CHAPTER 14

Ophthalmology in Aerospace Medicine

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> And God said, "Let there be light." Genesis 1:3

Vision has always held a dominant place in the attributes necessary for flying. This was recognized by early pioneers, such as Drs. William Wilmer and Conrad Berens, who established the first laboratory to study the visual problems of the flyer in 1918 at the Air Service Medical Research Laboratory at Mineola, Long Island, New York (1). This almost total dependence on vision is evident now, as astronauts have reported the necessity of vision for orientation in space. Vision occurs peripherally at the eye and centrally in the brain. In the eye, the retina receives electromagnetic energy (photons) and, through a photochemical reaction, converts it into electrical signals. The nervous impulses are relayed to the occipital area of the brain where the signals are processed and interpreted as vision.

APPLIED ANATOMY AND PHYSIOLOGY OF THE EYE

The human eyes are protected by bony orbits that are shaped like a quadrilateral pyramid, thereby allowing good exposure of the cornea anteriorly to facilitate vision. Posterior openings in the orbits allow cranial nerves and blood vessels from the brain to communicate with the eye. Six extraocular muscles rotate each eye in all directions of the visual field.

Globe

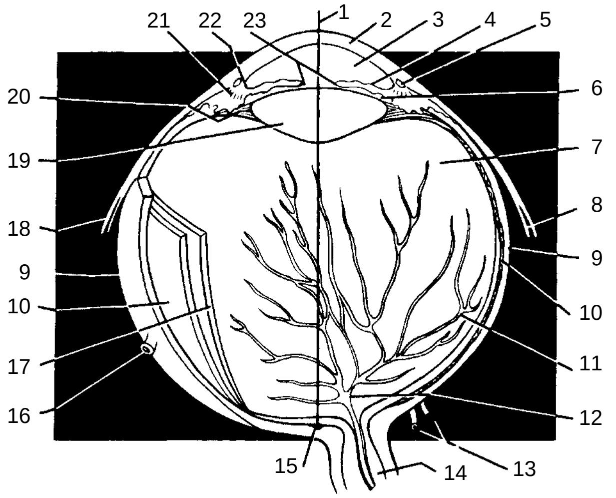
The globe measures approximately 25 mm in diameter and is composed of three coats. The two outer layers, the scleral and uveal coats, are involved with support, protection, and nutrition. The inner coat, the retina, contains the light sensitive elements. The clear cornea has a shorter radius (7.5 mm) than the sclera (12.0 mm) (Figure 14-1).

As shown in (Figure 14-2) the normal eye is a +60 D refractive system, +45 D supplied by the cornea and +15 D by the unaccommodated lens. Therefore, we see that small changes in the radius of curvature of the cornea can cause substantial changes in refraction. This can be accomplished by the use of contact lenses, (orthokeratology) or surgical procedures such as radial keratotomy (RK), photorefractive keratectomy (PRK), or laser *in situ* keratomileusis (LASIK), as well as other corneal refractive surgical (CRS) procedures.

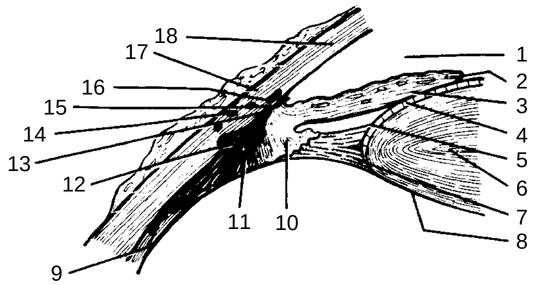
The uvea lies inside the scleral coat, it is the pigmented, vascular portion of the eye consisting of the choroid posteriorly, and the ciliary body and iris anteriorly. Aqueous humor is produced by diffusion and secretion in the epithelium of the ciliary processes. The ciliary muscle, innervated by the parasympathetic nervous system, supplies the contractile force necessary to change the shape of the lens during accommodation. The pupil is the opening in the iris. Its size is controlled by a delicate balance of the sympathetic and parasympathetic tone of the autonomic nervous system, principally in response to the level of illumination.

The intraocular lens lies just behind the iris, held in place by zonular fibers that are inserted into the lens capsule and the ciliary processes on the ciliary body (Figure 14-1). In order to see clearly at near, one must increase the power of the lens; this is known as *accommodation*. The parasympathetic impulse to the ciliary muscle constricts the circular part of the muscle, the zonular fibers then slacken, and the elastic capsule of the lens makes it more spherical thereby increasing its dioptric power. Accommodation decreases with age; by the mid forties, most aviators will be presbyopic and need spectacles to view clearly the panel, charts, and radios. Also of importance is that the eye is in focus for monochromatic yellow only, being hypermetropic for red and myopic for blue (2).

The retina is the innermost photosensitive layer. The neurosensory retina consists of ten layers. The light-sensitive elements are the rods and cones (Figure 14-3). The rods serve vision at low levels of illumination (scotopic vision) whereas the cones are effective both for medium and high levels of illumination (mesopic and photopic vision) and for color vision. The cones are mainly concentrated in the fovea centralis where the density has been measured at 47,000 cones/mm^2. The optic disc or blind spot is located



1. Visual axis
2. Cornea
3. Anterior chamber
4. Iris
5. Schlemm's canal
6. Posterior chamber
7. Vitreous
8. Medial rectus muscle
9. Sclera
10. Choroid
11. Retinal vessels
12. Central retinal vessels
13. Ciliary artery and nerve
14. Optic nerve
15. Fovea centralis
16. Vortex vein
17. Retina
18. Lateral rectus muscle
19. Lens
20. Ciliary zonule
21. Ciliary muscle
22. Angle of anterior chamber
23. Pupil



1. Anterior chamber
2. Iris sphincter muscle
3. Iris dilator muscle
4. Lens epithelium
5. Anterior lens capsule
6. Lens nucleus
7. Zonular fibers
8. Posterior lens capsule
9. Ciliary epithelium
10. Ciliary muscle (Circular)
11. Ciliary muscle (Radial)
11. Ciliary muscle (Meridional)
13. Angle of anterior chamber
14. Aqueous vein
15. Trabecular meshwork
16. Canal of schlemm
17. Sclera
18. Corneal stroma

FIGURE 14-1 Anatomy of the eye.

15 degrees nasal to the fovea and covers an area of 7 degrees in height and 5 degrees in width (Figure 14-4).

The vitreous, a clear colorless gel-like structure, fills the posterior four fifths of the globe. The vitreous is 99.6% water. The complaint of vitreous floaters is universal and usually innocuous. Floaters are usually due to the collapse of the protein/collagen scaffolding, thereby thickening and casting a shadow on the retina. More ominous floaters, which should be investigated at once, are often referred to as a *shower* of floaters; these are probably red blood cells. A dark floating membrane should be investigated for the possibility of a retinal detachment.

Adnexa

The adnexa of the eye are the extraocular muscles, the eyelids, and the lacrimal apparatus (Figure 14-5). There are six extraocular muscles attached to each globe, and because of the strong desire for fusion and the maintenance of single binocular vision both foveas are directed on the object of regard by both reflex and voluntary action. The lacrimal gland is located in a bony fossa on the frontal bone. It secretes the aqueous portion of the precorneal tear film. The corneal epithelium is covered by a three-layered film composed of an outer oily layer derived from the meibomian glands of the tarsal plate, the middle aqueous layer from the lacrimal gland, and the inner mucoid layer that arises from the goblet cells of the conjunctiva. The drainage system for tears consists of a small punctum or opening in the innermost edge of the upper and lower lids near the caruncle. These openings lead into a common canaliculus then into the lacrimal sac, exiting under the inferior turbinate in the nose.

The eyelids provide protection for the cornea, blinking six to eight times per minute; this blink also enhances the optical qualities of the cornea. The eyelids are closed by action of the

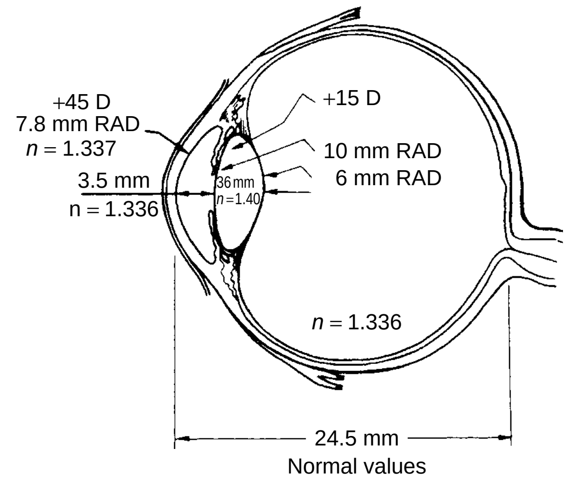


FIGURE 14-2 The normal values for the optical properties of the eye. RAD, radius; D, diopter; n, index of refraction.

orbicularis oculi muscles, which are innervated by the facial nerve (cranial nerve VII), and are opened by the levator palpebrae superioris muscles, innervated by the oculomotor nerve (cranial nerve III), elevation of the lids is assisted by Müller's muscle innervated by the sympathetic nervous system. Reduction of sympathetic tone to Müller's muscle can bring on the droopy eyelids seen on long, exhausting missions.

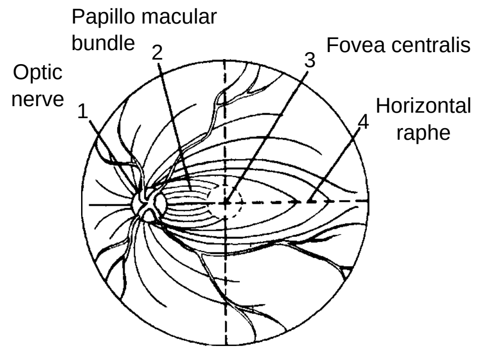


FIGURE 14-4 Fundus of the eye.

VISUAL PRINCIPLES

Vision is essential in all phases of flying and is most important in the identification of distant objects and in perceiving details of shape and color. The visual sense also allows the judgment of distances and gauging of movements in the visual field. In flying modern aircraft and spacecraft, near vision is also exceedingly important because it is absolutely necessary to be able to read the instrument panel, radio dials, charts, visual displays, and maps. At night, although one's vision is reduced, one must still rely on vision to safely fly the aircraft.

Physical Stimuli

The electromagnetic spectrum extends from the extremely short cosmic rays with wavelengths on the order of 10^{-16} m to the long radiowaves several kilometers in length (Figure 14-6). The part of the spectrum that stimulates the retina is known as *visible light* and extends from 380 nm (violet) to approximately 760 nm (red). A nanometer is a millionth of a millimeter, or 1×10^{-9} m. Adjacent portions of the spectrum, although not visible, affect the eye and are, therefore, of interest. Wavelengths of 380 nm and shorter, down to 180 nm, are known as *ultraviolet* or *abiotic rays.* Exposure of the eyes to this portion of the electromagnetic spectrum produces ocular tissue damage; the severity of the damage depends on the intensity and duration of exposure. Wavelengths longer than 760 nm, up to the microwaves, are known as *infrared* (IR) or *heat rays.* These rays, too, may cause ocular tissue damage, depending on the intensity and exposure time. The light intensity in extraterrestrial space above 30,000 m is approximately 13,600 footcandle (ft-c). At 3,000 m on a clear day, the light intensity is approximately

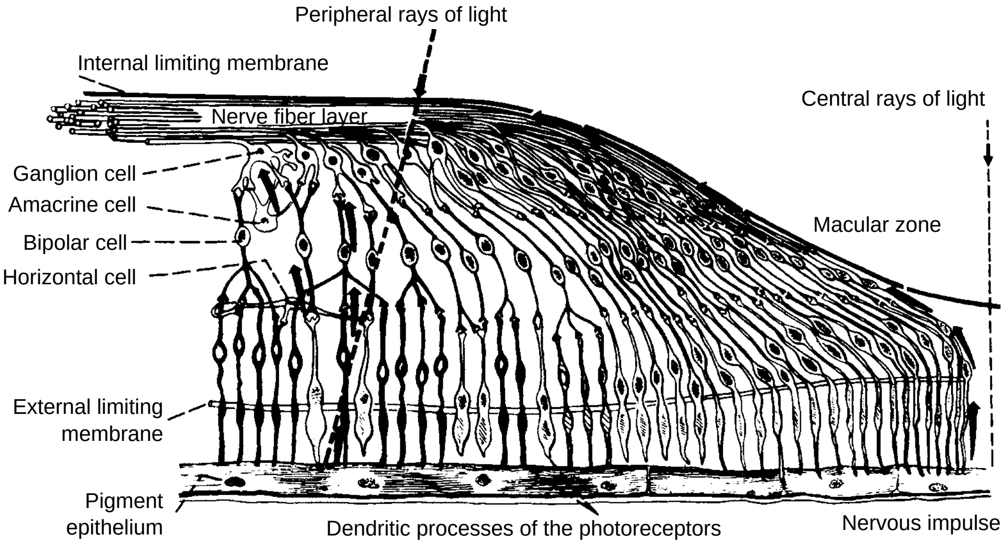
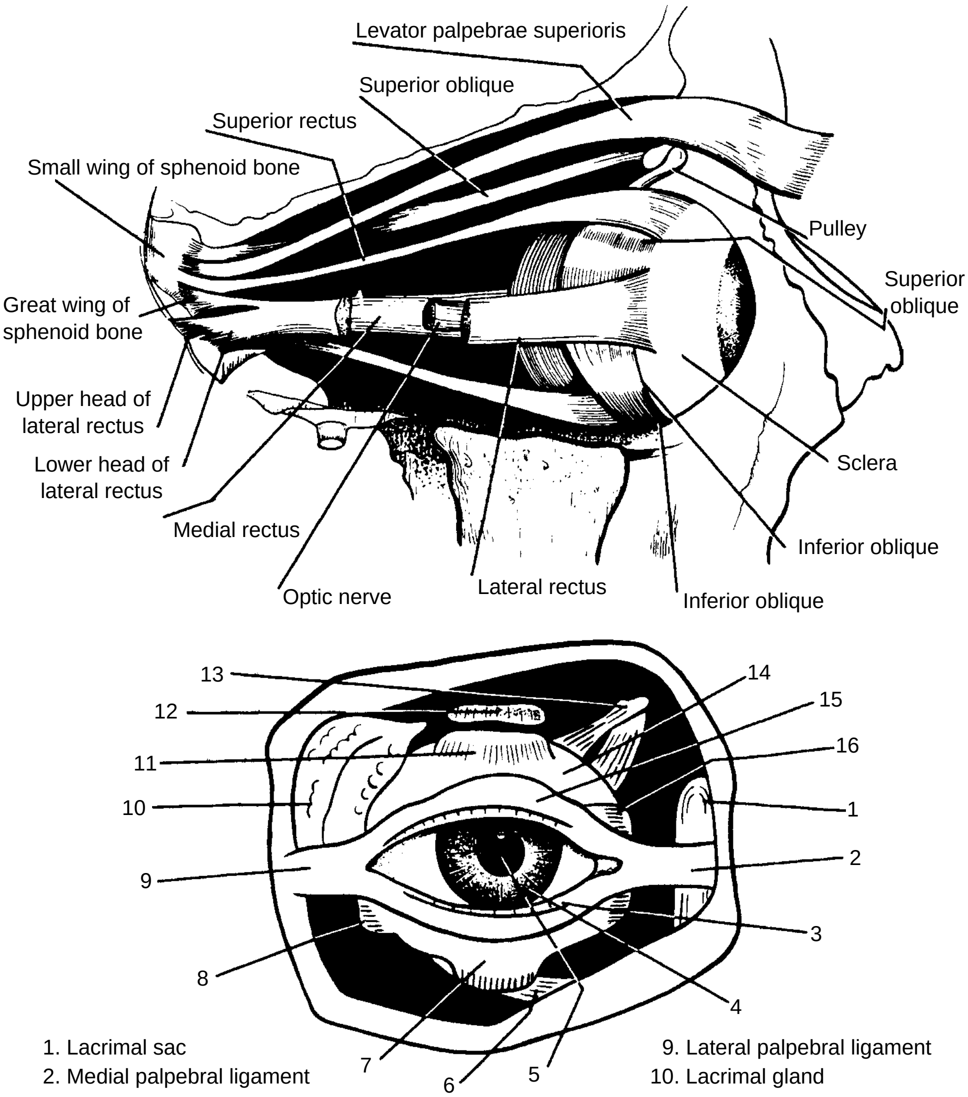


FIGURE 14-3 The retina.



1. Lacrimal sac
2. Medial palpebral ligament
3. Meibomian gland openings
4. Iris
5. Pupil
6. Inferior oblique muscle
7. Inferior rectus muscle
7. Lateral rectus muscle

9. Lateral palpebral ligament
10. Lacrimal gland
11 .Superior rectus muscle
12. Levator superioris muscle
13. Superior oblique muscle
14. Sclera
15. Eyelid
16. Medial rectus muscle

FIGURE 14-5 Ocular adnexa.

