GENERAL PRINCIPLES

The eye can only be considered as a *moderately* complex optical structure — certainly not as difficult to deal with optically as are many types of camera lens systems. The focusing power of the eye is dependent upon its many curved surfaces, each separated by media of different indices of refraction. By far, the most important surfaces are those of the cornea (front and back), and lens (front and back, *plus* many in between!). You should also know that *some* refractive power is even ascribed to the anterior face of the vitreous and the concave, curved surface of the foveal pit. However, the anterior corneal surface stands above all as the monarch in importance for the overall refractive power of the eye. (If you want to get "picky", it is not really the *corneal* surface but the "tear film" which first encounters any entering light rays; thus, the "tear film" exerts the most influence of any of the surfaces of the eye. Its curvature is, of course, obligatorily that of the anterior corneal surface.)

Model Eyes

To help us in our study of the refractive surfaces of the eye, we must make use of a standardized model. In creating such a model through a study of post-mortem and living eyes, many prominent scientists established a schematic eye whose size, dimensions, and optical properties seem close to those of the average living eye. The most important of these models was presented by Gullstrand, the only ophthalmologist to be honored by a Nobel Prize. Using a number of reasonable assumptions and measurements, he established the dimensions and located the optical cardinal points. These can be found in any standard textbook.*

The schematic eye, though useful for a better understanding of how the eye works optically, is simply too cumbersome a tool with which to begin. A much more useful model is created by further simplifying this Gullstrand schematic eye to a structure which has

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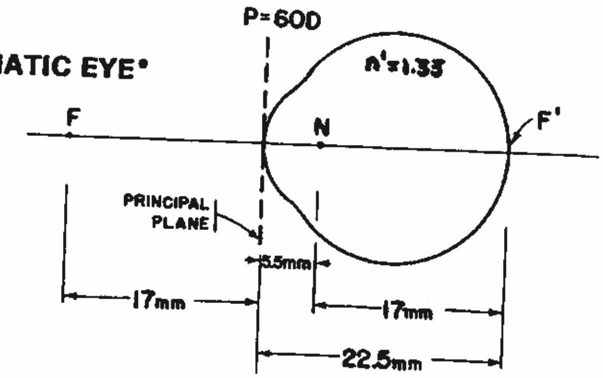
* Ogle, K.: OPTICS
C. C. Thomas, Springfield, 1968, pp. 156-7.

only one refracting surface and a unified intraocular medium of one refractive index. This model eye has the same overall dimensions of Gullstrand's, but the anterior surface curvature must be different, since we are replacing all the intraocular structures as well as the original cornea by a single refracting surface. It should thus be obvious that this new eye (called the *reduced schematic eye* or simply, *reduced* eye), must have a front surface power which is considerably greater than that of the corneal dimensions given by the Gullstrand eye or indeed, any real cornea.

The diagram below gives the dimensions of such a *reduced* eye. It is this eye which we will use in our discussions of refractive error and later, magnification.

THE REDUCED SCHEMATIC EYE*



* The RSE constants given above for the 60 D eye have been slightly fudged. Since $P = 60$ D, the *true* focal length $= \frac{1}{60} = 16.67$ mm; and this has been rounded off to an easier-to-handle figure of 17 mm. This little "white lie" will necessarily beget another, which asserts erroneously that the axial length is 22.5 mm.

How's this derived? Well, based on our assumptions of $P = 60$ D and $n' = 1.33$, the radius of curvature r of the "corneal" surface, (in this eye, the distance between the surface and N), is accurately calculated as you have been taught (pp 71-2):

$$P = \frac{n' - n}{r}\ ; \quad 60 = \frac{1.33 - 1.00}{r}\ ; \quad r = \frac{0.33}{60} = 5.5 \text{ mm}$$

Since the distance from N to F' is always also equal to f (here, 17 mm and a *very* key number), the total axial length of the RSE will be $5.5 + 17$ or 22.5 mm. This is the length given in the diagram above, but remember, it presupposes the approximation "17 mm" for f. The *actual* axial length is $5.5 + 16.67 = 22.2$ mm, which *should* also be the f' of this RSE. Let's check this:

$$f' = \frac{n'}{P} = \frac{1.33}{60} = 22.2 \text{ mm. It checks.}$$

Thus, in the diagram above, I have sacrificed some slight accuracy to maintain as "sacred" the figures of 60 D and 17 mm, the latter of which is especially important for the following discussion of Visual Size. Later (on pages 131-139), I will switch back and use the "accurate" axial length of 22.2 mm instead of the "fudged" 22.5.

Visual Size

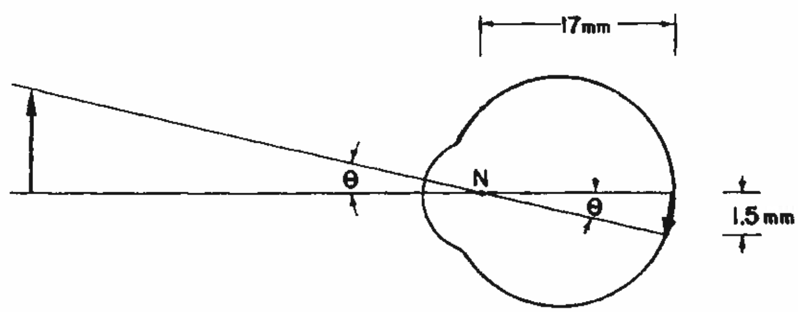
The anterior focal point of our reduced eye is 17 mm from the "cornea" ($\frac{1}{60\ D}$). The distance from the central, axial point of the corneal surface to the *secondary* focal point of the system (F') (which should be on the retina) is *n' f* or 1.33 times 17 or 22.5 mm. The distance from N, the nodal point of the eye, to F' is *also* equal to the primary focal length *f* (see previous diagram). This is so for *any* optical system. Here, it is 17 mm and that particular distance should be cemented in your brain.

