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REFRACTIVE ERROR, CLINICAL OPTICS, AND CONTACT LENSES*

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I. Physical optics affecting vision and correction of visual refractive errors

A. Wavelength of light.

Electromagnetic radiation exists in many forms. The characteristic of the radiation that determines the form in which it is encountered is the wavelength. Long wavelengths are encountered as radio transmissions or radar; these emit a low energy. Short wavelengths are encountered as cosmic rays and x-rays; these emit a high energy. The visible portion of the electromagnetic radiation spectrum occurs between the ultraviolet and infrared portions, from 380 nm at the violet end of the spectrum to 760 nm at the red end.xs

B. Frequency of light waves.

The frequency of electromagnetic radiation is the number of times a particular position on the wave passes a fixed point in a fixed interval of time. It is inversely related to the wavelength. For example, radio waves, which occur as long wavelength radiation, have a frequency of 10^4 to 10^8 cycles per second (cps), whereas the visible part of the spectrum is in the 10^{14} to 10^{15} cps range, and includes shorter wavelength radiation.

C. Velocity of light waves.

The entire spectrum of electromagnetic waves travels at a speed of 3×10^8 m per second (186,000 miles per second) in a vacuum. The wavelength and frequency of light can be spoken of interchangeably because they are related through the following equation: Wavelength × frequency = velocity of light = 3×10^8 m per second.

D. Index of refraction.

Although the frequency of light does not vary with the density of the medium through which it is traveling, the speed is reduced in a dense medium. The ratio of the velocity of light in a vacuum to the velocity of light in a particular medium (*n/n'*) is referred to as the index of refraction for that medium. Because the frequency of radiation does not vary with the medium and the speed does, it follows that the wavelength in a dense medium is less than it is in air and is proportional to the change in speed. Each medium, therefore, has a different refractive index for a given wavelength. Short wavelengths, or blue light, are slowed down or refracted more than long wavelengths, or red light. This accounts for the **chromatic aberration** present in the eye or in single-element lens systems. The visible spectrum is defined in relationship to chromatic aberration and is described by the use of the C (red) - F (blue) line.

E. Quanta or photons.

The energy in electromagnetic radiation is measured in units called *quanta* or *photons.* The energy of an individual photon is proportional to the frequency or inversely proportional to the wavelength. Therefore, the energy of a photon at 400 nm is twice as great as that of a photon at 800 nm. For example, red light is innocuous, ultraviolet light produces burns, and x-rays produce severe damage to tissues.

F. Loss of light by reflection or absorption.

With respect to the eye, the light incident on the retina from a light source is decreased by loss from reflection at the cornea, lens, and retinal surfaces. Although the cornea is quite transparent from 400 to 1,200 nm, the crystalline lens does absorb some of the radiant energy, particularly short wavelengths. The young, healthy lens transmits incident light of 320 nm. Absorption at the blue end of the visible spectrum increases with age as xanthochromic (yellow-brown) proteins accumulate in the lens. Some of the short wavelength radiation is also absorbed by the yellow pigment in the macular region of the retina.

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G. Color of light.

The physical stimulus that is responsible for the sensation of color is the wavelength of the radiation. Wavelength in the region around 430 nm produces a violet sensation, around 460 nm blue, around 520 nm green, around 575 nm yellow, around 600 nm orange, and around 650 nm red. A mixture of wavelengths, such as occurs in sunlight, produces a white sensation.

H. Reflection.

When light rays strike a smooth surface, they may bounce off the surface, or be reflected, rather than pass through. Reflection from a polished surface is referred to as “regular” or “specular” reflection. This does not occur randomly but follows a simple rule—the angle of reflection is equal to the angle of incidence and lies in the same plane. The angle of reflection and the angle of incidence are measured relative to the surface perpendicular at the point of impact. When light is reflected, a plane or flat mirror reverses the direction of the light rays only and does not effect vergence, so no magnification, minification, or image inversion occurs. Convex or concave reflective surfaces can change the vergence of light rays and focus them, resulting in an altered image. This has a practical significance for spectacle wearers. Reflections from the ocular surfaces of corrective lenses can produce virtual images near the far point plane of the eye, images that can be annoying to the patient. The images can be eliminated by **tilting the lenses** slightly or by using an **antireflective coating** if necessary. The cornea can also be used as a reflective surface. The principal of **keratometry** depends on the anterior surface of the cornea, which acts as a concave mirror. By measuring the size of the reflected image, the radius of curvature can be calculated. The cornea is also employed as a reflecting surface when checking it for irregularity with a **keratoscope.** By examining the reflected images of a series of concentric circles, one can check for distortion. It is also worth noting that objects appear as a particular color because they preferentially reflect wavelengths of that color and absorb the other wavelengths.

I. Refraction of light.

When rays of light traveling through air enter a denser transparent medium, the speed of the light is reduced and the light rays proceed at a different angle, i.e., they are refracted. The one exception is when the rays are incident perpendicular to the surface (collimated or paraxial light). In this case the speed of the light is reduced but the direction of the light is unchanged.

1. **Snell law of refraction.** The refraction of light at an interface is described whereby the angle of incidence and the angle of refraction are related to the density of the medium for a specific wavelength. When light passes from a medium of low density to a medium of high density, Snell law predicts that the light ray will be bent toward the normal, a line perpendicular to the surface at the point of impact (Fig. 14.1A). In other words, the angle of refraction is less than the angle of incidence when going from a low-density to a high-density medium. Conversely, when light passes from a high-density to a low-density medium (such as out of a tank of water into air), the angle of refraction is greater than the angle of incidence. By bending the surface of a transparent medium that has a high density, such as the cornea or a piece of glass, the angle of incidence can be altered, and by employing Snell law, the deviation of light rays by this altered surface can be predicted. All light rays from real objects diverge from one another; when these rays encounter a medium of high density, they can be made less divergent, parallel to one another, or convergent, depending on the shape and index of the refracting element or lens. By using simple formulas, the point at which the redirected rays come to a focus can be calculated quite easily.

Fig. 14.1. A: Refraction of light is the change in direction in passage of light between media of different densities. **B:** Measurement of lens-focusing power in diopters by plus **(A)** and minus **(B)** lenses. D, diopters.

2. **Measurement of lens power.** Lenses are measured in **diopters** (D). The power of a lens in D is the reciprocal of its focal length (f) in meters: D = 1/f. For example, a lens that focuses light from an object at infinity (parallel light rays or 0 vergence) at a plane 1 m beyond the lens is a 1-D lens (Fig. 14.1B). If it focuses the light at a plane 0.5 m beyond the lens, it is a 2-D lens: 2 = 1/0.5.

