index but also in convexity. This is evident when we compare the following two lenses, the thickness of which must not be more than a small fraction of the focal length. Let one of these lenses, *A*, be homogeneous and have the refractive index n'', the index of the surrounding medium being n, while the other lens, *B*, has only a core or nucleus more convex than the surface of the lens of the index n'', the superficial layer having an index n', intermediate between n and n''. If n' is now very nearly equal to n, we have practically a lens of the same index as that of the lens *A*, but of shorter radius of curvature, and hence of shorter focal length. If n', however, is very nearly equal to n'', the lens *B* will be practically of the same strength as the lens *A*, but never less. Hence, no matter in what ratio the index increases as we proceed toward the nucleus, the lens gains thereby in strength. The special advantages of this stratification over a homogeneous lens is the more regular refraction of rays very oblique to the axis, as has been shown mathematically by Hermann.[2] Thereby the images of objects situated laterally from the axis of the eye are not distorted as they would be when projected by a glass lens. The actual refraction of the excised human lens was found by Helmholtz in two measurements to be equal to that of a homogeneous lens of the same curvature, but with a refractive index = 1.4519 and 1.4414. But in his latest estimate (1874) he adopts 1.4371 as the more nearly correct average total refractive index of the lens in its normal attachment during life.

23. *Curvature of the Ocular Surfaces.*—The curvature of the surfaces cannot be measured with accuracy in the dead eye, on account of the altered tension of the eyeball. In the living eye the curvature can be calculated from a measurement of the size of images reflected from the surfaces. The cornea, for instance, acts as a polished convex mirror, producing diminutive images, apparently behind its surface. The size of such an image is to half the radius of curvature of the mirror as the size of the object is to the distance of the object from the cornea. The size of the image is most conveniently measured by means of Helmholtz's ophthalmometer. This consists of a telescope, in front of which there is a thick plate of glass with parallel surfaces, which has been cut in two, so that the line separating its two halves exactly bisects the field of the telescope. The two plates can be turned on an axis vertical to the line of separation. As long as the two plates are practically one, that is to say, lie in one and the same plane, objects are seen through them in their natural shape; but when the two plates are turned in opposite directions, the objects appear split into two halves, which are displaced laterally in opposite directions, in proportion to the rotation of the plates. The explanation of this displacement has been given in Section 3. For actual use the ophthalmometer is directed toward the observed eye, at a distance of several metres, and the images of two lights, one placed on either side of the telescope, or, rather, the ideal line uniting the two lights, are observed as reflected from the cornea. The two lights are, of course, placed in the prolongation of the line separating the two glass plates of the instrument. These plates are then turned by a screw until the image is doubled; that is to say, until the two halves are displaced laterally through the open space occupied by the image. From the observed degree of rotation, and the thickness of the plates, the extent of displacement, and hence the size of the image, can be calculated, and thereby the radius of curvature of the cornea be determined.

The radius of curvature, measured by reflection from the middle portion of the cornea, has been found to vary in different eyes from 7 to 8.2 mm., an average near 7.8 mm. being the most common. No definite relation has been found between this radius and any existing ametropia. On observing the reflection from the marginal portion of the cornea, it can be seen, even with the unaided eye, that the images are larger than in the centre; that is to say, that the convexity of the cornea diminishes from the centre toward the periphery. The cornea is therefore a segment of a sphere, only in its central area, while toward the periphery its shape approaches that of an ellipse, the major and minor axes of which are to each other in the ratio of about 9 to 10 or 11. The posterior surface of the cornea is found in the dead eye to be nearly concentric with the anterior surface. This fact, in connection with the rather slight difference in the indices of cornea and aqueous humor, allows us to regard the cornea, aqueous humor, and vitreous body as one optically homogeneous medium, bounded by a single surface.

The radius of curvature of the anterior surface of the lens has been found to vary between 9 and 12, and exceptionally even 14 mm.; and that of the posterior surface between 5.5 and 6.5. The images reflected from these surfaces are so faint, on account of the small difference in the refractive indices of aqueous humor and lens, that the ophthalmometer can be used to advantage only with sunlight. The apparent size of these images requires a correction, for the cornea and aqueous humor act as a magnifying lens, interposed both in the path of the rays from the object to the reflecting surface, and, again, between the latter and the ophthalmometer. In the case of the images reflected from the posterior surface of the lens, the substance of the lens must also be taken into account as part of the magnifying system. It is necessary hence to know the distance from the cornea to the anterior surface, and from the latter to the posterior surface of the lens in order to calculate the radii of curvature. The posterior surface of the lens acts as a concave mirror, giving an inverted and very small image.

24. *Distances between the Refracting Surfaces.*—The distance of the anterior surface of the lens from the cornea has been determined according to various methods by Helmholtz and his pupils. By means of a focussing microscope with graduated screw, or by means of the ophthalmometer with the aid of movable lights, it was learned how far the rim of the iris appears behind the cornea and the true position of the pupil was then calculated from the known refractive power of cornea and aqueous humor. Values between 3.2 and 4 mm. have been found in different eyes. Helmholtz adopted 3.6 mm. as a sufficiently accurate average to use in his diagrammatic eye. The distance of the posterior surface of the lens from the cornea can be measured only by complicated methods based on the observation of the parallax between the reflection from the cornea and that from the posterior surface of the lens, and by taking into account the influence of cornea, aqueous humor, and lens substance on the rays. It has been found to approximate very closely to 7.2 mm., which gives 3.6 mm. as the average thickness of the lens (while the eye is not accommodating). The lens taken out of the eye increases in thickness on account of elastic retraction, as will be explained in the section on Accommodation.

25. *Diagrammatic Eye.*—We learn thus that there are noticeable differences in the optic constants of normal eyes, so that two eyes, both emmetropic, are not necessarily identical in construction. But within the latitude of emmetropic eyes the deviations of the different figures from the average counterbalance each other, so that the object, the formation of sharp images of distant objects in the plane of the retina, is equally attained in all. From numerous measurements made by himself and others, Helmholtz has constructed the following diagrammatic eye, corresponding to the average figures of human emmetropic eyes:

	Millimetres.
Refractive index of cornea, aqueous, and vitreous humor	1.3365
Refractive index of the lens as a whole	1.4371
Radius of curvature of the cornea	7.829
Radius of curvature of the anterior surface of the lens.	10.
Radius of curvature of the posterior surface of the lens.	6.
Distance from the anterior surface of the cornea to the lens	3.6
Thickness of the lens	3.6

From these data are computed:

	Millimetres.
Anterior focal length of the cornea, aqueous and vitreous humor	23.266
Posterior focal length of the cornea, aqueous and vitreous humor	31.095
Focal length of the lens (in place)	50.671
Distance of first principal point of the lens from its anterior surface	2.12
Distance of second principal point of the lens from its posterior surface	1.274
Distance of the first principal point H' of the entire eye behind the cornea	1.750
Distance of the second principal point H'' of the entire eye behind the cornea	2.115
Distance of the first nodal point K' of the entire eye behind the cornea	6.966
Distance of the second nodal point K'' of the entire eye behind the cornea	7.331
Anterior focal length of the entire eye	15.508
Posterior focal length of the entire eye	20.719

This latter figure plus the distance of H'' from the cornea gives us 22.834 mm. as the optic axis from the anterior surface of the cornea to the sensitive plane of the retina and adding to this number the thickness of the sclerotic coat, viz., 1.3 mm., we obtain about 24.1 mm. as the length of the eyeball. Anatomical measurement has shown the eyeball to vary between 22.5 and 27 mm. in length, 24 to 24.6 mm. being the most common limits. Unfortunately these anatomical measurements refer mostly to eyes the refractive state of which was not determined during life. The diagrammatic eye of Helmholtz and the position of its cardinal points are illustrated by Fig. 2043, amplified twice.

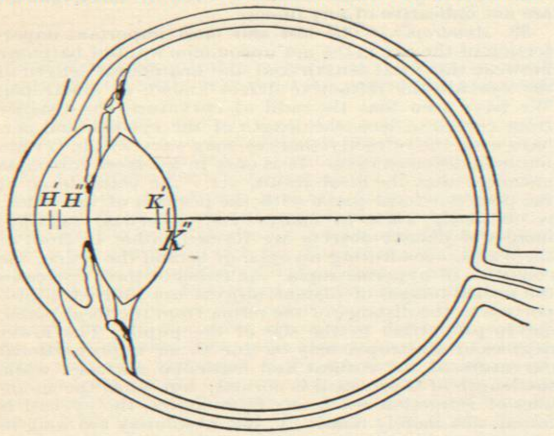

FIG. 2043.

26. In the calculation of the size of retinal images and of the influence of glasses on sight in fact, in almost all the problems not relating to the changes during accommodation, we can arrive at results sufficiently accurate by taking as a basis the simplified diagrammatic eye of Donders, in which the lens is omitted. It consists of a single refracting surface, representing the cornea with a radius of curvature of 5 mm. The single internal medium, optically identical with the cornea, has a refractive index of 1.333 ($\frac{4}{3}$). Thereby we deal with but one principal point, viz., in the plane of the cornea and but one nodal point, the centre of curvature of the cornea. The first focal length is 15 mm., the second 20 mm., which latter figure represents likewise the length of this eye.

The human eye has some advantages not possessed by artificial optic instruments, but also various faults which a skilful optician can avoid.

27. *Visual Field.*—There exists no instrument which has as extensive a field as the eye, since images are depicted on the retina of objects situated as far as 55° to 65° from the line of direct sight, and on the temporal side even as far as 90° to 100°. The fact that images formed near the periphery of the retina are not seen distinctly, is due principally to the relative dulness of sensibility of the peripheral portion of the retina. The images themselves are quite sharp, as we can learn by examining the periphery of the retina in the eye of another person with the ophthalmoscope. When the refraction is emmetropic in the centre of the retina, it is very nearly so also in the extreme periphery. This is due to the curvature of the rear of the eyeball and of the retina (compare Section 9). Moreover, the elliptical curvature of the cornea, and still more the stratified structure of the lens prevent the distortion of images, which ordinary spherical, homogeneous lenses would produce in the case of objects situated far laterally from the axis of the system.

28. *Spherical Aberration.*—Spherical lenses do not collect in the common focus those rays which are very oblique to the axis or strike the refracting surface far from its centre. This spherical aberration is shown in Fig. 2027. In the eye it is almost wholly obviated by the elliptical shape of the cornea and the stratification of the lens. The iris, moreover, serves the purpose of a diaphragm, so that the extreme marginal rays cannot ordinarily pass through the pupil.

29. *Chromatic Aberration.*—The chromatic aberration of lenses gives rise to colored rings around images otherwise well defined. It is due to the fact that the index of refraction is not the same for waves of light of different length. Hence there is necessarily a slight separation of the different colors when mixed or so-called white light is refracted by a lens. The eye is not free from this defect; it possesses it to about the same extent as if it consisted of water. If either end of a sharply defined spectrum be observed through an achromatic telescope the other end appears diffuse until the adjustment of the telescope (or of the eye) is altered. The difference in adjustment corresponds to about 1.5 to 2 dioptrics; that is to say, an eye forming a sharp image of an object emitting violet light, requires an additional convex lens of some 75 to 50 c.c. focal length, in order to bring the less refrangible red rays into a focus upon the retina. Ordinarily we are not conscious of this defect, because the eye is adjusted for the middle and brightest portion of the spectrum, viz., yellow and green to blue, while the red and violet rays form circles of diffusion around the image, which blend, and thereby diminish in distinctness of color, being, moreover, much less bright than the sharply defined image which they surround. But we can see these colored circles of diffusion quite distinctly on looking at some bright object, while covering one-half of the pupillary aperture with an opaque screen, for by thus cutting off half of the pencil of light, we prevent the blending of the color rings, and the object shows then a blue edge on one side and a yellow margin on the other. The chromatic aberration is also quite noticeable on observing a luminous point through a violet glass, which absorbs the middle part of the spectrum, whereupon we see either a red point surrounded by a blue halo, or a red margin around a blue point of light, according to the refractive state of the eye.

30. *Imperfect Centring.*—The optic system of the eye is not perfectly centred. The centre of the cornea coincides, indeed, with the vertex of its ellipse; but the major axis of this ellipse forms an angle with the visual line, or line of direct sight; that is to say, the line of the ray of direction passing from an observed point through the nodal points to the centre of the retina. The visual line deviates toward the nasal side of the corneal axis (proceeding outward) to an extent of from 4° to 8°. This relatively oblique direction of the corneal axis, when extreme, may give some eyes a false appearance of divergent squint. Still no noticeable deficiency of sight can be attributed to this want of centring.