All rays directed at N will pass through the cornea without deviation by it, so N forms the apex of all angles subtended at the eye by any object (called the angular object size) as well as the corresponding angular size of the retinal image. Thus, knowing that the distance from N to F' is 17 mm will allow you to determine the actual sizes and angles subtended at the eye by any object — a test target on a tangent screen, a particular Snellen letter, or even a 1 mm lesion on the retina.

A few examples will point this out:

PROBLEM:

What is the angular size (in degrees) of the optic nerve head (1.5 mm in diameter)?



ANSWER:

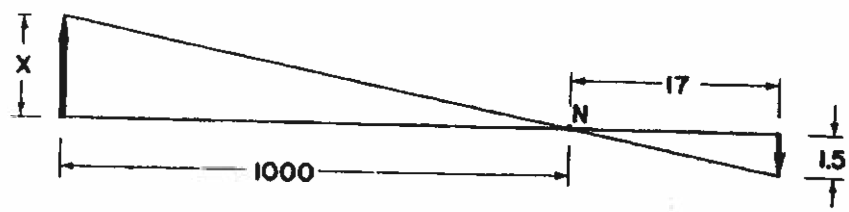
$$\theta = \frac{1.5}{17} = .088$$

But this answer is in *radians*. To convert it to degrees, remember

$$1 \text{ radian} = \frac{180°}{\pi} = 57.3°$$

Then, $$.088 \text{ rad} = .088 \times 57.3 = 5.0°$$

So, the optic nerve head subtends an angle of 5.0° and would project a blind area of this same angular subtents onto a tangent screen. If that screen were 1 meter away from the cornea, the *size* of the blind spot would be determined simply "by proportion" of comparable sides of similar triangles — (the *true* distance from N to the tangent screen would be 1000 + 5.5, but the 5.5 is so small compared with the 1000 that it can be safely neglected):



$$\frac{1.5}{17} = \frac{x}{1000}$$

$$x = 88 \text{ mm}$$

Thus, the size of the blind spot on a 1 meter tangent screen is about 88 mm in diameter.

PROBLEM:

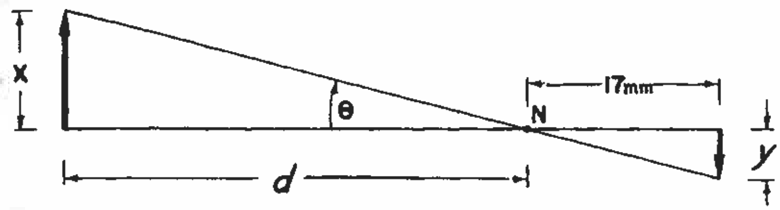
a) What overall size should we make a 20/200 letter on a Snellen acuity chart if it is to be used at 20 feet?

b) What is the actual size of the corresponding retinal image?

ANSWER:

First, you must know that the element to be discriminated in any test letter, say the "break" in a letter "C", is standardized. The angular size of the "break" for a 20/20 letter is 1 minute of arc. The *total* size of any test letter is always 5 times the angular size of the "break". So, a 20/200 letter would be 10 times as large as a 20/20 letter and, therefore, a 20/200 letter has a "break" of 10′ angular size, and its *overall* size must be 50′ subtended at the eye's nodal point.

a) In the sketch below, our similar triangles are labeled with what we know:



x = the height of the letter
$d = 20 \text{ ft} = 6000 \text{ mm}$
$\theta = 50$ minutes

To solve this problem we must have θ in radians rather than in minutes of arc.

$$50 \text{ minutes} = \frac{50}{60} \text{ degrees}$$

$1 \text{ degree} = \frac{\pi}{180}$ radians (for most of us that can't remember the decimal conversion factor!)

Therefore, $50 \text{ minutes} = \frac{50}{60} \cdot \frac{\pi}{180} \text{ radians}$

$$\theta = .0145 \text{ radians}$$

Now, $\theta = \frac{x}{d}$

$$x = d \cdot \theta$$

$x = 6000\ (.0145) = 87$ mm, the true height of the 20/200 letter.

b) y = the retinal image size (see sketch above).

$$\frac{x}{d} = \frac{y}{17}$$

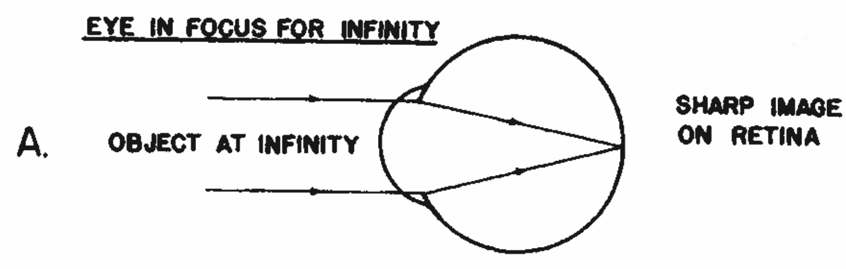
$$y = \frac{17 \cdot x}{d} = \frac{17\ (87)}{6000} = \frac{1479}{6000} = .246 \text{ mm}$$