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II. Types of corrective lenses

A. Spherical lenses

Spherical lenses have equal radii of curvature in all meridians.

1. **Convex or plus lenses.** By convention, high-density optical surfaces that are convex are referred to as **plus lenses.** They refract light rays so as to make them more convergent (or less divergent). Plus lenses of the same power can be made with a variety of radii, because it is the relationship of the two surfaces of a spectacle correcting lens that determines the power of the lens (Fig. 14.2A). A **meniscus form,** in which the front surface is more convex than the back surface is concave, results in the most desirable lens form for spectacles, because there is less spherical aberration over a wider area of the lens. A plano–convex-shaped plus lens will also reduce aberration. Plus lenses are used for the correction of **hyperopia, presbyopia,** and **aphakia.** When a nearby object is viewed through a plus lens, the object looks larger. If the lens is moved slightly from side to side, the object appears to move in the direction **opposite** to the movement of the lens. Plus lenses can also be identified by their physical characteristics; they are thicker in the middle and thinner at the edges.

Fig. 14.2. A: Spherical lens designs. Plus lenses for correction of hyperopia or presbyopia. **B:** Minus lenses for correction of myopia.

2. **Concave or minus lenses.** High-density optical surfaces that are concave are referred to as **minus lenses.** They refract light rays so as to make them more divergent (or less convergent). As stated previously, it is the relationship of the two surface radii that determines the resultant power. Minus lenses can also be made in many **forms** (Fig. 14.2B). The most common design used in minus spectacle lenses is the **meniscus,** wherein the back or ocular surface is more concave than the front surface is convex. **Myodisc** lenses (biconcave) are used on patients who need very strong minus lenses. They induce less peripheral distortion, but offer a smaller focused central field than the meniscus lens. High-density plastic (polycarbonate) lenses have a higher refractive index than crown glass and may be used to reduce the thickness of high minus lenses. Minus lenses are used to correct **myopia.** When a nearby object is viewed through a minus lens, the object looks smaller. If the lens is moved

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slightly from side to side, the object appears to move in the **same** direction as the lens. Minus lenses are thin in the middle and thick at the edges.

B. Toric lenses

Toric lenses are shaped like a section through a football. One meridian is more curved than all of the others, and the meridian at right angles to the steepest meridian is flatter than all of the other meridians. In a toric lens, the meridians of least curvature and the greatest curvature are always at right angles to one another and are referred to as the **principal meridians.** Toric lenses are prescribed to correct **astigmatism.** Toric lenses can be identified by observing a vertical contour such as a window or door frame through the center of the lens and rotating the lens in a vertical plane (parallel to the surface that is being observed). If the lens is a toric lens, the edge of the **vertical contour is broken** or discontinuous in the area viewed through the lens. The image will also appear to rotate clockwise or counterclockwise as the lens is rotated back and forth. If the same vertical contour is viewed through the center of a spherical lens, it remains continuous when viewed within and outside the borders of the lens, and does not appear to rotate when the lens is rotated. Toric lenses can be plus lenses, minus lenses, one principal meridian plus and the other minus, meniscus lenses, or they can be fabricated in a planocylinder form in which one principal meridian has zero optical power. Toric lenses are also referred to as **spherocylinders.**

C. Prisms.

A prism is an optical device composed of two refracting surfaces that are inclined toward one another so they are not parallel. The line at which the two surfaces intersect is the apex of the prism. The greater the angle formed at the apex, the stronger the prismatic effect [Fig. 14.3A(1)]. Because the two surfaces of a prism are usually flat, they alter the direction of the light rays, but not their vergence. An object viewed through a prism appears to be **displaced in the direction of the prism apex,** but the focus is not altered and no magnification or minification occurs. Prisms are usually prescribed to assist a patient with an **extraocular muscle imbalance,** which results in a deviation of one visual axis relative to the other, so that the patient may achieve single binocular vision or do so more comfortably. They may be oriented in the spectacle correction so as to produce horizontal, vertical, or both horizontal and vertical displacement, as needed. The strength

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of a prism is measured in **prism diopters (pds).** The prism power is equal to the displacement in centimeters of a light ray passing through the prism measured 1 m from the prism. (Each diopter displaces a ray of light 1 cm at a distance of 1 m.) Two prism diopters of displacement are approximately equal to 1 degree of arc. See Chapter 12 for prescribing prisms.

Fig. 14.3. A: Prism effects. **(1):** Prismatic displacement of image for assistance in muscle balance problems. **(2):** Chromatic aberration through varying degrees of refraction of lights of differing wavelength (color). **B:** Spherical aberration induced by varying degrees of light refraction from center of lens to edge.

D. Lensometers

Lensometers are precision instruments used to measure the spherical power, cylindrical (toric) power and the corresponding axis, and prism power, if present, of a spectacle or contact lens. Synonyms include: vertometer, vertexometer, dioptometer, and focimeter.

1. **Technique.** The lens to be measured is placed on the lensometer stage, and the **power wheel** is turned until the target mires are in focus. The mires cross each other at right angles; there are three lines in one meridian and one in the other. If the mires all focus simultaneously at a given power, no cylinder is present and the lens is completely spherical. The power is read directly off of the power wheel. The second wheel on the lensometer is an **axis wheel,** which can be rotated to turn the mires until they are lined up along the principal meridians of a lens containing a cylinder. Alignment is correct when the crossing lines are perfectly straight (not broken). The power wheel is then turned to focus the strongest plus power of the lens (single line meridian). When this is focused using the greatest plus power (or least minus power), the spherical power component is recorded. The power wheel is turned again to bring the weaker (more minus) meridian into focus (three-line target) and the cylindrical power component is noted as well as the axis of that meridian, which is read directly from the axis wheel. The lens prescription is the strongest plus power minus the **difference** in power between the two settings, and the axis of the cylinder is that of the more minus meridian, as indicated on the axis of the wheel.
2. **Example of *lensometer* calculations**
    a. Strongest plus meridian reading: +4.00

       Weaker plus meridian reading: +2.50

       Axis of weaker meridian: 80 degrees

       Final power: +4.00 = -1.50 × 80 degrees.

