The optics of fundus examination

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PERSPECTIVES IN REFRACTION

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The Optics of Fundus Examination

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Abstract. It has been 140 years since the invention of the ophthalmoscope in 1851 by Herman von Helmholtz. Since then, a considerable amount of time and effort has been devoted to improving the clinician's view of the fundus both for diagnostic and therapeutic reasons. Recently, there have been some notable advances in this respect, such as the 90 diopter lens, the "2.2 pan retinal" lens, and numerous "wide angle" fundus-viewing contact lenses to which the Volk Quadraspheric fundus lens has been the most recent addition. This paper is a review of the optical principles underlying the methods of fundus examination currently available. (**Surv Ophthalmol 36:**439–445, 1992)

Key words. fundus examination • laser therapy • ophthalmoscopy • optics • vitreoretinal surgery

The invention of the ophthalmoscope is attributed to Herman von Helmholtz in 1851, but Purkinje had some 30 years earlier viewed the fundus by reflecting a candlelight into a patient's eye by means of his concave spectacle lens. William Cumming of the London Hospital in 1846, Brucke of Vienna in 1847, and Charles Babbage all obtained views of the fundus by slightly separating a light source from their visual axis. Ophthalmoscopes until 1885 used a remote, oblique form of illumination, such as a candlelight, which was reflected by a concave mirror through which the observer looked. Dennett of New York in 1885 and Henry Juler of London a year later introduced the first electric ophthalmoscopes.[11]

Direct Ophthalmoscopy

The basic principle is simple. If a patient and observer are emmetropic, light rays from a point object on the patient's retina will emerge as a parallel beam, enter the observer's eye, and be brought to a point focus on the observer's retina (Fig. 1).

The fundus can only be seen where it is illuminated and, therefore, axial illumination will produce the greatest overlap between observed and illuminated areas. Semireflective mirrors, perforated mirrors and half mirrors or prisms have all been used to direct the illumination as axially as possible without obscuring the observer's view. The field of view is limited by the most oblique ray of light exiting the patient's pupil that still enters the observer's pupil and will therefore be increased by enlarging both pupils and bringing them close together. For practical reasons, the examiner's pupils are not routinely dilated.

Indirect Ophthalmoscopy

Direct ophthalmoscopy is limited by its field of view. In order to gain further field, light rays from more peripheral fundus diverging away from the observer's pupil need to be "caught" and redirected through the observer's pupil. This is the principle underlying indirect ophthalmoscopy, in which the condensing lens redirects peripheral rays toward

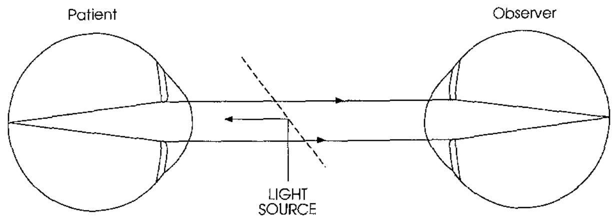


Fig. 1. Direct ophthalmoscopy with emmetropic observer and emmetropic patient.

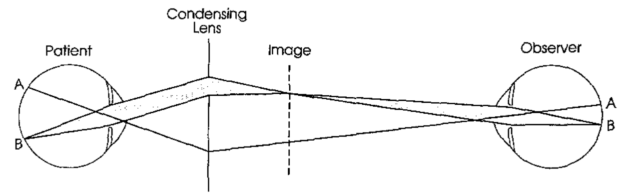


Fig. 2. Indirect ophthalmoscopy. The interrupted line signifies the inverted aerial image depicted as AB.

the observer's eye. The field of view is therefore governed by the diameter of the lens and its proximity to the patient's eye (which in turn is governed by its focal length – a high power lens having a shorter focal length). Expressed alternatively, the field of view in indirect ophthalmoscopy is governed by the relationship: lens diameter/focal length. If the patient is emmetropic, light rays leaving the eye with zero vergence and passing through the lens are brought to a focus in the focal plane of the ophthalmoscopy lens (Fig. 2).

