.e. the ray is perpendicular to the two media), the ray does not change direction in the second medium.[3]

Lenses. Lenses are formed from spherical surfaces and are most often made of glass or plastic. The *convex lens* illustrated in Fig. 2, has spherical surfaces that bulge outward

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[1] The human eye can perceive wavelengths of approximately 400 - 800 nanometers (nm) (1 nm = 10^{-9} m), that is, from the deep blue to the deep red.

[2] The relationship between the angles and indices is given by Snell's Law: $n_1 sin\theta_1 = n_2 sin\theta_2$

[3] Try proving this with Snell's Law.

from the center. The *optical axis* of the lens is a line perpendicular to the surfaces of the lens that goes through the center of the lens. Parallel rays of light impinging on the convex lens are refracted, causing the rays to *converge* and cross the optical axis at one point, the *focal point*. Thus, a convex lens focuses incoming light to the focal point. The distance from the lens to the focal point is called the "*focal length*." One can appreciate how a concave lens works using the ideas of refraction given above. Each parallel ray makes a slightly different angle with the front surface of the lens. Rays at the edges make a large angle while those near the center make smaller angles. Consequently rays near the edges of the lens are refracted more than those near the optic axis. A ray traveling along the optic axis is not refracted at all because it makes an angle of 0° with the lens surface.
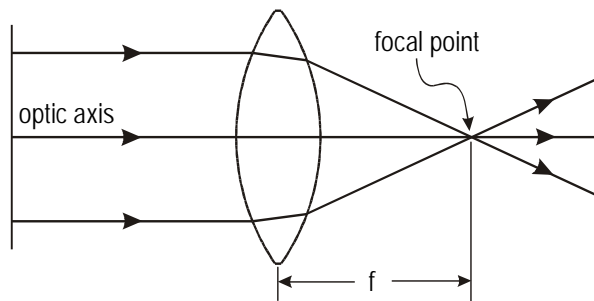

Fig. 2. Convex lens focuses parallel rays of light to a point. The focal point is a distance f (the focal length) from the lens.

A *concave* lens (Fig. 3) has spherical surfaces that bow inward (think of a "cave") toward the center of the lens. Parallel light rays impinging on a concave lens *diverge* after passing through the lens. The rays do not cross the optical axis, but diverge as though they originated at a point on the axis as shown by the dashed lines in the figure below. This is the focal point of a concave lens and by convention is given a negative value.
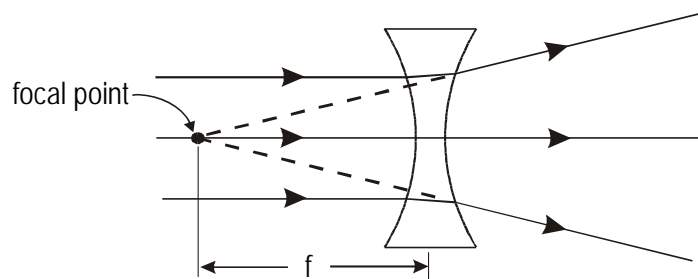

Fig. 3. Concave lens causes incoming parallel rays to diverge. The exiting rays appear to come from the focal point found by tracing the rays backward (dashed lines). Focal length is f.

Lens curvature and focal length. A lens's focal length is related to *the radius of curvature, R,* of the lens surface. This is illustrated in Fig. 4 using plano-convex lenses, that is, convex lenses that have one flat side. The important point here is that as the refractive

surface of the lens becomes less curved (i.e., its *R increases*), the focal length becomes longer. What would happen if $R = \infty$? Although the effect of lens curvature on focal length has been illustrated with convex lenses, the same principle applies to concave lenses: as the radius of curvature increases, rays leaving the lens diverge less, and consequently the focal length is longer.
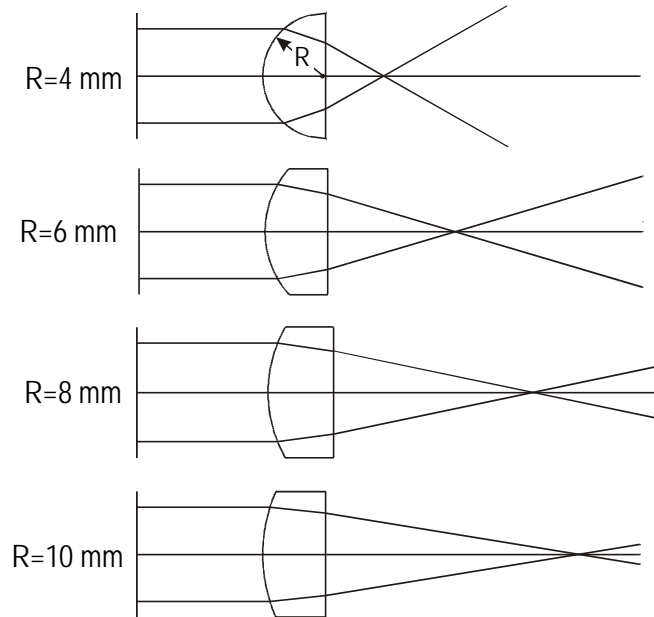

Fig. 4. As the radius of curvature of a lens increases, the lens surface becomes less curved, angles of refraction are less, and the focal length increases.

The *power* of a lens is an indication of how "strongly" it refracts (bends) incoming light rays. The power, *P*, is equal to one over the focal length *in meters* and has units of *Diopters (D).*

$$P(diopters) = \frac{1}{f(m)}$$

The focal length is positive (+) for convex lenses and negative (-) for concave lenses. Thus, the power of a concave lens is negative and that of a convex lens positive. (Problem: A detective's magnifying glass has a focal length of 10 cm. What is its power?)

II. Optics of the Eye

Optical model of the eye. Figure 5 shows a schematic diagram of the human eye generated by a computer optics program. This optical model was developed initially by Gullstrand in the late 19th Century, but is still widely used today. There are two major refractive components to the model, the *cornea* and the *crystalline lens*. These are both

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convex (+) lenses. Images are formed on the spherical surface of the *retina*. The *anterior chamber*, between the cornea and lens is filled with *aqueous humor* and the space between the crystalline lens and retina is filled with the *vitreous humor*. The iris of the eye contracts and expands to form a variable circular aperture for entering light rays. Using the computer optical model of the eye, it is possible to trace the paths of light rays as they enter the eye. Such computer generated raytraces have been used in the figures below.
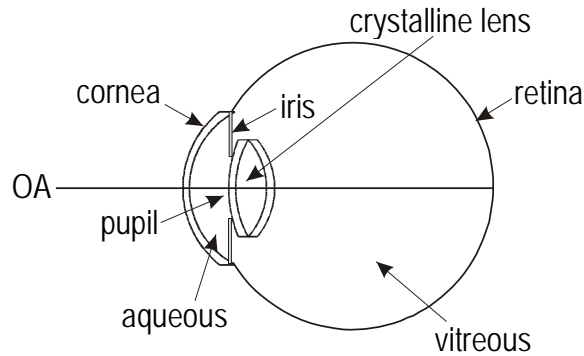

Fig. 5. Optical model of the eye. OA: optical axis. The overall length of the eye is 24 mm.

Emmetropic eye. Parallel rays of light entering the normal, *emmetropic* eye are brought to focus on the retina as shown in Fig. 6. Since rays from very distant objects are essentially parallel, this means that distant objects will be sharply focused on the emmetrope's retina. The box on the right in the figure below shows a computer-calculated image of a distant letter "F" on the retina. Image quality is very good and the person possessing this eye would easily be able to distinguish the three strokes that make up the letter "F." The portion of the retina on which rays are focused is the *fovea*. In the fovea, photoreceptors are densely packed and there are many cone photoreceptors subserving color vision. The fovea is the part of the retina used for fine, detail vision such as reading, looking at distant objects, or threading a needle.
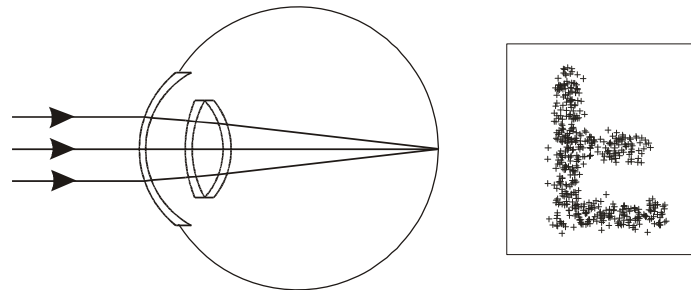

Fig. 6. Emmetropic eye. Raytrace shows that parallel rays are focused on retina. Box on right shows image of letter "F" on retina.

Power of the eye. The diagram of the emmetropic eye gives some indication of the power of the eye. Notice that incoming rays are refracted strongly by the cornea and somewhat less by the crystalline lens. In fact, most of the refractive power of the eye is at the air/cornea interface (i.e., the front surface of the cornea). The index of refraction of the cornea is 1.376 and that of the aqueous and vitreous is 1.336, a difference of only 0.04. This means that there is not a lot of refraction at the posterior surface of the cornea as light rays enter the aqueous. The eye has a total power of about +60 D. The cornea contributes approximately +40 D while the lens contributes about +20 D. The amount of power the lens contributes can change through accommodation.

Accommodation. For the emmetropic eye shown above, only very distant objects will be in focus on the retina. Fortunately, the eye acts somewhat like a "zoom" camera since the crystalline lens can change its curvature and hence its power. For looking at closer objects, the lens becomes more curved (i.e., has more power). To see distant objects the crystalline lens becomes less curved (i.e., has less power). This process is called *accommodation* and is illustrated in Fig. 7.
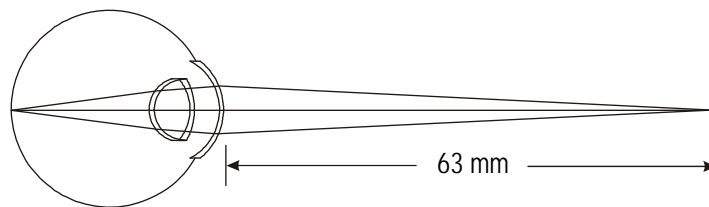

Fig. 7. Raytrace of emmetropic eye accommodated to a distance of 63 mm.
Note increased curvature of crystalline lens.

Accommodation is said to be "relaxed" when the lens is least curved, that is, when it is accommodated for seeing distant objects. Relaxed accommodation can also be achieved by topical instillation of drugs called cycloplegics.

III. Refractive errors of the eye & their correction.

Not all eyes are emmetropic. *Ametropic* eyes do not focus incoming parallel rays on the retina as does the emmetropic eye. There are two main types of ametropia: myopia and hyperopia.

Myopia. In the *myopic* eye, parallel rays come to focus in front of the retina as shown in Fig. 9. When the rays intersect the retina past the focal point, they are diverging. Consequently a blurred image is formed on the retina. The box to the right in the figure below shows a computer-generated image of a distant letter "F" in this myopic eye. Although one can see that it has roughly an "F" shape, it might also be a "P" or even a "T." The owner of this myopic eye would be hard-pressed to identify the letter.
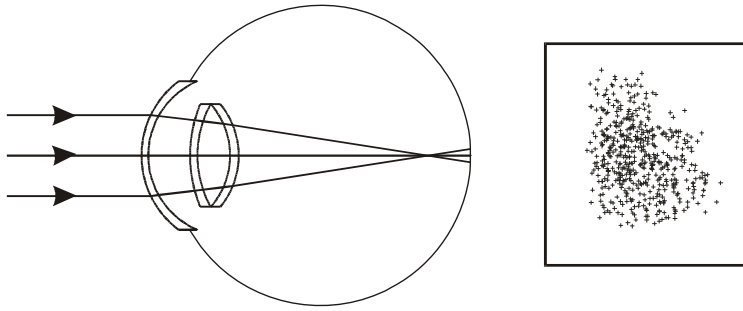
Fig. 9. Myopic ("nearsighted") eye. Parallel rays come to focus in front of the
retina. Box on right shows computer-generated image of "F" on retina.

