

Chapter 8

Endoscope Optics

Endoscopes are used to observe otherwise inaccessible areas within the human body either noninvasively or minimally invasively. Endoscopes have unparalleled ability to visualize lesions within internal organs with high resolution through natural body orifices, such as the mouth, nose, anus, and urethra. With high-resolution endoscopes, harvesting biopsy samples for later laboratory analysis may not be necessary.

The history and basic optics of endoscopes will be discussed in Secs. 8.1 and 8.2. Sections 8.3, 8.4, and 8.5 will discuss the optics and optical design of relay lenses, objective lenses, and illumination systems. Section 8.6 will focus on the imaging and illumination systems of wireless endoscopes.

8.1 Introduction

The earliest endoscope-using lens was called the cystoscope. It was invented by Maximilian Nitze in 1877 and was used to examine the interior of the urinary bladder through the urethra.¹ In 1932, G. Wolf introduced the first semiflexible gastroscope, and in 1956, Basil Hirschowitz performed the first image transmission with fiber bundles. In 1959, Harold H. Hopkins invented rod lenses for image transmission, and in 1963, Karl Storz combined rod lenses for image transmission with fiber bundles for illumination.² A video endoscope with a camera on the eyepiece was first introduced in 1987, and a video endoscope with a camera at the distal end of the endoscope was demonstrated in 1992.¹ In the late 1990s, with the advances in light sources, sensors, and electronics, a wireless endoscope was invented for small-bowel imaging.³

Traditional endoscopes comprise an airtight and waterproof elongated tube having a distal end with an objective lens for imaging and a proximal end with an eyepiece for viewing. The elongated tube includes a relay lens system, or a fiber bundle, to transmit the image formed by the objective lens to the proximal end of the tube. The function of the eyepiece is to magnify the image at the proximal end for the observer. Endoscopes used in clinical applications further consist of a work channel and an irrigation channel.

In the last five decades, the introduction of optical fibers, rod lenses, and then the electronic detector has advanced the development of endoscopes dramatically. Various endoscopes have been developed for general applications and to meet some special requirements. Some commonly used endoscopes are:

- Arthroscopes to examine joints,
- Bronchoscopes to examine air passages and lungs,
- Colonoscopes to examine the colon,
- Cystoscopes to examine the urinary bladder,
- Gastrosopes to examine the small intestine, stomach, and esophagus, and
- Hysteroscopes to examine the uterus.

8.2 Basic Optics for Endoscopes

In some form or another, all endoscopes use optical elements to guide light to a target and transfer an image to the eye or to a detector. The basic optical elements of an endoscope include an illumination system, an imaging system, an image transmission system (relay system), and a viewing system (eyepiece or electronic sensor).

Figure 8.1 is a diagram of a conventional optical system in a rigid endoscope where, for simplicity, only one relay stage is shown. The system consists of three basic and separate optical components, as follows:

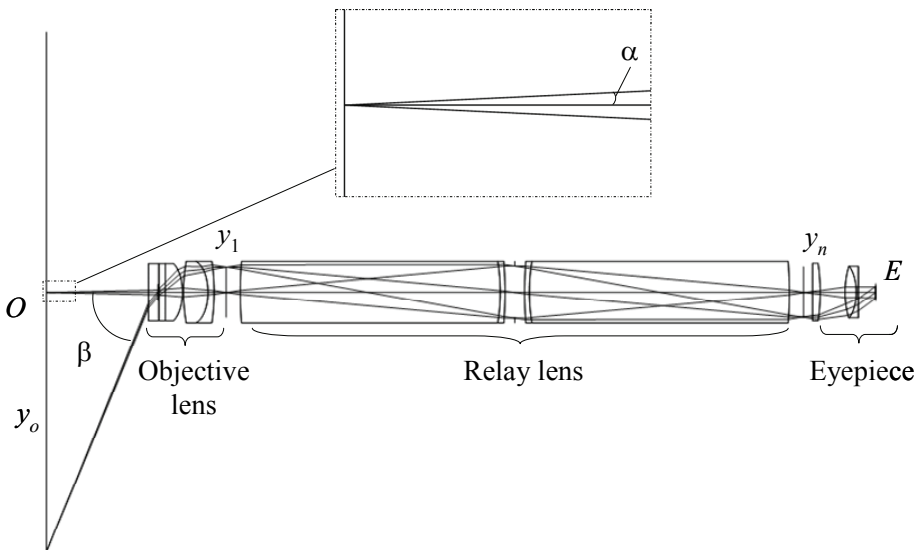


Figure 8.1 Typical optical layout of a conventional endoscope with a one-stage relay lens. It consists of three lenses: the objective lens, relay lens, and eyepiece. Here y_o is the height of the field, y_1 is the first intermediate image height, and y_n is the final image height through the relay lens. E is the exit pupil of the eyepiece, and it is the location for placement of the observer's pupil.

- An objective lens, which forms the first inverted intermediate image y_1 of the object y_o .
- A relay lens system, which reimages the first intermediate image y_1 to the final image y_n at the proximal end of the endoscopic tube. In most endoscopes, there are several unit-magnification relay lenses forming the intermediate images y_2, y_3, \dots , and the final image y_n .
- An eyepiece or a focusing lens, which presents the final image y_n to a sensor. Traditionally, an eyepiece is attached to the endoscope and produces a magnified virtual image for the observer. In modern endoscopes, a camera lens is attached to the endoscope, and it produces a real image on the electronic sensor. The image is then displayed on a monitor or other display device.

According to optical transmission systems, we can classify endoscopes into three groups: rigid, fiber optic, and video. In recent years, some new types of endoscopes, such as wireless, scanning, and stereo endoscopes, have been developed.

8.2.1 Illumination and imaging optics

Figure 8.2 illustrates a basic optical configuration at the distal end of an endoscope. The light from the fiber bundle illuminates the observation region. Part of the reflected light from the tissue is captured by the objective lens.

There are two major obstacles to designing an endoscope having a small diameter. The first obstacle is the lack of sufficient illumination. An endoscope with a small diameter does not provide enough space to transmit light. The second obstacle is light collection efficiency. The aperture is small because of the small diameter of the endoscope, which results in a low light collection efficiency.

The amount of light captured by the eye or an electronic sensor is principally determined by three factors:

- The intensity of the light incident upon the observation region,
- The optical characteristics of the observation surface, such as surface reflectivity and curvature, and
- The light collection efficiency of the objective lens and the transmission of the optical system.

The brightness of the image seen in an endoscope depends on the level of illumination falling on the region being viewed, as discussed below.²

The total amount of light captured by the endoscope from a uniformly diffuse reflecting surface is given by