31. *Astigmatism.*—More serious defects are those due to irregularities in the curvature of the refracting surfaces. We have so far considered only the refraction of rays which lie in one plane, with the tacit assumption that our refracting surfaces are the surfaces of true bodies of rotation, that is to say, that the radii of curvature are equal in all meridians. For, in this case, any of the figures illustrating the course of rays in the plane of the paper may be supposed rotating on their axis in order to illustrate the course of rays in all planes. But this assumption is scarcely ever correct in the case of the human

eye. On measuring with the ophthalmometer the corneal radius of curvature in the horizontal, and then in the vertical meridian, the two radii are found to differ from each other to a trifling extent even in the most normal eyes. More commonly, but not always, the radius is smallest in the vertical meridian. The two meridians presenting the greatest discrepancies are not necessarily horizontal and vertical; they may have any inclination. A difference of 0.1 mm. between the radii of two meridians at right angles to each other separates the focus of one meridian from that of the other to the extent of about 0.3 mm. Differences of 0.01 to 0.05 mm. in the radii are the most common. The cornea is hence the segment of an ellipsoid with three unequal axes. As a result, the focal length is not the same in any two meridians of unequal curvature, and hence the points of an object cannot be represented by points in the images formed in such an eye. If in Fig. 2044, *A*, we represent the ellipsoid cornea with the horizontal meridian *h h* having a greater radius of curvature than the vertical meridian *v v*, the focus in the former meridian *f h* must be farther off than *f v*, the focus of the vertical meridian. If we place a screen successively in the positions numbered 1, 2, 3, 4, and 5, the image of a distant point would appear as shown in an exaggerated manner at *B*, 1, 2,3, 4, and 5 of the same figure. The refraction by such an ellipsoid cornea can be imitated by means of an ordinary spherical lens, to which is added a cylindrical lens, the segment of a cylinder, thereby introducing a difference in the refractive strength in the two meridians, of which one is parallel with, and the other at right angles to, the axis of the cylinder. This defect of the eye is known as the regular astigmatism (from *a*, privative, and *στίγμα*, a point). There are very few, if any, eyes entirely free from it. When the inequality in the refraction of two meridians exceeds the strength of about one-half to one dioptric, it may necessitate correction by means of cylindrical glasses (see under *Astigmatism*). As the result of regular astigmatism, lines of different inclination are not seen equally distinctly. If, for instance, the eye be accurately emmetropic in the horizontal meridian, while the sharper curvature of the vertical meridian brings the focus behind the retina in the latter meridian, then only vertical lines at infinite distance will be sharply defined on the retina, while the more a line approaches the horizontal direction, the more diffuse will be its retinal image. The interference with sharp sight increases, of course, with the degree of astigmatism. A discrepancy between two meridians amounting to less than half a dioptric does not interfere with sight to any practical extent.

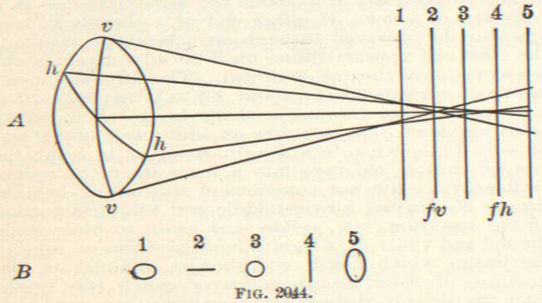

FIG. 2044.

Irregular Astigmatism gives rise to such slight imperfections of retinal images as the radiation of "rays" around stars and other small luminous points. It is due to optic inequalities in the different sectors of the lens, whereby some of the rays are deflected from the path which they would pursue in a perfect eye. This irregular astigmatism does not exist after the lens has been removed.

32. *Muscæ Volitantes.*—Few, if any, eyes do not at times see flying specks, so-called muscæ volitantes. They appear in the form of transparent rows of beads or groups of granules, or simply shadowy streaks floating about when the eye is moved. They are due to the presence of similarly shaped objects floating in the vitreous body, cells and groups of cells, and shreds of membranes, transparent, but of an index of refraction slightly different from that of the medium surrounding them. Their rims hence cast shadows similar to those of a glass ball between a light and a screen. These shadows are most marked when the rays of light are parallel in the vitreous body, when the source of light is in the anterior focus of the eye. We can observe them well by using as source of light a pinhole in an opaque screen held close to the eye and toward the sky, or on looking into a microscope. When the attention has once been called to them they may continue to annoy nervous persons, mentally rather than optically. These shadows, even if inconvenient, are not indicative of any disease.

33. *Ametropia.*—The last and most important imperfection of the eye is the not uncommon want of harmony between the focal length and the anatomical length of the eyeball, the refractive defect known as ametropia. We have seen that the radii of curvature, the distance from cornea to lens, the length of the eyeball, and perhaps even the refractive indices, may vary within certain limits in different eyes. It is only in the more fortunate instances that the ideal result, viz.: the coincidence of the posterior focal plane with the position of the retina, is obtained, while in many eyes, otherwise healthy, images of distant objects are formed, either in front of the retina, constituting myopia, or behind the retina, the condition of hypermetropia. In either of these two cases the retinal images of distant objects are blurred in proportion to the distance of the retina from the focal plane, and in proportion to the size of the pupil. The lower degrees of ametropia may be due to an unproportional curvature of the corneal and lenticular surfaces, while the length of the eyeball is normal; but when the anomalies of refraction reach any high degree, the eyeball is found, not merely relatively, but absolutely too long in myopia, too short in hypermetropia.

While emmetropia is the most fortunate refractive condition, it is not necessarily the most common. Statistics show that in the upper classes of schools, and especially high schools, in European countries, from one-third to one-half, and sometimes even two-thirds of the eyes are near-sighted, and some five to ten per cent. are far-sighted. In this country the figures are a little more favorable, as regards the frequency of emmetropia. Fuller details of these statistics will be given under the heading *Myopia*.

34. *Refraction during the Growth of the Eye.*—In the infantile eye all the dimensions are, of course, smaller than in the adult organ. The shorter axis of the eyeball is, however, proportionate to the shorter radii of curvature of cornea and lens, so that emmetropia can exist. Indeed, during childhood there are more emmetropic eyes than in adult life. The eyes of babes, however, are most frequently far-sighted, as shown by ophthalmoscopic examination. Jaeger formerly asserted the contrary, having found 78 eyes myopic out of 100, and but 5 accurately emmetropic in new-born babes. He seems to have been misled, however, by the accommodated condition of the infantile eye, for later observers, who paralyzed the accommodation by means of atropine, have arrived at different results. Thus Eli[3] found but 11 eyes myopic, 17 emmetropic, and 72 hypermetropic in 100 eyes of infants. Bjerrum[4] noted 61 hypermetropes, 23 emmetropes, and 3 myopes on examining 87 babes. Horstmann[5] found in 50 new-born infants 88 far-sighted eyes, 10 emmetropic, and but 2 short-sighted eyes. In 50 children, of the age of one or two years, 84 eyes were far-sighted, 10 normal, and 6 short-sighted; while in 50 children, four to five years old, hypermetropia had diminished, involving 74 eyes; myopia had increased to 13 eyes; 13 eyes being emmetropic. These figures show that the refraction increases ordinarily as the child advances in years. During the years of school attendance this growth leads, in many instances, to a myopic refraction. Indeed, as we pass from the lower to the higher classes in schools, we find myopia increasing steadily in frequency and in degree. The refraction remains stationary from the time of puberty, in healthy eyes. The increase of myopia so often noted from this time on until about the thirtieth year must be considered a morbid change.