Axial myopia occurs when the axial length of the eye is too long and the eye assumes
an egg shape rather than a spherical shape. *Refractive myopia* occurs when the refractive
surfaces, principally the cornea, have too much curvature and refract incoming rays too
strongly. Although myopes see distant objects as blurry, objects close to the eye are in focus
on the retina, hence are seen clearly. Thus, myopes are sometimes referred to as
"*nearsighted.*"

Correction of myopia. The most common means of correcting myopia is through
spectacles. Inspecting Fig. 9, one can see intuitively that if the rays could be made to diverge
somewhat as they approach the eye, it might be possible to "move" the focal point toward the
retina. This is exactly what is done to correct myopia. Fig. 10 shows the same eye as above,
but with a diverging, concave lens placed 15 mm in front of the eye. The index of refraction
of the glass and the curvatures of the surfaces have been calculated to cause the incoming
parallel rays to diverge just enough to move the focal point to the retina. The box in the
right-hand part of the figure shows the computer-generated image of the letter "F" on the
retina when the corrective lens is in place. The myope would have no difficulty in
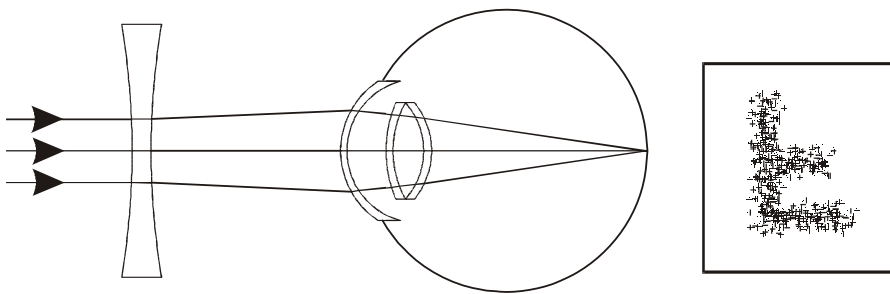distinguishing this letter from others.

Fig. 10. Correction of myopia using a bi-concave lens. Rays diverge after
passing through the lens. The corrective lens is typically placed 15 mm from
the cornea.

Hyperopia. In the *hyperopic* eye, parallel rays come to focus "behind" the retina
(Fig. 13) because the total refractive power of the eye is less than that of an emmetropic eye.
Of course, the rays do not actually travel past the retina, but if they could, they would be
focused well past the eyeball. Consequently, the image at the retina is blurred. The box in
the figure below shows a computer generated image of the letter "F" on the retina of this

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hyperopic eye. It would be almost impossible for this person to recognize the letter from this highly blurred image.
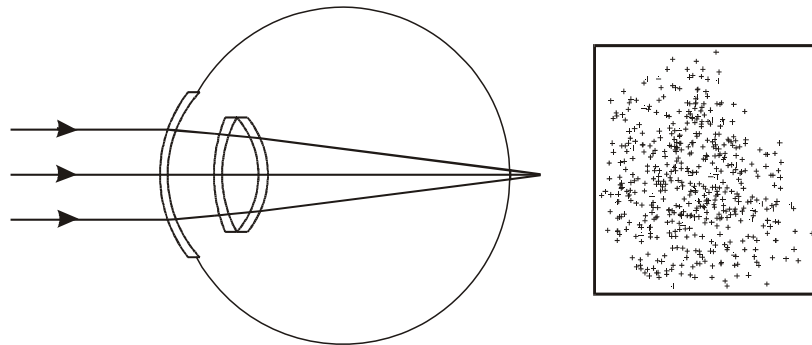
Fig. 13. Hyperopic ("Farsighted") eye. Rays come to focus "behind" the retina. Box on right shows computer-generated image of "F" on the retina.

Correction of hyperopia. As with myopia, the most common method of correcting hyperopia is by means of spectacles. Inspection of the optical path of rays in the figure above suggests that one might bring rays to focus on the retina if the convergence of the rays could be increased. We saw earlier that this is precisely what a convex lens does. Fig. 14 shows a bi-convex lens placed 15 mm in front of the same hyperopic eye shown above. Rays leaving the lens are no longer parallel, but are converging. This additional convergence is just enough to bring the focus to the retina. The computer-generate image of "F" shown on the right indicates that the correction was quite good.
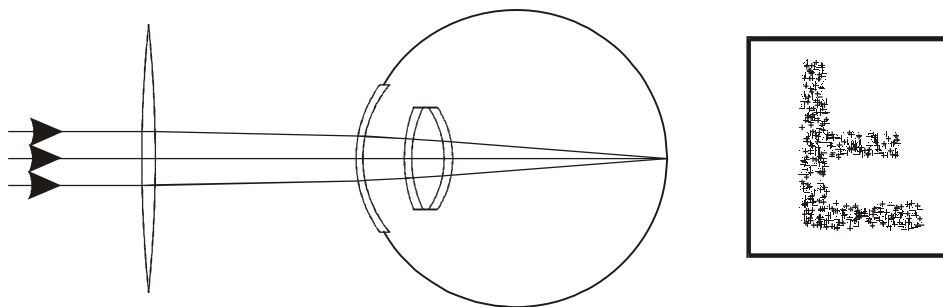
Fig. 14. Correction of hyperopia with convex lens. Rays converge after passing through the lens. This additional convergence is just enough to bring the focus in to the retina. Image quality (box on right) is excellent.

Chapter 2

IV. Introduction to the Direct Ophthalmoscope

Ordinarily when we look into another person's eye, the pupil appears black. We are unable to see the person's retina even though there is a transparent optical pathway from the cornea to the retina. There was a great deal of interest in this "black pupil" phenomenon in the 18th and 19th Centuries, particularly because the eyes of animals, unlike humans, *did* sometimes appear luminous. It was thought at the time that animal eyes actually generated light and that the more excited the animal, the brighter the light. This idea was ultimately put to rest by Prevost (1818) who showed that one never saw a luminous eye when the animal and observer were in a totally dark room. At about the same time Gruithuisen discovered that the eyes of some animals (e.g., dogs and cats) contain a unique layer behind the retina, the *tapetum lucidum*, that reflects light and is responsible for the luminous appearance of animal eyes.

Alligator eyes at night.

Although humans do not have a *tapetum lucidum*, the retina is somewhat reflective, so why can't we see it? There are two principal reasons. First, the retina is *not very* reflective. Only about 1/10,000 - 1/100,000 of light entering the eye is reflected back out. Thus, one would need an extremely bright light source entering the eye to be able to see enough light coming out. Second, and more importantly, the observer's eye (and head) block the rays of light that illuminate the part of the retina he or she is trying to observe. This situation is illustrated in Fig. 1 in which the eye of a subject is accommodated to a large, bright screen (ABC). For the moment, assume the observer's eye is not present.
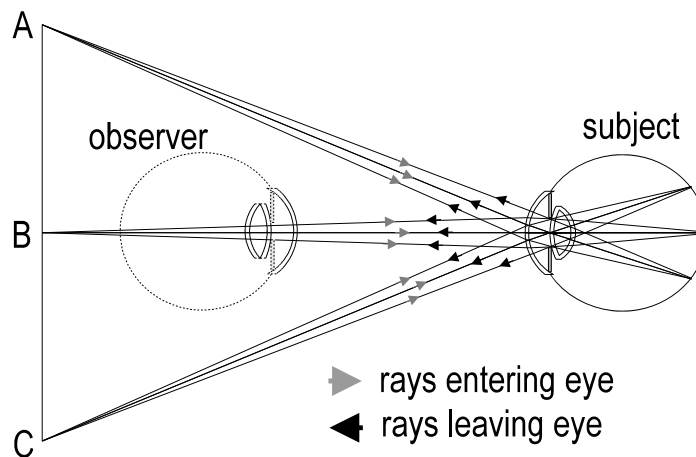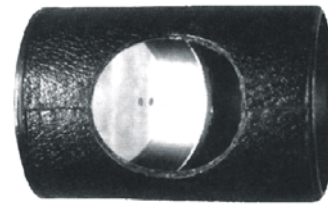

Fig. 1. Illustration of why the pupil appears dark. ABC represents a brightly lit screen to which the subject is accommodated. Sample rays from the screen (light arrows) are shown entering the eye. Reflected rays are indicated by dark arrows.

Since the subject is accommodated for the screen, rays of light from points A, B, and C on the screen come to focus on the retina. This is true for every ray from any point on the screen. Light reflected from the subject's retina travels back toward the screen along the same path as the rays going in. Now, if the observer puts his or her eye in place to try to observe the subject's retina, rays from the screen along the viewing axis will be blocked, so it will be impossible to see the retina because it is not illuminated. What about the rays reflected from the subject's retina that are not blocked by the observer? The observer cannot see these rays because they do not enter the observer's eye. If he or she moves in order to see the rays, then the illumination rays are blocked.

Babbage and his direct ophthalmoscope

Even though the analysis given above makes it seem hopeless ever to see into the eye, in the mid-19th Century, several scientists noticed that the human eye could be made to appear luminous under special circumstances. Their method is illustrated in Fig. 2. Here, the light source that illuminates the subject's eye is placed adjacent to the observer's eye and the two eyes are far apart. The subject is an emmetrope and accommodated to infinity, thus light rays reflected from the eye are parallel. Most of the rays reflected from the subject's eye will travel back toward the light source, but some of the parallel rays will enter the observer's eye. The subject's retina will thus appear luminous. You have probably observed this same phenomenon when taking photographs using a flash attachment. Often the eyes of the individual photographed appear red. The reason is that the illumination--the flash--and the viewing system--the camera lenses--are close together and relatively far from the subject. This is the key idea in the invention of the ophthalmoscope: the illumination axis and the observer's viewing axis have to be as close as possible.
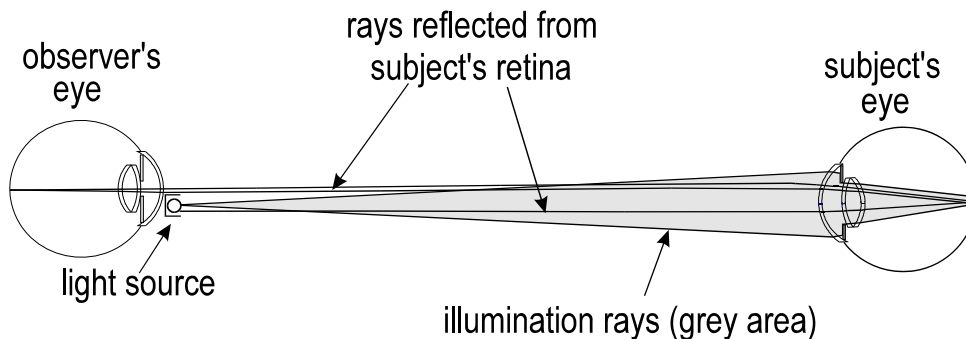

Fig. 2. Making the human eye appear luminous. Light source shielded from the observer's eye.

The first practical ophthalmoscopes placed the observer's viewing axis and the illumination axis close together by using mirrors or plates of glass. Perhaps the first ophthalmoscope was invented by Charles Babbage[4] in 1849. Babbage's ophthalmoscope was simply a piece of mirror with a small, circular patch of the silver scraped off in the center (Fig. 3). Light from a source (a gas flame) is reflected by the mirror towards the subject's eye. Some of the ray pass through the hole in the mirror, but do not enter the eye of either the observer or subject. Light reflected from the subject's retina passes back along the illumination axis, but goes through the small hole in the mirror to the observer's eye. In essence, the mirror with small hole allows the illumination and viewing axes to be coincident. In Fig. 3, the image of the subject's retina is formed *directly* on the observer's retina (there is no intermediate image in air) and for this reason, the ophthalmoscope is referred to as a *direct ophthalmoscope*.
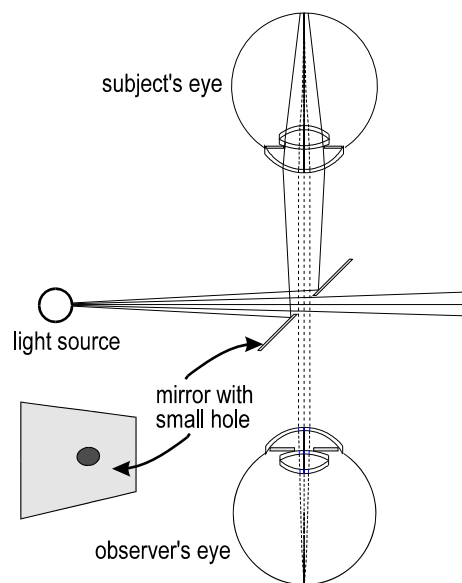

Fig. 3. Fundamental design of the direct ophthalmoscope realized by Babbage and Helmholtz. Illumination rays from light source indicated by dark lines; rays reflected from subject's retina indicted by dashed lines.