$$\Phi = LR(\pi y_o^2)(\pi \sin^2 \alpha), \quad (8.1)$$

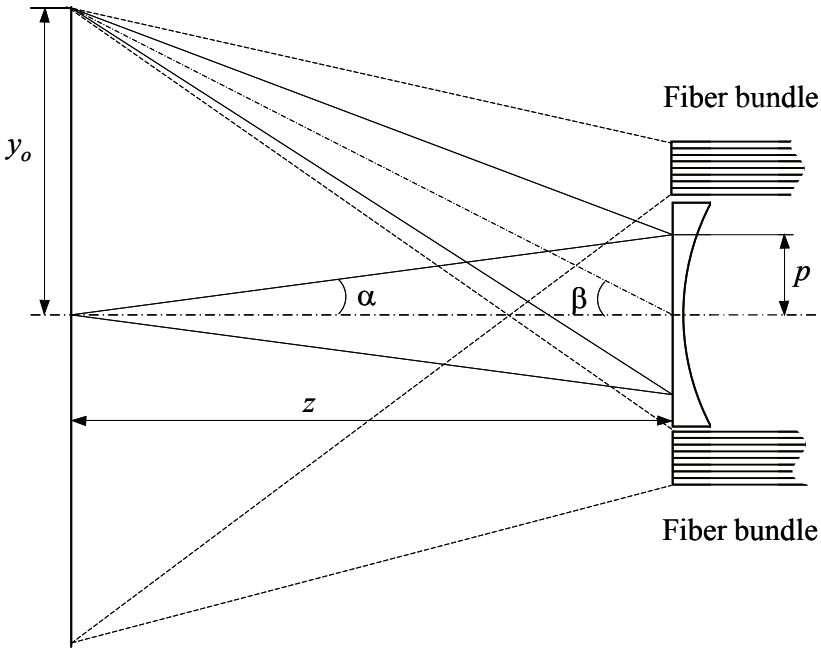


Figure 8.2 Basic optical configuration at the distal end of an endoscope. The light from the fiber bundle illuminates the tissue. Part of the reflected light is captured by the objective lens.

where L is the radiance from the fiber bundle, R is the reflection coefficient, y_o is the object height, and πy_o^2 is the area of the object, assuming that the FOV is circular, α is the cone angle of the light accepted by the objective lens, and $\pi \sin^2 \alpha$ measures the on-axis solid angle of the cone of rays accepted by the endoscope. All of the parameters are shown in Figs. 8.1 and 8.2.

The cone angle α of the light accepted by objective lens is approximately determined by the radius p of the entrance pupil of the objective lens and the working distance z :

$$\sin \alpha = \frac{p}{z}. \quad (8.2)$$

Therefore, Eq. (8.1) becomes

$$\Phi = \pi^2 L R y_o^2 \left(\frac{p}{z} \right)^2. \quad (8.3)$$

The total amount of light accepted by the endoscope is proportional to the radiance L and inversely proportional to the square of the working distance z .

In object space, the optical invariant is defined as

$$H = n \sin(\alpha) y_o, \quad (8.4)$$

where n is the refractive index of the medium in object space. Equation (8.1) becomes

$$\Phi = \frac{\pi^2 LR}{n^2} H^2 \quad (8.5)$$

for the given illumination and the object distance. The total amount of light entering the endoscope is proportional to H^2 .

8.2.2 Rigid endoscopes

As the name suggests, rigid endoscopes have a rigid tube to house the refractive relay lenses and illumination fibers. The relay lenses transfer the image at the distal end to the proximal end of the tube so that the image can be directly viewed through an eyepiece or with an imaging detector. When the endoscope is designed for direct view through the eyepiece, an odd number of relay stages is required in order to correct for the inversion produced by the object because the eyepiece has a positive magnification and does not produce an inverted virtual image. When an electronic sensor is used in an endoscope, the parity of the number of relay stages is not important since the inversion can always be performed electronically or through software.

As seen from Fig. 8.1, the relay system determines the value of the optical invariant H of the entire imaging system. In object space, the optical invariant is determined by Eq. (8.4). While in the plane of the entrance pupil, the optical invariant is

$$H = n \sin(\beta) p, \quad (8.6)$$

where β is the field angle and p is the radius of the entrance pupil, as shown in Fig. 8.2.

Given the H of the relay system and the FOV, either the object height y_o or the field angle β and the semiangle of the on-axis marginal ray α or the radius of the entrance pupil p can be obtained from Eqs. (8.4) and (8.6). Once the FOV is determined, the size of the relay system governs the focal length f of the objective lens by

$$f \tan \beta = r, \quad (8.7)$$

where r is the radius of the clear aperture of the relay lens.

The depth of field of the rigid endoscope is determined by the viewing configuration. When an eyepiece is mounted at the proximal end of the endoscope, the accommodation of the human eye helps to extend the DOF. The normal human eye can focus from infinity to a near point, which is 250 mm from

the eye. Therefore, the depth of field is calculated by the difference between two working distances: the working distance of the objective lens when the final image is located 250 mm from the exit pupil of the eyepiece and the working distance when the image is at infinity.

When a CCD or CMOS sensor is used at the proximal end of an endoscope, the depth of field is smaller than that of an endoscope using an eyepiece. The depth of focus can be calculated from the requirement of the resolution and the size of the pixels in the CCD or CMOS sensor, as discussed in Chapter 2.