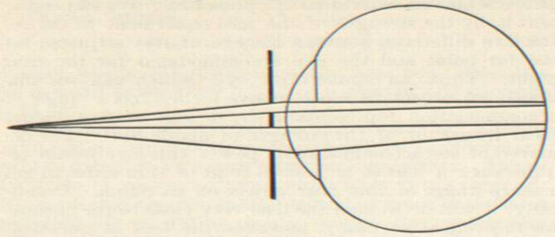

FIG. 2045.

35. Beyond the sixtieth year of age the refraction diminishes again, so that emmetropia turns into slight hypermetropia, on account of senile changes in the lens.

36. ACCOMMODATION.—According to the laws of refraction, the emmetropic eye can form sharp retinal images of those objects only which are situated at an infinite distance from the eye, or at least at a distance very large when compared with the dimensions of the refracting surfaces. Practically this amounts to any distance beyond 5 metres. But every-day experience teaches us that we can also see distinctly objects quite close to the eye; but we can never see equally distinctly, and at one and the same time, two objects, one far and the other near. On looking at a distant sign through a veil held in front of the eye, we can get alternately sharp images of the distant letters or of the threads of the adjacent veil, but we cannot see them both distinctly at one and the same time. This power of successive adjustment of the eye for distant and adjacent objects is termed the faculty of accommodation.

The exertion of the accommodation increases for the time being the refractive strength of the eye. It is evident that an eye accommodated for an object four inches distant must be equal in refractive strength to the emmetropic eye plus the strength of a convex lens of four inches focal length. For were the eye deprived of its power of accommodation it would be necessary to add to it the strength of this lens in order to get sharp retinal images of objects four inches off. The accommodative effort of an eye can therefore be represented by the strength of a convex lens of a focal length equal to the distance from the eye to the object accommodated for.

37. *Changes in the Eye during Accommodation.*—The optic changes upon which accommodation depends occur solely in the crystalline lens. Neither the corneal curvature nor the position of the retina is altered. Removal of the lens deprives the eye completely of its power of accommodation. Any eye, except one extremely myopic, becomes highly hypermetropic upon removal of the lens, requiring then a strong convex glass in order to see distinctly at a distance. On account of the impossibility to accommodate, the strength of this glass must be increased for near objects, and with a given glass accurate sight is possible only at one given distance. If the individual can read at different distances, it is done by ignoring the circles of diffusion, especially when they are small, on account of a narrow pupil. The most rigid test—whether in this or in any other case an eye is adjusted for a certain distance—is known as Scheiner's experiment.

38. *Scheiner's Experiment.*—If some luminous point—for instance, a pinhole in a screen in front of a light—be viewed through two pinholes in another screen which are closer together than the diameter of the pupil, the only effect of the latter screen held close to the eye will be to diminish the number of rays, and thereby reduce the brightness of the retinal image, if the latter be sharply defined on account of proper adjustment of the eye for the light. But if the eye is not adjusted for that distance, and circles of diffusion are formed on the retina, the screen with two perforations will cut off the rays forming the middle portion of the diffuse image, leaving instead two separate images of the luminous point, to which the eye is much more sensitive than to the circles of diffusion. Hence any want of adjustment causes the luminous point to appear double, as is evident from Fig. 2045.

39. *Changes in the Shape of the Lens.*—During accommodation the lens becomes more convex, especially its anterior surface, which also moves forward on account of the thickening of the lens. If we place a light slightly to one side of an observed eye and watch the images reflected from the various surfaces, they will appear as seen in Fig. 2046, *A*, while the observed eye looks as a distant object. When the eye observed is then adjusted for some near object, the images change, as seen in *B*, Fig. 2046. The corneal image, *a*, remains the same in both cases. The reflection from the anterior surface of the lens, *b*, diminishes in size, indicating increased curvature of the surface, and moves laterally toward the corneal image, a motion referable to the advancement of the anterior surface of the lens. The small, sharply defined, and inverted image (*c*) produced by the concave posterior surface of the lens shrinks likewise slightly in size, showing that the radius of curvature of that surface diminishes as well, though but little. No indication of any motion of the posterior surface can be observed. These changes in the curvature of the lens have been more accurately measured with the ophthalmometer, which shows that the radius of curvature can be reduced during a strong accommodative effort to about 6 mm. for the anterior surface, and about 5.5 mm. for the posterior surface of the lens, while the thickness of the lens may increase from 3.6 to 4 mm. Thereby the focal length of the lens in the diagrammatic eye would be reduced from 50.671 mm. during rest to 39 mm. during a strong accommodative effort. Calculating on this basis the refractive strength of the diagrammatic eye, we shall now find the principal posterior focus 1.644 mm. in front of the retina, while the retina itself is in the plane of focal reunion for rays coming from an object 146.6 mm. (not quite six inches) distant from the first principal point, which latter is 1.566 mm. behind the cornea in such an accommodated eye. Mathematical analysis thus confirms that the increased curvature and the advancement of the front surface of the lens suffice to account for the accommodative changes.

During accommodation the pupil diminishes in size. The utility of this contraction of the iris is evident on remembering that, according to Section 4, the spherical aberration would increase with the divergence of the rays, and hence with the proximity of the object. On account of the advancement of the front surface of the lens the iris is also moved forward, which can be seen on looking in profile view at an eye during accommodation.

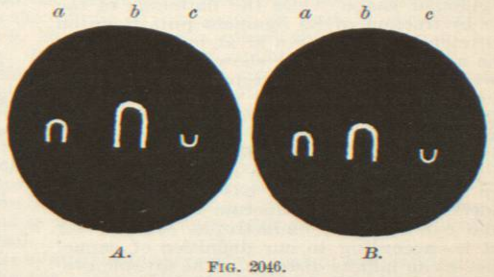

FIG. 2046.