Magnification of the image in indirect ophthalmoscopy may be considered in two stages: 1) magnification from the fundus to the real image (proportional to the power of the condensing lens), and 2) magnification from the image to the observer (proportional to the distance from which the observer views the image). Therefore, in emmetropia, the real image is formed at the focal plane of the lens (Fig. 3). Thus, magnification can be calculated according to the following equations, where M = magnification; f = focal length; D = dioptric power.

$$M = \frac{f_{lens} \sin \alpha}{f_{eye} \sin \alpha}, \text{ which simplifies to}$$

$$M = \frac{f_{lens} = D_{eye}}{f_{eye} = D_{lens}}$$

For example, magnification for a 15D lens $= \frac{60}{15} = 4\times$; for a 20D lens $= \frac{60}{20} = 3\times$; for a 30D lens $= \frac{60}{30} = 2X$.

Viewed at 25 cm, no further magnification occurs. If viewed at a distance greater than this, these figures will be minified slightly.

The patient's and observer's pupils are imaged in each other, and only light exiting the patient's pupil through the reciprocal image of the observer's will give a binocular fundus view. Monocular indirect ophthalmoscopy does not give a stereoscopic view, but can penetrate pupils too small for direct ophthalmoscopy or binocular indirect examination. Use of a low power but wide diameter lens will maintain the fundus detail without too much restriction in field for reasons given above.

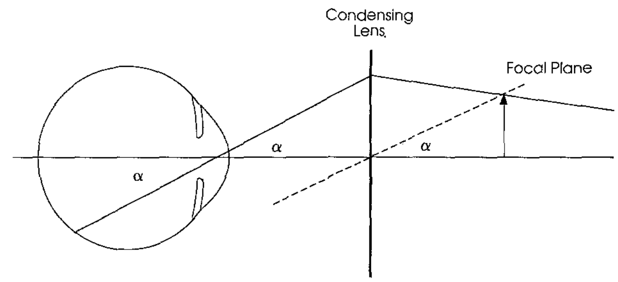


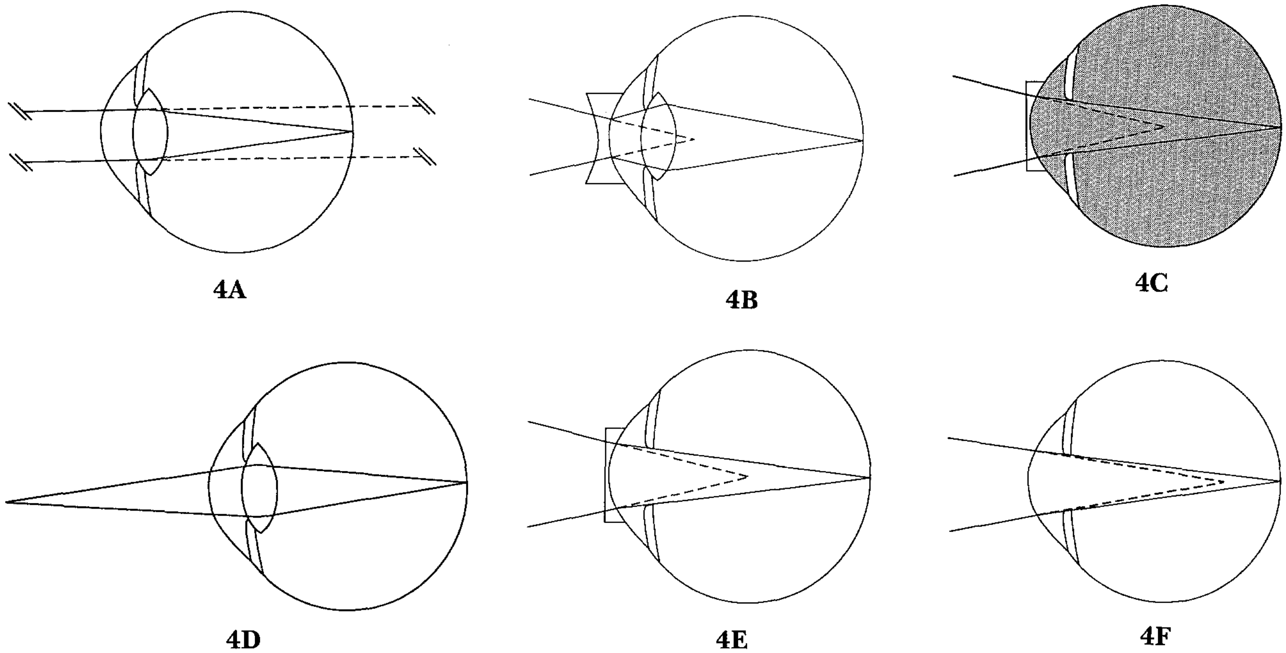
Fig. 3. Angular magnification α of aerial image in indirect ophthalmoscopy.