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[4] Charles Babbage (1791-1871). Professor of mathematics at Cambridge. Best known for his pioneering work on calculating engines, mechanical forerunners of modern computers. Babbage took his ophthalmoscope to a prominent ophthalmologist in London who was unable to use it, possibly because he was a myope. The ophthalmologist judged that Babbage's ophthalmoscope simply wouldn't work and was useless for examining the retina. Babbage subsequently turned his attention to other matters and his ophthalmoscope was forgotten for many years.

In 1851, only two years after Babbage's abortive attempt at producing a practical ophthalmoscope, the German physicist Hermann von Helmholtz[5] published a monograph entitled *Beschreibung eines Auges-Spiegels: zur Untersuchung der Netzhaut im lebenden Auge*, describing in detail the optical principles involved in ophthalmoscopy and the construction of a practical ophthalmoscope. Helmholtz is recognized today as the inventor of the direct ophthalmoscope and, as we will see in the next section, the modern direct ophthalmoscope is simply a refinement of his invention.

Fig. 4. Hermann von Helmholtz (left) and his ophthalmoscope (right).

V. The Modern Direct Ophthalmoscope

Overall Construction of the Ophthalmoscope.

Figure 5 shows the overall appearance of a modern direct ophthalmoscope. As in the Helmholtz-Babbage ophthalmoscope, the illumination and viewing axes are very close together. However, rather than using a mirror with a hole as did early ophthalmoscopes, a small, tilted mirror[4] is placed just beneath and adjacent to the viewing aperture, a hole, about 3 mm in diameter. This arrangement of mirror and viewing aperture became possible because of the invention of the electric incandescent lamp which allowed the light source to be physically combined with the rest of the ophthalmoscope. The ophthalmoscope also has two thumb-wheels. One of these is usually horizontally oriented and enables the operator to adjust the diameter, shape, and color of the illumination beam. The other, vertically oriented, thumb-wheel allows very small "compensating" lenses to be inserted just behind the viewing aperture.

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[5] Hermann von Helmholtz (1821-1894). Professor of physiology and physics. Performed fundamental research in physiological optics, hearing, electrodynamics, thermodynamics and nerve conduction.

[4] Most ophthalmoscopes actually use a small prism to reflect the light rays. The function of the prism is identical to that of a mirror, but a mirror is shown here for simplicity.
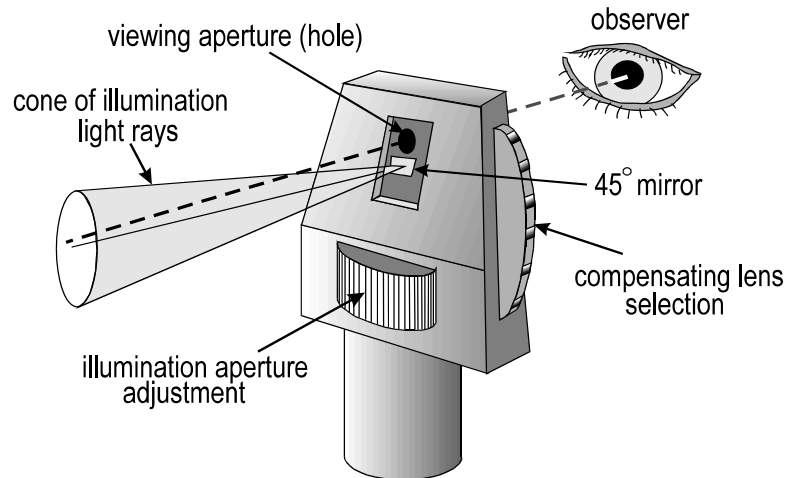
Fig. 5. Drawing of a modern, direct opthalmoscope showing key features.

Now let's take a closer look at the structure of the ophthalmoscope. In Fig. 6, the ophthalmoscope is shown in cross-section along with computer-generated model eyes of an observer and a subject. The subject's eye is 2 cm from the ophthalmoscope, a typical distance when observing the retina.

• The *illumination system* sends light into the subject's eye and consists of an electric incandescent lamp (about 1/8 in in diameter), an aperture, two lenses, and a small, 45° mirror. Light rays from the lamp are slightly converged by Lens 1. Lens 2 then focuses the rays so than an image of the lamp filament is produced on the mirror. The aperture between Lens 1 and Lens 2 allows different shapes or colors of illumination. These apertures are mounted on a horizontally oriented thumb-wheel so that different ones can be used at different times. Most ophthalmoscopes have several different apertures including two sizes of clear circular apertures, blue and green circular apertures, and a slit. The aperture is placed at a distance from Lens 2 such that the aperture is in focus on the subject's retina (at least for an emmetrope). This means that the observer will see a fairly-well focused disk of light on the subject's retina when using one of the circular apertures. Since there is an image of the filament on the mirror, it is as though the lamp filament is *on* the mirror and we can think of light rays as originating from that point. Light rays from the mirror diverge, forming a cone-shaped bundle of rays that enter the subject's eye. The bundle of rays passes through the cornea and anterior chamber. Some of the rays are stopped by the iris, but others pass through the pupil and then to the retina.
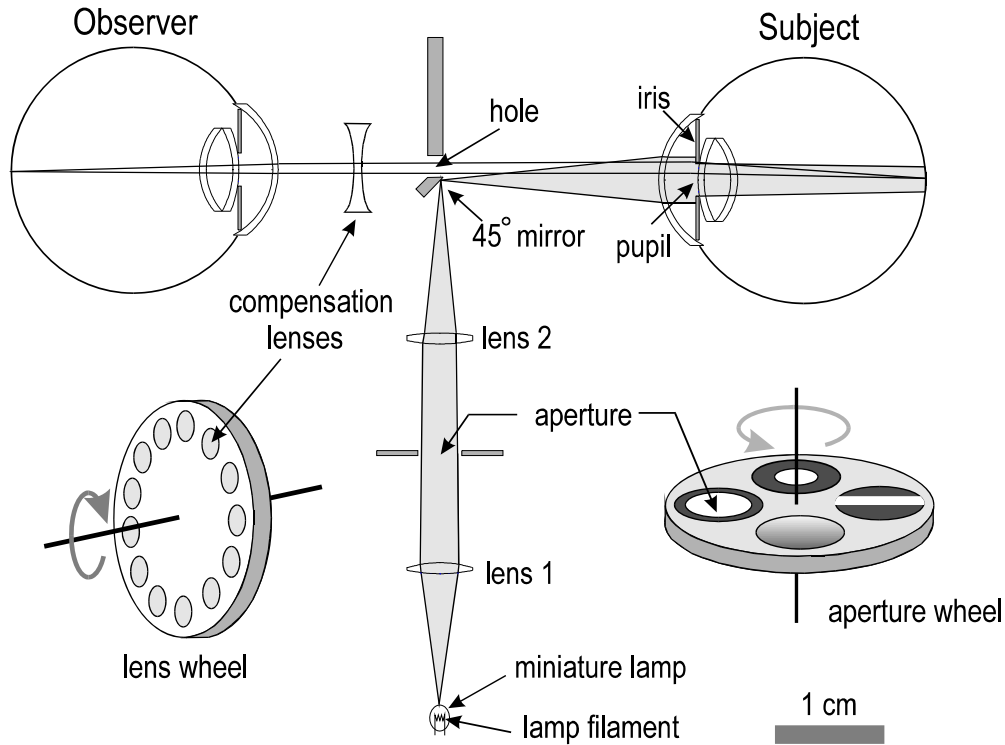
Fig. 6. Detailed structure of the direct ophthalmoscope showing the illumination and viewing optical systems.

- The *viewing system* allows the observer to see light reflected from the subject's eye. In Fig. 6, the illumination system has flooded a small circular area of the retina with light. Light from this illuminated area is reflected in all directions, but only some of the reflected rays pass through the crystalline lens, pupil, and cornea to the outside (other reflected rays are not shown in Fig. 6). The subject's eye in Fig. 6 has been made emmetropic, thus rays from any particular point in the illuminated area are parallel when the leave the cornea. Some of these parallel rays intersect the mirror and are lost to view, while others pass through the viewing aperture. Small diameter compensating lenses are placed just behind the viewing aperture. These lenses are exactly like the spectacle lenses we considered in the previous chapter, but smaller in diameter. They allow the observer to bring into focus the image from the subject's retina if the subject is not emmetropic. We will consider this in more detail in section IV, below.

Retinal nomenclature and directions.

Before proceeding to the imaging properties of the ophthalmoscope, it will be useful to consider the difference between the anatomical and clinical terms for retinal areas, nomenclature that is often confusing. The retinal photograph in Fig. 7 identifies the common anatomical and clinical terms. In addition, the optic disk is also sometimes referred to as the "papilla," or "optic nerve head." The major blood vessels that arc temporally from the optic disk are referred to as the "central arcade." Finally, when inspecting the retina with a direct

ophthalmosocpe, the retinal directions are as shown in Fig. 7. There is no image inversion with the direct ophthalmoscope, so, for example, when you look upward, you look more superiorly on the retina.
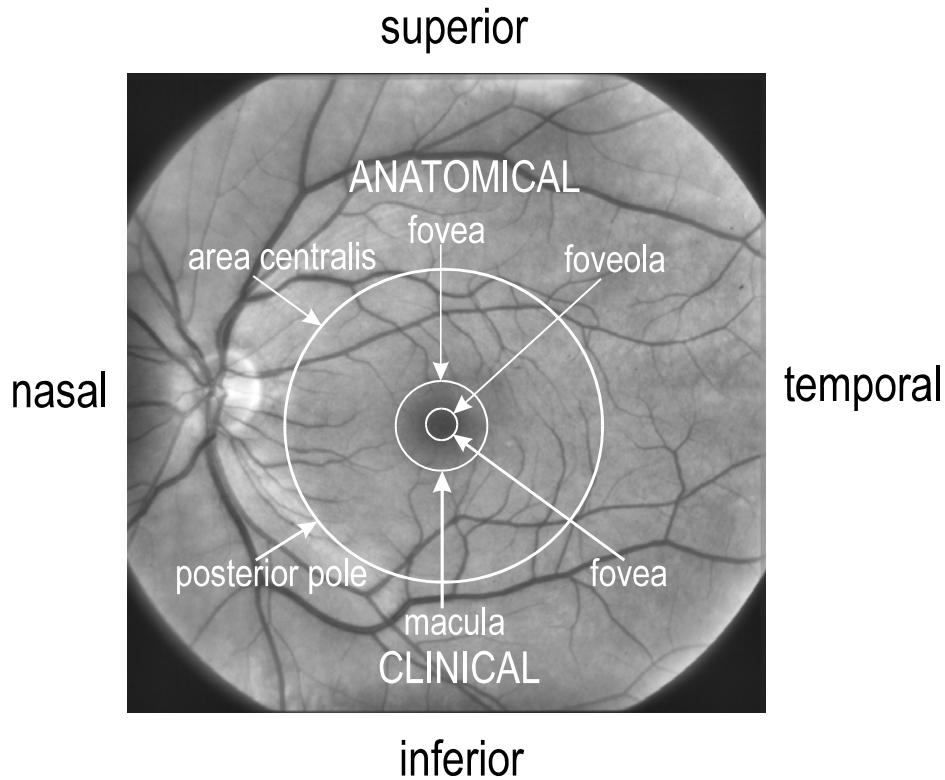

Fig. 7. Summary of anatomical and clinical nomenclature for retinal areas. Retinal directions are indicated.