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    b. Strongest plus (weakest minus) meridian reading: -2.00

       Weaker plus (stronger minus) meridian reading: -3.00

       Axis of weaker plus meridian: 40 degrees

       Final power: -2.00 = -1.00 × 40 degrees.
3. **Plus cylinder prescriptions** are less convenient and less frequently used, but may be done by reversing the above technique. For example: Weakest plus meridian: +1.00

   Strongest plus meridian: +2.50

   Axis of strongest plus meridian: 50 degrees

   Final power: +1.00 = +1.50 × 50 degrees.
4. **Conversion of minus cylinder prescriptions** to plus or the opposite is carried out by reversing the sign of the cylinder, adding the difference between the two lenses, and adding 90 degrees to its axis, e.g., +3.00 = -2.00 × 20 degrees converts to +1.00

= +2.00 × 110 degrees.

5. **Prism** power is measured by reading the amount of decentration, from the optical center, of the cross mires. This is measured by counting the number of circles or lines on the eyepiece reticule away from center. Base-in is noted if the power center is located on the nasal side of the lens; base-out is noted if temporal.

III. Refraction techniques.

Refraction is the term applied to the various testing procedures employed to measure the refractive errors of the eye to provide the proper correction. **Refractive error is by far the most common cause of poor vision.** Fortunately, it is generally the easiest to treat.

A. Retinoscopy

Retinoscopy is an objective method of analyzing the optics of the patient's eye to determine the refractive error. A retinoscope is a handheld instrument that the examiner uses to illuminate the inside of the patient's eye and observe the light rays (reflected from the retinal pigmented epithelium and choroid) as they emerge from the patient's eye. This is accomplished by using a mirror to reflect the light along the line connecting the examiner's and the patient's pupils, and by creating a small aperture in the mirror that allows the examiner to view the patient's illuminated pupil. The light reflected from the patient's retina is refracted by the ocular media and focused at the far point of the patient's eye or punctum remotum. The patient must observe an object at 6 m (20 ft) or beyond to control for the accommodative reflex. By placing plus or minus lenses in front of the patient's eye, the patient's focal point can be altered until it is brought to the examiner's pupil, which produces a visible end point. This process involves moving the streak of light back and forth across a series of lenses held in front of the patient's pupil, resulting in a linear light reflex moving in the same (hyperopia) or opposite direction (myopia) as the light. The filling of the entire pupil with light that does not move indicates neutralization of the refractive error in that meridian and is the end point reading for that meridian. The linear streak of light can be rotated 360 degrees through the pupil to examine different meridians of the eye. In the case of astigmatism, the retinoscope linear light must be empirically lined up along a principal meridian (the clearest light streak as the retinoscope light is rotated) and plus or minus lenses put up until movement of light in that meridian is neutralized and the lens power recorded. This is repeated in the meridian 90 degrees away for the second lens and axis. By knowing how far the examiner is from the patient and what lenses are required, it is a simple matter to calculate the amount of ametropia. This technique is highly accurate and useful when used by a skilled retinoscopist, with a pupil of reasonable diameter and clear media. Opacities of the media, tiny pupils, poor fixation by the patient, or distortion of the light reflex can all be troublesome, however. Prescribing lenses on the basis of retinoscopic findings alone can too often result in a prescription that is not well tolerated by the patient.

B. Subjective refraction

Subjective refraction is a tool whereby the examiner relies on patient responses to narrow the prescription further. Retinoscopy findings or habitual spectacle power may be the starting guide for subjective refraction. In

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the absence of astigmatism, the refraction is simply a matter of adding more plus or minus power until the patient reads his or her best visual acuity with the most plus or least minus power. In the presence of **astigmatism,** and to help test for it, the **fogging technique** is very effective (see sec. VI.B.3.e., below). Both retinoscopic and subjective refractions involving astigmatism may be refined by the **Jackson cross-cylinder (JCC) technique** (see sec. VI.B.3.f., below).

C. Automated refraction.

In recent years, electronic microcircuitry and computer technology have combined to develop sophisticated instruments for refracting patients. Currently, these instruments require a technician to operate them. The standard to which these instruments are compared is retinoscopy or subjective refraction, or both. In general, automated refractometers are reasonably accurate. To provide reliable and valid data, however, the instrument must be properly in line with the patient's visual axis, accommodation must be relaxed, the pupil must be of satisfactory size, and the media must be sufficiently clear. There is no evidence that indicates that automated refraction is better than, and there is considerable controversy as to whether it is as good as, retinoscopy and subjective refraction. The primary role for these instruments at this time would appear to be increasing the efficiency with which eye care can be delivered by indicating the approximate refractive error, which should then be manually refined by the refractionist to give the patient the most satisfactory vision. For example, an automated refractor may indicate cylinder axis of 15 degrees, but the patient has been wearing spectacles at axis 10 degrees without discomfort. It is wiser to give the axis 10 degrees with perhaps some sacrifice of visual clarity than axis 15 degrees, which is clear but feels “uncomfortable.”

D. Cycloplegic refraction.

Cycloplegia is the employment of pharmaceutical agents such as atropine, tropicamide, or cyclopentolate to paralyze the ciliary muscle temporarily to stabilize the accommodative reflex of the eye so that a definitive end point may be measured. It is useful in young patients with highly active accommodation to ensure complete relaxation of the ciliary muscle so that the ametropia can be measured accurately in young hyperopes, thereby avoiding overcorrection. **Methods of inducing cycloplegia** include 1% cyclopentolate or tropicamide, one drop q5min for two or three applications in the office just before refraction, or atropine 1%, one drop tid for 3 days before the refraction.

IV. Aberrations.

Optical systems generally contain imperfections referred to as *aberrations.* The important aberrations in the visual system and spectacle lenses are chromatic aberration, spherical aberration, radial astigmatism, and distortion.

A. Chromatic aberration.

The index of refraction for any transparent medium varies with the wavelength of the incident light. This variation is such that blue light is refracted more than red light [Fig. 14.3A (2)]. This accounts for the chromatic dispersion that occurs when white light is passed through a prism and a rainbow effect is produced. In a convex or plus lens, blue light is focused slightly closer to the lens than red light. The same is true of the human eye, in which blue light is focused slightly in front of red light.