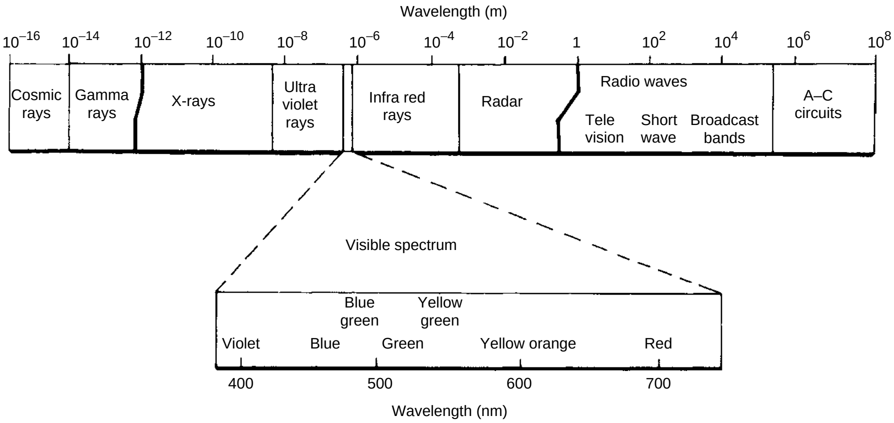


FIGURE 14-6 Electromagnetic spectrum.

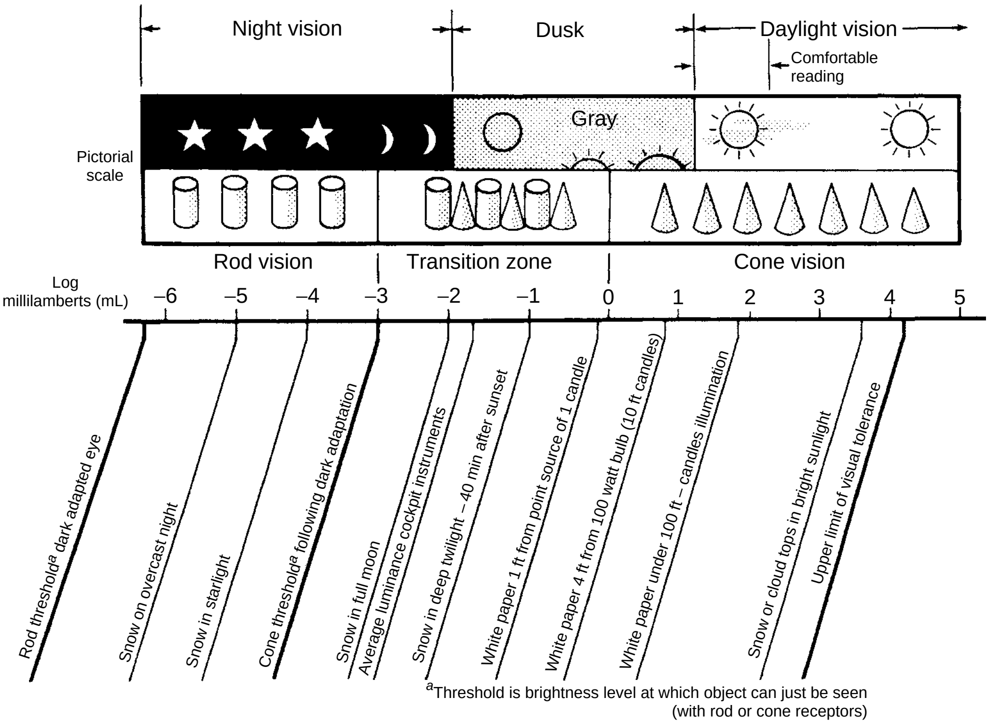


FIGURE 14-7 Luminance under varying conditions of illumination.

12,000 ft-c and approximately 10,000 ft-c at sea level. Water vapor, dust particles, and air in the atmosphere absorb some of the sun's light; in addition, selective absorption occurs. Ultraviolet light shorter than 200 nm is absorbed by dissociated oxygen. Ultraviolet light 200 to 300 nm is absorbed by the ozone layers in the atmosphere; this is fortunate because wavelengths 200 to 300 nm are the most damaging to the eye. These wavelengths produce the actinic keratoconjunctivitis that welders have when they fail to wear protective lenses. These wavelengths of 200 to 300 nm are no problem until an altitude of approximately 40,000 m is reached. This is approximately the height of the second ozone layer. Above this altitude, these ultraviolet wavelengths must be considered. Recent work done in the space program shows that the most abiotic rays have a wavelength of 270 nm (3). They must be filtered by protective visors, or they will severely limit the time that can be spent in extravehicular space activities. The rays that reach the earth, therefore, are 300 to 2,100 nm in wavelength, with an intensity varying between 10,000 ft-c at ground level to approximately 13,000 ft-c at presently attainable altitudes.

Visual Functions

The visual apparatus, stimulated by light, must primarily perform three basic functions. It must be able to perceive an object by the detection of light emitted or reflected from it; this is known as *light discrimination*. Second, it must be able to perceive the details of an object; this is known as *visual acuity*. Third, it must allow one to judge distances from objects and to perceive movement in the field of vision. These latter two functions combined are known as *spatial discrimination*. Obviously, all of these functions are perceived simultaneously; however, in this chapter, they will be discussed separately. Light discrimination consists of brightness sensitivity, which is the ability to detect a dim light; brightness discrimination, which is the ability to detect a change or difference in the brightness of light sources; and color discrimination, which is the ability to detect colors. As noted in Figure 14-7, when the illumination is below a certain intensity, approximately 10^{-6} log mL, the eye does not respond and there is total darkness. As the level of illumination increases, one begins to see shapes and objects; this is rod or scotopic vision. At best, this vision is on the order of 20/200 to 20/400 in scope. As illumination increases, such as with snow in full moonlight of 10^{-2} log mL, the threshold for the cones is reached, and this is known as *mesopic vision*; here, both rods and cones are functioning. A further increase in illumination (such as with white paper under 100 ft-c, equivalent to approximately 10^{2} log mL, causes the cones alone to be functional; this is known as *photopic vision*. The cones are now sensitive to color, and minute details can be appreciated. Increasing the illumination beyond 10^{2} log mL does little to enhance visual efficiency. The upper limit of tolerance for normal vision is 10^{4} to 10^{5} log mL of luminance. This would be equivalent to staring at the sun or at the detonation of a nuclear weapon. The eye can adapt to this tremendous range of illumination because of the dual system of rods and cones in the retina. The rods contain the photosensitive pigment rhodopsin and are sensitive to minute quantities of light energy. They are also sensitive to motion but not to color. The cones contain photosensitive pigments with maximum

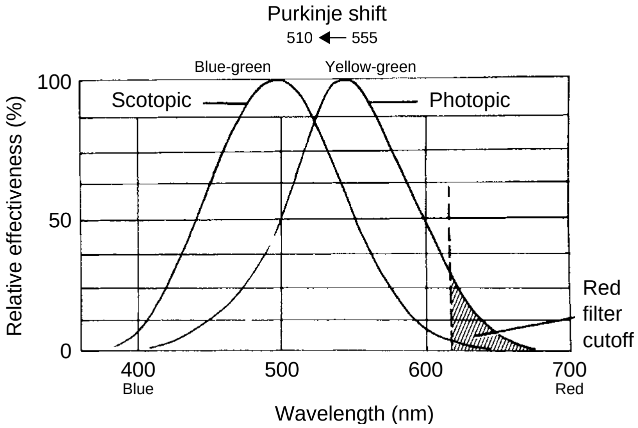


FIGURE 14-8 Luminosity curves for scotopic (rod) and photopic (cone) vision.

absorption at 445 nm (blue), 535 nm (green), and 570 nm (red). The cones must have much more light energy than the rods to be stimulated; however, the cones can perceive fine detail and discriminate colors.

The three psychologic components to color are hue, saturation, and brightness. Hue is the component denoted by naming a color, such as red, yellow, or orange. This is closely related to the wavelength of the light. Saturation refers to adding white light to the pure color so as to decrease the saturation of this color. For instance, a spectral red becomes pink when it is mixed with white light. The hue is still red, but its saturation has now been decreased. Finally, brightness relates to the amount of luminous flux reaching the eye. In essence, a source of high intensity or luminance seems brightly colored, for example, bright red or bright yellow, whereas a source of low intensity or luminance appears dark or dull colored (4).

At night or under low levels of illumination, the fovea, containing all cones, becomes a relative blind spot. Therefore, best vision is attained at night by looking 15 to 20 degrees off-center to utilize the part of the retina containing both cones and rods. As is noted in the dark adaptation curve (Figure 14.11), the cones adapt quickly, taking 6 to 8 minutes; however, the rods are much slower in adapting, requiring another 20 to 30 minutes in the dark. Rods and cones also have different peak sensitivities. The relative luminosity curves of photopic and scotopic vision show that scotopic vision (rod function) peaks at 510 nm, whereas photopic vision (cone function) peaks at 555 nm, as shown in Figure 14-8. The difference in these peak sensitivities is the basis of the Purkinje shift. The luminosity curves also show why red filter goggles with a cutoff at 610 nm allow the cones to receive enough light for the individual to function, while greatly reducing the light to the rods and allowing dark adaptation to take place.

The second of the basic functions, visual acuity, is the ability to see small objects, to distinguish separate details, or to detect changing contours. This is usually measured in terms of the reciprocal of the visual angle subtended by the detail. Central (foveal) visual acuity is high, whereas peripheral visual acuity is poor, less than 20/200. The retinal distribution pattern of rods and cones causes this difference in visual acuity, as shown in Figure 14-9. The cones are dense in the foveal and macular areas and even have a 1:1 nerve fiber-to-brain relationship in the fovea, whereas images outside of the macular area lose detail, becoming worse in the peripheral retina. In certain areas of the peripheral retina, many hundreds of rods may be connected to a single nerve fiber. This is an excellent system for picking up a minimum of light energy or detecting motion but poor for perceiving detail. Visual acuity is influenced by the refractive state of the eye. Visual acuity can be separated into four basic types: minimum visible, which is the ability to see a point source of light, with intensity determining whether it can be seen or not; minimum perceptible, which is the ability to see small objects against a plain background, where size (the angle subtended) and contrast become the determining factors; minimum separable, which

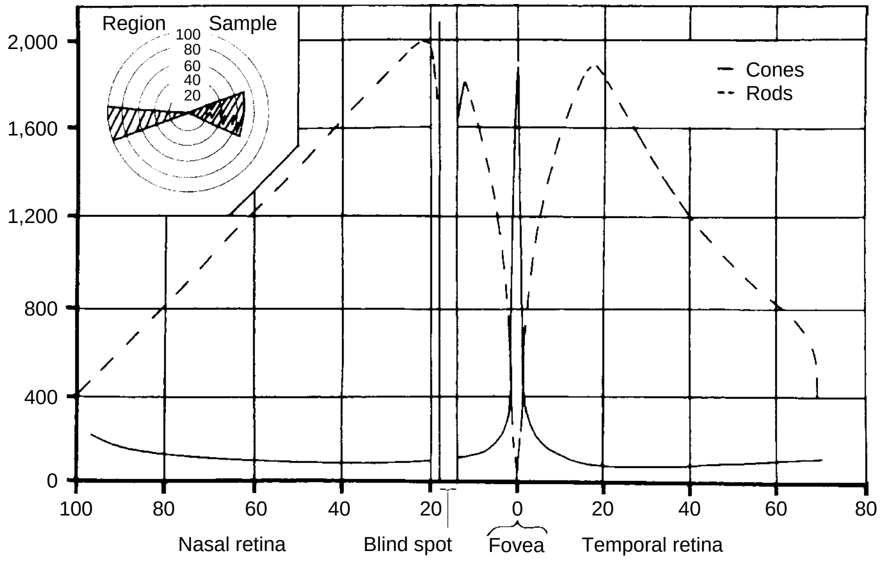


FIGURE 14-9 Rod and cone density in the retina. (Adapted from Chapanis RN. *Vision in military aviation.* Technical Report 58–399. Wright Field: Wright Aeronautical Development Center, 1958.)

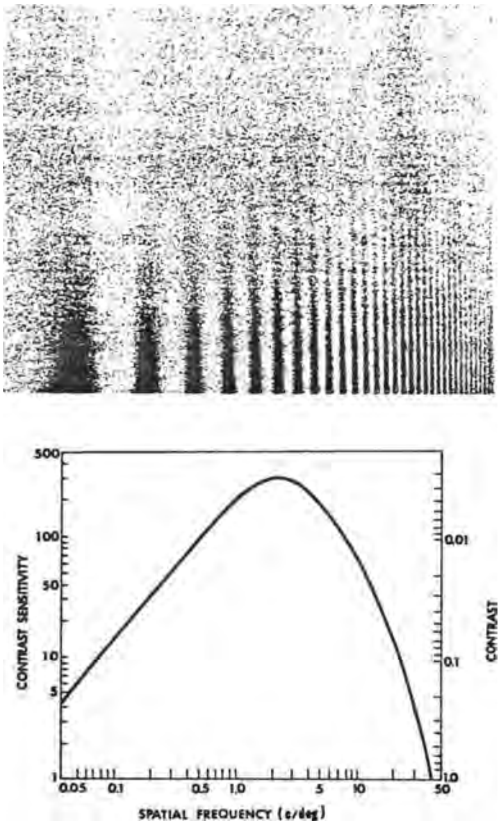


FIGURE 14-10 Contrast-sensitivity function. Upper half of figure: viewing, the sine gratings shows the effect of contrast and spatial frequency on visual resolution. Lower half of figure: normal contrast-sensitivity curve.

is the ability to see objects as separate when close together (also known as *two-point discrimination*); and minimum distinguishable, which is the form sense, usually measured on the Landolt C or Snellen charts and resolving 1 minute of arc break in the C or thickness in letters at 20/20 visual acuity.

Another form of testing visual resolving power is by the use of contrast sensitivity and gratings (Figure 14-10). The most useful form for visual testing is the sine form. The use of this sinusoidal form allows the ready application of a powerful mathematical tool, the Fourier transform. A sine grating of 30 cycles/degree visual angle may be compared with 1 minute of visual angle or 20/20 Snellen equivalent. A contrast sensitivity plot shows that the human visual system is most sensitive in the area of 2 to 4 cycles/degree (5). This method of testing may show reduced contrast sensitivity in conditions such as amblyopia, multiple sclerosis, optic neuritis, cataract, and possibly glaucoma.

Presently, this testing procedure has more value in the examination and evaluation of aircrew with ocular disease, unexplained visual loss, and research purposes (6).

The third important visual function necessary for aerospace flight is depth perception. This is the judging of distance and the perception of motion in the visual field. Distance judgment, or depth perception, is the ability to judge absolute distance or, more commonly, the relative distance of two or more objects. It is aided by conscious and subconscious cues learned from experience, such as aerial perspective, relative motion, relative size, distribution of light and shadow, overlapping contours, and, perhaps the most important of these monocular factors, motion parallax.

The binocular factors of convergence and stereopsis are also involved in this process. Stereopsis, resulting from the disparity of images on the retina of the two eyes, is the most important factor in judging the distance of near objects. In flying aircraft, however, maximum practical limit of stereopsis is believed to be only 200 m (600 ft).

Vision is a complex physiologic and psychological process that necessitates a decoding or interpretation of signals coming from the sensor (the eye) to the brain. Environmental stresses may disrupt the delicate physiologic balance necessary for maintaining clear vision and are discussed in ensuing sections.

VISION IN THE AEROSPACE ENVIRONMENT

The aviator and astronaut function in a hostile environment. In this section, the effects of this environment on the eye and vision are discussed. Some of the factors affecting vision include hypoxia, decompression, glare, high-speed acceleration, and, if one were to proceed into space, excessive electromagnetic energy, zero gravity, and other factors. All of these factors can degrade vision and, therefore, one's ability to perform duties at the most effective level possible.

Environment and the Eye

Hypoxia

Vision is the first of the special senses to be altered by a lack of oxygen, as evidenced by diminished night vision. The extraocular muscles become weakened and incoordinated and the range of accommodation is decreased, causing blurring of near vision and difficulty in carrying out near visual tasks. From sea level to 3,000 m is known as the *indifferent zone* because ordinary daytime vision is unaffected up to this altitude; however, slight impairment of night vision occurs such that all combat crews flying at night should use oxygen equipment from the ground up. From 3,000 to 5,000 m is the zone of adaptation. Some impairment of visual function occurs; however, this impairment can be overcome sufficiently for duties to be performed. At this altitude, retinal vessels become darker and cyanotic, arterioles show a compensatory increase of 10% to 20% in diameter, retinal blood volume increases up to four times, retinal arteriolar pressure, along with systemic blood pressure, increases slightly, the pupil constricts, and, at 5,000 m, a loss of approximately 40% in night vision occurs. Accommodation and convergence decrease, and one's ability to overcome heterophorias decreases. All of these changes can return to normal when the flyer returns to ground level or uses oxygen. Physiologic compensatory reactions enable flyers to perform normal tasks unless they remain at this altitude for long periods without oxygen. The zone of inadequate compensation is 5,000 to 8,000 m, so-called because the physiologic processes can no longer compensate for the lack of oxygen. The visual disturbance described above becomes more severe, with reaction time and response to visual stimuli becoming sluggish. Heterophorias can no longer be compensated for and become heterotropias with double vision. Accommodation and convergence are so weakened as to cause blurred vision and diplopia. Night vision is most seriously impaired. Once again, if one were not subjected to too long a stay at this altitude, all changes would be reversed by the use of oxygen or a return to sea level. Above 8,000 m is the zone of decompensation, or lethal altitude. Circulatory collapse occurs, with loss of vision and consciousness, and permanent damage to the retina and/or brain may result from the lack of circulation and hypoxia. Commercial aircraft and other aircraft with pressurized cabins maintain cabin-equivalent pressures of lower or equal to 2,500 m pressure altitude. None of the aforementioned visual effects is felt at this altitude except for an almost immeasurable effect on night vision. For smokers, the altitude zones can be considerably lower due to the effects of carbon monoxide (7).