VI. Retinal Imaging and the Illumination System

Illumination aperture size and pupil size

The size of the retinal area that can be seen with the ophthalmoscope depends on the area that is illuminated because one cannot see what is not illuminated. One might think that by increasing the illumination aperture size and making a large cone of illumination rays, that a larger area would be visible. This, however, is not necessarily the case as shown in Fig. 8. In the figure, the subject's eye has a 2 mm diameter pupil, a typical diameter when the eye is exposed to the relatively bright light from the ophthalmoscope. The left part of Fig. 8 shows illumination light rays with the large illumination aperture. Notice that a large part of the illumination simply falls on the iris and does not pass through the pupil to illuminate the retina. The right panel of Fig. 8 shows that with the smaller illumination aperture, all of the light rays just barely pass through the pupil and illuminate the retina. The illuminated retinal area is the same with both apertures, but the large aperture also shines

light on the eye that does not help to illuminate the retina and can cause difficulties in viewing the retina. Thus, for a natural, undilated pupil, it doesn't do any good to use the large illumination cone.
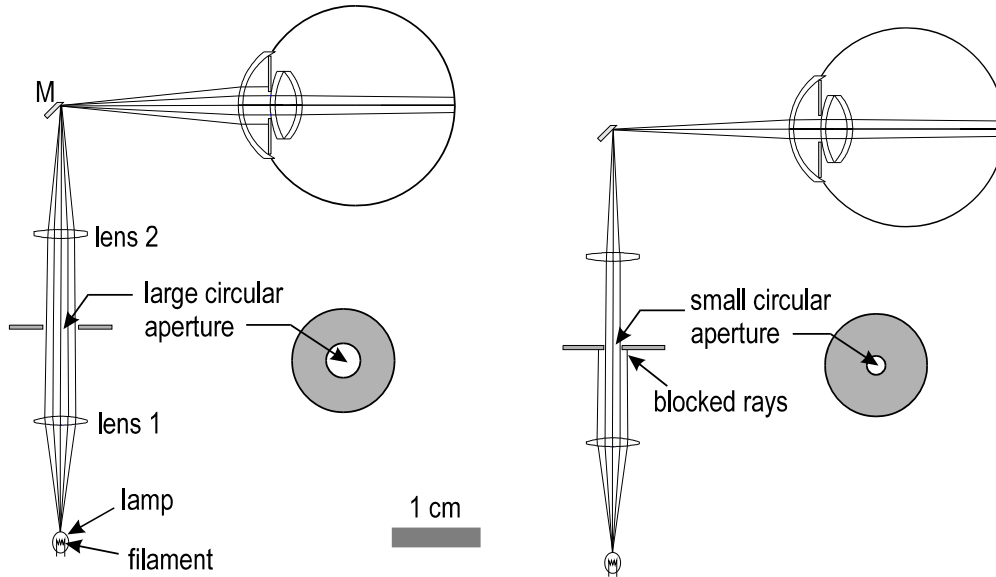

Fig. 8. Effect of illumination aperture size on the retinal area illuminated. Subject's pupil is 2 mm in diameter, and the eye is 2 cm from the ophthalmoscope in both cases.

Effect of distance from the eye and pupil size

There are two factors that strongly influence the size of the illuminated retinal area: (a) the distance of the eye from the ophthalmoscope (the filament image on the mirror), and (b) the pupil diameter. In Fig. 9*A*, the ophthalmoscope is relatively far (15 cm) from an emmetropic eye with a 2 mm diameter pupil. Notice that the illumination rays in the eye converge to a very small retinal area.[5] With the ophthalmoscope so far from the eye, we would only be able to see an extremely small portion of the retina, perhaps a short segment of a retinal vessel (200-300 μm in diameter) as shown to the right. When the

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[5] N.B. This makes sense because the farther the illumination source from the eye, the more parallel are the rays as they enter the eye and we know that parallel rays entering the emmetropic eye come to focus at a point on the retina.
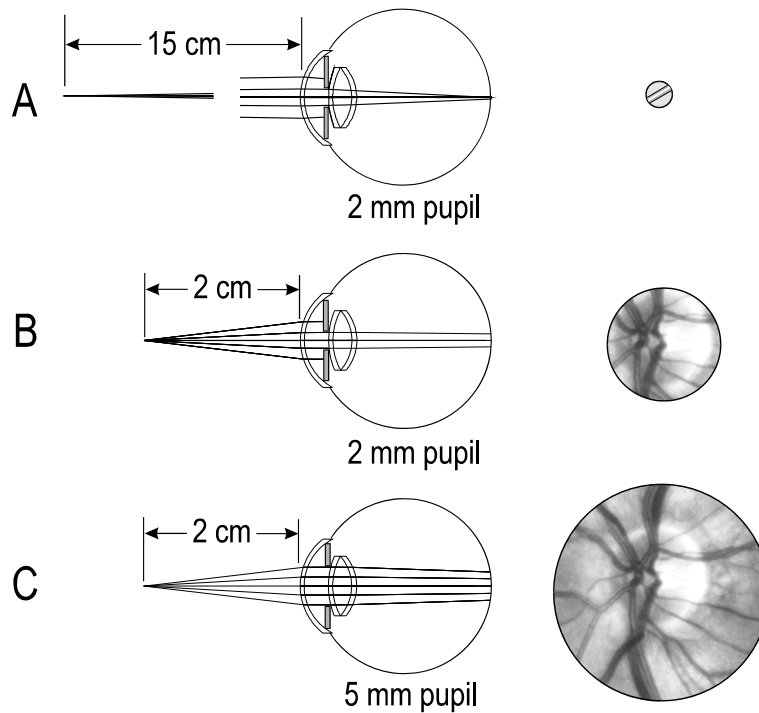
Fig. 9. Illustration of the effects of distance of the illumination source to the eye and pupil diameter on the area of visible retina. Illumination rays are shown as they leave the mirror in the ophthalmoscope (the rest of the illumination system is omitted for clarity). The large illumination aperture (i.e., large illumination cone) is used in A, B, and C. Emmetropic eye. The visible retinal area in the region of the optic disk is shown to the right.

ophthalmoscope is brought much closer to the eye, as shown in Fig. 9*B*, however, a much larger retinal area is illuminated, even with the same size pupil. In this case, we would be able to see the entire optic disk which is about 1.5 mm in diameter. Finally, if we are able to dilate the pupil, a much larger retinal area is visible as shown in Fig. 9*C*. There, the pupil is 5 mm in diameter while the illumination source is exactly as in 9*B*. The field of view as shown on the right is about 3 mm in diameter, twice as large as that in 9*B*. Dilating the pupil with a mydriatic will dramatically increase your ability to view the fundus.

Changing the illumination angle

As seen above, even with a dilated pupil, one can illuminate (and see) only about a 3 mm diameter patch of retina. This is a very small portion of the overall retina, so the ophthalmoscope must be rotated left-to-right, and up and down in order to scan the fundus. This is illustrated in Fig. 10 which shows a horizontal view of the eye and ophthalmoscope illumination beam. The beam has been rotated with respect to the optical axis of the eye various amounts and the corresponding fundus area is shown below. First, notice that the foveola is slightly off the eye's optical axis (~3°). If the ophthalmoscope is rotated nasally by about 10° the optic disk becomes visible. If it is rotated temporally by about 16°, an area of retina outside the posterior pole is just visible. Of course, vertical rotation are also possible and these will allow the observer to see the

vessels of the central arcade. Clinically, this is important since small "dot and blot" hemorrhages such as those found in diabetic retinopathy are often seen there. The biggest problem posed by the small field of view with an undilated pupil is the small field of view. With this small view, it is easy to "get lost" when exploring the fundus, much like trying to make one's way through a forest at night by shining a flashlight straight down onto the ground. One practical suggestion is to try to "pick up" a large retinal vessel, then follow it back to the optic disk. Finally, it is possible to "miss" large structures such as an area of retinal edema because it is seen one small bit at a time.
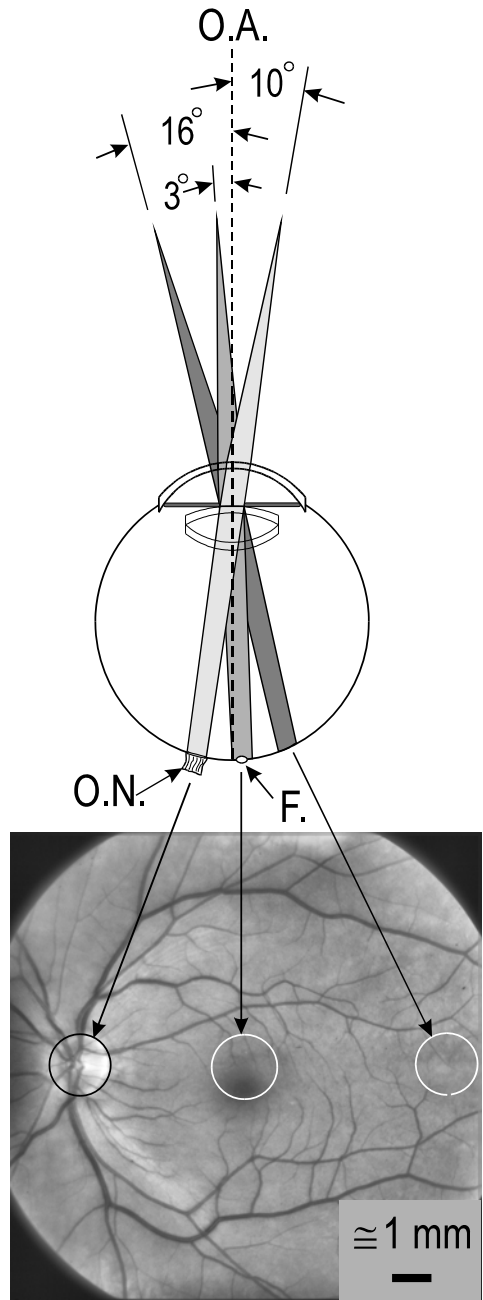
How far into the retinal periphery can we see? In principle, the ophthalmoscope can be rotated relative to the subject's optical axis enough to see retina to the "equator" of the eye. This is illustrated in Fig. 11 with a computer-modeled emmetropic eye with a 2 mm pupil. Illumination rays (grey area) enter the pupil at an oblique angle. In reality, without a fully dilated pupil this is extremely difficult.
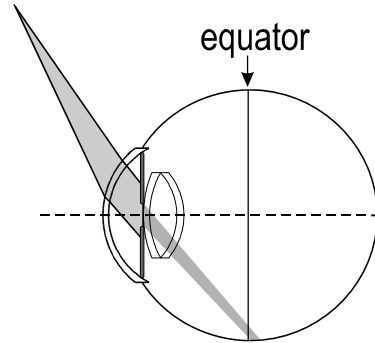

Fig. 11. In principle, it is possible to illuminate and see retina as far anteriorly as the equator.

IV. Retinal Imaging and the Viewing System

In the ophthalmoscope's viewing system, light rays reflected from the subject's retina exit the eye, pass through a compensating lens and enter the observer's eye, forming an image of the subject's retina on the observer's retina. The simplest example of this type of imaging is when an emmetropic observer looks at the retina of an emmetropic subject as shown in Fig. 12.   There, a circular area of the subject's retina has been illuminated (grey area). If we trace reflected light rays from the top edge of the illuminated area (dashed lines), the two rays just barely pass through the pupil. Outside of the eye, the two rays are parallel since the subject's eye is emmetropic. The two parallel rays then pass through the compensating lens of the ophthalmoscope: in this case, however, no lens has been selected and there is only an empty hole. The two parallel rays then enter the observer's eye, just passing by the pupil, and come to a focus on the observer's retina. Notice that rays from
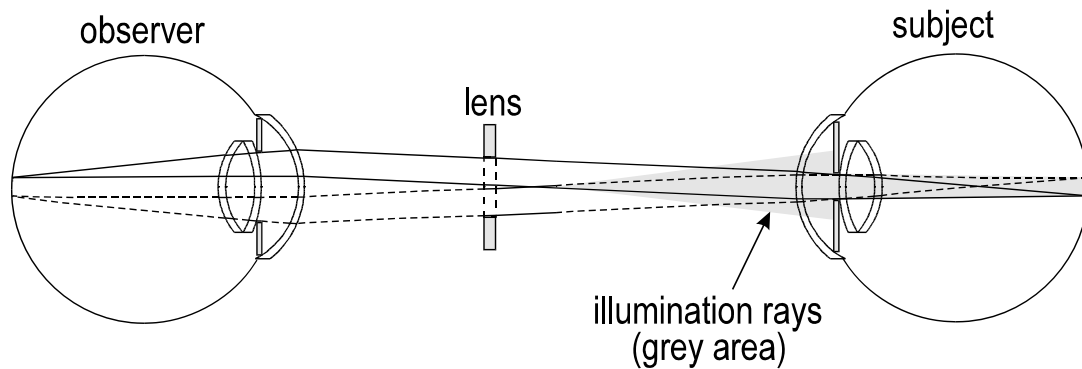

Fig. 12. Emmetropic observer looking at an illuminated retinal area of an emmetropic subject. Rays from subject's eye are parallel, thus are focused on the (emmetropic) observer's retina. No compensating lens is necessary.

the top edge of the illuminated area in the subject's eye come to focus at the bottom in the observer's eye. A similar ray trace for the bottom edge of the illuminated area (solid lines) shows that the rays come to focus at the top on the observer's retina. Thus, an inverted image of the illuminated area of the subject's retina is formed on the observer's retina. Although the image is inverted on the observer's retina, it will, appear un-inverted (why?). Other rays traced from any other location in the illuminated area will come to focus at a corresponding location on the observer's retina.