B. Spherical aberration.

In most discussions of optics, certain assumptions are made for the sake of simplicity. Higher-order optics become quite complex and contribute little to the understanding of the visual system or to measuring and prescribing for refractive errors. So far, it has been assumed that all light rays from an object that pass through a lens come to focus at a single image point. A closer analysis reveals that this is true only for light rays that are paraxial, i.e., that pass through the center of the lens. Those light rays that are parallel to the axis but that pass through the periphery of the lens are usually refracted more than the paraxial rays. Peripheral rays will focus closer to the lens (Fig. 14.3B). Every object point on the axis of the lens will then be represented by a blur circle rather than a point focus. The size of this blur circle can be reduced by restricting the passage of light through the lens

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to the central portion, as is done when an object is viewed through a pinhole aperture. This same effect accounts for the increased depth of focus obtained when the iris diaphragm of a camera is reduced in size or when the pupil of the eye is constricted. Spherical aberration can produce a variable concentric retinoscopic reflex in children, with the peripheral portions of the pupil appearing myopic (against motion) while the central portion is at neutrality.

C. Radial astigmatism

Radial astigmatism occurs when light rays pass through a lens obliquely. Instead of focusing a point of light as a point image, two linear images form at right angles to one another with a “circle of least confusion” between them. This form of aberration is of no great significance in the eye; however, it can create considerable blurring of the image formed by spectacle lenses.

D. Distortion

Distortion is the result of differential magnification in an optical system. This occurs because light from some parts of the object is focused by the central portion of the lens, while other parts are focused by peripheral portions of the lens. In other words, the shape of the image formed does not correspond exactly to the shape of the object. For practical purposes, this is not a problem in the eye, but it can be troublesome in higher-powered spectacle lenses. High plus lenses produce “pincushion” distortion, and high minus lenses result in “barrel” distortion.

V. The eye as an optical instrument.

The analogy of the eye and the camera is a useful one. The focusing elements of the eye are the cornea and the crystalline lens, and the “film” is the retina. To simplify discussions of the eye as an optical instrument, we use some approximations and resort to the schematic or reduced eye, wherein all light rays are assumed to be paraxial and all elements perfectly aligned on the visual axis.

A. The cornea

The cornea contributes approximately two-thirds of the refracting power of the eye. This is true because more deflection of light rays occurs at the air–cornea interface because of the large difference in index of refraction between these two media. The crystalline lens is in fact a more powerful refracting lens than the cornea in air because it is biconvex and each of its surfaces is more convex than the cornea. The lens, however, is in the aqueous–vitreous medium, and the difference in refractive index at the aqueous–lens and lens–vitreous interfaces is much less. The cornea has an index of refraction of 1.376 and contributes +**43 D** to the eye.

B. The crystalline lens

The crystalline lens has an index of refraction that increases from the cortex to the nucleus, but averages 1.41 with a power of +**20 D.** Because these two refracting elements are separated, the **total power of the eye** is not their sum but the equivalent power of +**58.7 D.**

C. The pupil

The pupil is also a significant component of the eye's optical system. It can constrict, reducing the amount of light that enters the eye, decreasing aberrations, and increasing the eye's depth of focus. This accounts for the ability of many people, who require glasses, to get along without them when the illumination is good.

D. The retina

The retina is a unique kind of film. It contains the “coarse grain” but highly sensitive rods for registering images at very low levels of illumination and the “fine grain” color-sensitive cones for high resolution and discrimination at high levels of illumination. Only one or two quanta of light energy are required to activate the rods. On the other hand, rapid neural adaptation and the more gradual process of adjusting the steady state between bleaching and regeneration of retinal visual pigments enable the retina to function perfectly at extremely high levels of illumination. What other film functions so well both in moonlight and at high noon? The manner in which visual images are formed, transmitted to the visual cortex, and interpreted is a fascinating story but not appropriate to this discussion.

VI. Refractive errors of the eye (Fig. 14.4).

Fig. 14.4. A: Far point (image distance focused on retina in accommodatively relaxed eye) in myopia, emmetropia, and hyperopia. **B:** Focal points of myopic, emmetropic, and hyperopic eye with reference

to the retinal plane. **C:** Focal points of astigmatic principal meridians (objects at infinity): **(1)** simple hyperopic astigmatism, emmetropia/hyperopia; **(2)** simple myopic astigmatism, emmetropia–myopia; **(3)** compound hyperopic astigmatism, hyperopia–hyperopia; **(4)** compound myopic astigmatism, myopia–myopia; **(5)** mixed astigmatism, hyperopia–myopia.

A. Emmetropia.

The eye is considered to be emmetropic if parallel light rays, from an object more than 6 m away, are focused at the plane of the retina when the eye is in a completely relaxed state. An emmetropic eye will have a clear image of a distant object without any internal adjustment of its

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optics. Although most emmetropic rays are approximately 24 mm in length, a larger eye can be emmetropic if its optical components are weaker, and a smaller eye can be emmetropic if its optical components are stronger.

B. Ametropias

1. **Hyperopia.** When the focused image is formed behind the plane of the retina in ametropia, the eye is "too short" and is considered hyperopic. This is also referred to as *farsightedness.* Near images can be blurred unless there is sufficient accommodation, as in a child. Unless the optical system of the eye is actively altered to produce an increase in its power, hyperopic eyes will have blurred images for distant objects also, as any elderly hyperope will confirm. Most children are born about +3 D hyperopic, but this usually resolves by age 12 years.
    a. **Structural hyperopia** is based on the anatomic configuration of the eye.
        1. In **axial hyperopia,** the eye is shorter than normal in its anteroposterior (AP) diameter, although the refracting portions (e.g., lens, cornea) are normal. These eyes are more prone to develop **angle-closure glaucoma** because of the shorter anterior segment with crowding of the filtration angle. The optic nerves are also smaller and more densely packed, because they are crowded at the disk. Physiologic cupping is uncommon, and **pseudopapilledema** may be noted. The latter is seen in eyes with

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           greater than +4 D of hyperopia, a normal blind spot on field testing, no venous congestion, and a disk that seems "swollen."
        2. **Curvature hyperopia** results when either the crystalline lens or the cornea has a weaker than normal curvature and consequently lower refractive power.
        3. **Index of refraction hyperopia** is the result of decreased index of

refraction due to decreased density in some or several parts of the optic system of the eye, thus lowering the refractive power of the eye.

b. **Accommodation in hyperopia** is of greater importance than the structural factors leading to it because accommodation is a key dynamic factor in correcting at least part of the refractive error. It is defined as latent, manifest facultative, and manifest absolute hyperopia.