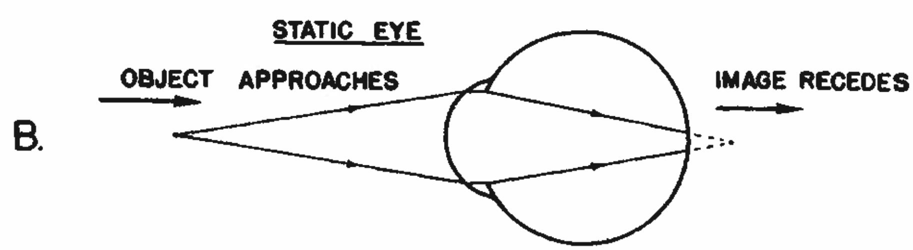
The retinal image size of the 20/200 letter is 0.246 mm.

So, if you keep the 17 mm figure in mind, you should have no difficulty with these types of determinations.

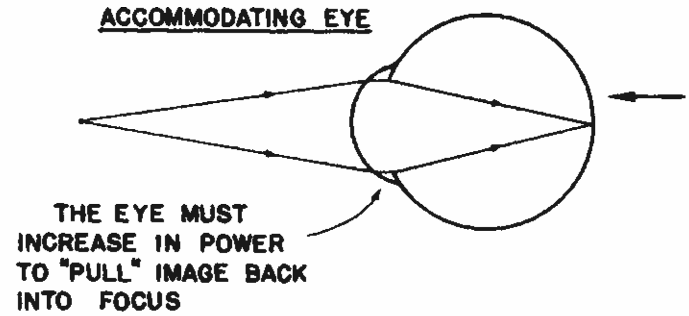
ACCOMMODATION

The normal eye has the ability to form sharp images and place them on the retina, and moreover, this ability is not limited to one, fixed object distance; the eye can *change* its power, within certain limits, to accommodate to a shift in the object distance. Say an eye were a *fixed* focus instrument and set for a perfect focus for an object at infinity (figure A below); since, as we have shown, objects and images always move in the same direction, if that object approached the eye, the corresponding image would move backward off the retina (figure B below). (We can speak of this movement happening *optically* even though we know that *physically* the opaque structures at the back of the eye would preclude it). To compensate for the increased divergence at the eye as the object approaches, the *total* eye power must increase (or the eyeball would have to elongate) to maintain a focused image on the retina. It should come as no surprise that the increase in eye power is by far the more important mechanism and serves to "pull" the sharp image onto the retina (figure C below). This increase can be as much as 18 additional diopters in a young eye, which you know already possesses about 60 diopters. This variable power (from 0 to 18 D) supplied "automatically" by the ocular lens is called *accommodation.*





C.



In the sketches above, we are "stretching" somewhat to compare the "reduced" (lensless) eye to its dynamic human counterpart — it is done here for simplicity. We will also assume that all of the increase in power of our model eye occurs at its front surface instead of somewhere within. The error in doing so is not great nor is it critical here.

The availability of 18 D accommodation in a child would allow objects to be brought close enough to present a divergence of up to — 18 D to the eye and still allow the image to be kept in focus on the retina. Since — 18 D corresponds to a *u* of $-\frac{1}{18\text{ D}}$ or — 5.5 cm, the object could approach as close as 5.5 cm and still maintain retinal conjugacy. We call the 5.5 cm position the *NEAR POINT OF ACCOMMODATION* — that point on the visual axis which is conjugate to the retina when accommodation is *maximally* active.

This remarkable capacity of the eye to accommodate is gradually lost with increasing age. It is one of those physiologic functions that begins to be taken away from us immediately after birth, and it is just about completely gone by age 70 with an almost straight-line loss in the intervening years. The accommodation loss (like taxes and aging) is relentless, predictable and inevitable. It results in *PRESBYOPIA* ("old-age" vision) and is based on rigidification of the ocular lens; it becomes clinically evident by a recession of the "Near Point of Accommodation".

TABLE III

ACCOMMODATION LOSS WITH AGE (Donder's Table)

Age in years	1	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
Total accom-modation (overall amplitude) in diopters	18	16	14	12	10	8.5	7.0	5.5	4.5	3.5	2.5	1.75	1.00	.75	.25	.00

The amount of accommodative loss only becomes symptomatic to each of us in our early forties, since it is only then that the *remaining* accommodation approximates the amount required for average *reading* distances. At that time, the required task demands the expenditure of a high percentage of the accommodative power that an individual possesses, leaving no reserve "in the storehouse".

An example should make this clear: reading at a distance of 33 cm normally requires an accommodation of 3 D. If an individual is 20 years old, he can easily supply that 3 D from his "storehouse" of say, 10 Diopters. However, if his accommodative reserve has been depleted by age or disease, he may only be able to supply the 3 D and no more; thus, he will be operating at his full capability with no reserve capacity. Since he cannot maintain this maximal effort for very long, he will tire quickly and the image of what he is reading will blur on his retina.