These features have been combined in the recently introduced Volk "2.2 Panretinal" condensing lens. A larger diameter (52 mm) gains field at a cost of slightly more awkward access in some pa-

TABLE 1

Comparison of Condensing Lens Sizes, Image Magnification, and Fields of View for Indirect Ophthalmoscopy

Lens		Image Magnification	Field of View	Working Distance from Cornea
Diopters	Size			
15D	52mm	3.92	40°	60
	45mm	3.89	35°	60.6
20D	50mm	2.97	46°	43.1
	35mm	2.93	32°	44.3
30D	43mm	2.05	58°	26.5
	31mm	1.99	42°	27.4
"PAN 2.2"	52mm	2.56	56°	34.1
90D	21.5mm	0.72	69°	6.5mm



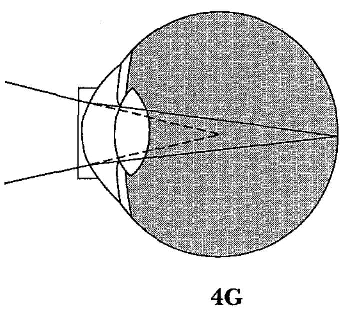


Fig. 4. Fundus visualization during vitrectomy. *A:* Phakic eye, no contact lens, image formed at infinity. *B:* Phakic eye with air-filled posterior segment using biconcave contact lens. *C:* Phakic eye with fluid/oil-filled posterior segment using plano/concave lens. *D:* Phakic eye with air-filled posterior segment using no contact lens showing aerial indirect image. *E:* Air-filled aphakic eye using plano/concave contact lens. *F:* Air-filled aphakic eye using no contact lens. *G:* Fluid-filled aphakic eye using plano/concave contact lens.

tients with a prominent brow or nose. It has a variable diopter (D) design, between 21D and 24D, to help provide linear magnification characteristics across the fundus image while stabilizing peripheral image aberations. The number "2.2" refers to the image magnification with the original design, although the presently marketed lens has a magnifying factor of 2.56× at its working distance of 34.1 mm from the cornea.

It has an estimated field of view of 56° compared with 32° for a 35 mm diameter 20D lens and 58° for a 43 mm diameter 30D lens (Table 1).

Imaging the Fundus of the Eye Containing Air or Silicone Oil

Recent advances in vitreoretinal surgery have led to the use of air or other gases or liquids, including silicone oil, to achieve retinal reattachment. Altering the refractive indices of the eye's contents means that optical modifications need to be made in order to visualize the fundus, and these have been clearly described by Stefansson and Tiedeman.[14]

In intraocular surgery, the magnification can be altered with the operating microscope, but a fundus view is dependent upon the image position. Generally speaking, the more minified the image, the wider the field of view. The operating microscope forms an image of a given object at a distance determined by its "working distance" lens, which is usually in the order of 15–20 cm. However, a typical Zeiss microscope has a 4–6 degree angle between light source and imaging optics. The illumination is blocked by the iris if the image is placed too far beyond the front of the eye, requiring that the microscope be close to the eye. When a fiberoptic intraocular light source is used, the illumination is not a limiting factor.

A reasonable aim of optical manipulations in vitreoretinal surgery is to place the image of the fundus inside the eye. This can be achieved either with a biconcave −63D or −93D lens in a phakic air-filled eye regardless of the anterior chamber contents. A plano-concave lens will do if the posterior segment is filled with saline or silicone oil (Fig. 4).