The detailed ray trace shown in Fig. 12 can be simplified considerably as shown in Fig. 13. There, the illumination rays have been eliminated and only one point on the subject's retina is traced to the observer's retina. This simplified diagram shows that when an emmetrope examines the retina of an emmetrope, no compensating lens is required and that points on the subject's retina come to focus on the observer's retina. This type of simplified diagram will be used in describing image formation in ametropia.
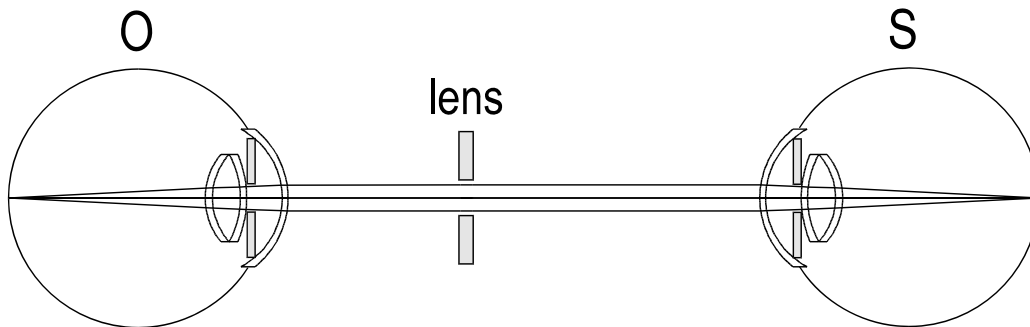

Fig. 13. Simplified raytrace of an emmetropic observer (O) inspecting the retina of an emmetropic subject (S).

Myopia

Light rays from the illuminated retina of a myope *converge* outside the eye as shown in Fig. 14. If no lens is placed in the optical path, the rays will come to focus in front of the observer's retina resulting in a very blurry image (Fig. 14, top). To correct this situation, the ophthalmoscope lens wheel is rotated so that a concave (negative) lens is in position. The concave lens diverges the rays, making them parallel (Fig. 14, bottom). The bundle of parallel rays enters the observer's emmetropic eye and come to focus at the retina, producing a sharp image of the subject's retina. The power of the concave lens needed depends on the degree of ametropia of the subject and the distance from the eye to the ophthalmoscope.
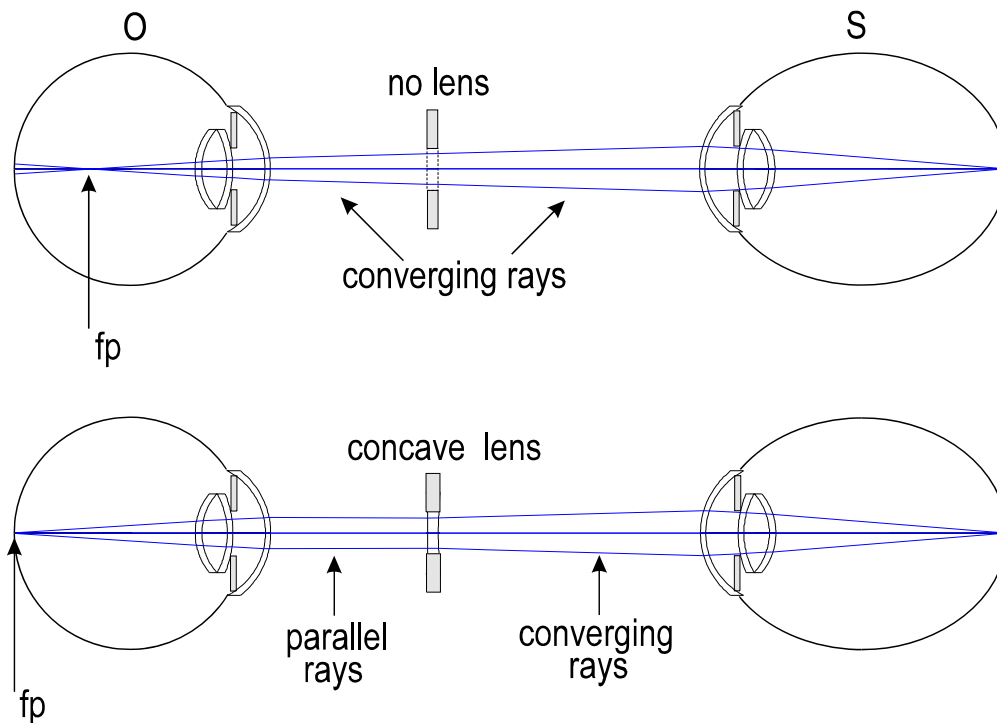
Fig. 14. Image formation when an emmetropic observer (O) views the retina of a myopic subject (S). With no lens in place (top), rays come to a focal point (fp) in front of O's retina. With appropriate negative lens in place, rays come to focus on O's retina.

Hyperopic Subject

Light rays from the illuminated retina of a hyperopic subject *diverge* after leaving the eye (Fig. 15). If no lens is selected in the ophthalmoscope, the rays will continue to diverge as they reach the observer's eye (Fig. 15, top). Consequently, the rays will be brought to focus "behind" the observer's retina, resulting in a blurred image. As you may suspect, this can be corrected by inserting a convex (positive) lens into the optical path so that the rays from the subject are "converged" somewhat to make them parallel (Fig. 15, bottom). Now the parallel rays come to focus on the retina of the emmetropic observer. The power of the concave lens depends on the amount of the subject's ametropia and the distance of the ophthalmoscope from the subject.

O   S
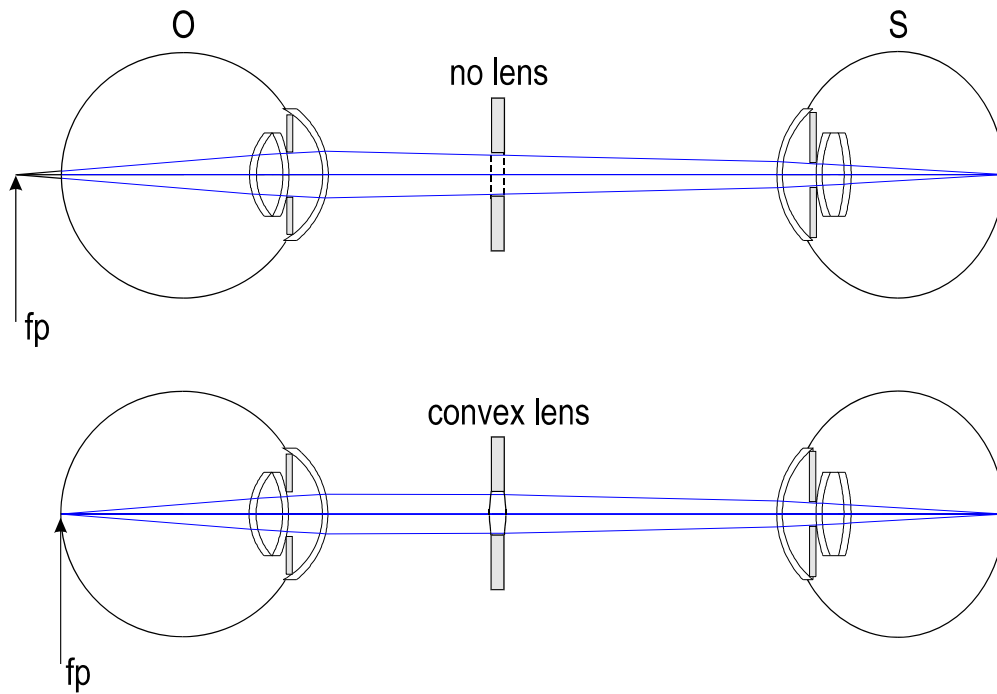
no lens

fp

convex lens

fp

Fig. 15. Image formation when an emmetropic observer (O) views the retina of a hyperopic subject (S). With no lens in place (top), diverging rays are focused (fp) "behind" O's retina. With appropriate convex lens in place, rays come to focus on O's retina.

V. Direct Ophthalmoscope Magnification

How much is the subject's retina magnified when observed with the direct ophthalmoscope? One approach to finding the magnification might be to compare the size of the illuminated area on the subject's retina to the size of its image on the observer's retina. This is done using the raytrace shown in Fig. 16 where an emmetropic observer inspects the retina of an emmetropic subject. Rays from the top and bottom (or left and right) edges of the illuminated area are shown. The illuminated area of the subject's retina is sharply imaged on the observer's retina. In optical terms, the illuminated retinal area is the "object" corresponding to the "image" on the observer's retina. A "blowup" of the object and image show that they are both 1 mm high. The magnification can be calculated as the ratio of the image size to the object size. For the example shown in Fig. 16, Magnification = 1mm/1mm =1. Put another way, there is no magnification!
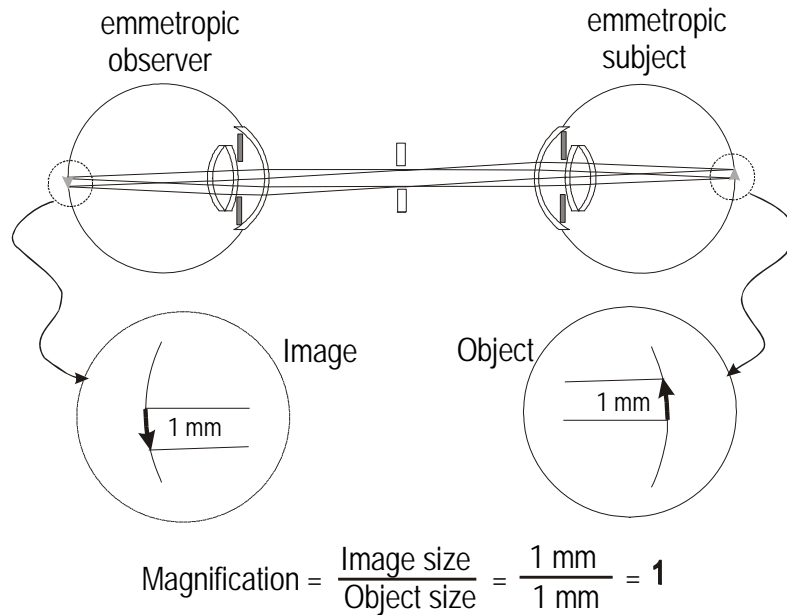
$$\text{Magnification} = \frac{\text{Image size}}{\text{Object size}} = \frac{1 \text{ mm}}{1 \text{ mm}} = \mathbf{1}$$

Fig. 16. Illustration of calculating linear magnification in the direct ophthalmoscope. An "object" on the subject's retina is imaged on the observer's retina.

The finding that there is no magnification of the subject's retina is clearly at odds with our impression when we use the direct ophthalmoscope. Retinal features *appear* to be highly magnified through the ophthalmoscope. To understand why this is the case, we need to consider the *angular* magnification, not the *linear* magnification described above. The apparent size of any object viewed with the unaided eye depends on the angle subtended by the object. This is illustrated in Fig. 17 which shows that as one approaches a tree, the angle subtended by the tree increases as does the retinal image of the tree and its apparent size.
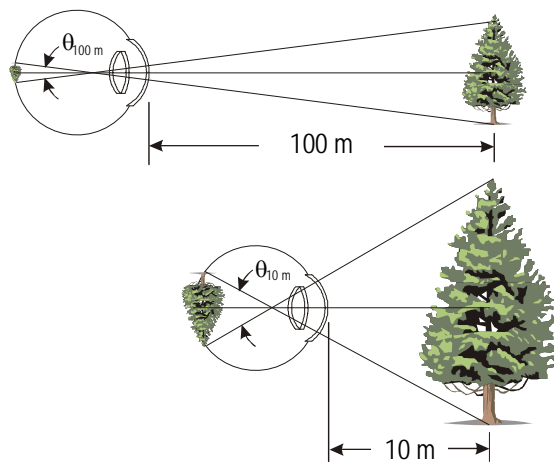

Fig. 17. Retinal image size and the angle subtended by the tree at the eye increase the closer the observer is to the tree.

