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The physics of image formation in the neuroendoscope

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Abstract *Introduction:* The development of the neuroendoscope has allowed neurosurgeons to visualize anatomic structures deep within the nervous system with minimal disruption of the critical overlying structures. This has enabled the development of an entire system of tools and techniques for maximum effective action at the target point through minimal corridors for the treatment of an entire spectrum of pathologies. *Discussion:* The design of an optical instrument with the ability to illuminate deep, hidden anatomic structures and transmit those images accurately and brightly to the eye of the neurosurgeon poses several challenges. These challenges have been met by advances in lens design and optical systems engineering over a period of several decades leading up to emergence of the modern neuroendoscope. In this paper, the basic concepts of the physics of image formation in optical systems are reviewed with emphasis on those elements critical to the endoscope. *Conclusion:* A consideration of these basic concepts is critical to the understanding of the limitations and capabilities of the key instrument for neuroendoscopy.

Keywords Endoscope · Optics · Design · Neuroendoscopy · Neurosurgery · Minimalism

Introduction

The development of the neuroendoscope has allowed neurosurgeons visual access to structures deep within the nervous system and its coverings. The very first endoscope was developed in 1890 by Nitze, taking the form of a miniature "train of lenses," representing the very first endoscope [6]. In neurosurgery, endoscopic applications have evolved to include the diagnosis and surgical treatment of pathologies within the ventricular system, the spinal canal, midline sellar-parasellar pathologies, and as adjuvants to microneurosurgery [3, 4, 7–10, 12, 13, 17, 22, 23, 25–27, 30].

The key enabling technology for the emergence of the entire field of neuroendoscopy is the development of the principal instrument, the neuroendoscope. The design of an instrument that allows illumination to deep, hidden anatomic structures in the brain requires the ability to achieve illumination and the subsequent ability to transmit the images accurately, clearly, and brightly to the eyes of the neurosurgeon. Critical to the design of the endoscope is an understanding of the underlying principles of physics for such instruments. Detailed treatments of these concepts can be found in the optical engineering literature [11, 16, 18, 28]. This paper briefly reviews these principles of optical imaging, with focus on the endoscope, aimed at providing neurosurgeons with a better understanding of the capabilities and limitations of their principal instrument.

Image formation in a perfect optical system—first order optics

Light has both particulate and wave natures. Waves emanating from a point light source travel away from the source in spherical fronts of decreasing curvature. The distance from successive wave fronts is the wavelength. In an isotropic medium that is one of homogeneous properties in all directions, a line connecting a point on each successive wavefront is straight and is known as a light ray. In a perfect vacuum, the velocity of light is approximately 3×10^{10} cm/s. However, the velocity of light decreases as the wave enters a medium other than a vacuum. In this medium, both the wavelength and velocity is decreased by a factor known as the index of refraction defined as the ratio of the velocity in the medium to that in a vacuum. For a light ray that traverses a surface separating media of differing indices of refraction, the angle between the ray and the surface is changed according to Snell's law. This phenomenon, known as refraction, forms the basis for the function of lenses and refracting prisms.

The behavior of a light ray though the components of an optical system is described by many equations. A rigorous derivation and discussion of the equations important in optical engineering and design is clearly beyond the scope of this paper. However, important terminology and concepts are presented briefly. Consider the behavior of light rays from a point source on an object as it traverses an optical system. The path of the light rays can be determined by the derivation of trigonometrical expressions created from the application of Snell's law at each surface. First order optics refers to the optics of a perfect optical system and is defined as the behavior of those light rays infinitely close to the optical axis in a region known as the paraxial region. In this region, the expressions that describe the behavior of the light rays are linear and much easier to use than the trigonometrical equations. These first order equations are used as a first approximation in optical design. For example, the familiar "thin lens" equations are strictly only applicable in the paraxial regions. Equations for image size and position in both single-component and multi-component optical systems can be quite complex, and first order approximations make them much easier to work with, especially in the preliminary design of optical instruments.

The overall behavior of each optical system can be understood in terms of its cardinal points, which include its first and second focal points, first and second principal points, and first and second nodal points [28]. The focal points are the points at which light rays parallel to the optical axis are brought to a common focus on the axis. The principal points are the points of intersection between the optical axis and the principal planes, which is defined as the plane of intersection between the rays entering and exiting the optical system. The nodal points are defined as the points on the optical axis where a ray directed at the first nodal point appears to emerge from the second nodal point in a path parallel to the incident ray. In the "thin lens" approximation, the principal points correspond to the location of the lens itself.