Reduced Barometric Pressure

Decompression sickness is a disturbance that affects the flyer as a result of reduced barometric pressure. Infrequently with decompression sickness, a transitory visual defect consisting of homonymous scotoma or even hemianopia may occur, followed by headache that closely resembles migraine. Even more rarely, the aviator may be afflicted by transitory hemiplegia, monoplegia, aphasia, and disorientation. In rare cases, permanent visual impairment occurs. See Chapter 3 for further detail and discussion of decompression sickness.

Visual Environment

The aviator's visual environment is constantly changing. One travels from night to day, from sunlight to shadow, from well-structured scenes to empty visual fields. Fortunately, the eye is quite adaptable, functioning in light levels from 1×10^{-6} log mL to 1×10^{5} log mL. For example, the brightness of the full sun on a cloud is approximately 6×10^{3} log mL, snow in full moonlight is 1×10^{-2} log mL, and snow in starlight is 1×10^{-4} log mL. As higher altitudes are attained, the sky darkens, being lighter at the horizon and darker at the zenith. This reverses what is considered normal light distribution, creating a bright view below and darkness above. At high altitudes, less haze is evident and the sun's rays are much more intense, so that 13,600 ft-c of illumination occurs at 30,000 m. A higher proportion of ultraviolet rays are also found at this altitude. For each kilometer (3,300 ft) increase in altitude, ultraviolet radiation increases by approximately 6%. Glass sunglass lenses decrease the intensity of light and protect against ultraviolet radiation as well. Plastic spectacle lenses must have attenuators in the plastic to filter out ultraviolet radiation. Newer materials, however, such as polycarbonate, being used in the windscreens of modern aircraft substantially reduce the amount of ultraviolet radiation that enters the cockpit. This material cuts off most of the ultraviolet light below 380 nm. The aviator's vision is also affected by the lack of detail in the sky at altitude. This empty field, or space myopia, causes a decrement in his visual capabilities. Finally, changes occur in the appearance of sunlight and areas of shadow. Areas in shadow are illuminated by scattered light, but less light scatter and brighter sunlight occur at high altitude, so that the contrast between the sunlit and shadowed areas increases.

Visibility

Much of modern flying is done in the cockpit. This necessitates good near vision and is dependent on having an adequate amount of visual accommodation. In spite of instruments and radar scopes, one must still see outside the cockpit to land and take off, fly formation, navigate, and, especially, watch for other aircraft. Multiple related factors allow the aviator to see objects in the environment (1): the size of the target, which is relative to its distance (2); the luminance or overall brightness (3); the degree of retinal adaptation (4); the brightness and color contrast between the target and background (5); the position of the target in the visual field (6); the focus of the eye (7); the length of time the object is seen; and (8) atmospheric attenuation.

The visibility of an object depends mostly on its size and contrast with the background. In daylight, with the best of contrast (a black object on a white background), an object would be seen at near the threshold of visual acuity, subtending 0.5 minute of arc, or the equivalent of 20/10 (Snellen) vision. A speck of light against a black background, such as a star, can be seen even when it is much smaller and obviously at enormous distances; however, this example is not a function of visual acuity but only of light perception. A star appears bigger because it is brighter not because it subtends a larger visual angle. The visibility of objects is lost as the contrast is reduced between the object and its background. In such a case, the object, now with lower contrast, must be much larger or nearer before it can be seen. In conditions of haze or mist, such a marked loss of contrast exists that even a large object may not be seen at all. Testing techniques, such as contrast sensitivity function tests, hold promise for the identification of individuals whose systems function more effectively at lower contrast thresholds. The visibility factors outlined in the preceding text are, to a certain extent, interrelated, so that a reduction in one may be compensated for by an increase in one of the others. For instance, an object may be so small or so far away that it is just below the threshold of visibility. It may be made visible by an increased illumination or by improving the contrast between it and its background or both. In other instances, the object may be better perceived when more time is spent viewing it.

Targets in the periphery of the visual field must be proportionally larger to be seen. To get maximum visibility, the target will have to be seen within 1 degree of fixation (fovea). When the object in the peripheral field is moving, it is easier to detect.

One final factor capable of degrading target acquisition is empty field or space myopia. Older theories explained that the resting state of the eye was one of zero accommodation. More sophisticated testing techniques (laser optometer) show that in some individuals, the resting state of the eye is actually one in which a small amount of accommodation is exerted, thereby defocusing the eye for distance vision. In the so-called resting states, these individuals have 0.75 to 1.00 D of myopia thereby degrading their distance visual acuity because their resting focus is 1 to 1.5 m distant from the eye. This is said to occur in both emmetropic and myopic individuals. Moderately farsighted individuals (hypermetropes), however, may find that this accommodative tonus is actually advantageous and that their distance vision perhaps may be enhanced. In bright daylight, the small pupil produced compensates somewhat for the space myopia by increasing the depth of field; however, a better method of overcoming this induced myopia is to fix on a distant object. Actually, anything more distant than 15 to 18 m helps to relax the accommodation sufficiently to improve the distance visual acuity. Night myopia, which is similar to empty field and space myopia, is discussed in the following section on night vision.

Night (Scotopic) Vision

Night vision is extremely important in aviation. It is quite different from day (photopic) vision. The eyes must be used differently at night for the aviator to gain maximum usefulness of vision. The aviator must understand the principles of night vision and must practice using the eyes at night to gain efficient vision at night.

Not all parts of the retina are alike in their reaction to light. A small, central area containing only cones is responsible for maximum visual acuity and for color discrimination, but it fails to operate under low intensities of illumination. This is the fovea, the area with which one reads and where one focuses objects in the direct line of vision. It gives us central vision, which is useful in high and moderate illumination (photopic and mesopic conditions).

In the remaining peripheral area, both the rod-type and cone-type receptors are present. The peripheral retina is capable of less acute visual perception and of only poor color determination, but it functions under low illumination or scotopic conditions. According to the widely accepted duplicity theory of vision, the human eye is an eye within an eye. Central vision requires light of approximately 1×10^{-3} log mL intensity or greater. Bright moonlight gives approximately 1×10^{-2} log mL. Hence, in light that is less intense than moonlight, little central vision is evident. Peripheral vision requires only one-thousandth as great an intensity 1×10^{-6} log mL or more. On a dark, starlit night, the individual sees only with the peripheral area of the retina. This explains why pilots often complain that they are able to see an aircraft at night only to have it disappear when they look directly at it. To keep an object in sight at night, one must learn to look off to the side at approximately a 15- to 20-degree angle. When the light intensity is between 1×10^{-3} and 1×10 degrees log mL, both the rods and cones are functioning, and mesopic vision occurs (Figure 14-7).

Individuals can determine which type of vision they are using by noting whether they have color sense. The cones perceive all colors. Rods pick up colors only as shades of gray. Most of the cones are in the central area of the retina, so that if colors were recognized at night, one would have central vision; however, if everything were to appear in shades of gray, one would only have peripheral or rod vision.

Dark adaptation is the process by which the eye adjusts for maximum efficiency in low illumination. It is commonly experienced when one first enters a theater or walks into darkness from a brightly lit room. The central area of the retina dark-adapts in approximately 6 to 8 minutes, but this part of the retina is useless for night vision. The peripheral area dark-adapts in approximately 20 to 30 minutes, although further slight adaptation continues over a period of 2 days (Figure 14-11). This peripheral area is not sensitive to dark-red light (630 nm or longer in wavelength). Such light is not perceived even as gray, so dark adaptation occurs in the periphery in dark-red light as though no light existed. This characteristic is fortunate because, by wearing red, light-tight goggles before a flight, pilots can read or rest in a brightly lit room while the peripheral areas of their retinas are dark-adapting.

Dark adaptation is an independent process in each eye. It is slow to develop in the dark and is quickly lost in the light. The aircrew must be so familiar with the location of their equipment and controls that lights are unnecessary for making adjustments in flight. The aviator should avoid gazing at exhaust stacks or any other bright light sources. When using light at night in the plane, such as in reading instruments, maps, or charts, as little light as possible should be employed and for as brief a time as possible, and red light should be used; however, red lighting does create problems, such as accommodative fatigue and reduction of color perception. Therefore, red light is no longer favored for cockpit visual activities. When an individual who is exposed to bright light closes one eye, the closed eye remains dark-adapted, although the exposed retina of the open eye has been bleached.

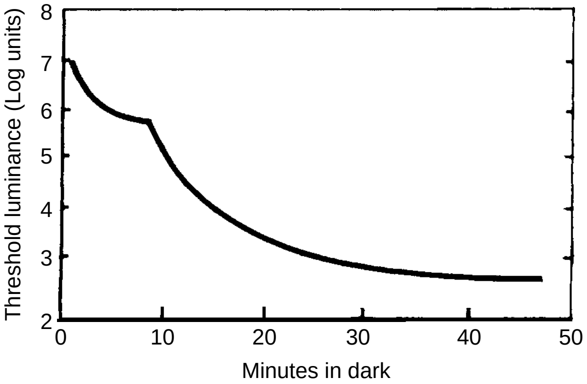


FIGURE 14-11 Dark-adaptation curve.

Dark adaptation also depends on an adequate supply of vitamin A in the diet. Vitamin A is found in vegetables that are green or were green at some stage of development, such as lettuce, carrots, cabbage, peaches, tomatoes, green peas, and bananas. Other sources of vitamin A include milk, eggs, butter, cheese, and liver. A deficient diet or an illness that decreases the vitamin A supply impairs night vision and a return to normal vision may take several months, even when large doses of vitamin A are ingested. Excessive vitamin A ingestion, such as taking in large doses of vitamin capsules, is worthless to a normal person. Various drugs have also been studied and have not been found to improve a normal person's dark adaptation.

Without supplemental oxygen, the average percentage decrease in night vision capability is 5% at 1,100 m altitude, 18% at 2,800 m, 35% at 4,000 m, and a 50% decrease in night vision capability at 5,000 m altitude. Lack of oxygen, fatigue, and excessive smoking all reduce the ability to see well at night. For military flying, oxygen should be used from the time of takeoff for maximum visual acuity. Fatigue should be prevented, insofar as possible, by obtaining adequate sleep before flying. Hypoxia resulting from carbon monoxide poisoning affects brightness discrimination and dark adaptation in the same way as altitude-induced hypoxia. As an example, 5% saturation with carbon monoxide has the same effect as flying at 3,000 m without oxygen. Smoking three cigarettes before a flight may cause a carbon monoxide saturation of 4%, with an effect on visual sensitivity equal to an altitude of 2,800 m or a 15% to 18% decrease in night vision.

During World War II, much work was done on the use of red cockpit illumination. The use of a red light having a wavelength greater than 630 nm illuminating the cockpit is desirable from the viewpoint of dark adaptation. The intent was to retain the greatest rod sensitivity possible while permitting an effective illumination for foveal vision; however, with the increasing use of electronic devices for navigation, the importance of the pilot's visual efficiency inside the cockpit has increased markedly. Therefore, low-intensity white cockpit lighting is presently advocated because it affords a more natural visual environment within the aircraft without degrading the color of objects that are not self-luminous. The disadvantage of the previously used red lighting caused red markings on aerial maps to be invisible when viewed in this light. Red light also tends to create or worsen near-point blur in prepresbyopic, presbyopic, and, at times, hypermetropic pilots. Because of the chromatic aberration of the eye, humans are hypermetropic for red (8).

Ultraviolet light has been used for cockpit illumination and has a disconcerting side effect if it were to become reflected directly into the eye. These radiations produce a fluorescence of the crystalline lens in the eye, giving the pilot a sensation that he is flying in a fog. Properly adjusting the ultraviolet lamps and reducing their intensity can overcome this fluorescence problem to some degree. Radiations from these lamps are not injurious to the eyes because, even at highest intensity, they are still far below the threshold for affecting the corneal epithelium.

During World War II, the problem of night vision was studied intensively by numerous scientists, but no single, satisfactory test of night vision was developed. The United States Air Force (USAF) did develop the radium plaque night-vision tester, which is a self-illuminating Landolt C target; however, because it contains radium, it is rarely used now (9).

At present, the best test of night vision is the Goldmann-Weekers Dark Adaptometer. This instrument is capable of determining the dark-adaptation curve of an individual with great detail and accuracy. It is obviously not something that should be done on everyone because it is time-consuming, the apparatus is expensive, and is available only in research institutions and larger clinics. With this instrument, one can establish the threshold of night vision in an individual. The testing results in the familiar dark-adaptation curve (Figure 14-11).

NIGHT-VISION GOGGLES

Modern technology has also introduced night-vision goggles (NVGs), which enhance vision at night over and above that possible by the naked eye (Figure 14-12). Currently available NVGs can intensify ambient light to approximately 1,000 times (×1,000). Several electro-optical devices are available to improve vision at night, including NVG and forward-looking infrared (FLIR) systems. Most NVG systems are helmet mounted and look like binoculars. To make objects and landscape visible at night, NVGs usually employ two image-intensifier tubes to amplify or intensify low levels of reflected and emitted ambient light. Image-intensifier tubes are sensitive to some visible and short-wave IR radiation, but a minimum amount of ambient light is needed to excite the green phosphor screen and produce visible images.

The NVG-intensified image resembles a black and white television image except that it is in shades of green instead of in shades of gray, due to the selected display phosphor.

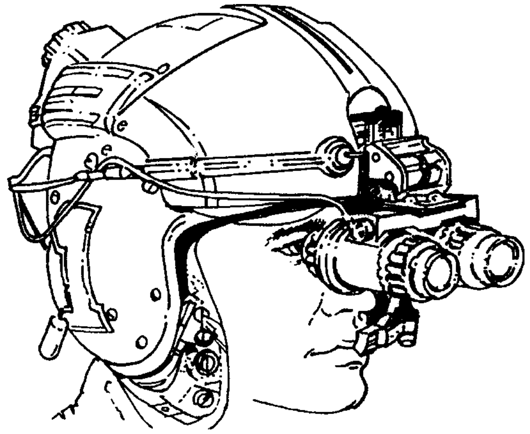


FIGURE 14-12 Anvis (III-Gen) Night-vision goggle.

The image that is seen by the aircrew member is not a direct view, but an image displayed on a phosphor screen. The NVG system is analogous to using a microphone, amplifier, and speaker to amplify a faint sound and make it audible. In both cases, some of the "natural fidelity" may be lost in the amplification process.

NVGs enhance night vision over unaided scotopic vision; however, they do have significant limitations. The performance limitations include visual acuity of approximately 20/40 at best, a field of view of 40 degrees or less, degraded depth perception, little or no stereopsis, and a different spectral sensitivity than the human eye. Therefore, training and experience with NVGs is critically important for flying safety.

A FLIR device consists of a cockpit-or helmet-mounted video monitor that displays picture from an internal IR sensor that is usually fixed forward (i.e., slaved to the nose of the airplane). These sensors are sensitive to the long wavelength IR (thermal) and provide excellent resolution. IR sensors can detect radiation in either the 3,000 to 5,000 nm or the 8,000 to 12,000 nm spectral range. A FLIR must have thermal radiation available, but many objects radiate measurable amounts of IR energy in the spectral range.

Electro-optical Design

A brief description of the operating principles of NVGs will make it easier to understand their workings and limitations. Ambient light entering the intensifier tubes is focused by an objective lens onto a photocathode. The schematic diagram of an intensifier tube is presented in Figure 14-13. When photons of ambient light strike the photocathode, which is sensitive to visible and near-IR radiation, electrons are released, creating a cascading effect. The number of electrons released from the photocathode is proportional to the number of photons striking it. The electrons are then accelerated and multiplied by a microchannel plate, which acts like a large array of photomicromultiplier tubes. The microchannel plate, approximately the size of a nickel, guides the accelerated electrons to a phosphor screen that produces an intensified light image. The light amplification is referred to as the *gain of the device*. The gain is the ratio of the light delivered to the eye by the phosphor screen to the light striking the objective lens. Modern NVGs have a gain of 400 to 1,000.

NVGs do *not* turn night into day. Although pilots are usually impressed the first time they look through NVGs, many complaints occur the first time they fly with them. Although it is true that visual function with NVGs is impressively enhanced over scotopic function in many ways, NVG performance is inferior compared to normal photopic function. The degradation in visual performance that NVGs impose must be emphasized to aircrew.

Much more detailed information on NVGs, operational issues, environmental considerations, and fitting techniques is explained in the publication, *Night Vision Manual for the Flight Surgeon* by Miller and Tredici (10).