There is a limit to how close one can approach an object and still see it clearly because accommodation is limited. Although this distance varies widely among people and with age (see

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"Physiological Optics"), 25 cm is ordinarily taken as the *average distance of most distinct vision for an emmetrope.*

      To understand the angular magnification of the ophthalmoscope, we need first to consider the angular magnification produced by a simple magnifying lens. When the unaided eye views an object (upright arrow in Fig. 18A) at the average distance of most distinct vision, the object subtends an angle θ at the eye. The same object can be placed much closer to the eye and viewed through a simple (convex) magnifying lens (Fig. 18B). With this arrangement, the eye sees a *virtual* image of the object (large gray arrow) at 25 cm, the average distance of most distinct vision. By tracing rays from the virtual image to the retina, we see that the angle subtended, θ', is much larger than θ and the image on the retina is much larger. The angular magnification (θ'/θ) is clearly larger than 1 since θ' > θ. In fact, the angular magnification, M_{ang}, when viewing the object with a magnifying lens is

$$M_{ang} = \frac{25\ cm}{f}$$

where *f* is the focal length of the lens. From the previous lecture, recall that the Power of the lens in Diopters (D) is $1/f$ (*f* in meters). So, we can rewrite the equation as
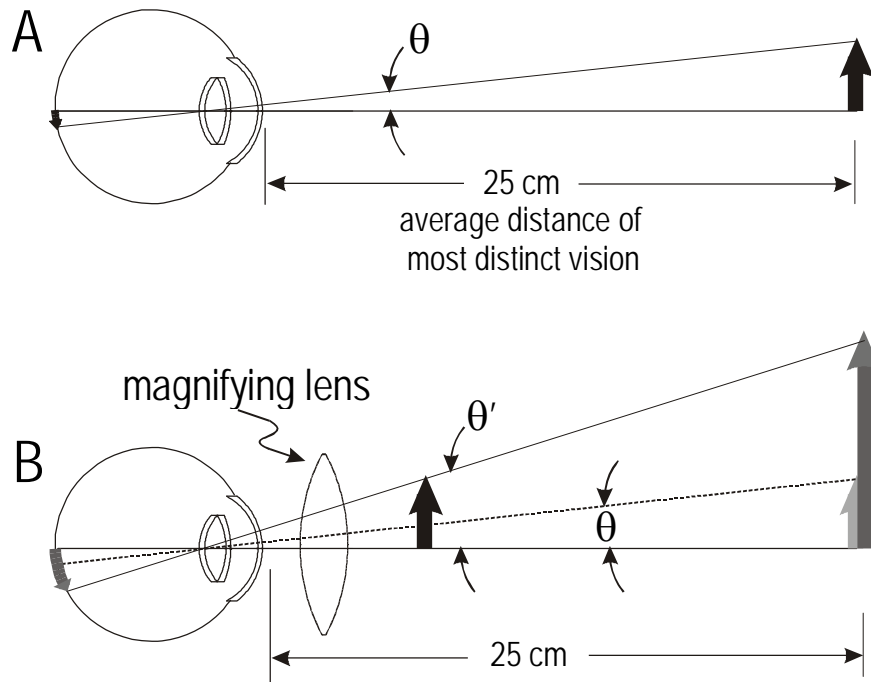
$$M_{ang} = 0.25\ m \times D$$

Fig. 18. A. Object (upright arrow) at 25 cm subtends angle θ at unaided observer's eye. B. Virtual image (large gray arrow) of the same object subtends angle θ' when viewed through magnifying lens.

For example, suppose you view a 1 mm long bug through a 40 D magnifying glass. The angular magnification would be

$$M_{ang} = 0.25 \times 40 = 10$$

and you would perceive the bug as being 1 cm long roughly 25 cm from your eye.[6]

With this background, we can now address the angular magnification of the direct ophthalmoscope. To do so, the optics of the subject's eye (cornea and crystalline lens) will be considered as a single magnifying lens of 60 D power (see "Physiological Optics"). The observer views the subject's retina through this "magnifying lens." The angular magnification is

$$M_{ang} = 0.25 \times 60 = 15$$

Thus, the direct ophthalmoscope provides an *angular magnification* of the subject's retina of 15 times. It is important to understand that the angular magnification of 15X is approximate and depends on a number of variables. First, we have assumed an emmetropic observer and a 60 D emmetropic subject. If either the subject or observer (or both) is hyperopic or myopic, the magnification will be different. Second, we have used the "average distance of most distinct vision" of 25 cm. Clearly this varies with the observer's accommodation, refraction, and age. Nevertheless, it is useful to have a magnification in mind when inspecting an important feature of a patient's retina with the direct ophthalmoscope or when answering exam questions.

VI. The Corneal Reflex

A common irritation when trying to observe a subject's retina is the bright reflection from the cornea. This reflection, known as the "corneal reflex," can obscure the portion of the fundus one is attempting to observe. The corneal reflex originates from illumination light rays that are reflected from the cornea as shown in Fig. 19. When the ophthalmoscope's illumination cone is centered on the cornea (Fig. 19*A*), some of the light is reflected by the cornea. The image formed by the reflected rays can be determined by tracing the reflected rays back into the eye (dashed lines, Fig. 19*A*). The traced lines all intersect at a point approximately in the plane of the pupil, thus the image is in the plane of the pupil. The image is not a "real" image because there is not really a bright light in the pupil, rather, it is a "virtual" image. Virtual or not, the corneal reflex appears to the observer as a bright light in the subject's pupil as shown in Fig. 19*A*, middle. If one were trying to observe the central portion of the illuminated retina (the macula in this case), the corneal reflex would obscure part of the desired retinal area.

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[6] The student will not be tested on the equations on this or the preceding page.
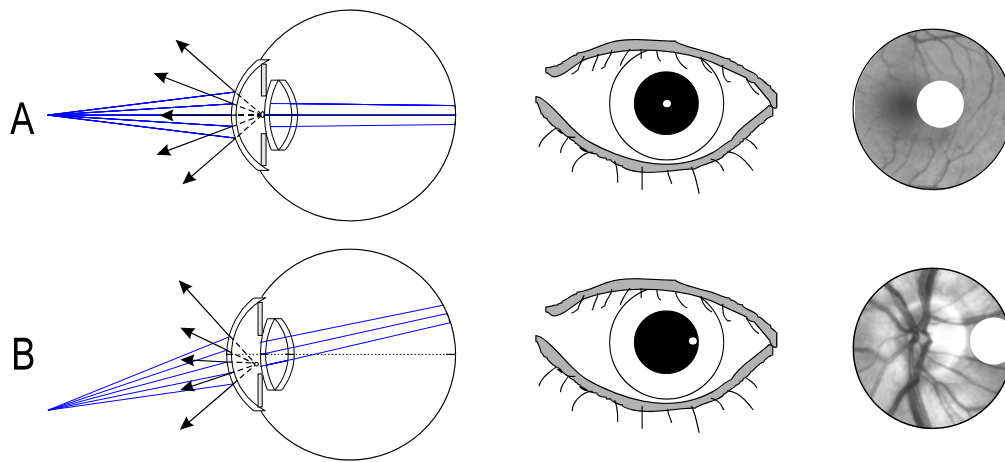
Fig. 19. Formation and appearance of the corneal reflex. A: (Left) Corneal reflex formed in center of pupil plane. (Middle) Reflex appears as bright point in center of pupil. (Right) Reflex obscures part of retina being inspected. B: Rotating ophthalmoscope (or subject's eye) shifts location of corneal reflex (left & middle). Retinal area under observation is less obscured (right).

Chapter 3

Using the Direct Ophthalmoscope with the Model Eye

The Model Eye uses a single plastic lens in place of the cornea and crystalline lens of the real eye (Fig. 20). The lens is mounted at one end of an open plastic tube into which another tube holding the "retina" is inserted. The model eye also has two different pupil sizes (2, and 4 mm in diameter) that are selected by moving the plastic pupil strip left or right. Taking the pupil strip out completely provides a pupil diameter of 8 mm.
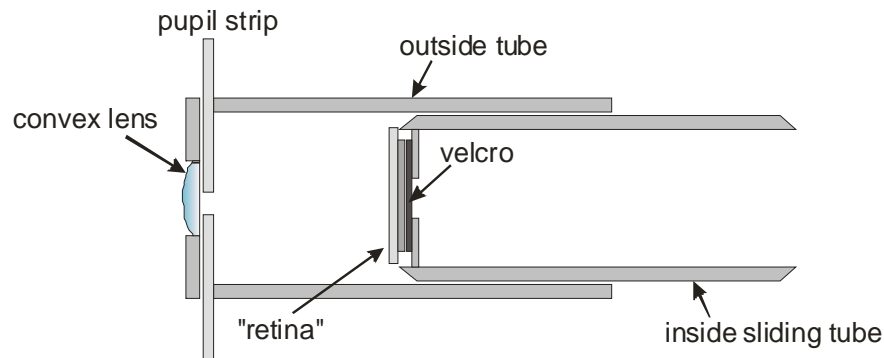

Fig. 20. Cross-section of the Model Eye.

Assembling the Model Eye

Each Model Eye kit contains:
    Stand
    Outer tube that mounts on the stand
    Inner tube that slides into the outer tube
    6 black plastic disks
    5 images of retinas and 1 mm grid with double-stick tape on back
    6 disks of "hook" Velcro
    2 disks of "loop" (fuzzy) Velcro

Attach the large, outer tube to the stand by pressing the black V-shaped plastic attached to the tube over the clear plastic ball on the stand. Next, insert the smaller-diameter inner tube into the Model Eye.

EXPERIMENT 1: Emmetropia

In a normal, emmetropic eye, parallel rays of light from a distant object come to focus on the retina(Fig. 21A). Light rays are "reversible", that is they travel the same path whether going into or out of an optical system. Consequently, if the retina of an emmetropic eye could "light up", light rays from a point on the retina would exit the eye as parallel rays (Fig. 21B).

LIGHT ENTERING EYE   LIGHT LEAVING EYE

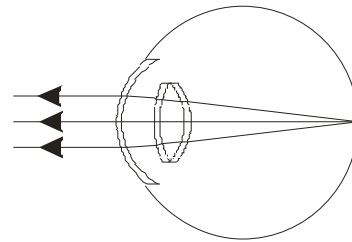crystalline lens

cornea

pupil

iris
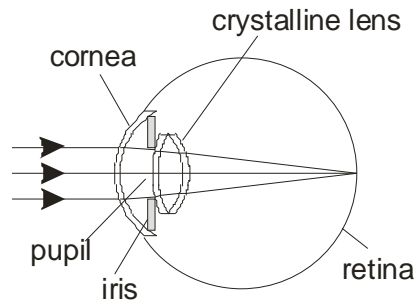
retina

Fig. 21. Light rays are "reversible" illustrated with an emmetropic eye.

The Model Eye will be emmetropic when the retinal surface is just far enough from the lens so that light coming from the retinal surface will be parallel when it leaves the lens (Fig. 22a). This means that an image of the retinal surface will be formed at infinity. A scale showing optical power of the eye is attached to the side of the inner tube. The scale shows the amount of ametropia (-4, -8 and +4, +8 Diopters). The "E" stands for "emmetropia." To verify that the "E" position of the inner tube produces emmetropia, shine a flashlight into the inner tube and move the tube in or out until you see an image of the hole on a distant wall. You will need to perform this experiment in a very dark room. The "E" should line up with the outer edge of the outer tube as shown in Fig. 22B.