He can help the situation somewhat by moving the reading material further away, placing it beyond his *near point* of accommodation and lessening the accommodative demand. At some point, however, this becomes self-defeating since an increase in the object distance also will *decrease* the image size on the retina. (Remember our magnification relationship; if u increases relative to v, the image size will decrease). Thus the increase in object distance can make it *harder* for him to read a given print size. So, any patient entering the presbyopic world will try to move the reading material further away to reduce the accommodative demand, but the distance to which he can move it will be limited by the following: 1) the minimal size of print which is legible by the individual and 2) (more practically) the length of his arms!

When a patient comes to you with such complaints, what can you do to help? First suggest that he increase the illumination on his reading task. This will certainly help, since one's ability to resolve fine image detail increases with an increase in light in the retinal image.* However, this will almost assuredly have been discovered empirically by the patient himself and he will already be using strong illumination. What else do you have to offer? The answer is clear. When a short object distance makes an intolerable demand on the accommodation supply and the presbyopic eye itself cannot increase its own power, the optical lens manufacturer is ready and eager to step in. For a small charge, he will supply (to your prescription) an accessory lens to be worn in a spectacle frame (also at a small charge). This lens will replace some or all of the accommodative power required for close work.

For average reading distances, say around 40 cm, 2.5 D accommodation is required of every eye. The early presbyope will seldom require more than about 1.0 D help in his "reading spectacles"; his own eye will easily supply the 1.5 D balance. In the best attitude of self-reliance, the typical patient will want to use as much of his own accommodative power as possible. (Later, we will see optically why it is to his benefit to do so.) But, by the time he is about 62, his own total accommodative power will have grown so feeble, he will likely need all the lens help he can get to read at 40 cm; then, he will probably require the "full help" of a 2.50 D lens. More about presbyopia and its correction later on, but you should understand now why a typical 70 year old presbyope does not require any *more* than 2.50 D of add at 40 cm. If, however, he *has* to read at a closer distance (say 10 cm) because some macular lesion demands that he have a larger retinal image, then he *will* obviously require a greater add than 2.50 D (here it would be + 10 D) to see with at this ultra-close distance.

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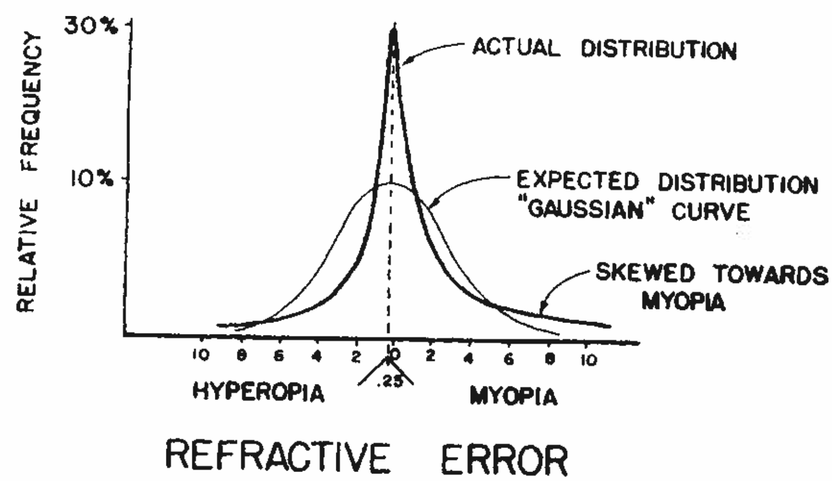
* Rubin, M. D. and Walls, G. L.: *Fundamentals of Visual Science*, C. C. Thomas, Springfield, 1969, p. 173.

REFRACTIVE ERROR

If an eye is to serve its beholder well, it must provide sharp imagery; to do this, there must be a "proper", coordinated match between the *power* of the various refracting surfaces and the *length* of the eye. When a perfect match exists for distant object vergences, we say *EMMETROPIA* is present; if not and a mismatch occurs, a *refractive error* (or *AMETROPIA*) supervenes.

What is surprising is *not* that the eye power and eye length are often inappropriately coupled; the real mystery is why a mismatch is *less* frequent than chance. If we plot a frequency distribution curve of refractive error as it exists in the population, we will find that the distribution is not "normal" as it *is* with height, weight, head circumference, etc. There is a *much* greater frequency of emmetropia (or *near* emmetropia — since the actual mean is about 0.25 D on the hypermetropic side) than one expects to find in a truly randomized "normal" distribution. (See graph.)



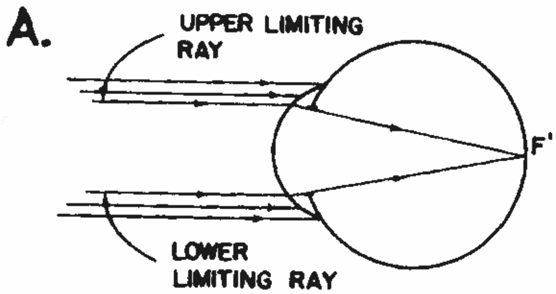
You might be surprised to learn that the individual components of eye refraction — corneal curvature, lens power, axial length (neglecting degenerative elongation) *are* all "normally" distributed. Some "thing" must happen to coordinate these individual parameters, so that when the eyeball grows too long, the corneal radius tends also to be greater than usual and therefore, of less power — this balances the increase of the eye length; conversely, the shorter eyeball tends to be coupled with a steeper cornea than "normal".