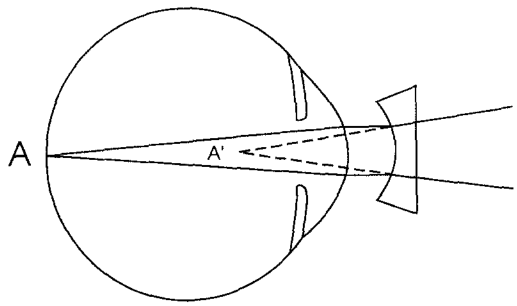


Fig. 5. Plano/concave Hruby lens forming image in anterior vitreous cavity.

There are two situations where a contact lens is not required to visualize the fundus – in an air-filled aphakic eye (Fig. 4f) and in an air-filled posterior segment of a phakic eye when an image will be formed at about 16 mm in front of the eye (Fig. 4d).

As a byproduct of altering the refractive indices of the various compartments of the eye, there will be a postoperative change in the patient's refractive error.

In a phakic eye with silicone oil in the posterior segment, its higher refractive index will convert the posterior lens surface from a converging interface to a diverging one, causing a hypermetropic shift in the order of 5–7D. Conversely, in an aphakic eye containing silicone oil in the posterior segment, the anterior curved surface of the oil globule will provide a more powerful converging refractive change than the previous lens, resulting in a myoptic shift. This leaves a previously emmetropic patient with only about 4–6 D hypermetropia in their new aphakic state – the exact degree is dependent on the curvature of the oil front surface, which in turn depends on position and percentage oil-fill.

When the posterior segment of a phakic eye is filled with air, this greatly increases the refractive power of the posterior lens surface, causing a large myopic shift and producing an indirect ophthalmoscopic image without the need for a condensing lens, as in some cases of high myopia. In an aphakic air-filled eye the posterior corneal surface changes from a low minus power to a high minus power, which neutralizes the refractive power of the anterior corneal surface. The cornea is thus reduced to virtually no power and the fundus can be visualized through it with no additional optical aids.

Fundus Contact Lenses Used in Vitrectomy

Various optical designs of contact lenses serve different purposes when used in vitrectomy.[5] With a plano/concave lens, the fundus with a fluid-filled posterior segment can be visualized. A biconcave lens allows visualization of the fundus of a phakic eye with a gas-filled posterior segment. A convex/concave lens produces a magnified fundus image of a fluid-filled eye. An angled plano/concave lens surface permits a peripheral fundus view analogous to that seen with a three-mirror contact lens.

Lenses are usually constructed of quartz, PMMA or optical crown glass and anchoring mechanisms include scleral suturing, vacuum-sealed or free-floating (hand-held). Irrigation is usually supplied via the scleral ring in the fixed varieties and the handle with the free-floating lenses.

Biomicroscopic Slit-lamp Fundus Examination

The slit-lamp provides a binocular fixed focus view on a plane about 10 cm in front of its objective lenses, and since the image of the fundus in an emmetrope is at infinity, it cannot be visualized without some form of optical aid. There are basically two means of slit-lamp fundus examination that are analogous to the direct and indirect ophthalmoscopic methods.

NEGATIVE LENS (Fig. 5)

A negative lens is placed in front of the objective of the microscope to move the microscope focus to infinity. This technique was first developed and described by Hruby of Vienna in 1942, using a −55D lens.[6] If the lens is held progressively closer to the eye, it will eventually become a contact lens. However, the optical principles remain unchanged, and this is the basis underlying the Goldmann, Ruiz, and other similar fundus-viewing contact lenses.[4,8,9,12]