A

hole in plastic disk
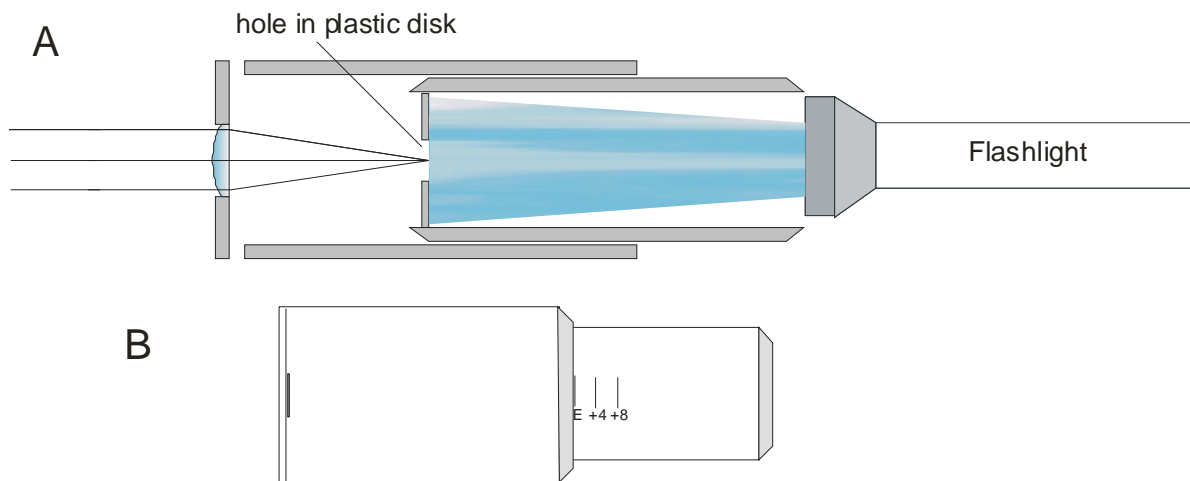
Flashlight

B

E +4 +8

Fig. 22. A. Setup for adjusting Model Eye to emmetropia. B. The "E" (for emmetropia) lines up with the edge of the outer tube when the eye is adjusted for emmetropia.

You can gain some appreciation of the retinal image of a myopic ("nearsighted") or hyperopic ("farsighted") individual by moving the box outward or inward respectively from the "E" and observing the image of the hole on the wall.

Preparing the "retinas." Using scissors carefully cut around the black edge of each of the photos of retinas. Remove the covering from the double-stick tape on the back side of the retina to expose the adhesive. Stick the retina onto one of the black disks being careful to align the edges of the retina and disk (excess can be trimmed off with a razor blade). Cut the 1 mm grid along the edges and mount on a plastic disk. Attach a ¾ inch diameter Velcro "hook" disk (6 are provided) to the back

of each of the plastic disks. Next, gently press one of the Velcro "loop" (fuzzy) disks on the black plastic disk with the hole in the inner tube. Do not press too hard or the disk will detach from the white plastic tube. Center the Velcro disk over the hole. If additional pressure is needed to firmly stick the Velcro, put one finger against the black disk from the inside of the tube before pressing on the outside.

EXPERIMENT 2. Observing the emmetropic retina

The fundamental idea in operating the ophthalmoscope is to illuminate the Subject's (S) retina and then make rays of light coming from the Subject's eye parallel so that they come to focus on the retina of your (i.e., the Observer, "O") emmetropic eye. This is no problem with an emmetropic subject since the rays coming from his/her retina are already parallel when they exit the eye. Consequently, no lens is needed in the ophthalmoscope (Fig. 23).
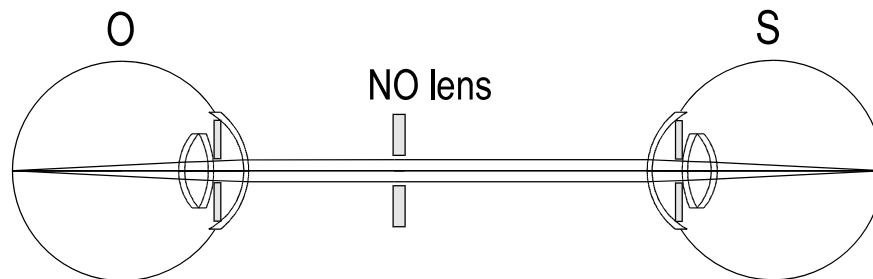

Fig. 23. Optical arrangement when an emmetropic observer (O) views the retina of an emmetropic subject (S) using the direct ophthalmoscope.

Remove the inner tube from the Model Eye and attach the disk with the mm grid to the Velcro on the retinal surface. Reinsert the tube and set it to "E." Turn on your ophthalmoscope and select the smallest diameter white light illumination. Set the ophthalmoscope lens selection wheel to "0" so that there is no compensating lens between your eye and the Model Eye. If you wear spectacles or contact lenses, leave them on or in so you are emmetropic.

Tilt the Model Eye to a convenient position. Starting about 12 inches from the eye, look through the ophthalmoscope and move it around until you see the light on the front of the model eye. You should then begin to see the grid retina. Now, move closer and closer to the eye. Do the 1 mm grids appear to become larger or smaller or remain the same? Do you get a sharper image by changing lenses in the lens wheel? Get as close as possible to the eye without touching the lens. Move the ophthalmoscope (and your head) around and try to see the edges of the grid. How far can you see temporally and nasally? Superiorly and inferiorly?

EXPERIMENT 3. Observing the hyperopic retina.

The eye of a hyperopic ("farsighted") person is often shorter in axial length than normal. Light rays entering the eye come to focus "behind" the retina, so the image is out of focus at the retina. When the retina is illuminated by the ophthalmoscope, light rays from the retina *diverge* when they leave the eye (Fig. 24).

HYPEROPIC

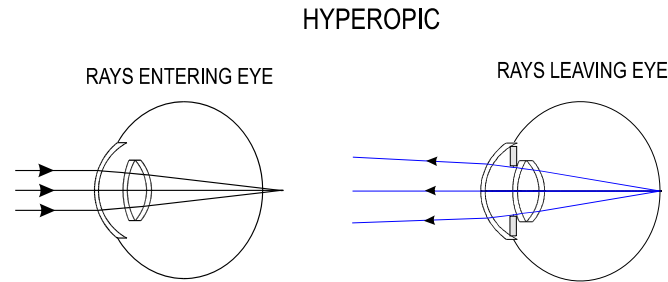RAYS ENTERING EYE   RAYS LEAVING EYE

Fig. 24. Light entering and leaving the hyperopic eye.

When trying to observe the hyperopic retina, we must insert positive (convex) lenses in the ophthalmoscope as shown below in order to converge the diverging rays from the eye enough to make them parallel before entering the observer's eye (Fig. 25).

O   S

convex lens

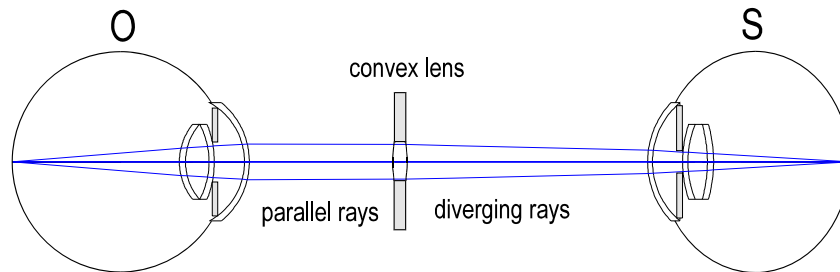parallel rays   diverging rays

Fig. 25. To observe the retina of a hyperopic eye, convex lenses must be selected in the ophthalmoscope to converge the diverging rays from the hyperopic eye.

Set the model eye for +8 (Diopters) of hyperopia by sliding the inner tube until the +8 mark lines up with the edge of the outer tube. Use the grid "retina" and the 8 mm pupil. Hold the ophthalmoscope about 12 inches from the eye and observe the grid retina. Rotate the lens wheel on the ophthalmoscope until the retina is in focus and note the lens number. Now, gradually move closer and closer to the eye, changing the lens as necessary to keep the retina in focus. Did you increase or decrease the power of the convex lens as you moved inward toward the eye? Did the 1 mm grids appear to become larger or smaller as you moved in closer to the eye?

EXPERIMENT 4. Observing the myopic retina.

The eye of a myopic ("nearsighted") person is often longer than normal. Consequently, rays of light entering the eye come to focus before reaching the retina with the result that the image is out of focus at the retina. Rays of light *leaving* the myopic eye come to focus at a point in front of the eye known as the "far point" (Fig. 26A). Thus, rays from the eye first *converge*, then *diverge* once past the far point. This means that you must use either concave or convex lenses to make the rays parallel, depending on your position relative to the far point. The use of a concave lens, when the ophthalmoscope is "inside" the far point, is illustrated in Fig. 26 B.
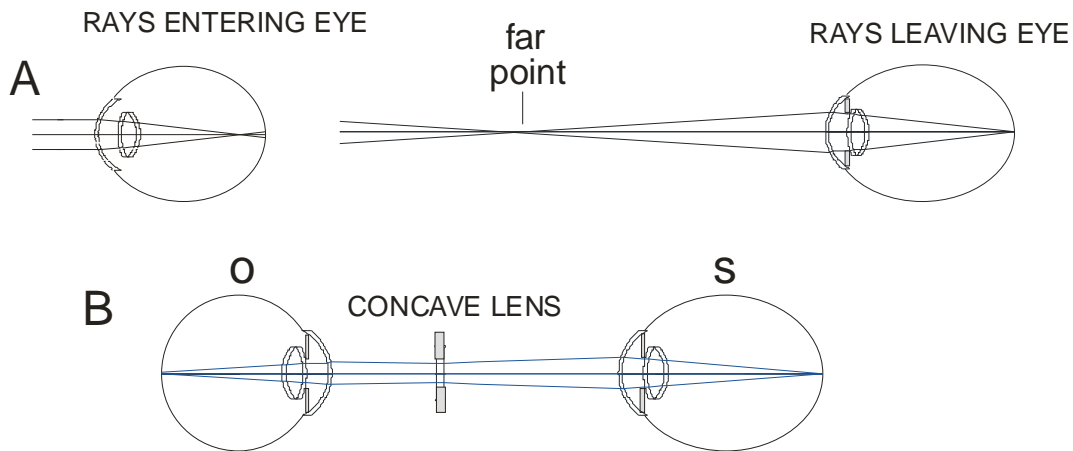
26

Fig. 26. A. Light rays leaving the myopic eye come to focus at the far point. B. A concave lens is selected in the ophthalmoscope when the observer is nearer to the eye than the far point.

Set the model eye for -8 D of myopia. When the model eye is set for -8 D, the far point is 125 mm (i.e., 1/8 m or ~ 5 inches) in front of the lens. Start with the ophthalmoscope about 12 inches from the eye and turn the lens wheel until the grid retina is in focus. Note the number of the lens. As you move closer to the eye, rotate the lens wheel to keep the retina in focus. Are you increasing or decreasing the lens power? When you reach the far point, you will find that you cannot see the retina with any lens setting. Continue moving inward from the far point, but now try concave (negative lenses). How did the magnification of the grid change as you moved inward?

EXPERIMENT 5. Changing pupil size.

Thus far, we have used the 8 mm diameter pupil, approximately equivalent to a dilated human pupil. In the clinic, however, one often must examine the retina with an undilated pupil (~2 mm in diameter) when the eye is exposed to the light from the ophthalmoscope. It requires more skill to view the retina with a smaller pupil. In addition, the size of the pupil can limit your field of view of the retina. With a small pupil, the field of view is relatively small making it easier to "get lost" when exploring the retina.

Before inserting the pupil strip into the model eye, observe the grid retina at a very close distance and note how many grid squares you can see. Now, insert the pupil strip into the model eye as follows. There are two 15 mm long slits on either side of the lens in the front of the outer tube of the model eye. The pupil strip slides through these two slits. Push the pupil strip through one of the slits. Slide the strip toward the opposite slit and through it. If the strip meets resistance, try wiggling it slightly as you push forward, or remove it and insert it through the opposite slit. Move the strip so that the 4 mm pupil holes lines up with the center of the lens.

With the 4 mm pupil, observe the grid retina at a very close distance and note how many grid squares you can see. Now change to the 2 mm pupil, making sure it is centered behind the lens. How many grid squares are visible? Finally, set the ophthalmoscope illumination to the largest diameter and repeat the steps above. Did increasing the diameter of illumination have any effect on what you saw?

EXPERIMENT 6. Scanning the retina.

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The direct ophthalmoscope illuminates only a small area of retina and it is usually necessary to move the illumination beam to various parts of the retina in order to see them. It is easiest to practice this with the model eye since it does not move and does not have eyelids!