40. *Mechanism of Accommodation.*—The accommodative changes of the lens are brought about by the action of the ciliary muscle. The lens itself is not a muscular organ, it is devoid of contractility. It is, however, an

elastic body kept stretched by its attachment to the annular ligament, as an elastic hoop would be flattened by the traction of two cords attached at two opposite points. Relieved of this traction the lens increases in convexity and becomes more nearly globular, so that the lens removed from the eye is more convex and thicker than while in place. During the accommodation effort the ciliary muscle contracts. Its meridional fibres pull the choroid forward. This has been shown by Hensen and Voelkers, by the movements of a needle put through the sclera and choroid on sending an electric current through the ciliary muscle in the eyes of animals and in a human eye just extirpated on account of disease. The circular, ring-shaped muscular fibres of the ciliary body on contracting cause the ciliary processes to project further toward the centre of the pupil, which movement of the processes is favored by the above-described traction on the choroid and consequent relaxation of its anterior insertion. In eyes in which a sufficiently extensive segment of the iris has been removed by the operation of iridectomy, and through the translucent intact iris of albinos, this advancement of the ciliary processes toward the centre of the pupil has been directly observed. Since the ligament of the lens is attached to the ciliary processes the crowding of this ring-shaped structure into a narrower space necessarily relaxes the circular band stretched across the aperture within this ciliary ring. Thus the lens is permitted to retract by yielding to the tension of its own elastic substance; for the arrangement of the fibres of the lens substance is such that they are relaxed by the approach of the lens toward the globular shape, while the flattening of the same by traction of its ligament puts them on the stretch. The changes in an eye during extreme accommodation are shown in Fig. 2047, in which the upper half represents the front half of the eye at rest, and the lower half the contraction of the ciliary muscle and its effect upon the shape of the lens.

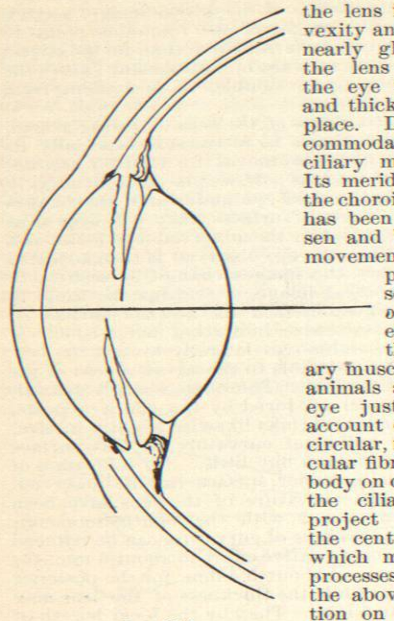

FIG. 2047.

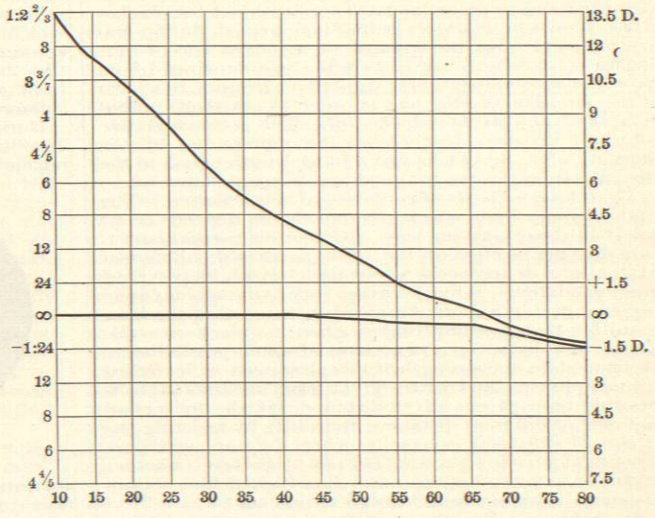

FIG. 2048.

41. *Range of Accommodation.*—The most distant point of which the eye at rest can form a sharp image on its retina has been termed by Donders the *far point* (punctum remotum = R) of the eye. In the emmetropic eye the far point is—according to our definition of emmetropia—at an infinite distance. The myopic eye, however, cannot see distinctly beyond a certain short finite distance, depending on the degree of shortsightedness, while in hypermetropia the eye cannot bring into focal reunion on the retina any but convergent rays, and the far point is therefore negative, that is to say, situated at some finite distance behind the eye. The fact that many hypermetropes can see distinctly at a distance with the unaided eye, is due to their using a part of their accommodation continuously in order to increase the actual refraction of the eye. The *near point* (punctum proximum = P) on the other hand, is the nearest point of which the accommodated eye can get a well-defined image. The range of accommodation is the total accommodative power which an individual eye possesses. We can represent it by the strength of the lens equivalent to the refractive difference between the eye at rest adjusted for the far point and the eye accommodated for the near point. Thus, an emmetropic eye, which can see distinctly an object as close as five inches, has a range of accommodation representable by a lens of five inches focal length or of the strength of about 8 D. For deprived of its accommodative power this eye would require such a lens to be held in front of it in order to get a sharp image of this near object on its retina. Practically, it will do to hold the lens very close to the cornea; for theoretical accuracy, however, the lens in question, of an infinite thinness, must be assumed situated in the first principal plane of the eye. The significance of the range of accommodation is made plainer by the use of Donders' formula,

$$\frac{1}{A}=\frac{1}{P}-\frac{1}{R},$$

in which we represent by A the range of accommodation, by P the near point, and by R the far point. This formula is applicable to ametropic eyes as well as to emmetropia, for anomalies of the refraction do not necessarily alter the range of accommodation. Thus a myope whose far point is at twelve inches' distance, and who can accommodate for objects four inches from the eye has an accommodative range $= \frac{1}{4} - \frac{1}{12} = \frac{1}{6}$. Another instance will illustrate both the condition in hypermetropia and the use of the dioptric system. Suppose a certain hypermetropic eye, the axis of which is so short that it requires a correcting glass of 4 D in order to obtain sharp retinal images of distant objects. In this eye the far point is negative, that is to say, it is situated 25 cm. behind the anterior principal point. If this eye possesses an accommodative range equal to eight dioptrics, four of them are required to see distinctly at a distance and only 4 D are left, enabling the person to get distinct images of objects 25 cm. distant by the extreme employment of his accommodation. Donders' formula reversed expresses this on using centimetres as follows:

$$\frac{1}{P}=\frac{1}{R}+\frac{1}{A},$$

which is in numerals

$$\frac{1}{P}=-\frac{1}{25}+\frac{1}{12\frac{1}{2}}=\frac{1}{25},$$

or employing dioptric notation, which is the reciprocal of the focal length,

$$P=-4\,D+8\,D=4\,D;$$

in other words, the distance of the near point from the eye is equal to the focal length of a glass of 4 D strength = 25 cm.