   1. **Latent hyperopia** is that part of the refractive error completely corrected by accommodation. It is measurable not by manifest refraction but only with paralysis of accommodation via cycloplegic refraction. Latent hyperopia is the difference in measurement between manifest hyperopia and the results of the cycloplegic refraction, which reveals total hyperopia, latent and manifest.

   2. **Manifest facultative hyperopia** is that portion of hyperopia that may be corrected by the patient's own powers of accommodation, by corrective lenses, or both. Vision is normal with or without corrective plus lenses, but accommodation is not relaxed without the glasses.

   3. **Manifest absolute hyperopia** is that part of the refractive error that cannot be compensated for by the patient's accommodation. Distance vision is still blurred no matter how much accommodative power the patient uses. These patients readily accept the aid of plus lenses.

c. **The effect of aging** on hyperopia results from progressive loss of accommodative power, thus moving the eye from latent and facultative hyperopia to greater degrees of absolute hyperopia.

d. **Symptoms of hyperopia**

   1. **Frontal headaches** worsening as the day progresses and aggravated by prolonged use of near vision.

   2. **"Uncomfortable" vision** (asthenopia) when the patient must focus at a fixed distance for prolonged periods, e.g., a televised baseball game. Accommodation tires more quickly when held in a fixed level of tension.

   3. **Blurred distance vision** with refractive errors greater than 3 to 4 D or in older patients with decreasing amplitude of accommodation.

   4. **Near visual acuity** blurs at a younger age than in the emmetrope, e.g., in the late 30s. This is aggravated when the patient is tired, when print is indistinct, or lighting conditions suboptimal.

   5. **Light sensitivity** is common in hyperopes, is of unknown etiology, and is relieved by correcting the hyperopia without needing to tint the lenses.

   6. **Intermittent sudden blurring of vision** is due to a quick change in or **spasm of accommodation.** A shift toward myopia is present (pseudomyopia) and vision temporarily clears with minus lenses. The

accommodative spasm may be detected by cycloplegic refraction, which will reveal the underlying hyperopia.

7. **“Crossed-eyes” sensation** without diplopia is also due to excessive accommodation in a patient with an esophoria that is being pushed by the accommodation–convergence reflex into a symptom-producing state that “the eyes are crossing.”

e. **Treatment of hyperopia** is usually most satisfactory when slightly less power (1 D) than the total of facultative and absolute hyperopia is given to a patient with no extraocular muscle imbalance. If an accommodative esotropia (convergence) is present, then the full correction should be given. In exophoria, the hyperopia should be undercorrected by 1 to 2 D (see Chapter 12). If the total manifest refractive error is small, e.g., 1 D or less, correction is given only if the patient is symptomatic.

2. **Myopia.** When the focused image is formed in front of the plane of the retina in ametropia, the eye is “too long” and is considered myopic. This is referred to as *nearsightedness,* because there is a point less than 6 m in front of the eye that will be coincident with the retina when the optical system of the eye is relaxed.

a. **Types of myopia**

1. In **axial myopia,** the AP diameter of the eye is longer than normal, although the corneal and lens curvatures are normal and the lens is in the normal anatomic position. In this form of myopia may be found pseudoproptosis resulting from the abnormally large anterior segment, a peripapillary myopic crescent from an exaggerated scleral ring, and a posterior staphyloma.

2. In **curvature myopia** the eye has a normal AP diameter, but the curvature of the cornea is steeper than average, e.g., congenitally or in keratoconus, or the lens curvature is increased as in moderate to severe hyperglycemia, which causes lens intumescence.

3. **Increased index of refraction** in the lens due to onset of early to moderate nuclear sclerotic cataracts is a common cause of myopia in the elderly. The sclerotic change increases the index of refraction, thus making the eye myopic. Many people find themselves ultimately able to read without glasses or having gained “second sight.” They may usually be given normal distance vision for years simply by increasing the minus power in their corrective lenses, thus avoiding surgery.

4. **Anterior movement of the lens** is often seen after glaucoma surgery and will increase the myopic error in the eye.

b. **Clinical course.** Myopia is rarely present at birth, but often begins to develop as the child grows. It is usually detected by age 9 or 10 years in the school vision tests and will increase during the years of growth until stabilizing around the mid-teens, usually at about 5 D or less.

1. **Pathological (progressive) myopia** is a rare form of myopia that increases by as much as 4 D yearly and is associated with vitreous floaters, liquefaction, and chorioretinal changes. The refractive changes usually stabilize at about age 20 years, but occasionally may progress until the mid-30s, and frequently results in degrees of myopia of 10 to 20 D.
2. **Congenital high myopia** is usually a refractive error of 10 D or greater and is detected in infants who seem to be unaware of a visual world beyond their immediate surroundings, but who, fortunately, usually develop normal vision focusing on small objects held an inch or two from their eyes. This myopia is not generally progressive, but should be corrected as soon as discovered to help the child develop normal distance vision and perception of the world.

c. **Symptoms of myopia**

1. **Blurred distance vision.**
2. **Squinting** to sharpen distance vision by attempting a pinhole effect through narrowing of the palpebral fissures.
3. **Headaches** are rare, but may be seen in patients with uncorrected low myopic errors.

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d. **Treatment of myopia**

1. **Children** should be fully corrected and, if under 8 years of age, instructed to wear their glasses constantly both to avoid developing the habit of squinting and to enhance developing a normal accommodation–convergence reflex (see sec. VI.B.5., below). If the refractive error is low, the child may wear the glasses intermittently as needed, e.g., at school.
2. **Adults** under the age of 30 years are usually comfortable with their full myopic correction. Patients older than 30 years may not be able to tolerate a full correction over 3 D if they have never worn glasses before and may prefer a less than full correction, with resulting undercorrected distance vision but clear reading vision. The patient should be told that full correction might be given in the future if desired. Wearing full correction in a trial frame for about 30 minutes, with the patient both reading and looking at distance in the waiting room, may answer the question of whether to give full correction.
3. **Undercorrection of myopia** in childhood may result in an adult who has never developed a normal amount of accommodation for near focus. This person will be uncomfortable in full correction and complain that

the glasses are too strong and “pull” his or her eyes.