Aberrations—deviations from perfection in lenses

The first order equations are strictly only applicable to an infinitesimally narrow region around the optical axis. However, the behavior of practical optical components with finite apertures and fields of view can deviate considerably from this approximation. These deviations in behavior are termed aberrations [11, 18, 28]. Once corrected, the behavior of real lenses can be very nearly predicted by the first order paraxial equations.

Spherical aberration is defined as the variation of focus with aperture, and for a given aperture and focal length is a function of the object position and lens shape. Coma is another aberration that varies with aperture and refers to a bundle of oblique rays (those that are incident on the lens at a angle to the optical axis) being imaged at different heights, depending on whether the rays are passing near the edge versus central portions of the lens. When the images formed by rays in the meridional or tangential plane and the sagittal plane do not coincide, astigmatism is said to occur. In this case, the image of a point source takes the form of two separate lines rather than a point, resulting in an elliptical blur. Distortion occurs when an image of a point off the optical axis is formed either closer to or farther from the axis than the image height as predicted by the paraxial equations. This type of aberration can be either positive or negative, where the image is farther from or closer to the axis than predicted by the paraxial image height respectively. The longitudinal variation of the image position, or focus, with wavelength is termed chromatic aberrations. With this type of aberration, the image of an axial point takes the form of a bright dot surrounded by a halo. Furthermore, the image height can also be affected by wavelength, termed chromatic difference of magnification.

From the above discussion, it is quite clear that accurate formation of an image through an optical system may require correction of aberrations. Alterations in lens shape and stop position are two ways of accomplishing such corrections. For higher levels of corrections, the aberrations of two different lenses can be used to cancel each other out. For example, in telescope objectives, a positive lens with under-corrected spherical aberration and under-corrected chromatic aberration can be combined with a negative lens in which these aberrations are over corrected. This design is known as an achromatic doublet. The aberrations do not cancel out exactly in all zones of the aperture of lens, and the amount of uncorrected aberration is termed residual.

Stops and apertures—field of view and illumination

The amount of energy or light that passes through an optical system is limited by apertures (or stops), which take the form of either the clear diameter of lenses or diaphragms. The aperture stop determines the diameter of a cone of energy that the system will accept from an axial point on the object. The field stop limits the size or angular extent of the object that the system will image. An oblique ray that passes through the center of the aperture stop is termed the chief or principal ray. The initial and final intersection of the chief ray with the optical axis is termed the entrance and exit pupils respectively, and they represent the image of the aperture stop in object and image space. These pupils determine the amount of radiation accepted and emitted by the optical system.

A chief ray farther from the optical axis will not pass through the system limited by the field stop of the system. Therefore, the angular field of view is determined by the size of the field stop. The images of the field stop in object and image space are termed the entrance and exit windows respectively.

In a multi-component optical system, situations may occur where the cone of energy that passes through the system is limited on its upper extent by the diameter of one optical element and on its lower extent by that of another. This is termed vignetting and can cause decreased illumination at the image point as well as limit the field of view.

Illumination is defined as the power per unit area at the image. When a lens forms an image, the amount of energy collected from a small area of an object is proportional to the area of the clear aperture, or entrance pupil, of the lens. Illumination is thus inversely proportional to the image area over which this object is spread. The ratio of the focal length to clear aperture is called the relative aperture, and the illumination in an image is inversely proportional to the square of this ratio. An alternative way of expressing this relationship is with the numerical aperture, which is defined as the index of refraction times the sine of the half angle of the cone of illumination.

Other concepts that are important in optical engineering include resolution and depth of focus. Due to its wave nature, passage of light through apertures results in diffraction patterns. This means that perfect point sources will not result in point images, even in perfect optical systems. The limit of the ability of an optical system to differentiate between the diffraction patterns of two very close point sources is its resolution. Since images formed by all optical systems will have a small amount of blur due to residual aberration, the amount of longitudinal shift in the image before the blur becomes unacceptable is termed depth of focus.