SPATIAL DISCRIMINATION, STEREOPSIS, AND DEPTH PERCEPTION

In aviation, it is important to accurately localize in three-dimensional space. When this cannot be done, one becomes spatially disoriented, which is a marked hazard to the flyer. Under $+1\ G_z$ acceleration, one orients to the earth by proprioceptive impulses from various parts of the body, from receptors in the semicircular canals and vestibular apparatus, and with the strongest cue to orientation, the visual system. Linear and angular accelerations are capable of producing spatial disorientation, especially when outside visual reference is excluded; however, when adequate external visual references are available, spatial disorientation usually does not occur. The pilot's ability to resist spatial disorientation, then, is greatly enhanced by adequate visual references and is diminished by mental stress. The visual cues to the perception of depth are both monocular and binocular. The monocular cues are learned, and some investigators believe that they can be improved by study and training. These cues, however, are the ones that can be the most easily tricked by illusions. Conversely, stereopsis, which is the most important binocular cue, is innate and inescapable. When flyers have this capability, it remains with them, even when the learned

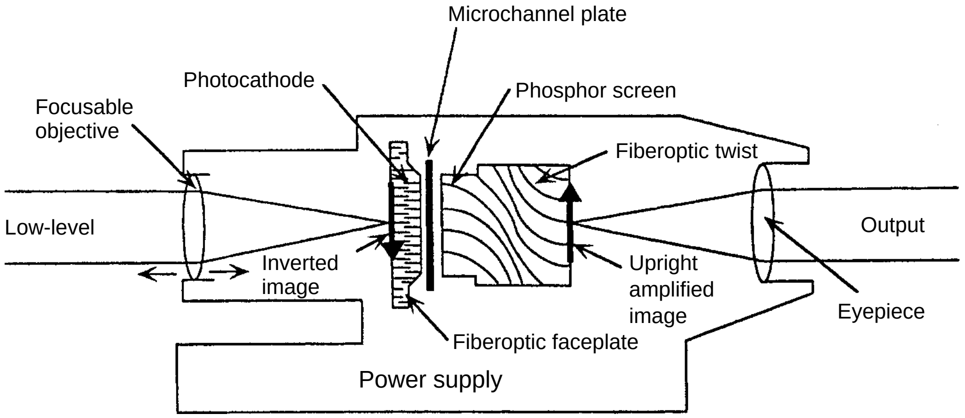


FIGURE 14-13 Photocathode tube schematic.

cues are sparse, such as at night, under conditions of low visibility, and in unfamiliar surroundings. Unfortunately for flyers, however, the maximum range at which their stereoscopic vision is useful is only up to 200 m. This is not to imply that stereopsis is required in flying an aircraft because numerous individuals who lack stereopsis still make good aviators; however, when the pilot does have stereopsis, so much the better. Therefore, stereoscopic testing procedures should be retained in the flight examination. The stereoscopic test for flying is probably the single most revealing component of the visual examination. Individuals who pass the stereoscopic test down to 15 to 20 seconds of arc must, of necessity, have well-functioning visual systems. They must have two eyes that are equally balanced: visual acuities must be excellent to attain this kind of arc disparity, they must have normal retinal correspondence, and their motility status must be functioning normally in at least the straight-ahead position. In essence, even if stereopsis had nothing to do with flying, retaining the stereopsis portion of the ophthalmologic examination is wise.

Depth Perception (Spatial Localization)

Depth perception is the mental projection onto visual space of a perceived object in real space. Correlation of the real object in real space with that projected in visual space results in accurate depth perception. Both monocular and binocular cues to depth perception exist.

The monocular cues are as follows:

1. Size of the retinal image (size constancy)—being able to judge the known and comparative size of objects is an important cue
2. Motion parallax—the relative speed of motion of images across the retina; objects nearer than fixation move against the observer's motion, distant objects move in the same direction as the observer's motion
3. Interposition—one object obscured from vision by another
4. Texture or gradient—detail loss at increasing distances
5. Linear perspective—parallel lines converging at distance
6. Apparent foreshortening—for example, a circle appears as an ellipse at an angle
7. Illumination perspective—light sources are usually assumed to be from above
8. Aerial perspective—distant objects appear more bluish and hazy than do near objects

The binocular cues are as follows:

1. Convergence—the value of this cue is questionable and is generally used only for near distances
2. Accommodation—also useful only for near distances
3. Stereopsis—this is the visual appreciation of three dimensions during binocular vision, occurring during fusion of signals from slightly disparate retinal points, which are disparate enough to stimulate stereopsis but not so disparate as to cause diplopia

The two most important monocular factors for flying are considered to be motion parallax and size of the retinal images. All monocular cues are derived from experience and are subject to interpretation. Stereopsis is believed to be the most important binocular cue and is based on a physiologic process that is innate and inescapable. Like visual acuity, stereopsis can be graded and is known as *stereo acuity*, which is measured in seconds of arc of disparity. Owing to the limiting factors such as the interpupillary distance, stereopsis is not reliable beyond 200 m (600 ft) (11).

Stereopsis (one element in the perception of depth) is measured by several different instruments. One can measure stereopsis for near distances, on the Verhoeff depth-perception apparatus, where stereo acuity is measured at 1 m without special optical devices. Stereopsis for near distances also can be measured by the Wirt (Titmus) circles. In this case, the eyes are dissociated with polarizing lenses. Stereoscopic vision for distance is measured in testing devices, such as the Bausch and Lomb Ortho-Rater, Titmus, Keystone, or Optec instruments. Using these instruments, separate images are presented to each eye, and lenses in the instruments project the images to infinity. In essence, these are tests of stereoscopic vision for distance, and many examiners are not aware that in some motility disturbances, such as microstrabismus, the candidate may have normal stereoscopic vision (depth perception) for near but not for distance or vice versa.

COLOR VISION

Aeromedical experts and flyers have emphasized the importance of normal color vision since World War I. In 1920, Drs. William H. Wilmer and Conrad Berens noted in their article, *The Eye in Aviation*, that the proper recognition of colors played an important part in the success of aviators (1). In modern aviation, both civil and military, color discrimination requirements have not diminished, but rather have expanded dramatically. For instance, aviators and aircrew must be able to identify assorted colored light signals and navigation lights, as well as the colors of various reflecting surfaces such as ground targets, flags, smoke, and flares. It is important to be able to identify colors used on maps and charts even in less than optimal lighting and, especially in the military, for ascertaining subtle color differences in targets and terrain. Modern aircraft now incorporate full spectral color in electronic flight information systems (EFIS) designed to speed up flight information to aircrew primarily because color increases efficiency without demanding further conscious effort. Under certain conditions, such as bright daylight, the color contrast of these displays decreases. With hypoxia and impoverished visual conditions, such as fog, smoke, haze, or in dim light, color perception degrades, with color defectives disproportionately degrading compared to normals under decreasing illumination, hypoxia, and fatigue (12–19). Chronic hypoxia at cabin altitudes between 8,000 to 10,000 ft above ground level (AGL), where supplemental oxygen has traditionally not been supplied, has emerged as an issue of concern, particularly in military operations. All of these factors place additional emphasis on an aviator having normal color vision than in the past.

Color vision deficiencies can be congenital, acquired, or induced artificially. Congenital color deficiencies are almost always red/green and are much more common in males, whereas blue/yellow defects affect both sexes equally and are rarely congenital, rather a result of ocular disease or toxicity. Congenital red/green defects are inherited as a sex-linked recessive trait. Approximately 10% of all males versus 0.5% of females are congenitally red/green color defective (20,21). Unlike sex-linked red/green color vision deficiencies, congenital blue/yellow defects are extremely rare, occurring equally in 0.001% to 0.007% of males and females (22,23). Acquired defects typically first present as blue/yellow deficiencies and are estimated to be present in 5% to 15% of the general population (24–28). As a result, identification of true color normalcy requires testing for red/green and blue/yellow defects, both congenital and acquired.

How much color deficiency is required for safe and effective flying remains under heavy debate, particularly in civil aviation. In July 2002, the National Transportation and Safety Board (NTSB) identified defective color vision as a contributing factor in the crash of a commercial aircraft in Tallahassee, Florida (29). As a consequence of that mishap, the NTSB recommended that the Federal Aviation Administration (FAA) reevaluate existing color vision requirements and adopt more effective testing methodologies. Consequently, there is no question that this accident and the proliferation of color in the modern cockpit mandates a fresh look at this relationship. For example, color defectives make more mistakes, take more time, and need to be closer to color-based targets when compared to color normals.

For most purposes, individuals with normal color vision can be effectively screened using pseudoisochromatic plates (PIPs). Few color normals will fail properly administrated PIP tests, whereas color abnormals will have great difficulty scoring like a normal, unless they have learned techniques to defeat these tests. In many cases, however, subjects with mild color vision deficits perform as poorly as those with deficiencies that are more significant. Lanterns, long used as secondary occupational tests since the 1800s, have fallen out of favor because of relative unavailability, lack of operational relevance in the modern environment, and other technical problems. For example, the color threshold test (CTT) developed at the Army Air Forces School of Aviation Medicine in World War II permitted mild color defectives to enter aviation training; however, the scores used for the CTT were based on field studies involving the ability to distinguish at the time between colored pyrotechnic flares, the biscuit gun, and wire coding schemes (30–33). It was eventually abandoned once replacement Wratten filters were no longer made. The U.S. Navy developed the Farnsworth lantern, or FALANT, during World War II for naval signalmen (34,35). It was designed to qualify 20% of color defectives, presumably mild defectives believed to be safe in the signal environment at the time, into Navy career fields that required "normal" color vision; however, it no longer remains linked to current operational requirements. Furthermore, recent studies have shown it to pass much more severe defects and its utility to reliably identify color normals for modern applications has been challenged, especially by the NTSB (36–47). Consequently, the USAF no longer uses it for color vision testing. In addition to assorted PIP tests, other tests of color vision such as Farnsworth's Dichotomous Test (Panel D-15) and FM-100 tests have been used for aviation. Many of these are effective in identifying dichromat subjects, but become unreliable in testing less severe color vision defectives. None is as effective as an anomaloscope based on Rayleigh and Moreland metameric equations. Recently devised tests based on spatiotemporal luminance masking, such as the color assessment and diagnosis (CAD) test, or those employing isolated cone-specific contrast principles, such as the cone color test (CCT), may even displace PIPs and anomaloscopes as more convenient and definitive screeners (48–53). Until then, the definitive gold standard color vision test against which all other color vision tests are compared is the anomaloscope (Table 14-1). The North Atlantic Treaty Organization (NATO)'s Working Group 24 (WG 24) recommended that color vision testing for modern aviation should involve an initial PIP test followed by an anomaloscope, if more definitive assessment is required (54). WG 24 also recommended abandoning use of all occupational lantern tests. However, all color vision tests that rely on reflected light, whether PIPs (Ishihara, Dvorine, AO, Hardy-Rand-Rittler, Igaku-Shoin, etc.) or hue discrimination tests (D15, Lanthony, FM100, etc.) must be presented with light of proper Kelvin temperature (Illuminant C). The most commonly used Illuminant C is the MacBeth light, with a temperature of approximately 6,000°K (13). All of these tests must also be properly administered, for example, given monocularly away from other light sources and applicable time limitations.

According to the Young-Helmholtz theory of color vision, three classes of cones are present in the primate retina. These cones absorb light with peak sensitivities of 445 nm (blue), 535 nm (green), and 570 nm (red), as shown in Figure 14-14. Modern terminology refers to them as *short* (S), *middle* (M), and *long* (L) wavelength sensitive cones. Any color of the spectrum may be constituted with varying

TABLE 14-1

Incidence of Color-Vision Deficiency

Males	*Percent*	*Females*	*Percent*
Protanopia	1.0	Protanopia	—
Deuteranopia	1.4	Deuteranopia	0.4
Protanomaly	0.78	Protanomaly	0.4
Deuteranomaly	4.6	Deuteranomaly	—
Total[a]	7.78	Total[a]	0.8

[a] Monochromatism occurs in 1/100,000 individuals.

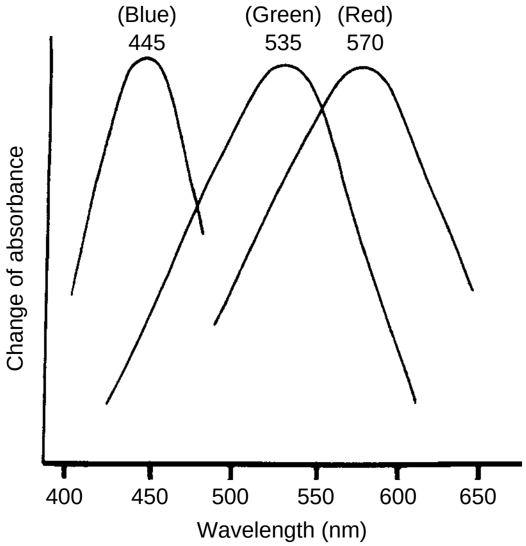


FIGURE 14-14 Cone-photosensitive pigments. Maximum absorption wavelengths.

combinations of these three primary colors, and when all three colors are stimulated, the color perceived is white.

The most severe color deficiency is known as *monochromatism*, a complete absence of color sensation. There are perhaps only 1:100,000 such individuals in the general population, and with central visual acuities in the 20/200 range, would never qualify for aviation. Colorblind individuals with only two cone types are called *dichromats* and constitute 2% of 3% of the males. Dichromatism includes protanopia (no L cones) in 1% of males, whose only color sensations are gray, blue, and yellow and who confuse reds with greens, blue-greens, and browns; deuteranopia (no M cones) also in 1% of males, whose only color sensations are gray, blue, and yellow and who confuses greens with reds, purples and browns; and tritanopia (no S cones) in those who do not see blues and yellows.

The vast majority of individuals with defective-color vision are color weak. These individuals are called *anomalous trichromats*. In red/green anomalous trichromats, the sensitivity curve of either the M or L cone shifts toward the other, resulting in neurologically distorted input and failure to respond to some visible wavelengths seen by color normals. Protanomaly, meaning "red-weak," results from a shift of the L cones and occurs in 1% of males. These individuals miss certain reds and require more red stimulation than normal to make an anomaloscopic color match. Deuteranomaly, meaning "green weak," results from shifted M cones occurring in approximately 5% of males. These individuals need more green stimulation to make anomaloscopic match. Tritanomaly results from shifted S cones and is a condition in which more blue or blue/green stimulation is required to make a color match.

Color vision defects can also be acquired from diseases, drugs, medications, intense lights, trauma, and other conditions that affect retinal cones, optic nerve fibers, and occasionally from direct brain injury. For example, early glaucoma may manifest unilaterally as a blue/yellow deficiency without impacting visual acuity, thereby making monocular color testing mandatory (55–68).

Since World War I, aircrew have been required to have normal color vision. Historical color vision testing strategies reflect red, green, and white signal and navigation light requirements in a male-dominated occupation at the time. Shape and other configurations were employed as secondary cues. Color use in modern displays exploits unique advantages in color normals to expedite information and improve situational awareness. Modern aviation, particularly military and air traffic control environments, increasingly employs multispectral color without noncolor redundancies. Merging input from diverse sensors, so-called sensor fusion and synthetic cockpit recreation of external scenes represents new technologic thrusts that will continue to challenge color perception in the future. Color vision defectives have well-known problems with EFIS displays regardless of degree of deficiency (69–78). Approximately 3% of males with congenital red/green deficiencies can be classified as mild, but regardless of degree, each color defective differs from another. Arguably, therefore, embracing color display designs that all color defectives can also use effectively, including dichromats, will degrade overall system capability by negating the efficiency of color usage.

Filter techniques have been advocated for decades to "cure" color-vision defects. For example, the "X-chrom lens," is a red, 15% to 20% transmitting-filter contact lens that is worn on only one eye. The lens was touted as the device to put individuals with defective color vision into the cockpit. Such lenses create a "new" color world to help defectives avoid their color confusion. However, other parts of that normal world are degraded to achieve this "cure" (79). Further, these lenses invalidate most color vision screening tests, particularly those based on carefully selected color confusion lines used to identify a color abnormal. Newer systems, such as ColorMax and ChromaGen lenses, have similar problems. Regrettably, no selective waveband filter (any colored filter) restores normal color vision to a color vision defective.

AIRCRAFT/ENGINEERING FACTORS

G Force (Gravity)

The visual system is profoundly affected in high-speed flight by acceleration (G forces), vibration, and a normal lag in human visual perception. On Earth, the human body is constantly affected by gravity, and this force is termed 1 G (sustained acceleration induced inertial forces). In flight, the speed, acceleration, and changes in direction can increase the amount and direction of this G force. These G effects are discussed in much more detail in Chapter 4 (Human Response to Acceleration); however, G forces have significant effects on the aviator's vision, and these effects will be discussed here. In flight, the aviator encounters linear acceleration, such as in catapult takeoff, aircraft

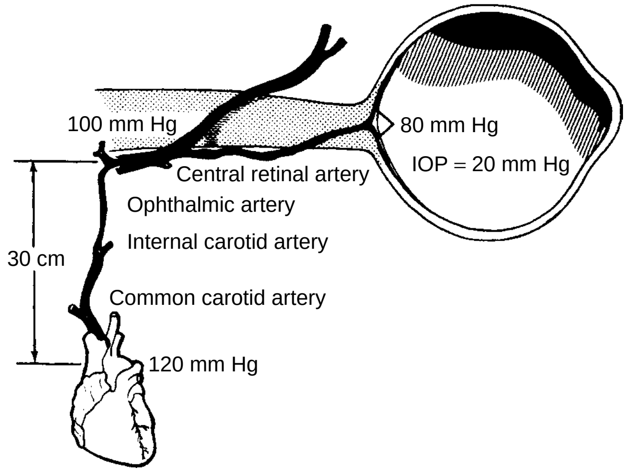


FIGURE 14-15 Normal arterial blood pressures from the heart to the eye.

carrier landings, ditching, and high-speed bailout. Radial acceleration is encountered in banks, turns, and pullouts from dives, loops, and rolls. Angular acceleration occurs in spins, in storms, and in tumbling following bailout from aircraft. It is the $+G_z$ acceleration that mainly concerns pilots, especially those in high-speed aircraft. When $+G_z$ are being pulled, the quantity of blood returning to the heart is diminished. The heart continues to beat, but diminution of the volume of systolic blood reduces the cardiac output, lowers the arterial tension, and causes a decrease in pressure. Figure 14-15 shows that with increasing G forces, a point will be reached when arterial pressure in the ophthalmic artery no longer exceeds intraocular pressure. It is at this point that visual function is definitely impaired and blackout ensues. However, sufficient perfusion pressure exists in the remainder of the central nervous system so that unconsciousness does not occur until the increasing G force further decreases the arterial pressure and the resulting pressure in the central nervous system is zero. On average, the pilot begins to lose peripheral vision at +3.5 to +4.5 G_z. Blackout, or a complete loss of vision, occurs at +4 to +5.5 G_z. Hearing, however, persists and orientation remains. From +4.5 to +6 G_z the pilot may lose consciousness. These are only average values, and they vary depending on the rapidity of onset of the G forces and the physical condition of the aviator. In the recent past, training, certain maneuvers, and protective clothing enabled the aviator to reach +8 to +9 G_z and maintain efficiency for longer periods. These factors entail improving one's physical condition, tensing of muscles, performing maneuvers, such as the M-1, and wearing improved anti-G suits. G-force protection could be further enhanced if reclining, tilting seats were available.