3. **Astigmatism.** The optical systems thus far discussed are spherical, that is, all the meridians of the lenses are of equal curvature, resulting in a surface that resembles a section through a spheroid. Many optical systems, however, are toric surfaces, in which the curvature varies in different meridians, thus refracting light unequally in those meridians and creating the condition known as astigmatism (see sec. II.B., above). Light rays passing through a steep meridian are thus deflected more than those passing through a flatter meridian. This results in the formation of a more complicated image, referred to as the “conoid of Sturm,” wherein a point source of light is represented by an image consisting of two lines that are at right angles to one another with a circle of least confusion in a plane midway between them (Fig. 14.5A). The steepest and flattest meridians of the eye are usually at right angles to one another, resulting in regular astigmatism. This is fortunate, because technology makes it possible to generate regular astigmatic surfaces in ophthalmic lenses easily so that astigmatism can be corrected economically.

Fig. 14.5. A: Effect of regular astigmatism on focal planes of eye, resulting in least blur (conoid of Sturm). **B(1):** Clock dial as seen by “fogged” patient with astigmatic error; 1 to 7 axis appears darker. **(2):** Two-line rotating dial is set at 1 to 7 position. Axis of correcting **minus** cylinder is 30 degrees (1 × 30). Minus cylinders are placed at 120 degrees (30 + 90 degrees) until all lines appear equal, thus indicating cylinder power and axis needed to correct astigmatic error. Patient is then “defogged.”

a. **Types of astigmatism**

1. **Corneal toricity** accounts for most of the astigmatism of the eye. If the **vertical meridian is steeper,** it is referred to as astigmatism **“with the rule,”** and if the **horizontal meridian is steeper** it is referred to as astigmatism **“against the rule.”** One meridian may be emmetropic and the other hyperopic or myopic, both may be hyperopic or myopic, or one may be hyperopic and the other myopic. In spherical ametropia, only one number is necessary to designate the power of the corrective lens, but in astigmatic corrections, three numbers are required to indicate the power needed in each principal meridian plus the axis to provide the correct orientation of the lens in front of the eye (e.g., +2.00 = -1.00 × 180 is a corrective lens prescription for with-the-rule astigmatism).

2. **Regular astigmatism** has principal meridians 90 degrees apart and **oblique astigmatism** has them more than 20 degrees from the horizontal or vertical meridians.

3. **Irregular astigmatism** results from an unevenness of the corneal surface such as in corneal scarring or keratoconus. The principal meridians are not 90 degrees apart and are so irregular that they cannot be completely corrected with ordinary toric lenses (cylinders). The **diagnosis** can be made by shining a light into the eye and observing

any irregularity of the pupillary reflex with the

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ophthalmoscope or retinoscope, by the use of a keratometer that measures the corneal curvature, by examination with a slitlamp, or by observing the corneal reflex with either a keratoscope or **Placido disk,** both of which contain concentric circles that are reflected by the surface of the cornea and that appear distorted in cases of irregular corneal astigmatism. Irregular astigmatism cannot be corrected with spectacle lenses, but can frequently be corrected by rigid contact lenses.

4. **Symmetric astigmatism** has principal meridians in each eye with similar but opposite axes, e.g., 20 degrees in the right eye and 160 degrees in the left eye, which together add up to 180 degrees.

b. **Symptoms of higher astigmatism** (>1.00 D) include:

   1. **Blurred vision.**
   2. **Tilting** of the head for oblique astigmatism.
   3. **Turning** of the head (rare).
   4. **Squinting** to achieve "pinhole" vision clarity.
   5. **Reading** material held **close to eyes** to achieve large (as in myopia) but blurred retinal image.

c. **Symptoms of lower astigmatism** (<1.00 D) include:

   1. **Asthenopia** ("tired eyes"), especially when doing precise work at a fixed distance. With-the-rule astigmatism produces more symptoms, but clearer vision than the same amount of against-the-rule astigmatism.
   2. **Transient blurred vision** relieved by closing or rubbing the eyes (as in hyperopia) when doing precise work at a fixed distance.

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   3. **Frontal headaches** with long periods of visual concentration on a task.

d. **Treating astigmatism** depends on the patient's visual needs and symptoms as noted above in terms of whether glasses are worn constantly or intermittently. It is not within the scope of this book to discuss in detail the many methods of measuring astigmatism for corrective lenses such as plus cylinders, Lancaster-Regan charts, or crossed cylinders, but the fogging technique followed by refinement with the JCC is a common method for **measuring regular astigmatic correction** using the clock dial and minus cylinders.

e. **Fogging technique.** Make the patient **artificially myopic (fogged)** to about 20/50 by putting enough plus sphere before the eye to focus all meridians anterior to the retina, i.e., to bring forward compound, simple, or mixed hyperopic astigmatism meridians where both (the former) or one (the latter two) focal plane is posterior to the retina. By making all meridians myopic, the refractionist **inhibits accommodation,** thus stabilizing the refractive error of the eye, and then may use minus cylinders to determine the principal meridians.

1. Have the patient **identify** the **darkest, most distinct line** on the spokes of the astigmatic clock chart (Fig. 14.5B), e.g., the 1 to 7 o'clock line, and multiply the lower number by 30 degrees to get the proposed axis of the correcting cylinder.
2. **Switch to a two-line rotating chart** with one line oriented along one principal meridian, e.g., 1 to 7 o'clock. As these lines cross perpendicularly, the other line will be on the opposite principal meridian.
3. Place **increasing strength minus cylinders** before the eye at an axis 90 degrees from the blackest line, e.g., 4 to 10 o'clock or 120 degrees (30 + 90 degrees). Add one -0.25- to -0.50-D cylinder at a time until both lines are equal in darkness and distinctness. They will still be blurred. For each -0.50 D of cylinder added after the original -0.75 cylinder is in, add a +0.25-D sphere to keep the patient artificially myopic.
4. Switch to a **distance vision chart** and reduce plus spheres until the patient achieves maximum clarity of vision.
5. **Example:**
   a. +2.00 fogs to 20/50.
   b. 4 to 10 line is darkest.
   c. 4 × 30 degrees = 120 degrees (axis of correcting cylinder).
   d. -1.00 × 30 degrees evens out darkness of the two-line chart.
   e. Reducing plus lenses to +0.25 gives sharpest vision on distant reading chart.
   f. Final prescription: +0.25 = -1.00 × 120.
6. **If axis falls between hours** on the clock, multiply by the lowest number plus half, i.e., between 1 and 2 o'clock = 1.5 × 30 degrees = 45 degrees is the correcting cylinder.
7. **Refine** the final prescription by using the JCC. If the final cylinder correction is greater than 3 D and the patient has never worn glasses before, giving one-half to two-thirds of the cylinder correction may be prudent to avoid intolerance and discomfort from an initial full correction.