Basic optics in afocal systems—telescopes and endoscopes

Telescopes and endoscope are examples of afocal systems since both the object and image are located at infinity for all practical purposes [11, 28]. Figure 1 shows a schematic of a simple two-element telescope. The device consists of an objective lens and an eye lens (ocular lens). Clearly, the field of view is limited by the diameter of the eye lens in this system. In the sketch, vignetting occurs when a bundle of light rays is incident on the lens at a greater angle than that represented by the solid lines. In the case when the bundle of light is represented by the dashed lines, it misses the eye lens entirely, and vignetting is complete. If a field lens is placed exactly at the internal image, it can bend the light rays back toward the optical axis so that they pass through the eye lens. This effectively increases the field of view of the system without increasing the diameter of the objective lens, a key consideration in the design of small diameter devices such as endoscopes. The eye must be placed at the exit pupil in order to see the entire field of view. Therefore, the distance between the vertex of the eye lens and the exit pupil is termed the eye relief. The field lens also decreases the length of the eye relief.

Periscopes and endoscopes are also examples of afocal systems. However, in these devices, the image must be carried a long distance from the objective lens to the eye. Furthermore, there are considerable limitations in the diameter of the lenses used. In these systems, a system of relay lenses is used. This is illustrated in Fig. 2, where the objective lens forms an image at field lens A. The power of lens A is chosen so that it forms an image of the objective at relay lens B. Field lens C and relay lens D function in the same way. In an endoscope or periscope, the number of relay stages depends on the length of the instrument. A large number of relay stages for any given instrument length is clearly undesirable. In order to reduce the number of relay stages, air spaces within the endoscope can be filled with glass. The equivalent air path is the actual air path divided by the index of refraction. This reduction in the equivalent air path leads to a reduction in the number of relay stages, with consequent improvement in both image quality and reduction in cost.

Development of the gradient-index rod lens endoscope

The basic design of an endoscope is an objective lens and an eye lens (or ocular lens) separated by a distance that is

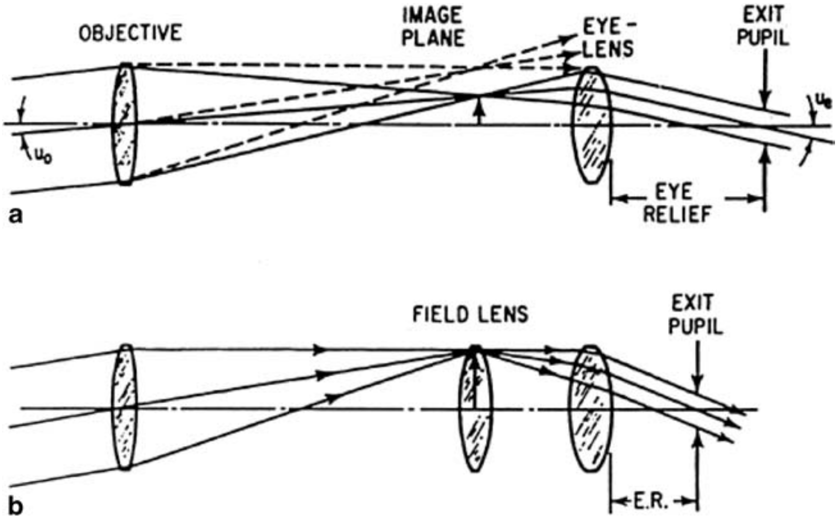

Fig. 1 **a** Schematic of a simple telescope consisting of an objective lens and an eye lens. In this system, the field of view is limited by the diameter of the eye lens. For example, a cone of light represented by the *dashed lines* misses the eye lens entirely, and vignetting is complete. **b** Insertion of a field lens exactly at the internal image can bend the light rays back toward the optical axis so that they pass through the eye lens, effectively increasing the field of view of the system without increasing the diameter of the objective lens. (Reproduced from [28] Figure 9.2)