Negative G forces are not often encountered. If these forces were prolonged, however, they would result in congestion of the blood vessels of the upper part of the body, leading to a violent headache. Visually, a so-called red out may occur. The actual cause of this phenomenon is still unknown; it may be due to looking through a congested lower lid, which then acts as a filter. At high speeds, in order to maintain functional vision, one must maintain a radius of turn large enough so as not to cause excessive G loading. Table 14-2 shows the radii of high-speed aircraft turns that produce +6 G forces. For example, at a speed of 3,200 kph, pilots could not make a turn in a circle smaller than 27 km in diameter or they would black out unless performing the aforementioned protective maneuvers and were wearing good anti-G suits. Figure 14-16 shows the effects of acceleration and time on vision.

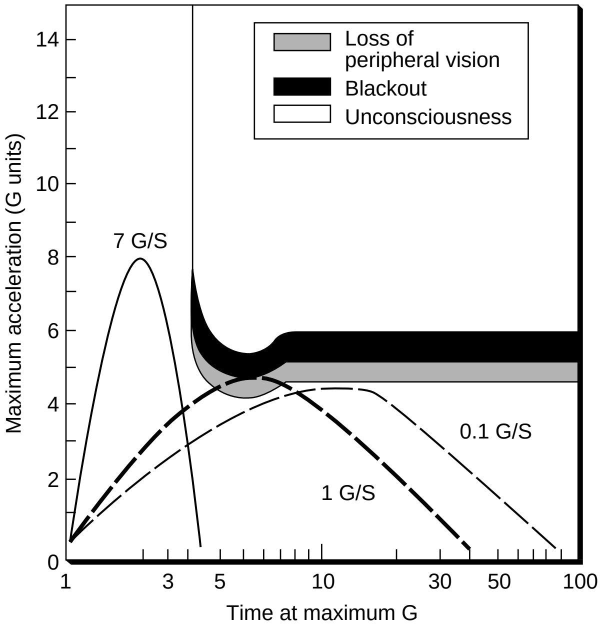
TABLE 14-2

Radii of High-Speed Aircraft Turns Producing +6 G Forces

Kilometers per Hour	*Meters*
400	209
1,200	1,882
1,600	3,395
3,200	13,597

Vibration

Vibration causes blurred vision and therefore reduces the visual efficiency of the aviator. Studies have shown that during vertical sinusoidal vibrations at frequencies above 15 Hz, visual acuity is degraded. Particularly degrading to



Acceleration and time at maximum G required to produce visual symptoms and unconsciousness. Curves showing different rates of G development are given to show the importance of this parameter for the occurrence of peripheral vision and blackout.

FIGURE 14-16 Visual effects produced by various $+G_z$ environments.

vision have been the frequency bands in the ranges of 25 to 40 and 60 to 90 Hz. When vibration cannot be avoided, its effect on visual performance can be reduced somewhat by the proper design of the visual instruments, displays, and printed materials, and an increase in their illumination and contrast.

Lag in Visual Perception

The length of time between an event and when the person sees the event depends on two factors: the length of time required for light to reach the eye and the conduction time in the visual pathways and brain tracts. Because of the speed of light, the interval between the event and the eye is an unimportant factor, but the lag in the visual mechanism is appreciable and, at supersonic speeds, turns out to be an important factor. This is demonstrated in Figure 14-17. Pilots flying at 1,000 kph see aircraft in their peripheral vision; they have traveled 28 m before the images are transmitted from the retina to the brain. They travel 300 m before they consciously recognize it. They travel more than 1 km before they have decided whether to climb, descend, or bank. They travel approximately 1.5 km before they can change their flight path. At 3,000 kph, speeds that can be attained in advanced fighter aircraft, all of these distances are tripled. The times noted here are probably absolute minimums and are not reducible by any mechanical or electronic ingenuity solely because they are unchanging characteristics of the human eye, mind, muscle, and nervous system. Conversely, the distance traveled at each interval will undoubtedly increase as the speed of new-generation aircraft increases. Further, one must also be aware that anything that would interfere with the pilot's vision, whether a structural component of the aircraft, the windscreen, his clothing, his spectacles, haze, or grayout induced by G forces, could greatly stretch out the time required to perceive and recognize an event. Pilots must not only identify the object as an aircraft, but also decide whether it is a friend or foe. The recognition time will then probably stretch out to perhaps 1.5 seconds, and duration time would probably be in the 4- to 8-second range rather than the 2 seconds indicated in the chart. A pilot may fly blind for thousands of feet while performing such simple operations as glancing at an instrument. At 1,000 kph, vision outside the aircraft is interrupted for approximately 1 km. At 3,000 kph, vision is interrupted for 2 km. In shifting sight from outside the aircraft to the instrument panel and back, the accommodation time (the time required for the eyes to focus on the instrument) becomes important. Accommodation and relaxation take up a total of 1 second, or 1 km at 3,000 kph (80). This is an important factor for the aging pilot who is losing the ability to accommodate. Recognition of the instruments consumes a good deal more than 0.8 second if they were poorly designed or poorly lit. Likewise, if the sky was bright and the panel dim, the pilot would first have to adapt to the dim light in the cockpit, then readapt to the brightness outside. One can do little to speed up these times. All of this shows that the modern pilot,

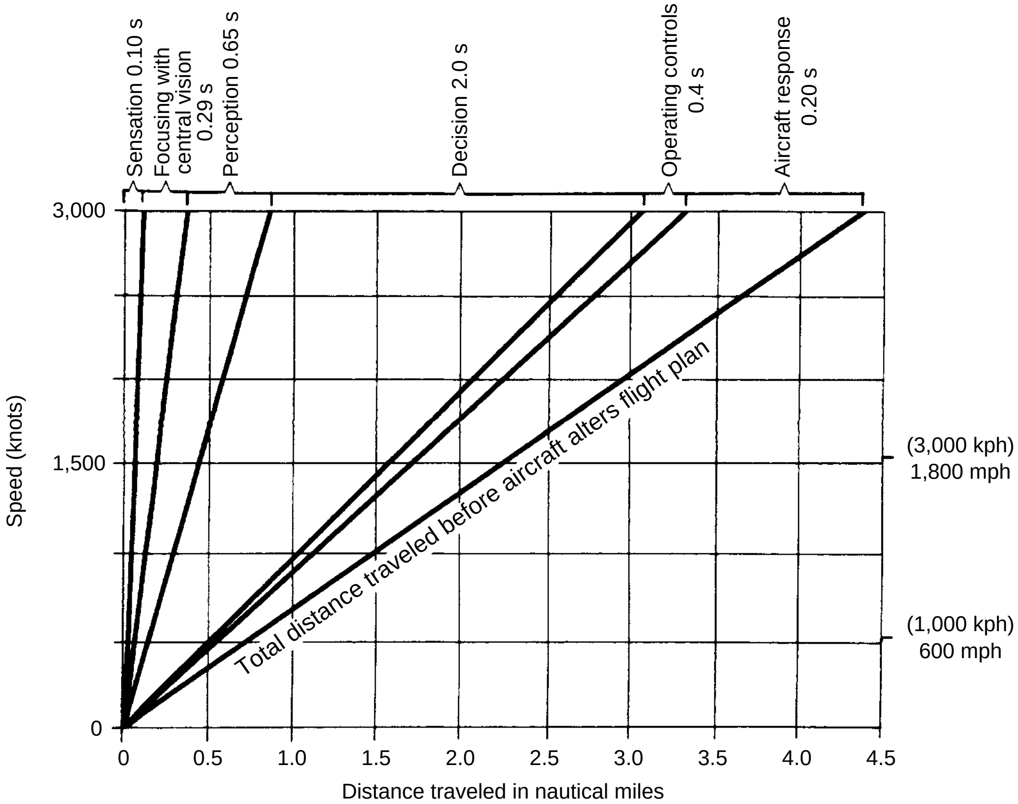


FIGURE 14-17 Distance traveled as a function of aircraft speed and visual processing.

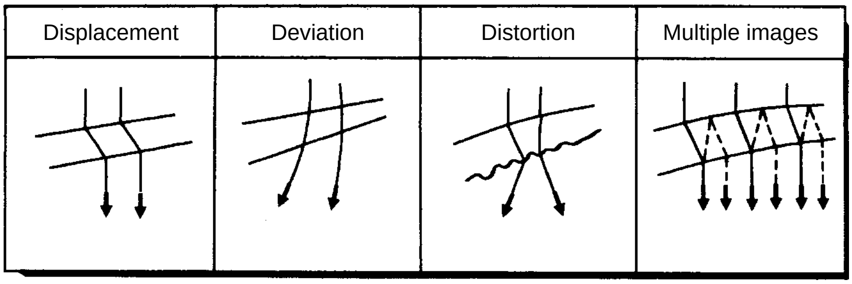


FIGURE 14-19 Windscreen optical effects.

especially in fighter aircraft, must be given the best design possible in illuminated cockpit instruments. Skimping in this area is unwise because a decrease in the pilot's visual efficiency does not allow for taking advantage of an otherwise superbly designed and powered aircraft.

Aircraft Windscreens

The pilot must, of necessity, look through several layers of transparent materials. One must look through the windscreen. One may also be using a visor, and, if one were ametropic, spectacles would have to be worn. Vision through these multiple transparencies may be distorted; therefore, it is imperative that the transparencies have a minimum amount of distortion and that the pilot should use as few as possible (Figure 14-18). Aircraft windscreens are shaped for aerodynamic reasons, and at times, these designs are not compatible with the requirements of good visibility. When only flat panels of glass were used in aircraft windscreens, the problems of distortion and multiple images were minimal. Newer aircraft demand compound shapes that can only be fabricated in plastic, and flying high-speed aircraft at low altitudes has introduced another peril: bird strikes. The combination of the aircraft and bird speeds can easily fracture any glass windscreen, necessitating multiple layers of new-generation plastic, such as polycarbonate, to withstand the impact created by bird strikes. This, however, has introduced another problem. Because the plastic windscreens are made of multiple layers of the material, a reflection of the image occurs at each layer, and these multiple images can become annoying and contribute to confusing visual effects for the pilot. Light rays striking the windscreen can be displaced, deviated, or distorted, or can cause multiple images, as shown in Figure 14-19. Optically, a flat, thin glass or plastic would be the most desirable from the visual standpoint. For the reasons mentioned previously, however, curved, thick, and laminated transparencies are a necessity in present-day aircraft. In the final design, a compromise has to be made between the aerodynamic, optical, and stress considerations (81).

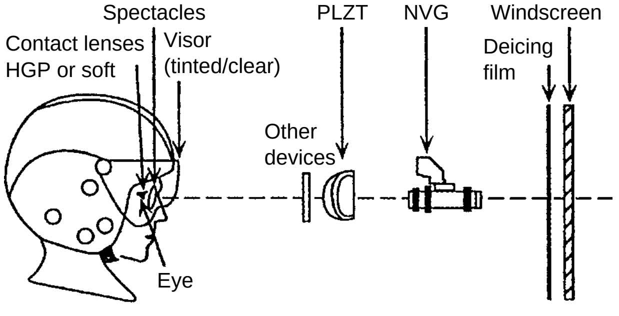


FIGURE 14-18 Different transparencies that may be interposed between a pilot and the world outside the aircraft. HGP, hard gas permeable; PLZT, lead lanthanum zirconate titanate; NVG, night vision goggles.

AVIATOR SELECTION—VISUAL STANDARDS

The visual selection of individuals for flying careers, the steps that need to be taken to maintain vision at peak efficiency, and the protection of the eyes from hazards that may affect the peak efficiency of the aviator's vision are discussed in this section. It cannot be denied that vision is the most important sense needed to fly an aircraft or spacecraft. In the early days of scarf, helmet, goggles, and open cockpits, good distance vision was by far most important. With the advent of closed cockpits and cluttered instrument panels, both distance and near vision became absolutely necessary. In modern closed aircraft, flying with spectacles is now acceptable when the refractive error is not too extreme. In military flying, especially in the new advanced fighters, however, spectacles are still a nuisance and, at times, are a definite disadvantage, because of the following:

1. They are uncomfortable on long missions.
2. High G forces may dislodge them.
3. A reduction of light transmission occurs through any transparency.
4. One more transparency is necessary to look through.
5. A limitation of the visual field occurs.
6. Spectacles have a tendency to fog.
7. They give annoying light reflections at night.
8. They are particularly difficult to integrate with other personal equipment.
9. High-refractive powers may cause aberrations and distortions of the image.
10. High-myopic corrections reduce the image size on the retina.

Selection of Candidates for Flying

The techniques used for the visual selection of candidates for flying should not be absolutely restrictive as to eliminate major segments of the population. Different visual demands are required for the aviator, depending on the mission and aircraft. Not all missions require maximum visual capabilities. The examination techniques should be able to select those who have an efficient and disease-free visual system.

Examination Techniques

History

One should attempt to elicit a complete ocular history from the patient. This would include any ocular disease, injury, medication, surgeries, loss of vision, double vision, and/or use of glasses or contact lenses. It would also be useful to get a family history of any ocular disorders, especially a history of glaucoma, night blindness, crossed eyes, cataracts, or color blindness.

Equipment for Ocular Examination

The following equipment will save time and make it easier to perform the ocular examination:

1. A flashlight and a second flashlight with a bare bulb that can be used as a point source of light
2. A distance target, which can be the flashlight with the point source of light
3. A near target, such as a tongue depressor with a small letter printed on it
4. Ophthalmoscope
5. Prisms to measure phorias and tropias if one were not using a vision screener
6. An occluder
7. A millimeter scale or a Prince rule
8. A loupe that magnifies approximately 2×

General Eye Examination

External Examination

The orbits are examined for any abnormality or asymmetry; exophthalmus or enophthalmus is noted. The eyes are then observed for any gross motility disorders or nystagmus. The presence of any tearing or discharge is noted. The lids are examined for symmetry and the presence of any ptosis. Lashes are observed and any inversion or eversion of the lids noted. Inflammation, cysts, or tumors of the lids and margins can quickly be discerned. The palpebral and bulbar conjunctivas can then be examined by everting the upper lid and depressing the lower lid. Here, one looks for hyperemia, injection, discharge, tumors, or pigmentation.

With the use of a flashlight, the pupils are examined. At this time, it should be noted whether any contact lenses are worn. Soft contact lenses are more difficult to detect, and it may be necessary to use the magnification of the loupe, or better yet a slit lamp, to see them. The pupils are examined for size, symmetry, position, and reaction (i.e., reaction to the light—direct, consensual, and accommodative). The Marcus Gunn pupillary sign is an extremely valuable indication of an optic nerve or retinal lesion. It is present when pupillary response to light is greater consensually than on direct stimulation, and it is elicited by the swinging light test.

The ocular examination is completed by observing the corneas, anterior chambers, irides, and as much of the lenses as possible with the flashlight and loupe. The corneas should be free of opacities and vascularization. With experience, the depth of the anterior chambers can be estimated, the irides are observed for any cysts, tumors, or unusual pigmentation and the lenses observed for opacities.

Corneal Topography

With the advent of refractive surgery, especially RK, PRK, and LASIK more advanced types of corneal examination and measurement have developed, allowing the examiner to know whether these procedures have been performed on the eye. Computer-assisted video keratography (corneal topography) has evolved as an instrument to accurately evaluate the status of the anterior corneal curvature (82). Early keratoconus can now be more readily diagnosed, and contact lens fitting is enhanced by having this more accurate corneal curvature data. Refractive surgical follow-up can also be more critically assessed.

Visual Acuity/Refractive Errors

At 6 m (20 ft), the entire letter on the 20/20 line subtends the visual angle of 5 minutes of arc. As shown in Figure 14-20, each component of the letter subtends 1 minute of arc, so that 20/20 indicates that at 6 m this individual can identify the component parts of the test letters. Vision should be tested in each eye separately, first without spectacles and then with spectacle correction. When they have below-normal visual acuity without correction and have no spectacles, patients may be tested with a pinhole of 2 to 2.5 mm in diameter. An improvement in visual acuity signifies that the subnormal vision is most likely due to a refractive error. If visual acuity was not to improve, most likely an opacity in the cornea or lens or a defect in the retina or optic nerve is present. If spectacles were used but did not improve the patient's visual acuity to 20/20, the pinhole test also can be used over the spectacles. An improvement in vision signifies that a change in the patient's prescription is indicated. Figure 14-21 shows the approximate visual acuity for spherical refractive errors up to +4 (hypermetropia) or −4 D (myopia).