42. *Influence of Age on the Accommodation.*—From childhood on, the rigidity of the crystalline lens increases, and the extent of its elastic retraction diminishes. Hence the range of accommodation diminishes as the years advance, because the lens cannot retract as much in the later period of life as during youth, though the contracting ciliary muscle relaxes the annular ligament. The range of accommodation sinks thus from beyond ten dioptrics, during childhood, to zero toward the age of sixty years. Donders has constructed a diagram (Fig. 2048), based on numerous observations, which illustrates this decline in a graphic manner. The heavy line (the lower one) represents the refraction of the eye at rest. As before stated, the emmetropic eye becomes slightly hypermetropic in advanced age, presumably from an actual flattening of the lens or a diminution of its refractive index. The range of accommodation extends from the heavier line of passive refraction to the thin line indicating the extreme active adjustment of the eye. The figures at the bottom give the age in years; those at the side the (active or passive) adjustment in French inches (or expressed in dioptrics on the right side). Occasionally deviations are found from this standard of decline. Thus, among others, the writer has seen a gentleman, seventy years of age, who could read the finest type up to eight inches' distance. He had a slight myopia and myopic astigmatism, less than 1 D, so that this accommodative range was still a trifle over 4 D, a very unusual amount for his age. Exceptions of the opposite kind, a falling short of the accommodative range normal to the age of the patient, are always due to disease of the eye or general impairment of the health.

43. *Innervation of the Accommodative Apparatus.*—The ciliary muscle derives its nerve supply from the third cranial nerve or motor oculi, which sends the motor root to the ciliary ganglion, whence issue the ciliary nerves which penetrate the sclera. It is a common clinical observation to find paralyses of other branches of this nerve accompanied by paralysis of the mechanism of accommodation. Experiments by Trautvetter[6] have shown that the fibres of accommodation run in the trunk of the motor oculi in pigeons, while in other animals the results were negative. In dogs, Hensen and Voelkers have traced the fibres up to the floor of the third ventricle of the brain, as shown by the result on stimulating those parts.

Although the ciliary muscle consists of unstriated fibres in mammals, its movements are both as rapid and as much under the control of the will as those of any striated muscle. In birds, indeed, having evidently a very energetic accommodative mechanism, the ciliary muscle is striated. While the ciliary movements are voluntary in a certain sense, we are ordinarily not conscious of any accommodative effort. The movements of the ciliary muscle are guided by the retinal impressions which we get of the objects viewed, and may hence be classed among the complicated cerebral reflex movements. The accuracy of these movements is wonderful, inasmuch as the most rapid changes of adjustment of the eyes for different distances never give rise to any blurring of the images for which the eye accommodates. The regulating mechanism does not miscalculate the distance of the objects. The accommodating movements are always accompanied by an exactly corresponding convergence of the two eyes, so that in normal instances the object accommodated for is also the one toward which both eyes are directed, so as to place its image in the centre of the retina of each eye. The association of the movements of accommodation and convergence is so intimate that we cannot voluntarily perform either movement to any appreciable extent without the other. But by optic means, which simulate the effect of one or the other movement, we can temporarily rupture the association. Thus, with a given degree of convergence for a certain fixed object, we can either force ourselves to a greater accommodative effort by looking through concave glasses, or relax the accommodation by means of convex spectacles. Similarly, we can vary the degree of convergence associated with a certain accommodative effort by placing prisms of variable strength and inclination in front of one or both eyes. The ability to separate these two movements ordinarily associated is increased by practice. It is evident that the correlation of the two movements, as well as the disturbance of this association by optic means, subserves the same purpose, viz., distinct vision without double images.

44. *Movements and Nerves of the Iris.*—On account of the association with the accommodation, the movements of the iris can be best discussed in this connection. The iris serves the purpose of an optic diaphragm, the aperture of which can vary in size according to necessity, the physiological limits being from 1 to 6 mm. diameter. By reflex action the pupil contracts with increasing illumination, thereby diminishing both the fatiguing brightness of the retinal image and the width of any circles of diffusion due to optic imperfections. When the light is relatively feeble, a large pupil, on the other hand, permits a relatively greater brightness of the retinal images, while the enlarged circles of diffusion do not blur the sight so much, on account of their feebler intensity. The pupil contracts also with each accommodative effort, thereby diminishing the spherical aberration, which the proximity of the object and the increased convexity of the lens would produce. Independently of external light, the pupil is very narrow during sleep and during artificial narcosis. The mechanism of this latter contraction is not yet known. When the narcosis is interrupted by any sensory stimulation, or by asphyxia, the pupil indicates this change by dilatation.

The nerves of the iris are the ciliary nerves, coming from the ciliary ganglion, which, in man, has three roots—the short root from the motor oculi, the long root from the naso-ciliary branch of the fifth nerve, and the sympathetic fibres reaching the ganglion along with its arteries. The motor oculi controls the sphincter muscle of the iris. Its experimental irritation contracts the pupil; its section, or accidental paralysis, allows it to remain dilated. The reflex pupillary contraction produced by light starts with the excitation of the optic nerve. When the optic nerves are rendered inactive by disease, the normal play of the pupils ceases, and they remain in a state of moderate dilatation. Excitation of one optic nerve, however, controls the pupils of both eyes, at least in those animals which, like man, have a visual field common to both eyes. Hence, in cases of unilateral blindness, the two pupils are usually alike in size. The centre concerned in this reflex action is the anterior half of the tubercula quadrigemina (Budge). Various instances of diseases of higher parts of the brain have been observed with integrity of these parts, and hence sensitiveness of the pupils to light, although conscious sight did not exist. According to Brown-Séquard the muscular tissue of the iris itself is somewhat sensitive to light, a tonic contraction being induced in it by strong light, even after extirpation of the eyeball.

The sympathetic nerve fibres control the dilator muscle of the iris. The existence of these radiating muscular fibres, which seemed pretty well established by the researches of Henle, Iwanoff, and Merkle, after much controversy with Gruenhagen, has lately been questioned again by Eversbusch (meeting of the Heidelberg Ophthalmological Society, September, 1884). He maintains that the radiating fibres in the posterior layer of the iris, which have been interpreted as smooth muscular fibres, are really nerve fibres, as shown by various staining methods. If these statements are corroborated, it will be impossible to account satisfactorily for the action of the sympathetic nerve on the iris. The view that these nerves change the size of the pupil, through their action upon the muscular walls of the blood-vessels of the iris, is not well supported by the facts.