f. **The Jackson cross-cylinder (JCC)** is a lens of equal-power plus (white dot) and minus (red dot) plano cylinders with axes 90 degrees apart. Lens powers range from -0.12 to -1.00 cylinder. To test if the patient's **lens axis is correct,** place the JCC before the eye with its handle parallel to the axis of the cylinder in the trial frame. Rotate the handle of the JCC in one direction and then turn it over to the other side, thus changing the combined cylinder axes. Turn the trial frame axis in the direction toward the JCC axis that gives better

vision on the distance chart and repeat the test. The end point is when rotating the JCC handle over makes no change in vision. To ascertain if the **cylinder strength is correct,** place the JCC with its handle at 45 degrees with the axis of the trial frame cylinder such that one axis of the JCC will be parallel to and the other 90 degrees from the trial frame cylinder. If vision is better when similar axes are parallel, e.g., minus over minus, the trial frame cylinder needs to be made stronger and vice versa. If rotating the JCC before the trial frame is equally bad in both directions, the cylinder is correct.

4. **Anisometropia** is a state in which there is a difference in the refractive errors of the two eyes, i.e., one eye is myopic and the other hyperopic, or both are hyperopic or myopic but to different degrees. This condition may be congenital or acquired due to asymmetric age changes or disease.

   a. In anisometropia, the patient may be made visually uncomfortable by

      1. **Visual acuity differences**between the two eyes.

      2. **Aniseikonia:** difference in size of the ocular image in each eye (possibly causing retinal rivalry).

      3. **Anisophoria:** varying heterophoria (muscle imbalance) in different fields of gaze depending on the eye used for fixation.

      4. **Suppression scotoma, amblyopia,** or **strabismus,** which may develop in young anisometropes. This may be mitigated by the proper refractive correction or even aggravated by the spectacle correction by inducing obstacles to fusion, such as anisophoria and aniseikonia.

   b. **Treatment**

      1. In **children,** both eyes should receive the best visual correction and any muscle imbalance identified and corrected with prisms or surgically.

      2. **Adults** should receive the best correction that will not result in ocular discomfort. Usually the more ametropic (poorer) eye is undercorrected.

5. **Accommodation.** The cornea is a static or fixed surface. The crystalline lens, however, is capable of increasing its plus power. This is referred to as *focus,* or *accommodation.* The lens is suspended in the eye by thousands of chemical strands, called *zonules,* that are attached to the ciliary body at one end, and the lens capsule at the opposite end. When the ciliary muscle is relaxed, the zonules maintain a slight tension on the capsule. Since the ciliary muscle is a circular sphincterlike muscle, constriction results in a slight decrease in the diameter of the circle. This reduces the tension of the zonules on the lens capsule, which is elastic. This action squeezes the lens fibers in such a way that the anterior pole, and to a lesser extent the posterior pole, becomes more convex, thereby increasing the power of the lens. This

change in power is called *accommodation.* An emmetrope who wants to view a nearby object contracts the ciliary muscle, which results in an increase of power or accommodation to focus the image back to the plane of the retina.

a. **Amplitude of accommodation** is the range of plus power the lens can produce. This varies with age and is a critical factor in the correction of hyperopia and presbyopia. Table 14.1 indicates a few of the Duane monocular and Donders binocular near point averages of accommodative power at various ages. It is useful to memorize at least the low-, middle-, and high-range figures.

Table 14.1. AMPLITUDE OF ACCOMMODATION (DIOPTERS)[a]

b. The **near point** or **punctum proximum (PP)** is the nearest point at which a person can see clearly. In the unaided (no glasses) emmetropic eye, the PP and retina are conjugate foci, and the amplitude of accommodation may be measured directly using this distance because it is unaltered by a refractive error. For example, a 20-year-old emmetrope is able to focus clearly at 10 cm, thus indicating a total accommodative power of 10 D by the formula d = 1/focal distance (m).

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Given the same accommodative power of 10 D, if this patient were a 2-D myope, the total focal length would be 8.3 cm because of the 12-D focal point (10 D accommodation plus 2 D myopic error). A 2-D hyperope with 10 D of accommodation would focus at 12.5 cm (10 D accommodation minus 2 D hyperopic error = 8 D focal length).

c. The **far point** or **punctum remotum** is the farthest point at which a patient can see clearly. In emmetropia, the retina is focused at (conjugate with) infinity. In myopia, the focal point is anterior to the retina; in hyperopia, it is behind the retina, i.e., beyond infinity.

d. **Determining the amplitude of accommodation** may be done by several methods: minus sphere test, Lebensohn target, cycloplegic testing. The simplest method is the **push up method** where, with a distance correction before the eyes (if needed), a fine-print target is gradually moved toward the patient's eyes until the patient notes onset of blurred vision. This test is done monocularly in each eye in the young because of possible extraocular muscle balance effect on the blur distance. The distance at which the blur begins is converted to diopters of accommodative power (D = 1/focal distance [m]).

e. **Symptoms of decreased accommodative powers** can occur as a result of presbyopia, exophoria, exotropia, convergence insufficiency, and accommodative insufficiency. Presbyopia (see sec. VI.B.6., below) is most common in patients older than 40 years and includes an inability to read or do close work for prolonged periods of time because of blurring of vision and "tiring" of the eyes. In all causes, intermittent diplopia at near may develop because of the interrelationship between accommodation and convergence. Symptoms are aggravated by fatigue, illness, fever, or other debilitating conditions, and may clear completely as the patient recovers and accommodative powers recompensate.

6. **Presbyopia** is a physiologic decrease in the amplitude of accommodation associated with aging. With time, changes occur in the crystalloids of the lens that result in a decreased elasticity of the lens fibers or a hardening of the lens. When the eye attempts to add plus power to the optical system or accommodate, there is less of a change in the curvature of the lens for each unit of contraction by the ciliary muscle. By the age of the early 40s, accommodative amplitude has usually decreased to less than 5 D, and objects less than 20 cm away cannot be brought into focus.

   a. **Symptoms of presbyopia** develop when the amount of accommodation needed to focus at near **exceeds more than half of the total amplitude of the eye.** A 48-year-old emmetropic patient with only 5 D of accommodative amplitude will experience presbyopic symptoms when attempting to read at 33 cm (about 14 in.), because he or she

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   is using 3 D (60%) of the total 5 D available to focus. An uncorrected hyperope and a chronically undercorrected myope who, as a result of the undercorrection, never developed full accommodative powers, will both develop presbyopic symptoms earlier than an emmetropic patient. The hyperope must use excess accommodation to overcome the hyperopia, thus reducing the available reserve for the early presbyopia. Symptoms of presbyopia include:

      1. **Longer reading distance** required.
      2. **Inability to focus on close work**.
      3. **Excessive illumination** required for close work.
      4. **Greater difficulty** with close work **as the day goes on.**

   b. **Testing for presbyopia** is done monocularly and binocularly. The latter often requires a weaker correction; this is the more comfortable one for the patient to receive. The patient holds a reading card at the distance desired for work, e.g., typing or closer reading, and the weakest additional plus sphere that will give the patient clear small newsprint or footnote vision is determined. Cards commonly used are the **Snellen, Jaeger,** or **Rosenbaum.** The vision obtained should be recorded for future reference. Visual efficiency may also be calculated based on the best-corrected near vision, e.g., J-2 is 95% efficient (Table 14.2).