Refractive errors are only rarely due to disease processes. They are mainly a mismatch between the diopteric power of the refractive system of the eye and the length of the globe.

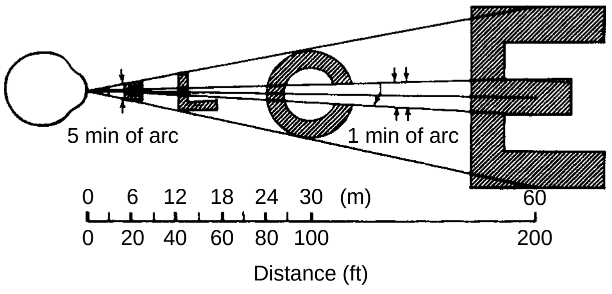


FIGURE 14-20 Geometry of visual acuity. (Adapted from Adler FH. *Physiology of the eye: clinical application. St. Louis*: C.V. Mosby Co., 1970.)

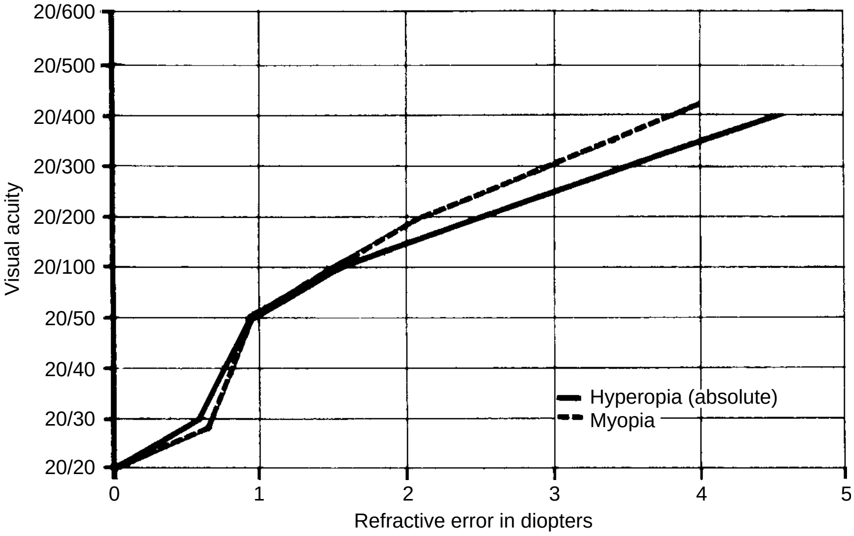


FIGURE 14-21 Visual acuity as a function of refractive error.

With a close match of these components, the individual is nearly or actually emmetropic. A mismatch can lead to hypermetropia (farsightedness) when the globe is too short for the refractive power, or the individual can be myopic (nearsighted) when the diopteric power of the refractive surfaces is too strong; therefore, the eye is relatively too long. The third and most common aberration is astigmatism. This is most often due to an asphericity of the cornea; that is, one meridian of the cornea has a higher dioptric power or is more curved than a second meridian located at 90 degrees from it. The rays of light passing through an astigmatic eye form a path known as *Sturm's conoid*. This form of astigmatism is known as *regular astigmatism* and can be corrected by cylindric and spherocylinder lenses. Occasionally, an eye is encountered that has irregular astigmatism; in this case, the maximum and minimum powers of astigmatism are not at 90 degrees, and this form of astigmatism can only be corrected by contact lenses. The hard contact lens can uniquely correct this deficiency because the tear film layer beneath the contact lens fills in the irregularities of the astigmatic cornea. However, a toric soft contact lens can also be used to correct the astigmatic error. If the candidate's vision were worse than 20/20, refraction should be required. A cycloplegic refraction is preferable because it totally relaxes the accommodation and therefore yields the true and total refractive error. This especially helps to delineate the refractive errors in hypermetropes because these young, farsighted individuals obscure the total amount of their error by exerting an accommodative effort, which corrects some part of the spherical error; however, accommodation does not help to correct a myopic error. In fact, accommodation increases myopia and makes the refractive error even worse. Astigmatic individuals may not be able to see clearly at either near or far distances. Only a cylinder or spherocylinder or contact lens correction can clear their vision. Accommodation may be of some help in mildly astigmatic individuals by shifting Sturm's conoid on the retina to the circle of least confusion. As is the case with the hypermetropic individual, however, this takes ciliary muscle effort, and symptoms of visual fatigue and blurred vision would ensue if the refractive errors were not corrected.

To see clearly at near distances, the dioptric power of the crystalline lens must be increased to an appropriate level for the distance of the object seen. After the age of 45, most individuals do not retain sufficient accommodation to see clearly at reading distances of 33 to 35 cm. This condition is known as *presbyopia* and must be corrected by plus lenses when one wishes to be able to read at near distances.

Distant visual acuity can be examined in a 6-m (20-ft) lane with an eye chart or a projector chart. A smaller room, such as a 3 to 4 m room, can be used with reverse charts and mirrors. Perhaps the best way for a flight surgeon or aeromedical examiner to check the visual acuity and other visual functions as well is by using a vision screener, such as the one shown in Figure 14-22. These instruments conveniently check a patient's distance and near visual acuities, phorias, and stereopsis. Without a screener, near vision can also be examined with a near vision test card held at 33 to 35 cm as per the instructions on the card. Each eye is tested separately.

Accommodation is tested in each eye separately using a Prince rule or its equivalent. One must be aware that

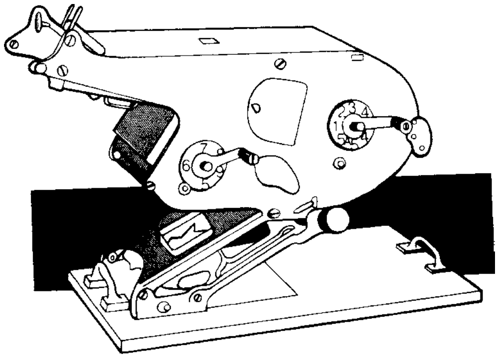


FIGURE 14-22 Vision screener used to assess visual function.

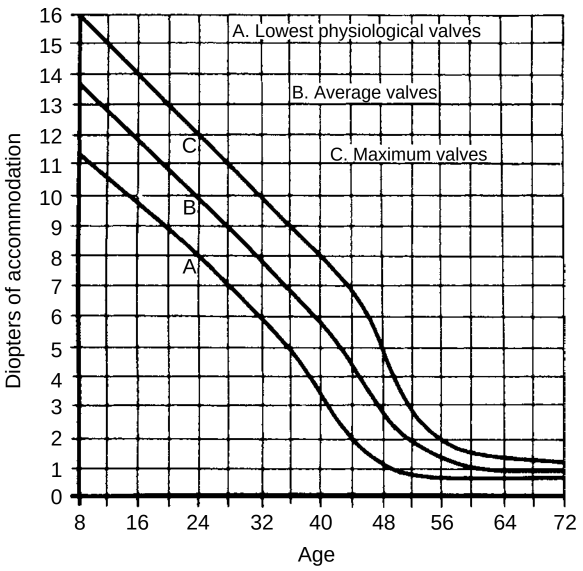


FIGURE 14-23 Accommodation-age curve.

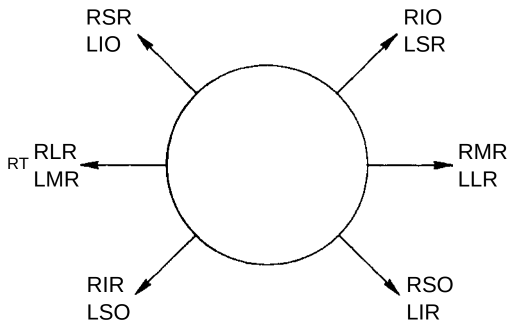


FIGURE 14-25 Yoke muscles. RSR, right superior rectus; LIO, left inferior oblique; RLR, right lateral rectus; LMR, left medial rectus; RIR, right inferior rectus; LSO, left superior oblique; RSO, right superior oblique; LIR, left inferior rectus; RMR, right medial rectus; LLR, left lateral rectus; RIO, right inferior oblique; LSR, left superior rectus.

when the patient has a refractive error, accommodation is tested through the spectacles. Should patients be presbyopic and wearing bifocals or trifocals, they must be tested only through the upper, or distance, part of the spectacles and not through the bifocal or trifocal. Allowing the patient to look through the bifocal portion alters the test and adds accommodative amplitude equal to the value of the strength of the bifocal. Figure 14-23 shows that accommodation normally decreases with age at an almost constant rate. It becomes manifest at approximately age 45 because most reading materials subtend a visual angle that is too small to see if held much beyond 0.3 m from the eye.

Motility

Normal ocular motility is expected in individuals who will be controlling aircraft. Diplopia or loss of stereopsis at a critical phase in flight could be devastating. The physician looks for straight eyes in the primary position of gaze and ensures that they remain so when taken into the six cardinal positions of gaze, as shown in Figure 14-24. As discussed earlier in this chapter, the six extraocular muscles rotate the eyes into infinite positions of gaze by the use of the yoke muscles operating under Hering's law of equal and simultaneous innervation to each yoke muscle. The yoke muscles and their actions are shown in Figure 14-25. A manifest deviation of the eyes is known as a *tropia* and can usually be observed by inspection and quantitated by the Hirschberg test, that is, observing the position of the corneal light reflex in the deviating versus the fixing eye, as shown in Figure 14-26. A phoria, conversely, is a latent deviation. It is only present when fusion (binocular viewing) is interrupted, such as by an occluder, a Maddox rod, or a red lens placed over one eye. Tropias are present in approximately 3% of the population, whereas phorias are present in approximately 100% of the population, meaning that, in essence, a phoria is normal unless it is extreme. It measures the resting state of the eyes. The eyes can be deviated inward, which is an esotropia or esophoria; deviated outward, which is an exotropia or exophoria; or deviated upward or downward, signifying hyper- or hypotropia or phoria.

An individual with a tropia (strabismus) may be seeing double, suppressing the vision in the deviated eye, or the eye may be amblyopic, with ensuing poor vision in that eye. Because almost all individuals have a phoria, it is not of too great a concern unless it is excessive. If the phoria were excessive, a large neuromuscular effort would be required to maintain fusion and, therefore, single binocular vision. Any added stress may cause a breakdown of fusion thereby leading to diplopia and loss of stereopsis. Hypoxia and fatigue are common stresses to the aviator, which can alter phorias; this is the principal reason for taking phoria measurements as part of the visual examination for flying. The easiest way for an aeromedical examiner to accurately measure phorias is by

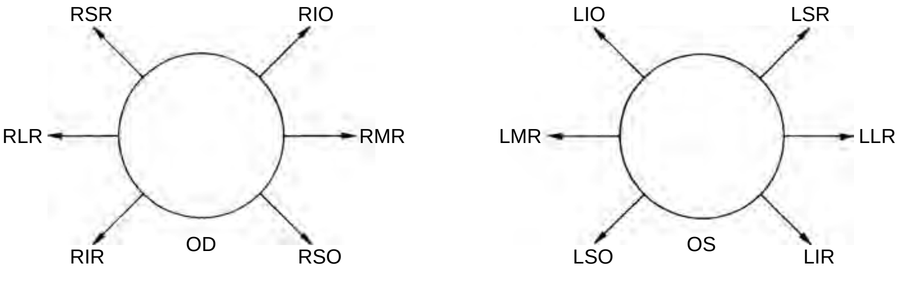


FIGURE 14-24 Muscle actions in the cardinal positions of gaze. RSR, right superior rectus; RLR, right lateral rectus; RIR, right inferior rectus; OD, right eye; RSO, right superior oblique; RMR, right medial rectus; RIO, right inferior oblique; LIO, left inferior oblique; LMR, left medial rectus; LSO, left superior oblique; OS, left eye; LIR, left inferior rectus; LLR, left lateral rectus; LSR, left superior rectus.

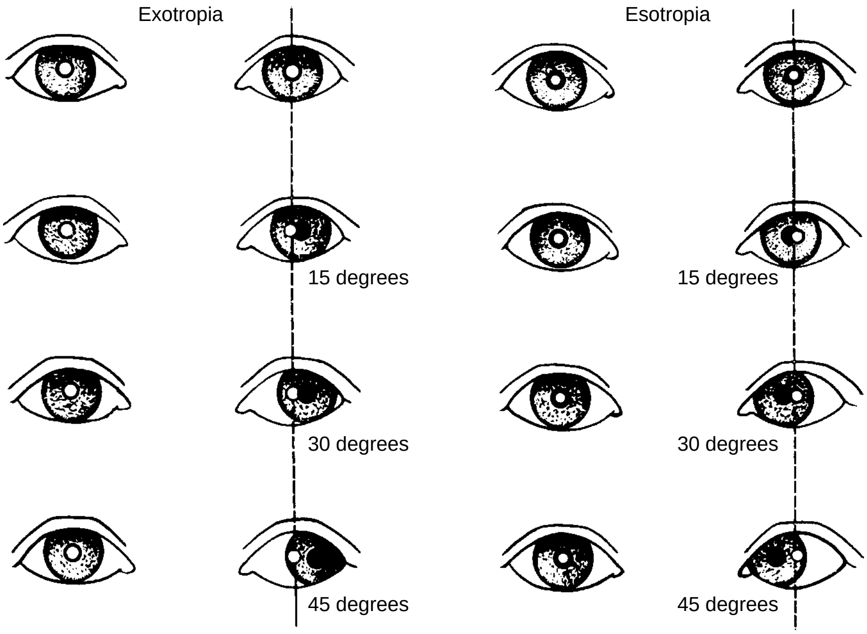


FIGURE 14-26 Hirschberg reflex test used to detect tropias.

use of a vision screener. Ophthalmologists and optometrists mainly use a Maddox rod, occluder, and prisms in the eye lane to detect and measure phorias. As has already been mentioned, the Hirschberg (inspection) test delineates a large-angle tropia. Small-angle tropias can only be detected by the cover test.

The near point of convergence is also important in this examination because it too is influenced by hypoxia and fatigue. The near point has a tendency to recede under these conditions. Normally, the near point of convergence is 100 to 120 mm from the eye, but in military aviators, the near point of convergence is expected to be 70 mm or less. The Prince rule can be used to do this test. A small, dim light or a small test target is brought forward along the rule until the patient breaks fusion and sees double. Simultaneously, the examiner notes that one of the eyes deviates out. A measurement at that point is the near point of convergence and should be within acceptable limits.

When the examiner notes nystagmus, whether it is pendular or rotary, when occluding an eye, the patient should be sent to an ophthalmologist for a complete evaluation.

Color Vision

A variety of tests is available to test for color vision defects. They have been discussed in the section **Color Vision**.

Stereopsis/Depth Perception

Tests of binocular vision given to aviators are usually referred to as *depth perception tests*. In reality, they are tests of stereopsis, one component in the perception of depth. Visual screeners, such as the Bausch and Lomb, Titmus, Keystone, or OPTEC, with excellent test slides quantify stereopsis down to as fine as 15 seconds of arc. Military flyers are expected to have stereopsis of at least 25 seconds of arc disparity. These tests, done in visual screeners, are at optical infinity; therefore, they are distance tests. Near tests of stereopsis are also available, such as the Verhoeff, with its three bars of varying width. This test is administered at 1 m without any special optical devices. The patient should be wearing spectacles, when needed, to correct for distance, and the patient must have no failures in the eight presentations to pass the Verhoeff depth perception test. This equals approximately 32 seconds of arc disparity. Another commonly used near-stereoscopic test is the Wirt. This test necessitates using polarizing glasses but has the disadvantage of only going to 40 seconds of arc disparity. Normal room illumination is used for all three stereo tests.

Field of Vision

Aeromedical examiners need only do confrontation fields, which compare the monocular field of the examiner and the patient. Any aberration in this field examination or history of neurologic disease or increase in intraocular pressure necessitates that a more precise perimetric study be done on a tangent screen or perimeter. Perimeters, such as the Goldmann hemispheric, have been the standard since the late 1950s. However, over the recent past, automated static threshold perimetry has become the new standard for evaluating the visual field, especially in patients with glaucoma. The Humphrey and Octopus models are the most popular. The extent of normal visual fields is shown in Figure 14-27.

Night Vision

Night vision is not routinely tested unless indicated by history. If a history of difficulty in seeing at night were elicited, dark adaptometry would be indicated. This test must be accomplished by referring the patient to a center that has an adaptometer.