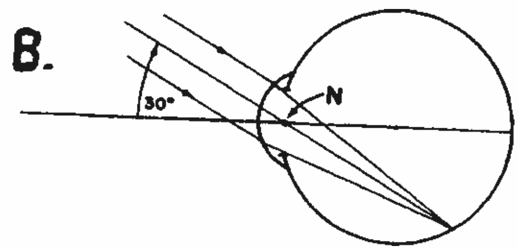
So, it seems clear that some wonderful mechanism keeps eyes close to emmetropia. Arnold Sorsby calls this tendency, the "emmetropization process." Alas, sometimes it fails, and ametropia enters the picture (and provides job opportunities for optometrists, ophthalmologists, and electronic refraction machines)!

An important point to remember is that an emmetropic eyeball (with no refractive error) can be a big eyeball or a little eyeball; the absolute size (or its correlate, absolute power in diopters) is immaterial — just as long as the power is exactly proper for the length as it exists, no refractive error will be present. Thus, a small turtle's tiny eyeball (perhaps 6 mm long) and that of a horse (perhaps 60 mm long) both can be emmetropic and allow sharp vision when their refractive components are sufficiently strong to compensate perfectly for their lengths; in these instances the dioptric powers would be 270 D and 23 D, respectively. So, you cannot tell the degree or direction of ametropia by knowing the dioptric power alone. What you must know is how well that power correlates with the corresponding axial length.

The "average" *human* emmetropic eye is roughly 60 D, though of course, it may still be emmetropic yet of greater or lesser power than this. In our optical diagrams of the eye, we will assume the emmetropic reduced schematic eye is 60 D in power, is composed of one ocular medium of $n' = 1.33$ (water), and has only one refracting surface of radius 5.5 mm — a convenient, though distorted model of a real eye.

When emmetropia exists, light from a distant object will be focused onto the retina so that a clear image is present there. That is, each object point is represented by an image point which will lie on the retinal surface. A distant point located straight ahead along the visual axis would be imaged at the secondary focal point F', which will be on the retina in the emmetropic eye (as shown in A below):





(In both of the above diagrams, the upper and lower most rays signify those which just barely pass the upper and lower edges of the pupil. Any rays which are more peripheralward cannot enter the eye and cannot help form the retinal image. These two extreme rays are called the "limiting rays". The axial line is shown for orientation.)

In Figure B above, if the rays from the object at infinity arise from an off-axis point (say 30° above the axis), the particular ray which goes through the eye nodal point will be undeviated and will, therefore, locate the position of the *image* point. That image will be in the retinal plane only if the eye is emmetropic. (Actually, the image point will *have* to lie somewhere along this ray no matter what the power or refractive error of the eye. That is what makes this ray so valuable.) The nodal point in our reduced eye must be located exactly at the center of curvature, 5.5 mm from the front surface, and any ray which passes through a center of curvature must strike that surface perpendicularly — the angle of incidence at the surface is then *zero* degrees — and is therefore undeviated by it.

The distance between the surface and the retina can be easily calculated if you don't happen to remember it; P of the surface is 60 D and $n' = 1.33$; $U + P = V$

Since the object is at infinity

$$U = 0.$$

Image distance $v = f'$ (the secondary focal length).

$$\therefore \quad P = \frac{n'}{f'};\ 60 = \frac{1.33}{f'};\ f' = \frac{1.33}{60} = 22.2 \text{ mm}^*$$

Therefore F′ (which is *on* the retina in an emmetropic eye) is 22.2 mm from the surface.

If an eye is not emmetropic, it may either be too strong in power or too weak, or too long in length or too short. The "too" is a relative term; it refers only to what *would* be required to make that eye "correct". Whenever one wants to express the degree of ametropia present, he has only to state how much *power* difference there is "away from" emmetropia for *that* eye — *not* a difference from "normality" or from some "average" power or from some other arbitrary standard.

Myopia

If the power of an eye is too strong *for its size*, we say that the eye is myopic or "nearsighted." A myopic eye, then, has its F′ located somewhere in front of the retina — the more in front it is, the greater the myopic refractive error.

Say an eye is 5 D myopic; this means the dioptric components are relatively too strong by this amount *or* the eyeball is too long by an amount which causes 5 D of myopia. Either possibility exists and simply knowing that 5 D of myopic error exists does not tell us which parameter is at fault (or whether some proportion of the error is contributed by both) or what the *total* power of the eye is. No; all we know is that there is the 5 D of error, and that it errs by being *relatively* too strong — the actual power and the actual length may be any value. These points must be well ingrained.

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* Reread footnote, page 120.

The Far Point Plane

It doesn't matter whether the myopic fault is with too great a refractive power or with too long an eyeball; in either case, when an object is at infinity, F′ of the eye is where the sharp image is located and that is in front of the retina, somewhere in the vitreous. We can move that sharp image backwards onto the retina by bringing the object closer to the eye, since as the object approaches the eye, the image plane will move in the same direction. (This obeys our law about object and image motion.)