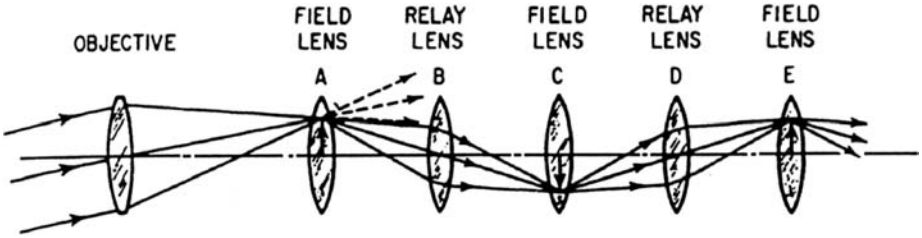

Fig. 2 A periscope or endoscope consists of a series of relay stages between the objective lens and the eye lens. Each relay stage consists of a field lens and a relay lens. The number of relay stages required depends on the length of the instrument. (Reproduced from [28] Figure 9.3)

bridged by a series of relay stages consisting of field and relay lenses [11, 16, 19, 28]. This could be accomplished by a series of conventional lenses mounted in a metal cylinder, as Max Nitze did in 1879 with his “train of lenses.” However, mounting a series of conventional lenses can be challenging, as even small amounts of tilting in any one of the lenses results in dramatic malfunction.

One key enabling development in the evolution of the modern neuroendoscope is the emergence of gradient index glass. A conventional lens can only bend light at its surfaces according to Snell’s law, discussed earlier. This is because the conventional lenses are made of optical glass that has uniform index of refraction throughout. By carefully designing the shape and surface of the lens, rays of light can be brought to focus and images formed. This process can be very costly and painstaking, especially with decreasing dimension of the lenses, as required in a neuroendoscope. A new type of glass was developed in the 1960s that had an index of refraction that was not uniform throughout. Instead, it varied with the radial dimension of the lens. In materials with non-uniform index of refraction, the rays of light travel in curved rather than straight paths, curving toward the regions of higher index of refraction. If these changes in index of refraction can be perfectly controlled, images can be formed without conventional lens surfaces. The variation of the index of refraction can be achieved by a high-temperature ion exchange process. This effect forms the basis for the SELFOC lens. Figure 3 shows a schematic of a SELFOC rod. In this lens, light rays travel in a sinusoidal path as a result of the index of refraction being higher in the center than at the periphery of the lens. In this example, the SELFOC rod functions as the equivalent of two relay lenses and a field lens. A shorter length of rod can function as a single lens element, while a longer rod can function as a periscope or endoscope with multiple relay stages.

In 1966, H.H. Hopkins and Karl Storz collaborated to create a rigid endoscope that took advantage of the

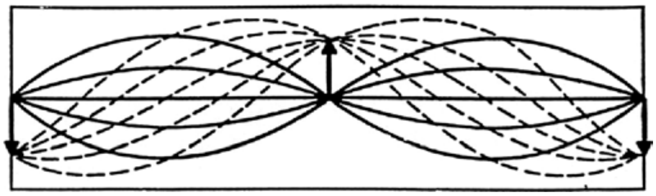

Fig. 3 The index of refraction in a SELFOC rod is higher in the center of the rod and decreases moving toward the periphery. In this lens, light rays travel in a sinusoidal path, and the SELFOC rod functions as the equivalent of two relay lenses and a field lens. (Reproduced from [28] Figure 9.25)

SELFOC lens [15] (Fig. 4). In this device, the conventional achromatic doublets that functioned as field and relay lenses are replaced by SELFOC rods. This initial device, for which a patent was issued, represents a key development in rigid endoscope design. A good summary of the key design points of modern rigid endoscopes can be found in a tutorial on the Internet [19]. In sum, the objective lens and relay lens are made of two different types of SELFOC materials bonded together in such a way that the thinner objective rod forms an image onto its rear face. The entrance pupil is telecentric between the objective and relay lenses and is located at the front of the focal plane of the objective lens. From Fig. 3, it is clear that the first natural aperture stop is the wall of the relay lens at a distance of one quarter period from the back of the objective lens. Similarly, additional aperture stops recur every half period from the first. The image positions within the relay lens are found at quarter-periods from each aperture stop, with the first being the image focused by the objective lens onto the face of the relay lens. The length of the relay lens required in a rigid endoscope can be determined by the desired length of the instrument and must be an integral multiple of half-periods. Ultimately, the brightness of an image in an endoscope is dependent on the optical invariant of its relay lens. This constant is proportional to the numerical aperture and diameter of the relay lens in gradient index lenses. The optical invariant is greater and thus the image is brighter in gradient index systems than conventional systems of equal diameter due to the absence of glass-to-air refractions. Currently, the field of view in SELFOC objective lenses is limited to about 55°. Given the small diameters of endoscopes, this limitation would result in very narrow fields of view. A negative lens placed in front of the objective lens would increase the field of view [24]. Finally, the eye lens or ocular lens magnifies the relayed image. This general design has many advantages over endoscopes of conventional design with respect to reduction in vignetting as well as logistical difficulties with the optimal mounting of serial lenses.