Intraocular Pressures

Glaucoma is a disease of maturity. Most of the glaucoma seen in aircrew members is of the open-angle variety, which

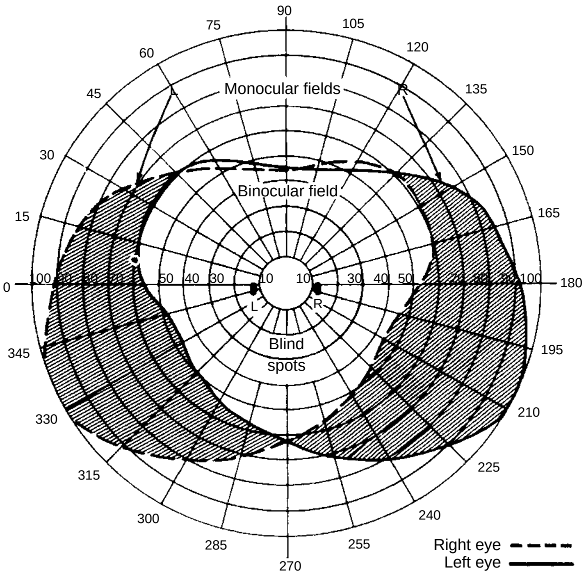


FIGURE 14-27 Normal visual fields.

is not commonly found in individuals younger than 40. The intraocular pressure measurements should be done in individuals aged 30 or older. If, however, a family history of glaucoma were to exist, intraocular pressure measurements should be done at any age. Yet, recently more patients with "pigmentary glaucoma" are being diagnosed. This is an open-angle type of glaucoma with pigment derived from the iris, causing a blockage of the trabecular meshwork (83). These individuals, who are usually mildly myopic, are first noted to have pigmentary dispersion syndrome, with a worsening of this condition to pigmentary glaucoma. The USAF now screens aviators for an increase in intraocular pressure beginning at age 29 and at each complete physical thereafter. Schiøtz (indentation) tonometry is most readily available for the aeromedical examiner. Applanation tonometry is an excellent technique; however, this takes more practice and requires the availability of an expensive slit lamp or handheld Tono-Pen tonometer. In any case, the results are comparable regardless of which instrument is used. Space-age technology has brought us the air or puff tonometer. It also gives reliable results in experienced hands. Any intraocular pressures consistently greater than 21 mm Hg should be referred for a full glaucoma workup. Most of these individuals will be found to have only intraocular hypertension; that is, they will show an increase in intraocular pressure without any field loss or disc cupping. This condition generally requires no treatment; however, these individuals must be followed up carefully at regular intervals, such as every 3 to 6 months, with intraocular pressure measurements, ophthalmoscopy, and visual field examinations. If their conditions were to deteriorate, as indicated by scotomas in the visual field or abnormal cup-to-disc ratios, treatment would be indicated and consultation should be sought from an ophthalmologist immediately. New objective techniques are in development that will analyze the optic nerve and nerve fiber layer for evidence of glaucomatous damage. Presently these consist of stereo-video cameras, confocal laser systems, scanning laser ophthalmoscopes, and optical coherence tomography (84).

Internal Ocular Examination

The final part of the examination for flying is an examination of the clear media and fundus of the eye. To get a good look at the fundus, the pupils should be dilated. In light-colored irides, two drops of 2.5% phenylephrine will suffice to dilate the pupil without altering the accommodation. With a darker-colored iris, a short-acting cycloplegic agent will probably have to be added to dilate the pupil sufficiently to view the fundus. One drop of 1% cyclopentolate or 1% tropicamide along with one drop of 2.5% phenylephrine will dilate the pupil for several hours. The examiner views the patient's right fundus with the right eye, and then switches the direct ophthalmoscope to the left eye to view the left fundus. A +6 or +8 D lens is rotated in the ophthalmoscope, and the red reflex is visualized at approximately 15 cm from the eye and examined for opacities, streaks, or any other alterations. If any of these conditions were noted, the patient should be referred for a consultation.

Normal fundus details are shown in Figure 14-28. Individuals with any fundus abnormalities should be referred to an ophthalmologist for diagnosis and possible treatment.

Maintenance of Vision

Individuals preparing for a lifelong career in aviation should have a thorough ophthalmologic examination. For a civilian or military flying career, long-term prediction of the health of the visual system is extremely important because it is expected that the aviator will serve for at least 20 years. Examiners should strive to select individuals with excellent visual capabilities who are up to the visual demands of the duties to be performed. The selection of individuals with disease-free visual systems will go a long way toward assuring a 20+ year flying career. Periodic reexaminations will aid in maintaining a disease-free ocular system. Proper nutrition is vital to the maintenance of the visual system. Vitamin A is necessary for night vision and to aid in the production of visual pigments, whereas the water-soluble B vitamins protect against nutritional amblyopia. Protection from physical forces in daily activities, sports, and in the aircraft is important. Protection from excess electromagnetic

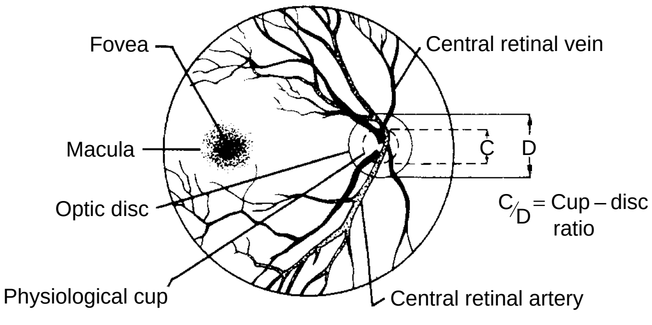


FIGURE 14-28 Normal fundus details.

energy is also a necessity. This energy can be an occupational hazard encountered in aviation. If ocular disease or injury were found, proper, timely, and correct treatment would speed recovery. This treatment should be followed by a reevaluation to consider the degree of impairment, if any, and its possible effects on the aviator's flying efficiency. Finally, the aeromedical examiner or flight surgeon should educate all aircrew in the proper use and care of their eyes and vision.

Many drugs are used to diagnose and treat ocular conditions. Most of these drugs should be left to the use of the ophthalmologist; however, the aeromedical examiner should have a basic knowledge of the action of certain commonly used drugs on the eye. The eye is an excellent field to observe the pharmacodynamics of the autonomic nervous system. Both the sympathetic and parasympathetic parts of the autonomic nervous system innervate the pupil and ciliary body. The dilator muscle of the pupil is innervated by the sympathetic nervous system, and the sphincter is innervated by the parasympathetic nervous system. The ciliary muscle involved in accommodation is innervated by the parasympathetic nervous system. Some common ophthalmic drugs and their actions are summarized in Table 14-3.

The aeromedical examiner should consult an ophthalmologist when atropine or steroid preparations are to be prescribed. Finally, one should never prescribe ocular anesthetic agents for use by the patient.

CONDITIONS AFFECTING THE AVIATOR'S VISION

Once selected with a disease-free visual system, the aviator usually remains so for several decades except for minor refractive changes and the universal onset of presbyopia in the fifth decade of life. Young flyers, especially those who do not use spectacles, may become victims of ocular trauma. Ocular trauma can be devastating to a flying career. Aeromedical examiners should warn their patients to use protective goggles or impact-resistant spectacles for all sports in which a high-speed missile may be involved, such as handball, tennis, squash, and hockey. Injuries to the eye should be referred at once for definitive diagnosis and treatment. In the older aviators, glaucoma or ocular hypertension is often encountered. With the latest medical philosophy on when treatment for glaucoma should be instituted and with new medications that do not secondarily affect vision, one need not fear the effects of glaucoma on a flyer's career. Observation and the treatment regimen pioneered at the USAF School of Aerospace Medicine (USAFSAM) have kept 95% of these Air Force patients on flying status for a full career (85). Those individuals with intraocular hypertension (intraocular pressure >21 mm Hg but <30 mm Hg, without field defects) are observed at regular intervals without treatment. Those individuals

TABLE 14-3

Common Ophthalmic Drugs

Dilate pupil	
Adrenergic (Sympathomimetic; Dilating, Direct-Acting)	*Anticholinergic (Parasympatholytic; Competitive Antagonists to Acetylcholine)*
Epinephrine (α and β)	Atropine
Norepinephrine (α)	Scopolamine
Phenylephrine (α)	Homatropine
Isoproterenol (α)	Cyclopentolate
Timolol (β-blocking)	Tropicamide
Constrict pupil—cholinergic (parasympathomimetic)	
Direct-Acting	*Indirect-Acting (Anticholinesterase)*
Pilocarpine	Edrophonium
Carbachol	Isofluorophosphate (DFP)
Methacholine	Echothiophate

Drug	*Concentration (%)*	*Begin Effect*	*Duration*
Pilocarpine	0.5–6	15 min	4–6 hr
Tetracaine (Pontocaine)	0.25–0.5	1 min	15 min
Proparacaine (Ophthaine)	0.5	30 s	10 min
Lidocaine (Xylocaine)	1, 2	5 min	3–4 hr
Phenylephrine (Neo-Synephrine)	2.5, 10	10 min	2 hr
Atropine	0.5–2	2 hr	7–14 d
Homatropine	2–5	30 min	6 hr
Cyclopentolate (Cyclogyl)	0.5, 1, 2	15–30 min	24 hr
Tropicamide (Mydriacyl)	0.5, 1	15–20 min	2–3 hr

with glaucoma (>30 mm Hg or with visual field or optic disc changes at any pressure) are treated with either levo-epinephrine, β-blocker, or prostaglandin analog eye drops with remarkable success without creating secondary visual aberrations. Further, a number of new ocular drugs such as topical carbonic anhydrase inhibitors, α-adrenergic agonists, and prostaglandin analogs are now available for treatment of glaucoma and ocular hypertension (86). The laser has also been used to treat glaucomatous conditions. For instance, trabeculoplasty is now often used for open-angle glaucoma treatment. Microscopic laser burns are placed in the trabecular meshwork. This enhances the outflow of aqueous and may eliminate the need for ocular medications. In the more rare, narrow-angle glaucoma, the laser can be used to create an iridotomy. Previously, this necessitated surgical iridectomy. Both of these procedures are used in aviators, allowing them to return to full flying duties.

Retinal disorders are also seen in the younger patients. Central serous retinopathy, an edema of the macula of unknown origin, plays havoc with a pilot's stereopsis/depth perception. Fortunately, 97% of these afflicted individuals recovered and were returned to full flight status as noted in a review of USAF aviators with this condition (87). Older flyers may develop macular degeneration that may eventually end their flying careers because presently no effective treatment exists for this condition.

A small number of flyers may develop keratoconus or irregular astigmatism, but many of these individuals can be returned to full flight status by the proper fitting of toric or hard-contact lenses. A USAF study showed that 82% of USAF aviators with a diagnosis of keratoconus were returned to full flight status (88).

A fair number of individuals have migraine, but only a few flyers complain of it to the aeromedical examiner. The most significant aspect of this condition for flying personnel is developing a central scotoma during an attack or becoming incapacitated by the headache that may follow.

Cataracts are commonly seen in the older flying population or as a result of ocular trauma at any age. If the opacity is dense enough, it could affect vision and, therefore, a flyer's career. Modern surgical procedures and postoperative optical correction either by an intraocular lens placed into the eye at surgery or by a contact lens fitted after surgery may allow many individuals to pass the visual examination and return to flying. Recent data shows that these procedures are quite successful, even in military aviators. In 80 eyes with intraocular lenses, 96% attained 20/20 visual acuity and 86% of those affected were returned to full flight status, 3 being grounded for nonophthalmologic disease, and 3 for ocular complications. The longest follow-up in these patients has been 20 years (89).

Correction of Refractive Errors

Standard Techniques

Refraction is a procedure used to determine the lens power needed to correct a patient to emmetropia. The refractive error can be estimated by retinoscopy, which is usually done following the use of cycloplegic eye drops. A manifest or subjective refraction is done with lenses, crossed cylinders, or astigmatic dials, and a third and common way of calculating the refractive error is with a lensometer, which measures the patient's present spectacle correction. If spectacles were to correct the patient's vision to 20/20, nothing further would need to be done concerning the refraction. The aviator's distance refraction changes little during the ages of 20 to 40. After the age of 40, although the error for distance may remain static, a correction for early presbyopia is often necessary. Spherical plus lenses correct the deficient accommodation. Once presbyopia has commenced, the patient needs to be reexamined every 2 years to maintain clear, comfortable near vision. A half-eye spectacle will suffice for the patient with no error in distance vision, but bifocals will be needed to correct the error in those who also require a correction for distance. Trifocals and newer progressive lenses may be helpful to the older pilot needing correction for both near (reading) and intermediate (panel) distances.

The use of contact lenses to correct refractive errors began more than 50 years ago. They have found acceptance in civilian aviation and since 1989 have been used in military aviation.

After a formidable research effort, the USAF now allows its aviators to use soft contact lenses in place of spectacles. A limited number of tested soft contact lenses are approved for use. Flyers with astigmatism over 0.75 D are fitted with toric soft lenses. The major problem encountered has been the dry cockpit environment. To date, the USAF Soft Contact Lens Program has been a success (90). Hard gas permeable (HGP) lenses are made of silicone-acrylate, and soft contact lenses of hydroxyethylmethacrylate (HEMA) and silicone plastics. The hard lenses are used in a limited manner to correct visual defects, such as irregular astigmatism, keratoconus, and aphakia. The soft contact lens is more comfortable to wear, less time is needed for adaptation, and the soft lens rarely alters the corneal curvature. Soft lenses, however, do have a significant drawback for aviators in that they cannot correct astigmatism of more than 0.75 D. In certain individuals, hard lenses may temporarily or permanently mold the cornea to a different refractive status or curvature. This could fortuitously improve the vision or it could lead to corneal warping and degrade visual acuity.

Newer Techniques for Refractive Error Correction

Orthokeratology

More than three decades ago, some practitioners began using contact lenses purposely fitted flat to reduce corneal contour and improve uncorrected vision, a procedure called *orthokeratology* (to straighten the cornea). While this technique can alter the corneal curvature, it is highly unpredictable and not permanent (91). It requires the use of so-called retainer contact lenses to maintain the effect; however, most corneas revert to their original curvatures and refractive errors in several weeks once these lenses are discontinued. Regrettably, this procedure can cause "with-the-rule" astigmatism that mimics keratoconus or even a decrease in vision from corneal scarring.

Refractive Surgery

CRS procedures have now been developed to more permanently alter the refractive status of the eye. Although, most of these procedures were developed to correct myopia, CRS techniques are now also available to correct hyperopia and astigmatism. One of the earliest myopic procedures was a rediscovered technique from the 1950s called *radial keratotomy* (RK). RK involves making four or more radial incisions in the corneal stroma down to the depth of Descemet's membrane, reaching radially to the limbus, but sparing the central 3 to 4 mm optical zone over the pupil. These weakening incisions flatten the central cornea, thereby decreasing the amount of overall myopia. As with orthokeratology, corneal response to RK incisions is variable and unpredictable; but much more permanent (92). Although rarely performed now, pilot aspirants in the past willingly underwent RK hoping to qualify for aviation careers. Presently, most military services do not allow RK because of reduced corneal integrity, long-term instability (progressive hyperopic shift), daily fluctuations in vision, glare, altitude effects and because even longer-term consequences of RK remain unknown (93,94). Fortunately, RK has been almost completely replaced by newer and more effective CRS procedures in most countries.

More recently, newer forms of CRS have emerged using lasers, such as the 193 nm ultraviolet excimer laser, to ablate and flatten the central cornea. Myopic procedures using this laser can be categorized into surface ablations, most notably PRK and its variants [laser epithelial keratomileusis (LASEK) and epi-LASIK], or deeper ablations performed beneath a hinged corneal flap, known as *laser in-situ keratomileusis* (LASIK). LASIK flaps can be created with a mechanical microtome, or more recently, using a femtosecond infrared laser (IntraLase) (95,96).

In general, corneal haze following CRS appears more of a problem with PRK than LASIK. However, the LASIK corneal flap never heals completely and remains chronically unstable, which may be problematic in certain vocations and occupations. For example, incidental levels of corneal trauma have been shown to dislocate LASIK flaps up to 6 years after the procedure, so far (97). In addition, altitude, windblast, water-blast, and G effects remain significant potential threats to LASIK eyes long-term. Adequate aeromedical studies to investigate these LASIK concerns have not yet been done. Despite this, LASIK has become more popular than PRK because of faster results, less corneal haze, and reduced ocular pain in the immediate postoperative period. However, this gap is narrowing because newer analgesics have made PRK virtually pain-free and advanced wave-front analysis (custom-CRS) appears more effective with surface ablations, making custom-PRK a potentially more suitable procedure for the aviator (98).

Both PRK and LASIK are mainly used for the correction of myopia up to −8.00 D, but more recently also for treating hyperopia and astigmatism. Complications, however, increase as the amount of myopia increases. Other hyperopic CRS techniques, for example laser thermal keratoplasty, use IR lasers to induce central corneal steepening from circumferential thermal burns. Nonlaser CRS techniques, such as intrastromal corneal implants (Intacs) and implantable intraocular contact lenses (ICLs) exist, but each of these has more limited application because aeromedical uncertainties will limit their indications and appeal (99–101).

The literature reports that 89% to 98% of low myopes obtain 20/40, and 65% to 80%, 20/20 or better visual acuity, following CRS (102). Accuracy to within ±1.00 D varies between 75% and 95%, depending on amount of preoperative myopia (103). Questions remain, however, whether the postoperative goal of 20/20 is adequate, given preoperative best-corrected means of 20/13 in trained and applicant aircrew populations around the world (104–106). Postoperative corneal haze and induced higher-order wave aberrations from CRS can affect the overall quality of vision and cause haloes and glare, especially under low light when the pupil dilates. Contrast sensitivity function, the ability to see under less-than-ideal conditions, has also been shown to be decreased even beyond 12 months following both procedures. Predictability for aviation remains a problem. If one were corrected to within the "1.00 diopter" accuracy, the 20/20 uncorrected visual acuity desired for a pilot would not be met. Finally, the possibility of regression and the risks of retinal detachment long-term remain after CRS. Regardless, PRK and LASIK have been approved by the U.S. Federal Drug Administration (FDA), FAA, and are now allowed by the U.S. military for most career fields to include flying. Continued studies, however, are needed to determine the full operational impact of modern CRS on aviators, particularly for military aviation.