As the object comes closer, it will reach a certain object plane position so that its image will fall squarely on the retina. That particular object position is called the *FAR POINT PLANE* of that myopic eye; its axial point is known as the *FAR POINT.* All rays leaving an object point in that plane (and entering the eye) will form sharply focused image points on the retina. By definition then, the far point plane is that object plane which is conjugate to the retina when the eye is *not* accommodating. (This definition holds true for *any* type of ametropia.)

When the object rays leave the myopic far point plane, they will have a certain divergence. This divergence of object rays is necessary to compensate for the "overpower" of the myopic eye and enables it to create sharp retinal imagery. The specific amount of the divergence required is *equal* to the amount of "overpower", that is, it is a quantitative measure of the existing myopia. Thus, all we have to know is where the far point is and we *know* the amount of myopic error. So, find the axial position where a myopic patient can just see details of an object clearly, measure the distance from the eye and convert it into diopters and *Bingo!* If a far point plane is located 23 cm in front of an eye, that eye must be $\frac{1}{.23\text{ m}}$ or 4.35 D myopic.

With a real patient, you have to be careful in trying to determine myopic error by locating the far point plane in this way since you may stimulate accommodation with your test target. As any target is brought steadily closer, the eye will be able to see finer detail more easily; so, you might be led astray in thinking you had not yet reached the far point, when , in reality, you may have passed it and are now only forcing the eye to accommodate (if it can) in an effort to keep up with the approaching target. Since you are attempting to locate that far point and our definition of *far point* specifies that *no* accommodation should be active, you must make sure the patient does *not* accommodate during your determination. If you paralyze the eye's accommodative power with a cycloplegic drug (like Cyclogyl® or atropine), you need not fear accommodation as a contaminant of measuring the position of the far point plane. With care, however, you *can* do this without cycloplegia if you always move the target *from* a blurred zone *towards* the clear range, and stop at the position of *initial* clarity of a small target letter. That is the position of the far point plane.

A myope will see everything beyond his far point blurredly; but at, or closer than this plane, his eye will create sharp imagery as well as the emmetropic one. At distances nearer than the far point, the myope also has to accommodate to see sharply, but he has a "head start" on the emmetrope and will need to exert less accommodation at a comparable distance. It is as if the myope's eye had a "built-in" plus lens of a magnitude equal to his myopic "error"; so, let's begin now to think of the myopic eye's error as being a *plus* error.

A 5 D myope has an extra + 5 D of power and allows him to see clearly at 20 cm with no accommodative exertion at all; this same surplus + 5 D "built-in" lens provides him with the means to see at a 10 cm distance by using only 5 D of his own accommodation. The myope will have a closer near-point-of-accommodation than an age-comparable emmetrope, and 10 D actual accommodation will allow the myope to see at closer distance than that same 10 D exerted by the emmetrope.

Working a sample problem will help cement some of these points:

PROBLEM:

A 4 D myopic eye has a near point of accommodation of 8 cm. Determine the following:

a) far point

b) amplitude of accommodation

c) range of accommodation

d) How much accommodation must he exert to see detailed print at 10 cm?

ANSWER:

a) Far point $= \frac{1}{-4\text{ D}}$ or 25 cm in front of the eye.

b) The "amplitude of accommodation" is the total number of diopters of accommodation available to an individual — his maximal capacity for focusing — the dioptric difference between his near point and his far point. This myope's near point of accommodation is at 8 cm. This means that with maximal accommodation active, he can see a point which has a vergence of $\frac{1}{-.08} = -12.5$ D.

Since he is 4 D myopic, he will need to exert only 12.5 − 4 or 8.5 D of accommodation to see at a distance of 8 cm. (The emmetrope has to accommodate the full 12.5 D). Thus, the amplitude of accommodation is 8.5 D.

c) The "range of accommodation" is that actual distance through which the eye can see clearly in going from no accommodative effort to a maximal one.

With no accommodation, the far point is at 25 cm.

With maximal accommodation, the near point is at 8 cm.

Therefore, his range is 25 to 8 cm (17 cm long).

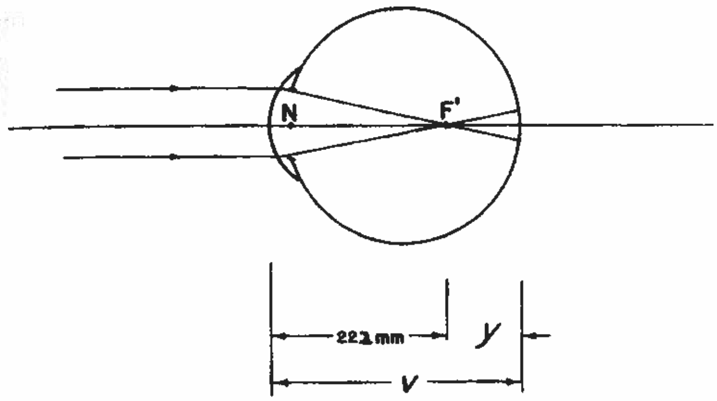
d) A point 10 cm away has a vergence of − 10 D, and from an emmetrope would demand 10 D accommodation. Since this eye is 4 D myopic, it has a "head start"; it will need to accommodate only (10 − 4) or 6 D to see this object point clearly.