Optics of flexible endoscopes

So far, the discussion has focused principally on rigid endoscopes. Flexible endoscopes became a reality with the development of fiber optic technology [6, 12, 14]. The optics of fiber optic endoscopes is in fact far simpler than that of rigid endoscopes, since the image formed by the objective lens is relayed to the eye lens by a fiber optic bundle.

Prisms for angles of view

In certain applications, the ability to alter the angle of view is desirable. To achieve this in an endoscope, prisms can be added to the front of the objective lens [19]. Refraction prisms and reflections prisms are both used for this purpose. Refraction endoscopes are less costly, but they are also much more limited with respect to optical quality and degree of alteration of angle of view. For example, refraction prisms can only alter the angle of view by less than 10°. In contrast, endoscopes with up to 120° view angles employing reflecting endoscopes are commercially available (Fig. 5).

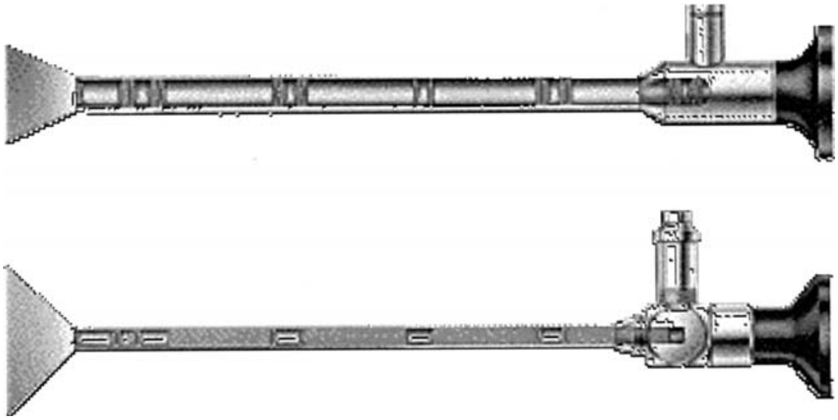

Fig. 4 The Hopkins type rod-lens endoscope replaces the conventional lenses (*top*) with SELFOC rod lenses (*bottom*). This represented a major improvement in rigid endoscope design

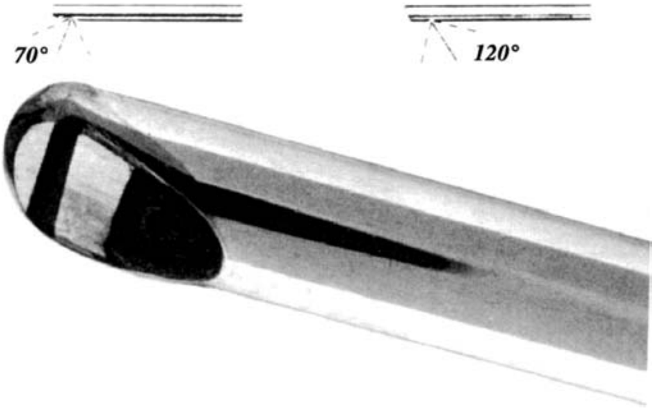

Fig. 5 The angle of view of an endoscope can be altered by the inclusion of prisms in front of the objective lens. With this configuration, up to 120° of angulation can be achieved. (Reproduced from [3])

Conclusion

The modern neuroendoscope is a marvelous device that has the ability to transmit clear and accurate images of deep-seated anatomic structures. This has been achieved through decades of improvements and modifications in the optical design of the telescope, a very basic optical device. There are of course limitations to the capabilities of all neurosurgical instruments, and these capabilities are constantly being expanded as the entire arsenal of tools for neurosurgery and its operating environment evolve [1, 2, 5, 20, 21, 29]. The future role of neuroendoscopy will clearly depend on its concurrent refinement and advancements in the design of its specific tools. Clearly, neurosurgeons with a better understanding of the technical limitations and capabilities of their instruments will be in a better position to guide this evolution.

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