One special requirement for objective lenses used in rigid endoscopes is the telecentricity that prevents light loss during image transmission from the distal end to the proximal end. As shown in Fig. 8.3(a), when the objective lens is not telecentric, the off-axis ray may miss the relay lens, for example, ray 1, or it cannot be transferred to the next intermediate image plane, such as ray 2, because it hits the edge of the relay lens. The ray may be absorbed by the lens edge or may be reflected back to the relay lens. Generally, rays reflected from the edge of the relay lens degrade image quality and should be minimized. The objective lens

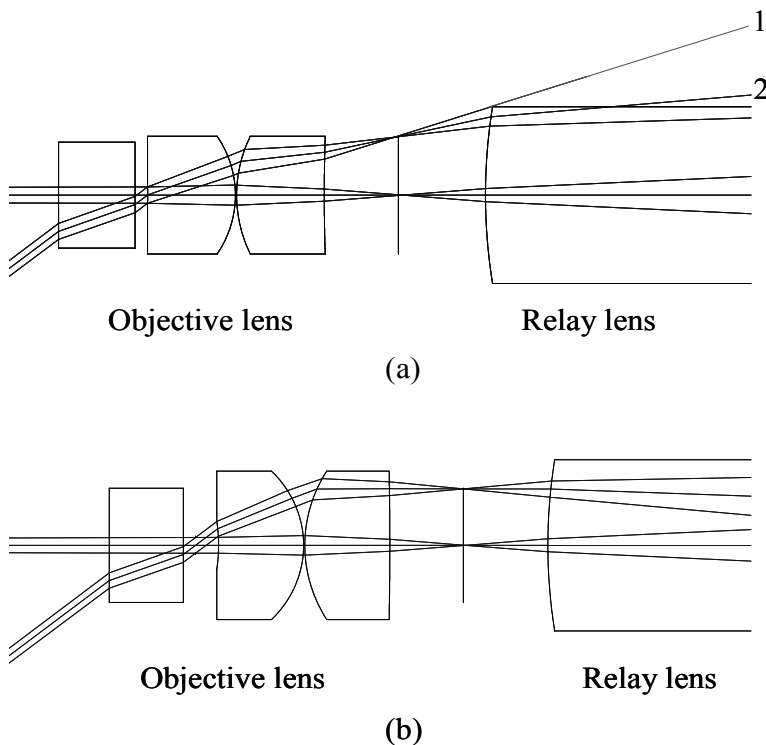


Figure 8.3 (a) Ray diagram of a nontelecentric objective lens. Rays 1 and 2 cannot be relayed to the next intermediate image. (b) Ray diagram of a telecentric objective lens. All of the rays are relayed to the next intermediate image.

in Fig. 8.3(b) is telecentric in the image space where the chief ray is parallel to the optical axis. All of the off-axis rays enter the relay lens and can be transferred to the next intermediate image.

There are three types of relay systems used in rigid endoscopes, namely, traditional lenses, rod lenses, and GRIN lenses. Section 8.3 will discuss the properties and design of each relay system.

8.2.3 Flexible endoscopes

Flexible endoscopes use imaging fiber bundles to transfer the image from the distal end of the endoscope to the imaging lens or eyepiece, as shown in Fig. 8.4. With fiber bundles, the diameter of the space required for the image relay is reduced significantly, leaving more space for other instrument channels. Other advantages of fiber-optic endoscopes include transmitting the image over long distances and observing around corners.

An imaging fiber bundle typically contains about 3000 or more optical fibers packed into a hexagonal array. The spatial arrangement of the fibers at both ends is identical, enabling a spatially coherent transmission of the image. The optical fibers are multimode and preserve the color of light. The core diameter is typically $3\ \mu\text{m}$, the overall diameter of the imaging bundle varies between 0.2 and 3 mm, and the fiber bundle may be over 2 m in length.

The resolution of a flexible endoscope is limited by the core diameter of the fiber bundle. Because of the pixelated nature of the fiber bundle, flexible endoscopes have a smaller depth of field than the conventional endoscopes with refractive relay lenses. The calculation of the depth of field is discussed in detail in Chapter 3. The telecentricity of the objective lens on the fiber side is required in order to couple more light into and out of the fiber bundle.