HIGH POWER POSITIVE LENS

In 1953, El Bayadi described using a +60D lens and producing an inverted image 16 mm (1/60th m) in front of it.[3] Although the image was inverted, it gave a 40° field of view (6 disc diameters) compared to 2 disc diameters achieved with the Hruby lens. The currently popular 90D and 78D lenses work along identical principles (Fig. 6). A fundus view based upon a slight variation of principle may be achieved using a spare slit-lamp eyepiece. The eyepiece contains two converging lenses which can be used as an astronomical telescope arrangement to provide a real image (but inverted) that can be viewed with the biomicroscope. Volk designed and patented an ingenious fundus viewing device based on this arrangement, but incorporating a third lens to right the image (Fig. 7). Volk designed two arrangements – one for slit-lamp use and one for

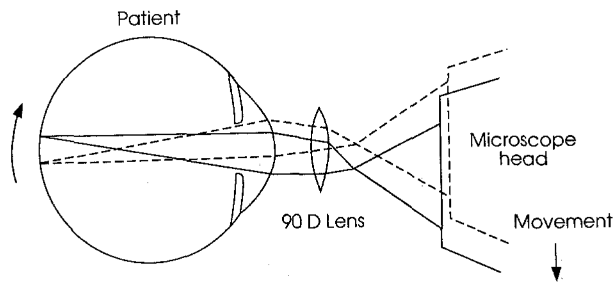


Fig. 6. Biomicroscopic indirect fundus view with high power plus lens.

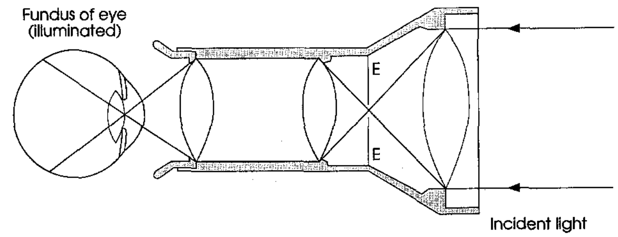


Fig. 7. Volk condensing image forming optical system for indirect ophthalmoscopy (see text).

indirect ophthalmoscopy – both providing the advantage of a normally orientated view, but the device does not appear to have gained widespread popularity.[15]

With the indirect ophthalmoscope, the field of view is limited by 1) those peripheral rays of light leaving the eye that are captured by the condensing lens, and 2) those peripheral rays leaving the ariel image that still enter the observers pupil. Schlegel considered both these aspects independently, and by a series of logical steps and brilliant reasoning was able to design his "Panfundoskop" lens, a description of which he published in 1964.[13] The optical principles described by Schlegel are the basis for the various "wide angle" fundus viewing contact lenses used today. His reasoning was as follows:

1) If the illuminated fundus is considered as a secondary source of light, the light coming out of the eye occupies an area which has the shape of a hemisphere.

2) To view this hemisphere, one either needs to use an optical arrangement which can extend to such a wide angle of projection, or, to make the hemisphere smaller. The size of the angle of projection depends to a large degree on the difference between the two refractive indices of air and cornea.

3) If the precorneal air is replaced by a contact medium of higher refractive index (Fig. 8a), the rays leaving the eye will not be deflected (significantly) within the contact medium. When they leave the contact medium they will diverge again in a hemispherical way. Some of the outer rays will be lost by total internal reflection.

4) There is a fundamental change if the anterior surface of the contact medium is made spherical (Fig. 8b). If the focal point of the spherical area coincides with the nodal point of the rays of light from the eye, the rays of light become radii of the hemispherical medium, exiting perpendicular to its surface, and are therefore not deflected when they leave the contact medium. In this way the angle of projection has been reduced when the rays enter the air. This still applies if the radius of the contact medium is reduced, provided that its focal point coincides with the nodal point of the rays. In the extreme, the contact medium is reduced to the shape of a meniscus lens.

5) If the refractive index of the meniscus is changed to that of glass (1.50), the situation changes further. The principle planes of such a lens lie in front of the convex side (Fig. 8c). The principle planes of the combined system (lens + eye) lie within the meniscus lens, and this change in the position of the principle planes gives a further reduction in the area of projection.

6) Fig. 8d shows that the eye with meniscus lens becomes very myopic (−50D), giving an inverted real image about 2 cm in front of the eye. The spherical image (depicted by the interrupted line) needs further modification by a so-called "field lens."