Table 14.2. EQUIVALENT VISUAL ACUITY NOTATIONS FOR NEAR

c. **Correcting presbyopia** is done through supplementing accommodation with plus lenses that do part of the focusing for the eye. The difference between the distance correction and the strength needed for clear near vision is called the **add.** An effective physiologic rule for prescribing the near correction is to give the add that will leave half of the amplitude of accommodation in reserve.

1. **The average eyeglass adds for various age levels:**

   a. 45 years: +1.00 to +1.25 D

   b. 50 years: +1.50 to +1.75 D.

   c. 55 years: +2.00 to +2.25 D.

   d. 60 years: +2.50 to +2.75 D.

2. **Adjustments for work distance.** The strength of the adds must be adjusted up or down depending on whether the patient wants a longer or shorter working distance. For a patient in his or her late 40s with only 3 D total amplitude left, the following adds give varying work distance and leave a comfortable (50%) amount of accommodation in reserve. (See Table 14.2 for range of adds, working distances, and amplitude reserve.)

   a. +2.50: 10 in.

   b. +1.50: 13 in.

   c. +1.00: 16 in.

   d. +0.50: 20 in.

7. **Aphakia.** If the crystalline lens becomes sufficiently opaque to interfere with vision, it must be removed by **cataract surgery** so that light may reach the retina. Removal of the lens produces a condition referred to as *aphakia* and results in an eye with one of its major optical elements missing. The eye in this state is extremely farsighted and lacks the ability to accommodate.

   a. **Correction of aphakia** is accomplished by prescribing strong plus (convex) lenses. Unfortunately, removing the crystalline lens from within the eye and replacing it with a spectacle lens positioned in front of the eye results in considerable **magnification of the retinal image,** usually 25% to 30%. The aphake is required to make a considerable adaptation to the visual environment, because the larger image of a familiar object is interpreted as indicating that the object is much closer than it really is. In the case of **monocular aphakia,** the difference in the size of the aphakic and phakic images precludes

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combining them in the visual cortex to achieve single binocular vision, and results in double vision resulting from the different image sizes. In addition, strong plus lenses result in a significant increase in lens-induced aberrations that can be very annoying and can limit visual efficiency. It is for these reasons that strong convex contact lenses, and even more frequently, secondary intraocular lenses (IOLs), are being placed in eyes that did not receive them as part of the primary procedure (see Chapter 7).

b. **Refraction technique in aphakia** may be by retinoscopy (see sec. III.A., above) or by a simple **subjective test** as follows:

1. Check potential visual acuity on the distance chart with the pinhole test before starting. If no maculopathy or keratopathy is present, the refractionist should be able to achieve approximately the same vision with lenses as by pinhole.
2. Place a +12-D lens before the eye (trial frame or Phoroptor), making sure the patient's visual axis passes perpendicularly through the plane of the correcting lenses. If the patient preoperatively was a high hyperope, a +14-to +16-D lens may be a better starting lens; if the patient is a high myope, use a +8-to +10-D lens to start.
3. Increase or decrease the amount of plus sphere until the maximum spherical visual acuity is obtained.
4. Place a -1.5-or -2.0-D cylinder in front of the plus lens and rotate the cylinder slowly until the axis that gives the patient the clearest vision on the distance chart is reached. If no letters are visible, increase or decrease the plus lens power until some letters are seen, and rotate the cylinder again until they are at their clearest.
5. Using the JCC technique (see sec. VI.B.3.f., above) increase or decrease the amount of cylinder at the clearest axis found until the patient again feels the vision is clearest.
6. Increase or decrease the amount of plus sphere, keeping 90% of the plus power closest to the eye, i.e., rear cell of the trial frame, until vision is best. To keep the patient's vision comfortable, maintain a spherical equivalent power by adding +0.25D of power to the sphere for every -0.50 D of cylinder power that the patient accepts.
7. Note the prescription and the vertex distance (distance between most posterior plus lens and cornea in millimeters) and record both. The vertex distance notation is important and will be used to calculate the final spherical lens strength by the optician.

c. **Aphakic contact lenses and monocular aphakia correction.** One alternative to the spectacle correction of aphakia is the use of **contact lenses.** By placing the lens element on the surface of the cornea, which is closer to the original site of the crystalline lens, magnification is reduced to between 5% and 10%, and this is usually compatible with fusion of the images in the visual cortex in the monocular aphakic. A contact lens correction results in less alteration of the visual environment by magnification and also eliminates most of the aberrations of aphakic spectacles. The use of a contact lens also restores peripheral vision.

d. **IOLs** are now by far the most common means of correcting surgical aphakia, with approximately 95% of all cataract surgery today including their implantation. A well-placed IOL has the visual advantages of the original crystalline lens but, as with any surgical device, may also cause complications. These are seen far less frequently now with improved lens design and materials. IOLs are discussed further in Chapter 7.

VII. Glasses in correction of ametropia.

Most forms of ametropia can be corrected by spectacles. Plus (convex) lenses are used to correct hyperopia,

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presbyopia, and aphakia. Minus (concave) lenses are used to correct myopia. Toric lenses are employed for the correction of regular astigmatism. Most corrective lenses are made in the meniscus form to reduce aberrations and to provide a better cosmetic effect.

A. Safety factors.

Lenses are generally made impact resistant; that is, they must comply with American National Standards Institute (ANSI) standard Z-87.1-1989 and withstand the impact of a 1.5-cm steel ball dropped from a height of 127 cm. Industrial safety glasses must withstand a greater impac