PROTECTION OF VISION

Ocular Protective Materials

Since June 1972, all spectacle lenses used in the United States have had to be impact resistant by an FDA ruling. Impact resistant does not mean that they are unbreakable, just that a glass lens must withstand a 5/8-in. diameter steel ball dropped on it from a 50-in. height. Glass lenses are hardened to withstand the drop-ball test by heat or chemical tempering.

A plastic, allyldiglycol carbonate (CR-39) lens may also be used in place of glass. A transparent plastic polycarbonate (Lexan) is being used in helmet-mounted visors and as a cockpit transparency that is strong enough to withstand bird strikes. Bird strikes are hazardous to low-flying, high-speed aircraft. The combination of a multilayered polycarbonate windshield and a visor of similar material for the aviator's helmet have markedly improved the protection against this lethal hazard. A dual-visor system, one clear and one tinted, allows for maximum protection under all flight conditions. Polycarbonate lenses are now available in lenses to correct refractive errors. For sports and occupational activities, polycarbonate can be used as a protective goggle over ordinary spectacles, or can be placed directly into spectacle frames, thereby correcting the visual acuity and protecting the eyes. This material also has a secondary benefit in that it protects against ultraviolet light. It begins to transmit at 385 nm, blocking all shorter wavelengths. However, it is susceptible to scratching and costs more (107).

Filters and Sunglasses

The extent and effects of electromagnetic energy (light) on the eye have been previously discussed. As noted, light intensities in the aviation environment can be up to 30% higher than on earth. Abiotic ultraviolet radiation (200 to 295 nm) is filtered by the atmosphere but does begin to become significant at high altitudes. Ultraviolet radiation 300 to 400 nm, which is abundant on Earth, is now reputed to have some damaging effect on the human lens following long-term, chronic exposure and may be linked to macular degeneration. IR radiation above 760 nm is a contributor to solar and nuclear retinal burns. Sunlight falling on the earth is composed of 58% IR energy (760–2,100 nm), 40% visible light (400–760 nm), and only 2% ultraviolet radiation (295–400 nm). At high altitude, ultraviolet radiation may be as high 4% to 6% and makes up 8% to 10% of the solar energy spectrum in space. Sunglasses can protect the aviator from excessive and harmful electromagnetic energy.

The ideal sunglasses for the aviator should do the following:

1. Correct refractive errors and presbyopia
2. Protect against physical energy (wind or foreign objects)
3. Reduce overall light intensity
4. Transmit all visible energy but attenuate ultraviolet and IR radiation
5. Not distort colors
6. Not interfere with stereopsis (depth perception)
7. Be compatible with headgear and flying equipment
8. Be rugged, inexpensive, and need minimal care

Five types of sunglasses are now in common use: colored filters, neutral filters, reflecting filters, polarizing filters, and photochromic filters. They all allow only a certain percentage of the total amount of incident light to get through to the eye but produce this effect in different ways. The colored, neutral, polarizing, and photochromic filters do this by absorbing some of the light and allowing the rest to pass. Spectral filtering is achieved in glass lenses by adding specific chemicals to the melt, producing a through-and-through tint. The anterior surface of the glass lens also may only be tinted, but this method is subject to scratching. Plastic lenses are usually dipped into dyes to produce their filtering effect.

Colored filters have the disadvantage of altering the color of viewed objects and may reduce color discrimination of color vision–deficient persons.

Neutral filters adequately reduce the amount of light. Mainly, they do not distort colors and most will adequately eliminate excessive IR and ultraviolet radiation.

Reflecting filters can be coated uniformly. They eliminate the ultraviolet and IR energy; however, this type of coating scratches and peels easily and gives a greenish tint to objects.

Polarizing filters reduce glare off water or highways. For the aviator, they can cause a problem, such as blind spots in windshields and canopies, due to stress polarization induced by the canopy, matching that in the spectacles. Plastic polarized filters scratch easily and, when laminated in glass, are expensive and heavy.

Photochromic filters (variable light transmission) are photodynamic lenses that vary in intensity in response to the ultraviolet content of the incident light. Some flyers may find the darkest density sufficient; however, for aviation use, the range of transmission variation is not adequate. The darker lenses remain too dark in the "open" state, and the lighter lenses are not dark enough at their maximum density (108). Density and cycling time can be reduced, particularly in hot and low-ultraviolet environments, such as inside automobiles or cockpits, where ambient light is altered traversing another transparency. This is shown in Figure 14-29, which also compares these lenses with other filters.

Selection of Sunglasses for the Aviator

The lens material should be CR-39 or polycarbonate plastic or impact-resistant glass. After much experimentation, a 15% neutral density–transmitting lens probably represents the best all-around compromise for aviation. Some individuals prefer a 25% transmitting lens for daily use (e.g., driving or sports) but switch to the 15% transmitting lens for aviation use. The lens should have a fairly flat transmission curve in the visible energy range to preserve normal color vision but attenuate the ultraviolet and IR radiation. An ideal transmission curve is shown in Figure 14-30.

The difference in overall transmission between the two spectacle lenses should not be greater than 10%; otherwise, this disparity will induce the Pulfrich effect as that may

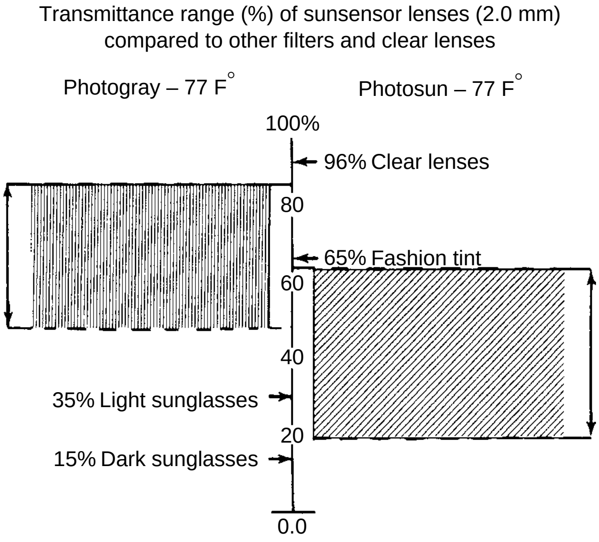


FIGURE 14-29 Effectiveness of various tints of lenses in reducing light transmission.

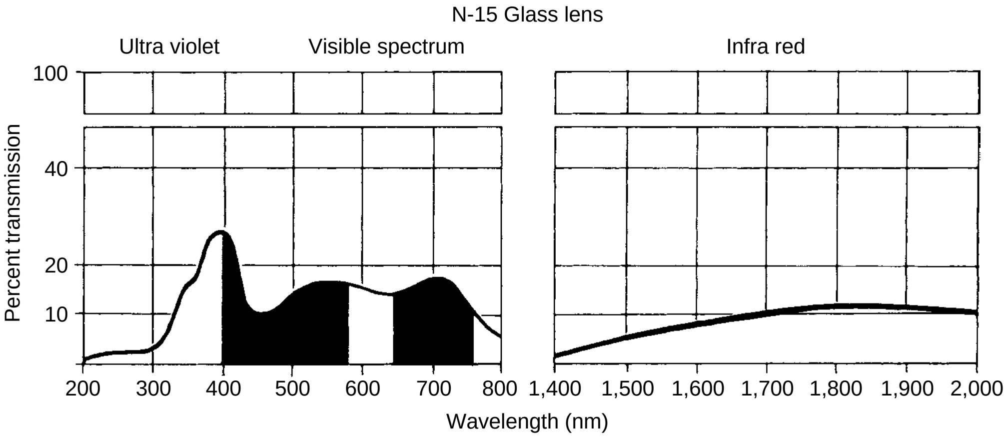


FIGURE 14-30 Idle transmission curve for sunglasses for the aviator.

degrade stereoscopic vision and depth perception. When sufficient overall light intensity is present, such as in daylight, visual acuity through 15% neutral density, transmitting lenses will be as good as in the eye lane without filters. Under low-light levels, such as at dawn or evening and on dark cloudy days, sunglasses reduce both contrast sensitivity and central visual acuity and, therefore, should be removed. Much has been said concerning certain selective waveband filters known as *blue blockers* that cut off all ultraviolet and blue portion of the spectrum. Cutting out any of the colors in the spectrum is not desirable in aviation. The aviator's "neutral density" sunglass lenses allow all colors through and effectively reduce ultraviolet light as well.

Under extraordinary conditions, electromagnetic energy may reach such a magnitude that ordinary protective devices will not be adequate. Such tremendous amounts of energy can be released during a nuclear detonation or packaged in a laser beam making protection of the eye against these energy sources is a must; otherwise, permanent injury to the eye will ensue (109).

Nuclear Flash Protection

In spite of the fact that the nuclear weapons threat has been dramatically reduced, it still remains; therefore, the material to follow has more than an historical interest.

The eye is more susceptible to injury from nuclear explosions at far greater distances than any other organ or tissue of the body. When a pupil of a given size is exposed to a nuclear detonation at a given distance, it will result in a certain amount of energy being distributed over the image on the retina. When one doubles the distance from the detonation, the amount of energy passing through the same size pupil will be only one fourth as great. The image area on the retina, however, will be only one fourth as large; therefore, the energy per unit area will remain constant irrespective of the distance from the detonation except for the attenuation due to the atmosphere and ocular media. The potential danger of flashblindness and chorioretinal burns resulting from viewing nuclear fireballs remains a threat to aircrew members.

During daylight, with high-ambient illumination and through a small pupillary diameter, the retinal burn and flashblindness problems are greatly diminished. At night, with a large pupil, protection is a must. Many different ideas for eye protection have been advocated. Fixed-density filters, on either the pilot or the windscreen, electromechanical and electro-optical goggles, explosive lens filters, and phototropic devices have been developed. The sum total of all this work is that a 2% transmission-fixed filter, gold-plated visor gives adequate protection against retinal burns and reduces flashblindness to manageable proportions during daylight. This filter, however, cannot be used at night. Another aid, a readily available countermeasure to flashblindness, day or night, is the ability to raise instrument panel illumination by auxiliary panel lighting to 125 ft-c. This increased illumination significantly reduces visual recovery time. The ideal "omni" protector against nuclear flash is still being sought. The most recently developed material for protecting against nuclear flash is a transparent ferroelectroceramic material (lead lanthanum zirconate titanate, PLZT) placed between crossed polarizers, as shown in Figure 14-31, reacts to the light energy of detonation within 50 to 100

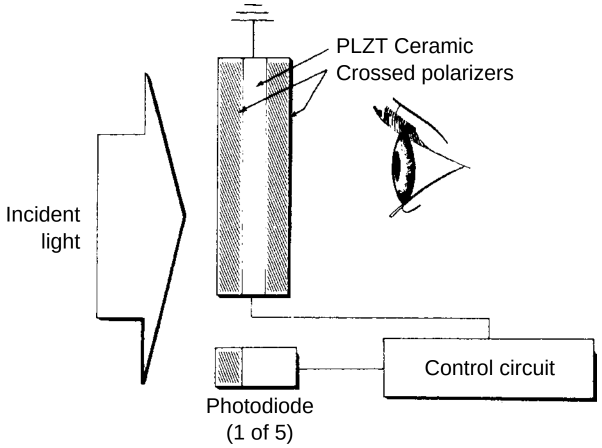


FIGURE 14-31 Flash-blindness-protective goggles. PLZT, lead lanthanum zirconate titanate.

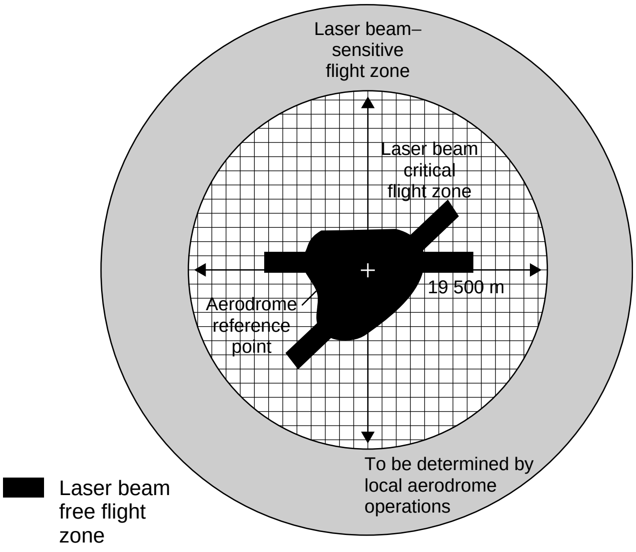
milliseconds, reaching an optical density of 3. Its largest drawback is that in its open state, it transmits only 20% of the light. It may also be of interest that the 2%-transmitting gold-plated visor, developed at the USAFSAM for protection of aircrew against the flash of enemy nuclear weapons, was never used for that purpose. Instead, it was used as the outermost visor by astronauts in the peaceful exploration of the moon and space.

Laser Eye Protection

Lasers (light amplification by stimulated emission of radiation) produce monochromatic, coherent, collimated light. The laser beam diverges little, so that the energy of the beam decreases only minimally with increasing distance from the source. Laser energy is capable of severely injuring tissue in the eye that absorbs the beam energy. For example, Argon (480 nm), frequency-doubled YAG (532 nm), ruby (693 nm), neodymium (1,064 nm) lasers can injure the retina and choroid because these tissues absorb these wavelengths. Laser classification has been recently revised by the American National Standards Institute standard Z-136.1 as follows (110):

Laser Class	*Allowed Continuous Wave (CW) Laser Power*
Class 1	40 μw for blue and 400 μw for red
Class 1M	Same as class 1
Class 2	1 mW
Class 2M	Same as class 2
Class 3R (visible)	5 mW
Class 3R (nonvisible)	5 times class 1
Class 3B	500 mW
Class 4	Not limited

The military applications of lasers are increasing in the areas of target ranging and illumination. Pilots themselves are not usually at hazard from their own laser beams, but technicians and others working with such instruments should wear protective goggles or visors with an optical density that is considered safe at the laser wavelength being employed. The laser itself may be used as a weapon. Here it would be helpful if one knew the threat and used a filter to protect from that waveband. Ideally, an agile filter would be in the open state but close down when struck by a laser beam. Unfortunately, this type of protection is as yet not available. Another area of interest especially for aviation is the use of lasers around aiports. The International Civil Aviation Organization (ICAO) recently adopted an international standard that controls lasers emitted in and around international airports (111). Those restrictions were based on earlier FAA limitation established to protect U.S. airports from laser beam intrusions (Figure 14-32). The medical management of laser eye injuries is fully covered in a USAFSAM technical report, TR-88-21 (112). Injuries to the external eye, cornea, and lids can be treated. Retinal injuries affect vision, depending on the energy density absorbed by the retina and, more importantly, the location of the injury on the retina. A direct hit to the fovea markedly reduces central vision and is permanent, with little recovery of function. Other safety factors should also be considered, such as educating the worker in laser safety, not looking at the laser beam, examining for reflective materials in the laboratory or shop, posting warning signs, and operating a laser in well-lit rooms when possible (small pupils). Laser-safe working distances, the selection of protective materials, and safety programs are becoming quite complicated and involved for the flight surgeon to manage alone. One should have help from a bioenvironmental engineer or health physicist when possible.



Note — The dimensions indicated are given as guidance only.

FIGURE 14-32 Protected flight zones.

The flight surgeon or aeromedical examiner, however, is responsible for setting up and performing ocular surveillance programs. Minimally, the examiner should give laser workers complete ocular examinations before they begin their assignments or employment. This should include a distance and near-central visual acuity examination, both corrected and uncorrected, an Amsler grid examination, color vision and an ophthalmoscopic examination of the fundus, with special attention to the fovea (any anomalies of the fundus should be meticulously recorded or a retinal photograph taken). A similar examination should be performed at the termination of the assignment or employment. Annual ocular examinations are not considered necessary; however, anyone working with lasers who has an ocular complaint or claims to have been injured by a laser should be examined and the complaint evaluated (113).

As stated at the beginning of this chapter, vision plays the most important role in data gathering for humans; anything affecting vision is significant for the aviator. The flight surgeon and aeromedical examiner who care for aviators and attempt to increase their effectiveness should pay special attention to the vision and visual systems of aviators.

Instantaneous, clear vision assures us of receiving uncluttered and accurate visual data into our mental computers. The integrating and processing of this information after its reception is in the domain of the central nervous system and is enhanced by training and education of the aviator. If inaccurate or incomplete visual information were received, however, we would almost be assured of failing to perform the task. With the time element for decision making becoming ever shorter in modern aviation, there is added impetus to look carefully at the visual system.

This chapter examined the physical, physiologic, medical, and bioengineering aspects of vision. With visual selection and enhancement by visual aids, the aviator's visual range has been extended, thereby giving more time for reaction and decision making. After selecting aviators with exceptional visual capabilities, it is important to employ the techniques for maintaining and protecting their vision and visual apparatus so that they enjoy full flying careers. Ophthalmology and the other visual sciences are now complex, scientific specialties. This chapter, however, has attempted to give information and data in a manner that is understandable and useful for all physicians and others interested in the subject.

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