7) Figs. 8e and 8f depict the use of such a lens. Lens A projects an image of an object as shown. The observer cannot see the image in its entirety because the lens surround of A (angle x) acts as a "shutter." Peripheral rays do not enter the observer's eye. If a convex lens B is placed at the image position of Lens A which converges the peripheral rays towards the observer's eye, the observer can see the whole of the image formed by Lens A. The lens surround of B becomes the new shutter, which means the visual field is opened up.

The minification produced by this arrangement is between 0.7 and 1.0, depending on the choice of the two optical parts. In Schlegel's original design, he employed a spherical field lens. More recent advances have involved the use of aspheric surfaces to extend even further the field of view with these lenses. Referring back to Fig. 8b, it can be appreciated that if the anterior surface of the contact medium has an even steeper (aspheric) curvature, peripheral light rays will exit at an angle beyond the perpen-

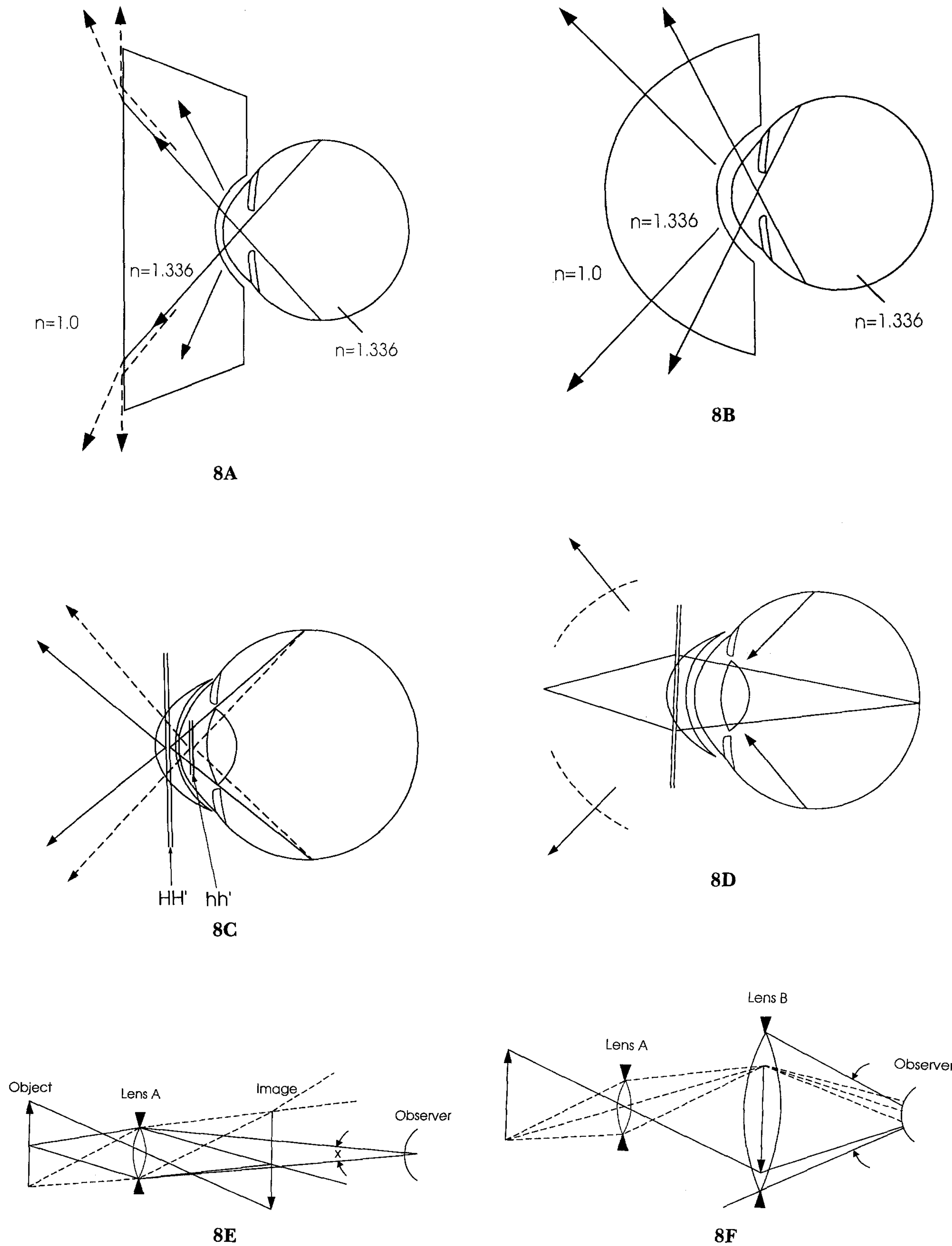


Fig. 8. Principles of Schlegel "Panfundoskop" fundus view. (see text). *A:* Plano isorefractive contact medium. *B:* Spherical isorefractive contact medium. *C:* Meniscus lens refractive index 1.50 showing shift of principle planes hh' to HH'. *D:* Image formation from 8c depicted by interrupted line. *F:* Use of field lens (B) for viewing indirect image of lens (A).

dicular and be refracted toward the field lens in a manner that will further reduce the area of projection. An aspheric design to the field lens can improve its peripheral "ray gathering" ability while maintaining a stable relatively aberration-free image. It is on this basis that such lenses as the Mainster, Mainster Wide Field (which incorporates two field lenses) and Volk Quadraspheric have been introduced, giving reported fields of view of 45, 125 and 125°, respectively.[1] The optical changes incorporated in these lenses result in a shift in the image to a position in front of the lens combination.