Their course toward the eyeball is partly along the walls of the arteries, partly along anastomoses which join the fifth cranial nerve. Section or paralysis of the sympathetic nerve of the neck is followed by contraction of the pupil, while its irritation dilates that aperture. These fibres can be traced through the rami communicantes of the last two cervical and the first two dorsal nerves into the spinal cord (Budge and Waller). The reflex centre of these fibres is partly in the corresponding region of the spinal cord, and partly in the medulla oblongata. Reflex dilatation of the pupil through this nerve channel can be readily induced by any sensory impression through almost any sensory nerve, at least when the pupil is not contracted by strong light, especially during sleep and incomplete narcosis. The pupil, indeed, is very sensitive to irritations of sensory nerves. It is not known that this reflex dilatation is of any utility.

It has recently been asserted by Tuwim[7] that the superior cervical sympathetic ganglion maintains a slight tonus of the dilator nerves of the iris, independently of, and even after, its separation from the central nervous system. Although his experiments seem conclusive, the question should be further investigated, since this would be the first instance known of tonic activity of nerves maintained by a sympathetic ganglion.

The fifth cranial nerve is the sensory nerve of the iris, endowing it with very great sensibility. Irritation of this nerve contracts the pupil very energetically in some animals, for instance the rabbit. Section of the nerve has the same effect, temporarily, the fibres being evidently kept in a state of transitory irritation by the injury, as occurs as well in certain other nerves. This influence of the fifth nerve upon the pupil does not exist in carnivorous animals. The observations in disease of that nerve in man are too conflicting to be decisive. The study of eye diseases attended with irritation renders it very likely that in man the fifth nerve is the vaso-dilator nerve of the iris, and that its reflex excitation congests the iris and contracts the pupil mechanically by the engorgement of the vessels. This is also the most plausible explanation of the intense pupillary contraction obtained on puncturing the anterior chamber, which result does not occur on operating on the dead eye.

Bibliography.—The optic properties of the eye were not understood until Kepler, in 1602, evolved the theory of optical instruments in general. The importance of the various parts of the eye in refraction was further elucidated by the Jesuit Scheiner in 1619. Minor additions were successively brought out by the labor of different authors, but it was only after Gauss had published his mathematical investigation of the cardinal points ("Dioptrische Untersuchungen," Göttingen, 1841) that the complete theory of the refraction in the eye could be deduced. This was done successfully by Listing, in the article "Dioptrik des Auges" in Wagner's "Handwörterbuch der Physiologie" (1853), who, by a critical selection of the older measurements of the refractive indices of the eye by Chossat and by Brewster, of the anatomical measurements of dimensions and curvature by Kraus, Kohlrausch, and others, determined the position of the ocular cardinal points with considerable accuracy. The most marvellously accurate methods, however, for measurements of the living eye, were first introduced by Helmholtz, who, in his "Handbuch der physiologischen Optik" (1867; 2d edition, revised, 1896), has produced a masterly treatise of rare originality, which every student of the subject must consult in the original. Since the publication of his large work, the first part of which on refraction appeared in 1856, Helmholtz has pursued these studies with the aid of numerous students, most of whose articles have appeared in the running numbers of the *Archiv für Ophthalmologie*. In an article by Reich (*Arch. f. Ophth.*, 1874, vol. xx., 1), Helmholtz corrects some of his former measurements and figures, and accepts as more nearly representing the values of the cardinal points in the average eye the figures which we have reproduced in the text of this article. Extensive measurements, especially of the curvature of the cornea, have also been made by Donders ("Anomalies of Accommodation and Refraction," 1864) and by Mauthner ("Vorlesungen ueber d. optischen Fehler des Auges," 1872), and more recently by Reuss (*Arch. f Ophthalmologie*, xvii., 1, p. 27). The entire theory of the formation of images in the eye, including physiological optics in general, is most exhaustively treated in Aubert's "Grundzüge der phys. Optik," in vol. ii. of Graefe and Saemisch's "Handbuch der gesammten Augenheilkunde" (1876), while important recent additions are to be found in Nagel's "Anomalien der Refraction," in vol. vi. of the same work. Very complete is also the treatise of Fick in vol. iii. of Hermann's "Handbuch der Physiologie." * All of these works must be consulted for the complete literature of the subject. In the English language the most extensive but older treatise is the work by Donders on "Anomalies of Accommodation and Refraction" (1864), which book marked quite an era in our knowledge of the physics of the different refractive conditions of the eye. In connection with this latter subject the work of Jaeger ("Einstellungen d. dioptrischen Apparats," 1861) must also be mentioned.

The mechanism of accommodation has been extensively discussed by former authors, by whom, however, no facts were brought forth beyond those taught by every-day observation. By some the accommodative changes were referred to the variations in the size of the pupil, while others even denied the existence of any accommodation. The most complete mathematical discussion was furnished by Th. Young in the "Philosophical Transactions" of 1801, in which it was shown by experiments and by deductions that the accommodation cannot depend on any changes except those in the form of the lens. The experimental proof that such changes do occur was furnished simultaneously and independently of each other by Cramer (in various publications in the Dutch language, between 1851 and 1855) and by Helmholtz (*Monatsberichte d. Berliner Academie*, February, 1853). The mode of action of the ciliary muscle was first explained by Helmholtz theoretically, and has since been confirmed experimentally by Hensen and Voelkers, who have likewise studied the innervation of the accommodative apparatus ("Experimentaluntersuchung über den Mechanismus der Accommodation," 1868, and *Archiv f. Ophthalmologie*, 1873, vol. xix.). Important measurements of the changes in the curvature of the lens during accommodation, and a mathematical inquiry into their efficiency were published by Knapp (*Archiv f. Ophth.*, 1860, vols. vi. and vii.).† Our knowledge of the range of accommodation in health and disease is due mainly to the researches of Donders ("Anomalies of Accommodation and Refraction").

On the innervation of the iris there exists an extensive literature, scattered throughout numerous physiological and ophthalmic serials. The older literature is exhaustively compiled in Budge's "Bewegungen der Iris," 1855. The present writer presented likewise a full review of the physiology of the iris in the Chicago *Journal of Nervous and Mental Diseases* (April and July, 1874), in which the complete literature up to that date can be found. Whatever has been done since 1874 is explicitly referred to in the text.

H. Gradle.

[1] Nagel: Anomal. d. Refraction, in Graefe and Saemisch's Handb. d. ges. Augenheilkunde, p. 461.

[2] Ueber schiefen Durchgang von Strahlenbündeln durch Linsen, Gratulationschrift an C. Ludwig, 1874.

[3] Archives of Ophthalmology, vol. ix., p. 29.

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* The most recent compilation with many original measurements is Tscherning's "Physiological Optics," trans. by C. Weiland.