The handling of problems of this type should become second nature to you.

Now after introducing the concept of the far point, I want you to consider *axial* myopia — myopia due only to the fact that the axial length is too long for the eye. So, assume the dioptric power is "normal" here, at 60 D.

PROBLEM:

How *much* longer is this eye than the "reduced eye" if it presents 5 D of myopic error?



ANSWER:

Let y = number of mm increase in length over the emmetropic eye to yield 5 D of error.

What we must *first* find is the image distance v which corresponds to the object distance u for an object located at the far point; then we can determine y, which will be equal to $v - 22.2$.

Since the myopia was given as 5 D, the far point must be located 20 cm in front of the front surface of the eye; and $U = -5$ D

$$U = -5 \text{ D}$$
$$P = 60$$
$$V = ?$$
$$U + P = V$$
$$-5 + 60 = V$$
$$+55 = V$$

Since the image vergence $V = \frac{n'}{v}$,

then $$v = \frac{n'}{V}$$

and $$v = \frac{1.33}{55} = 24.2 \text{ mm}$$

since $$y = v - 22.2$$
$$y = 24.2 - 22.2 = 2.0 \text{ mm}$$

This linear distance represents 5 D of axial myopia, so, *each* diopter is equivalent to $\frac{2.0}{5 \text{ D}}$ or 0.4 mm of axial elongation.

Look now at an example of *refractive* myopia where only the dioptric power of the eye is at fault; here, it is too strong. Again, use our "reduced" eye as a model; the "corneal" power would be 65 D instead of 60 D if we assume the presence of 5 D of refractive myopia.

PROBLEM:

What is the axial equivalent of 1 D of myopic refractive error?

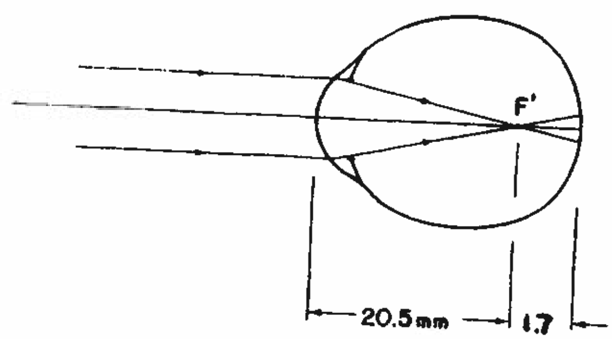
ANSWER:

The focal plane F' for images at infinity would be located as follows:

$$P = \frac{n'}{f'}$$

$$f' = \frac{1.33}{65} = 20.5 \text{ mm from the "cornea".}$$

REFRACTIVE MYOPIC EYE



Thus, F' is short of the retina by (22.2 — 20.5) mm or 1.7 mm.

Each diopter of error would be roughly equivalent to $\frac{1.7 \text{ mm}}{5 \text{ D}} = .34$ mm of axial distance.

To summarize these last two calculations:

With pure *axial* myopia, 0.4 mm of axial elongation is equivalent to 1 D of error.

With pure *refractive* myopia, 0.34 mm of axial distance is equivalent to 1 D of error.

These figures are approximations for a *model* eye with an *assumed* refractive power located exactly at the "corneal" plane. This is not so with an actual human eye which additionally may be of *any* reasonable refractive power. In spite of this, the approximations given above are fair ones; you will not be far off if you assume an average of .37 mm as the axial equivalent of 1 D of "average" myopia. (Besides, clinically, you cannot determine whether a refractive error is axial or refractive anyway!)

CLINICAL POINT:

The typical ametropias tend to arise gradually, probably through some slight aberration or exaggeration of the normal growth processes of the eye. Occasionally, however, something abnormal occurs to cause the refractive error to change rather abruptly.

For example, the eye will be made functionally too short by something which pushes from behind, indenting the eye or shoving the retina towards the vitreous: a retrobulbar mass, a choroidal tumor (melanoma or metastatic lesion — most commonly breast), a retinal elevation (as seen in a pigment epithelial detachment or even central serous choroidopathy). These problems serve to shorten the axial *length*, thereby increasing the refractive error in a *hyperopic* direction.

On the other hand, if the change in error happens to be toward the *myopic* side, a problem will usually be found with the *refractive* components (except in degenerative myopia): keratoconus, spasm of accommodation, incipient nuclear cataract, subluxed or anteriorly dislocated lens, or any condition which causes rapid shifts in location of the body fluids (as pregnancy, diabetes, acidosis, assorted drugs — sulfonamides, osmotic agents, etc.) — all tend to create a myopic error.

Keep alert to all of the above diagnostic possibilities whenever there are sudden (or relatively rapid) changes in the patient's preexisting refractive state.

* * *

Resuming our discussion of the far point, we shall demonstrate that *every* eye has its own far point — that axial point conjugate to the retina when accommodation is inactive. As we have shown, the myopic eye has a far point which is always located between infinity and the anterior corneal surface, but even the emmetropic eye has a far point; it is located at infinity!