The optical design of these lenses leads to a degree of minification of the retinal image, which has important implications in regard to therapeutic laser delivery, which is their principle use. This is almost negligible with the standard Mainster lens. However, the size of the retinal burn increases by a factor of about 1.5 with the Panfunduscope and Mainster Wide View lenses according to some sources,[7] and by a factor of over 2.0 according to others.[2]

References

1. Barker FM, Ling JT: Ultra-wide field fundus biomicroscopy with the Volk quadraspheric lens. *J Am Optom Assoc 61:*573–575, 1990
2. Blankenship GW: Panretinal laser photocoagulation with a wide angle fundus contact lens. *Ann Ophthalmol 14:*362–363, 1982
3. El Bayadi G: New method of slit-lamp micro-ophthalmoscopy. *Br J Ophthalmol 37:*625–628, 1953
4. Goldmann H: Slit-lamp examination of the vitreous and the fundus. *Br J Ophthalmol 33:*242–247, 1949
5. Ho PC, Mainster MA, et al: Fundus contact lenses for closed pars plana vitrectomy. *Ophthalmology 90:*106–114, 1983
6. Hruby K: Spaltlampenmikroscopie des hinteren Augenabschnittes ohne Kontaktglas. *Klin Monatsbl Augenheilkd 108:*195–200, 1942
7. Mainster MA, Crossman JL, et al: Retinal laser lenses: Magnification, spot size, and field of view. *Br J Ophthalmol 74:*177–179, 1990
8. Rol P, Fankhauser F, Kwasniewska S: New contact lens for observation and coagulation of the retina and choroid. *Am J Ophthalmol 105:*479–482, 1988
9. Rotter H: Technique of biomicroscopy of the posterior eye. *Am J Ophthalmol 42:*409–415, 1956
10. Rubin ML: Optics of indirect ophthalmoscopy. *Surv Ophthalmol 9:*449–464, 1964
11. Rucker CW: *A History of the Ophthalmoscope.* Whiting Publ, 1971
12. Ruiz RS: A contact lens for biomicroscopy of the posterior segment. *Trans Am Acad Ophthalmol Otolaryngol 67:*747–748, 1963
13. Schlegel HJ: Eine einfache Weitwinkeloptik zur Spaltlampenmikroskopischen untersuchung des Augenhintergrundes (Panfunoskop). *Doc Ophthalmol 26:*300–308, 1964
14. Stefansson E, Tiedeman J: Optics of the eye with air or silicone oil. *Retina 8:*10–19, 1988
15. Volk D: United States patent No. 4,721,378, Jan 26, 1988

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