Unlike endoscopes with refractive relay lenses, where the eyepiece can be designed to compensate for the residual aberrations accumulated from the objective and relay lenses, the eyepiece in fiber endoscopes can only give a sharp image of what appears at the proximal end of the fiber bundle, and it cannot

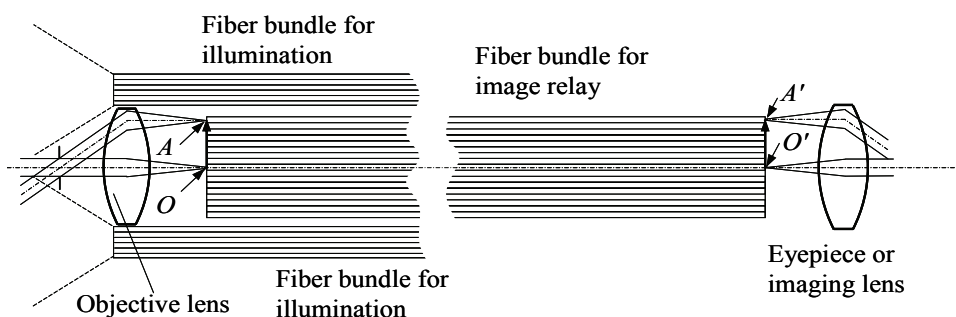


Figure 8.4 Optical layout of a typical fiber-optic endoscope.

correct the blur of the image formed at the distal end by the objective lens and transmitted by the fiber bundle.

8.2.4 Video endoscopes

One of the most important advances in endoscopes is the introduction of video-chip technology on the distal end of the device. Image relay is not necessary given that the objective lens images the observation surface directly to the sensing elements in the imaging detector. As shown in Fig. 8.5, the imaging head of a video endoscope generally consists of an imaging detector, objective lens, and illumination optics. Two types of imaging detectors, CCD and CMOS, are commonly used in video endoscopes.

Video endoscopes have revolutionized many surgical procedures by improving visualization while minimizing the tissue damage that is generally caused by invasive approaches. The advantages of a video endoscope over a fiber-optic endoscope include:

- The number of pixels in an imaging detector is typically greater than the number of fibers in a fiber bundle, giving a sharper image.
- In a conventional fiber-optic endoscope, the hexagonal sampling, which is due to the arrangement of the fibers, is followed by a rectangular sampling through the imaging detector. The mismatch between these two sequential sampling operations makes processing fiber-optic endoscope images difficult.

The objective lens of a video endoscope must have a short structural length, a small diameter, and a wide field angle. Compared to objective lenses used in rigid and flexible endoscopes, telecentricity is not a requirement for lenses in video endoscopes, even if it is desired to obtain uniform QE across the field of view. The incident angle of the chief ray on the image surface increases in proportion to the field. The chief ray angle should be smaller than the specification of the imaging detector for a reasonable QE.

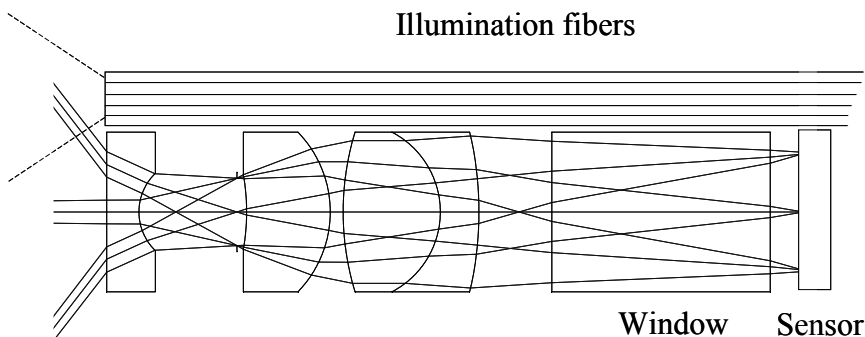


Figure 8.5 Optical layout of a video endoscope.