† Various doubts raised concerning Helmholtz theory of accommodation have been satisfactorily answered by confirmatory researches published by C. Hess in von Graefe's Archiv f. Ophthalmologie in a series of articles from 1897 to 1901.

[4] Proceedings of the International Congress at Copenhagen, 1884, Ophthalmic Section.

[5] Report of the Heidelberg Ophth. Society in Deutsche med. Wochenschrift, October 9th, 1884.

[6] Archiv f. Ophthalmologie, 1866, xii., p. 95.

[7] Archiv f. d. gesammte Physiologie, Bd. xxiv., p. 115.

EYE DISEASES. See under *Cataract*, *Choroid*, *Conjunctiva*, *Cornea*, *Glaucoma*, *Hypermetropia*, *Myopia*, etc.

EYE, INJURIES OF.—It will be proper, in writing on injuries of the eye, to take for granted that the reader is well acquainted with the anatomy and physiology of that organ, and such of its appendages and surroundings as, on account of structure, function, or situation, are likely, in case of injury, to require treatment differing in any way from that which would be suggested by the principles of general medicine and surgery.

It is understood, too, that the reader has acquired the art of using easily and well all the instruments and methods needed by the oculist for the diagnosis and treatment of those affections which are not traumatic. One requires, in handling cases of injury, not only to have at command an ophthalmoscope and a full case of surgical instruments, but to be well drilled in their use, and to possess also a certain adaptability to the situation and independence of thought and action, which will allow him to depart occasionally from conventionalities, and in emergency to use instruments for what they are worth, not necessarily for what they are made. For, though the results of violence may be routined off and classified as to the kind of operative interference that they may require, it is oftener in this branch than in any other that the surgeon will discover new and unprecedented situations or conditions which occur so infrequently as to have existed in literature only as forgotten curiosities.

Physical Conditions.—A word or two relative to the physical conditions which exist in the healthy eye may be of service in helping to appreciate those which are likely to exist in the injured organ, or in one in which inflammatory changes following injury have not been met by the necessary surgical interference.

The eye is a globe; it is filled with fluid, semifluid, or gelatinous matter which is practically incompressible. Its walls, though elastic and flexible, cannot be stretched very much, and as the sphere is that form which will contain the largest amount of matter within a given area of covering, the result is, there being no outlet, that if pressure is put upon this globe it will not change its shape very much without rupture. The physical conditions are very much the same as those of a leather ball filled with water—not those that exist in a rubber ball filled with air. The walls of this globe are very flexible, and when the globe itself is emptied any part of the sclerotic or cornea can be bent on itself like cloth. Neither of these tissues, either with or without its lining membrane, is subject to fracture in the true sense of the word, and when there is any complete and violent solution of continuity in these parts it is due either to laceration, to puncture, to cutting from some sharp substance, or to tension, erosion, or chemical action. The particular part at which rupture takes place will be the part at which the enveloping material is the weakest, unless, perchance, that part, at the time of the stress, is better supported by the pressure of neighboring parts, or unless some other portion is made comparatively weak by the pressure of some foreign substance which bends or indents it, and so places on it a local strain that cannot be transmitted. Rupture by contre-coup is not possible in the eye, though it is sometimes spoken of as having taken place.

Before considering each separate tissue in order, it may be well to supplement what has already been said by calling attention to the fact that the enclosing tunics of the healthy eye are more than full, and once their integrity is broken a small part of the contents is likely to be forced out by the elasticity of the tissues; that the secretion of aqueous and vitreous, and the supply of blood to the interior of the organ, keep its elastic covering always in a state of tension, and when, by rupture, cut, or puncture, or by ulceration, or decay of injured tissue, there is any solution of continuity, a part of the contents will have a tendency to escape; and while the opening remains, the constant building up of material to supply the place of what has been lost often forms a serious obstacle to the rapid healing of the wound, or the successful return of any part of its contents, such as protruding iris or vitreous, to the eye.

Without having at hand any experiments which may be quoted as giving definite knowledge of the actual strength of the materials used in the structure of the eye, it is possible to state, from records kept in cases of injury, that the part which is least capable of resisting strain put upon it by external pressure is the sclerotic, 3 or 4 mm. from the sclero-corneal margin. This is by far the most frequent seat of rupture, which nearly always takes place in a direction parallel to the sclero-corneal margin. The fact that it is usually found to have broken through the meridional fibres in the upper and inner quadrant is probably explained by the position of the surrounding parts, which are such as to protect it from external pressure, and yet to give little or no support when the eye is pressed upon from some other direction. The cornea rarely ruptures, and when it does, it is from some ragged extension of an irregular sclerotic tear, and is not to be looked upon as primarily a corneal lesion. The thickness of the sclerotic and cornea in the accompanying cut is not to show the actual size, but to indicate diagrammatically the relative liability of different parts to give way whenever, from any cause, sufficient pressure is put upon the eye itself to make a rupture of its tunics inevitable. In the same figure the choroid is drawn as if it were attached to the inner side of the sclera only at the nerve, at the venæ vorticosæ, and at the ciliary processes (Nos. 1, 2, 3). This is not really the fact, but it is so much more loosely attached at the intermediate points that, whenever the choroid itself ruptures—as it sometimes does if pressure so distorts the eye as to pull this membrane away from the overlying sclera—the break does not ordinarily occur at any of the three points named above, but at some intermediate place. Such ruptures are most frequently seen, of course, in the posterior part of the eye, often nearer the nerve than the equator. They also do occur anteriorly to the venæ vorticosæ, and sometimes so far forward as to be unrecognizable during

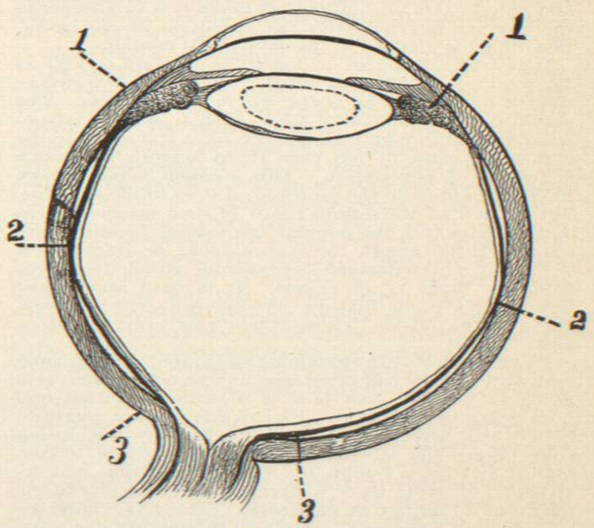

Fig. 2049.