Hypermetropia

We have dealt so far with one type of refractive error — the "over-powered," myopic eye. There is another side to the coin — the eye that has *insufficient* refractive power or is "too short", or both. This eye is the hypermetropic (hyperopic) or "farsighted" eye. It too must have a far point (an object) which is conjugate to the retina, but where? Let's find out by solving for U in our old standby $U + P = V$. Attribute a "weak" refractive power P of 55 D to our reduced eye; this makes it 5 D hyperopic. Its length is still 22.2 mm.

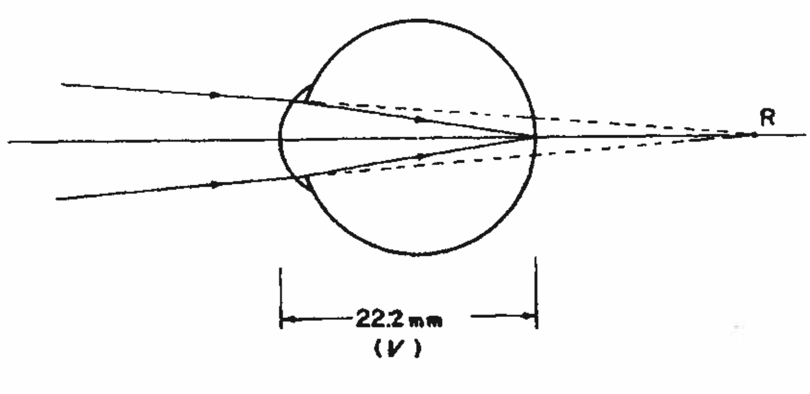
$$U + P = V = \frac{n'}{v}$$

$$U + 55 = \frac{1.33}{22.2}$$

$$U + 55 = 60$$

$$U = +5\text{ D}$$

HYPERMETROPIC EYE



Recall our sign conventions? A U of $+5$ D means that the object which is conjugate to an image on the retina must be located 20 cm *behind* the eye. That is, object rays must be convergent to a point 20 cm behind the eye to be focused sharply on the retina when no accommodation is active. This point, R, signifies the location of the far point plane for this eye since it fulfills our definition.

We already know that no real object emits *convergent* object rays; we can therefore surmise that the hypermetropic eye will never produce sharp point images from real objects, that is, *unless* it can increase its resting eye power (which in this case is too weak) by accommodating.

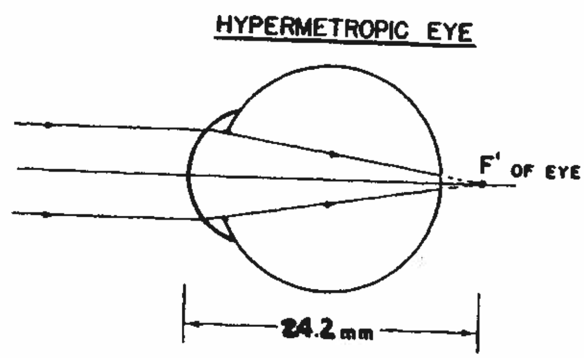
When this hyperopic eye looks at infinity without accommodating, $U = 0$.

$$U + P = V$$

$$0 + 55 = \frac{n'}{f'}$$

$$55 = \frac{1.33}{f'}$$

$$f' = \frac{1.33}{55} = 24.2 \text{ mm}$$



This eyeball is too short by (24.2 — 22.2) or 2.0 mm, and F' falls *behind* the retina. There is, therefore, a blurred spot on the retina instead of a sharp image point. But, that is exactly what we saw when we investigated the *emmetropic* eye's response to near objects and learned that as an object approached the eye, its image tended to move back off the retina (optically) and blur the retinal image; it was accommodation that "pulled" this image forward onto the retina. So, also here with the *hyperopic* eye; a blurred image on the retina stimulates accommodation which "pulls" the sharp image forward into focus on the retina.

The unaccommodated *emmetropic* eye is "too weak" only in regards to a near object and its associated divergent object rays. For the hyperopic eye, it is *not* object proximity alone that causes the image to recede behind the retina; it is simply that the hyperopic eye is relatively too weak for *all* distances — too weak even to bring *parallel* object rays to a sharp focus on the retina. In emmetropia, accommodation is required for near only, but in hyperopia, accommodation is necessary even for distance and still more so for near.

A hyperope of 2 D will require 2 D of accommodation just to see clearly in the distance. To read material held 20 cm from his eye, he must accommodate as much as the emmetrope ($\frac{1}{.20}$ D) *plus* 2 D more to overcome his hyperopia, for a total of 7 D. Since he must constantly use a higher proportion of his accommodative reserve than his age-matched emmetropic friend, he may well exhibit symptoms of presbyopia at an earlier age than his confrere.

Go back to the last diagram: the fact that R, the far point, is "behind" the retina and also F', the eye's secondary focal point, is "behind" the retina leads some to confuse the two. It shouldn't; the distinction between these entities should be crystal clear.

1) F' is an *image* which is conjugate to an object at infinity, while R is the *object* which is conjugate to its image on the retina.

2) The distance from the retina to F' is very short (usually in *milli*meters or fractions thereof), while the distance from the retina to R is very long, relatively; it is almost never closer than about 8 or 9 centimeters, but may be "infinitely" long.

Don't confuse F' and R in diagrams.

This discussion of the far point in myopia and hypermetropia will be of utmost value to you. Of all the subjects you have covered so far and will cover later, this one is probably *the* most important since the