Remove the grid retina and attach the disk with an image of a normal human retina. Set the eye for emmetropia and remove the pupil strip so there is an 8 mm pupil. Start about 12 inches from the eye and move in until you are very close. Rotate your head and the ophthalmoscope until you find the optic disk, macula, and the vessels of the central arcade. Now insert the 4 mm pupil and repeat the procedure. Do the same thing with the 2 mm pupil. Finally, set the eye for 8 D hyperopia and then -8 D myopia and repeat.

EXPERIMENT 7. Practice observing retinal pathology.

Five retinal photographs are included with the Model Eye, four of which show various pathologies (see figure below). You should try observing each retina with the direct ophthalmoscope with the Model Eye set to emmetropia, hyperopia, and myopia. In addition, start with the 8 mm pupil and then work down to the 2 mm pupil. Try observing the relevant pathological features with each pupil and ammetropic combination.

In clinical practice, you will rarely know whether the patient's eye is emmetropic, hyperopic, or myopic. As a result, the systematic manner of changing the ophthalmoscope lenses described in the experiments above is rarely used. Instead, most clinicians simply turn the lens wheel until some aspect of the patient's eye is in focus (for example, the iris) and then readjust the lenses until the retina is in focus. As you move the ophthalmoscope closer to the eye, the lens wheel is adjusted clockwise or counter-clockwise to keep the retina in focus. You may find it worthwhile to let someone else adjust the model eye for some amount of ametropia and then (without looking at the setting) attempt to observe the retina.
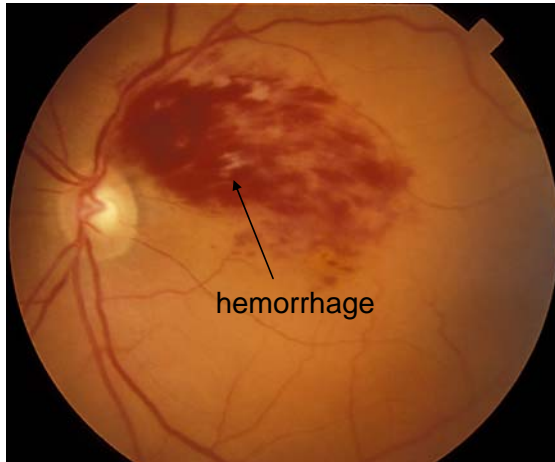
28
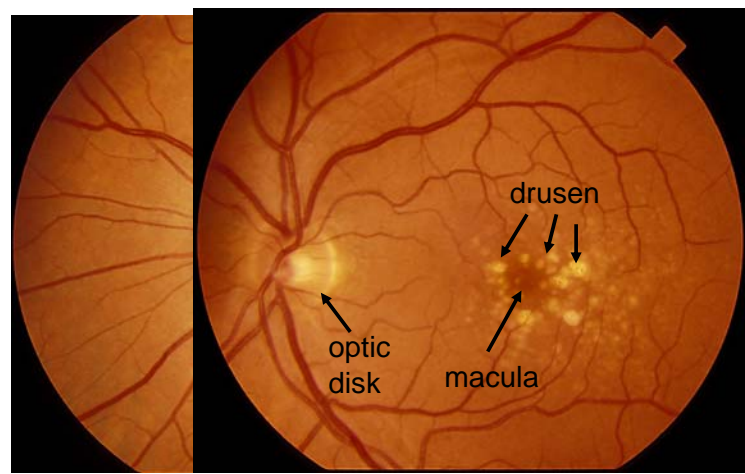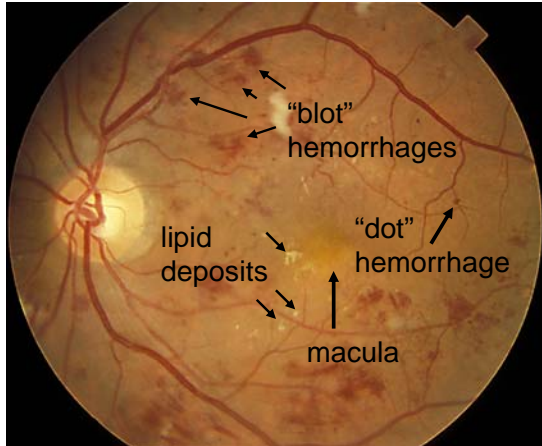
Non-proliferative diabetic retinopathy
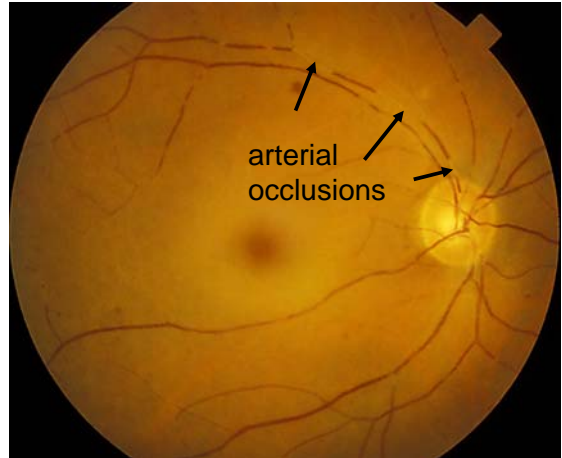
Central retinal artery occlusion with
cherry red spot

Branch retinal vein occlusion

Drusen in Aging Macular Degeneration

Chapter 4

Clinical Ophthalmoscopic Exam

Now that you have mastered the exam on the eye model it is time to move to an actual subject. An
adequate direct ophthalmoscopic exam (DOE) is an essential part of the basic physical exam. Many
common medical conditions including hypertension, diabetes mellitus, and lipid disorders have
secondary changes in the retina associated with them. Clinical information vital to the progression of
the associated disease and indicative of other end organ damage due to these various disease states is

gained from this simple, painless exam technique also called the fundoscopic examination. Additionally, many primary eye diseases can be diagnosed and managed using this same skill. Students often find the technique of the DOE difficult to master. The eye exam can be fatiguing to the patient. This limits the time available to the student to practice examining the retina. Students attempting to master recognizing disease states with DOE are also limited due to the lack of abnormal subjects. Using the model eye in the previous chapter as a practice "subject" will allow you to master the basic techniques used to perform the exam. Practice with this model until you feel comfortable with the controls of the ophthalmoscope and visualizing the retina at various settings of hyperopia and myopia. Have a friend set the eye model to an "unknown" degree of ametropia and examine the retina. Then when the skills have been mastered the transition to the real patient will be smooth. You can then test your skills in the ICM lab sessions with teaching patients.

Review the Instrument

Review the figures and the controls of the ophthalmoscope. Master the controls so that you can change the various settings "on the fly" with automatic ease. This will enable you to concentrate on the patient. For the first attempts at the actual exam use the following settings:

- Chose a low light setting from the source light

- Set the aperture to the large circle and white color

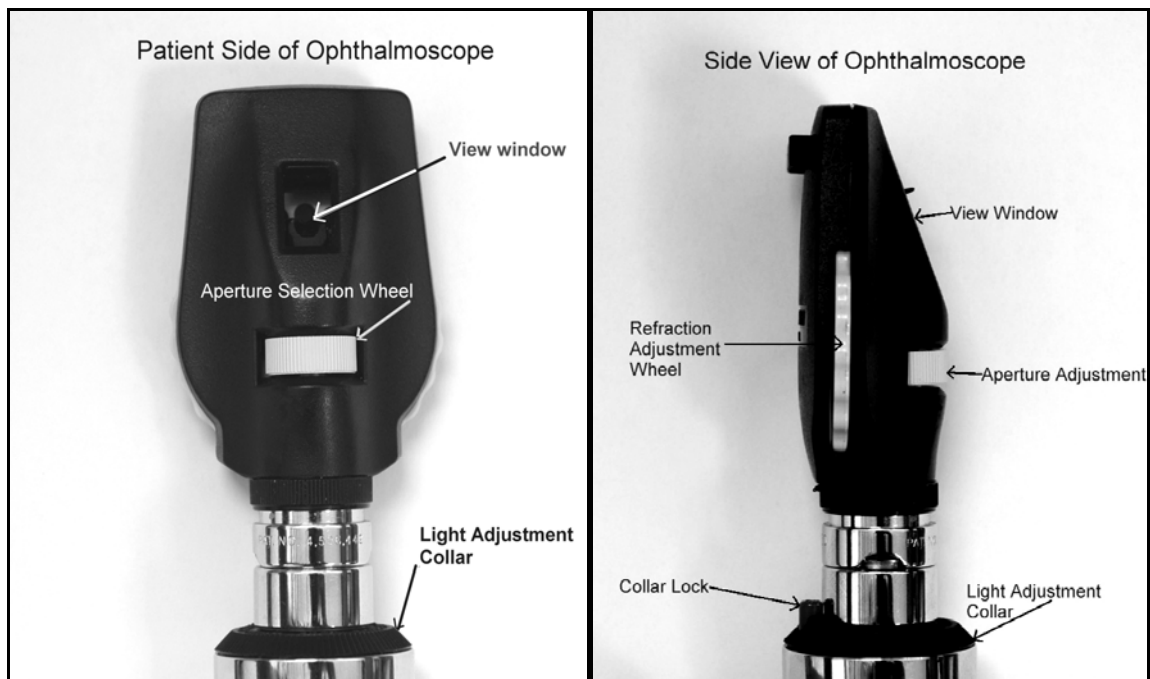- No filtration

- No refractive correction

Figure 1 – Patient side and Side view of the ophthalmoscope.

Using the Ophthalmoscope on a Human Subject

Patient preparation

The patient should be informed of what you plan to do. You should ask permission to examine their eyes. It is important to make sure the patient understands that you'll be using a bright light and that occasionally this makes eyes water and they may actually see "spots" after you have examined them. It is generally not necessary to use mydriatics (medications to dilate the pupil) for this exam, but the student should remain cognizant that an undilated eye exam is not as complete. You should have the patient sit in a comfortable position so that their head is about the level of yours. You should then dim the lights in the room or turn the lights out open the door enough to allow a small amount of light in the room. Have the patient then fix their gaze on an object across the room and instruct the patient to not look directly at the light or directly at you but to maintain their gaze fixed across the room.

Direct Ophthalmoscopy

When the patient is comfortable the examiner should then start at least at arms length. You should examine the patients left eye with your left eye and vice a versa. This is suggested to avoid touching

noses during when examining the patient. Usually, it is not necessary to remove your glasses (N.B. having your glasses on makes you emmetropic); however, you should remove the patient's glasses (they do not need to remove their contacts) In order to maintain a good reference of the distance between you and your patient you should put your hand on their shoulder. At this point put the ophthalmoscope up to your eye and look through the view hole at the patient's eye. You should be able to see the "red reflex" of the retina. You should then approach the patient from about a 15 degree angle to avoid the glare of the cornea. All the while the patient maintains their direct forward gaze at an object across the room. You can then slowly move closer to the patient following the red reflex until you are an inch or two from the patient's eye. As you move in turn the refraction adjustment wheel to compensate for any difference of refraction with the patient's lens. Once the retina is in good focus it is critical to then maintain this axis of alignment. Slowly move your head and the ophthalmoscope as a unit to find the optic nerve. One of the common sources of error is when moving to turn the ophthalmoscope slightly or to move the view hole out of alignment. Occasionally, you will need to back away and start again with the red reflex. From there proceed with the rest of the fundoscopic exam. Identify the landmarks as illustrated in Chapter 3. Through the process it is important to remember that the direct ophthalmoscopic exam can be uncomfortable to the patient due to the brightness of the light and can actually cause some

mild pain and discomfort. Avoiding blinking can cause the eyes to burn and tear. A significant amount of pain is pathologic. The exam should be limited to about 30 – 35 seconds at a time. If further examination is required you should give the patient a break by perhaps examining the opposite eye. There are several aspects of the fundoscopic exam that should be observed (refer to the diagrams in Chapter 3):

1   The size, shape and borders of the optic disc

2   The disc to cup ratio

3   The relative size of the arteries and veins

4   The texture of the retina

5   The color of the retina

6   Trace the vascular structure to the equator of the retina.

7   Find the macula and note its color and size

Remember to keep the "line of sight" between examiner, ophthalmoscope and patient while moving to see all the above structures. Move away from your patient and reset to exam the opposite eye. Frequent practice of this examination technique will help in your proficiency and ability to identify abnormal findings.