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Optical imaging technology in minimally invasive surgery

Current status and future directions

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Abstract. Optical engineering and imaging technology have played a major role in the evolving field of minimally invasive surgery (MIS) by making it possible to visualize the manipulation of tissue at remote internal sites. We assess and review the optical imaging technology used during a variety of MIS procedures from an engineering perspective. The field of MIS is evolving rapidly. Optic-based technologies have the potential to further improve diagnostic capabilities of MIS. Optical imaging technologies and instrument designs are discussed in relation to their current and future use in MIS procedures. Technical limitations in imaging technology are described, along with potential solutions. We review the current status and future role of optical imaging technology in MIS. In the future, synergistic benefits from engineering, imaging technology, and MIS are likely to improve diagnostic ability and patient care.

Key words: Imaging — Minimally invasive surgery — Noninvasive surgery — Laparoscopy — Endoscopy

Minimally invasive surgery (MIS) has contributed significantly to patient care by reducing the morbidity associated with more invasive procedures. MIS procedures have become standard treatment for gallbladder disease and tubal ligation, and they may play a vital role in staging some intraabdominal malignancies [7, 11, 19]. The increase in performance of MIS procedures has, in turn, resulted in advancements in optical instrument design and optical imaging technology for specific tissue or organ system access.

Imaging instrument designs

There are two general classes of optical instruments used in minimally invasive surgery—rigid and flexible. Rigid instruments include the laparoscope and the arthroscope; flexible fiber-optic devices include instruments such as the bronchoscope, gastroscope, and colonoscope. The rigid instrument design permits the use of glass lenses and rods. These designs offer an improvement in light transmission and image quality over the fiber-optic–based flexible designs, largely because the image is not pixelated by the individual fibers within the bundle. Common to all optical instruments are design features that permit entry via narrow incisions or natural body openings. Instruments range from 0.1 to 2 cm in diameter and from 10 cm to over 1 m in length, depending on the particular application.

In a generic rigid instrument design (Fig. 1A), the imaging optics pass down the center of the instrument with white-light illumination fibers located on the periphery. The image of the distal tissue is relayed to the proximal end, where the image is viewed, typically with a color CCD (charge-coupled device) camera. It is then displayed on one or more monitors within the surgical suite. The CCD camera resembles a flat computer chip with a focusing lens. The chip is a light detector divided up into individual pixels. When an image of an object is projected onto the chip, a digital image is recorded and sent to a computer or monitor for display. White light illumination is provided from a high-intensity xenon, mercury, or halogen lamp and delivered via a fiber-optic bundle. Prior to imaging, the CCD camera must be white-balanced to more accurately represent the color of the tissue being imaged. Even after white-balancing, variations in camera designs result in subtle color variations that may be distracting to the surgeon accustomed to particular color cues. Currently, CCD cameras and video systems allow the surgeon to adjust gain and contrast to optimize the video image, but this optimization can also impart color variations from patient to patient, thereby removing some elements of "standard" color cues.

The optical image relay system consists of a train of one

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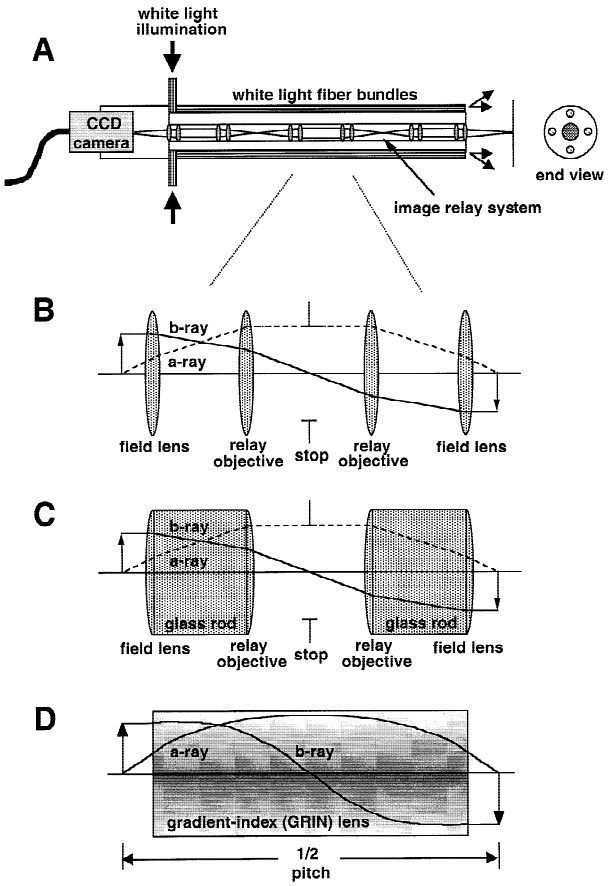

Fig. 1. Optical image relay systems. **A** Rigid laparoscopes utilize an optical system to relay a distal image of the tissue to either the eye or CCD (charge-coupled device) camera located proximally. Image relay systems have evolved over time from early, biconvex lens relay system **(B)** to Hopkins-type relay system with improved light transmissions **(C)** to gradient-index (GRIN) lens relay utilizing a single glass rod **(D)**. All three relay an image with unit magnification. Multiple elements can be used to produce laparoscopes of variable lengths.

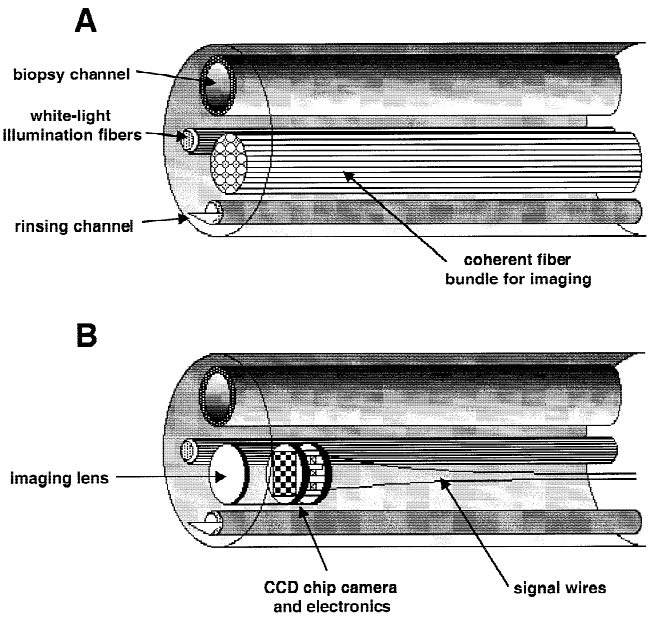

Fig. 2. Flexible endoscope optical elements. **A** Coherent fiber-optic imaging bundle used to relay image of tissue. **B** A single miniature CCD (charge-coupled device) camera can be located at the tip of a flexible endoscope. Images are digitized and converted to electrical signals for transmission to the proximal end, where the digital image is displayed on a video monitor.

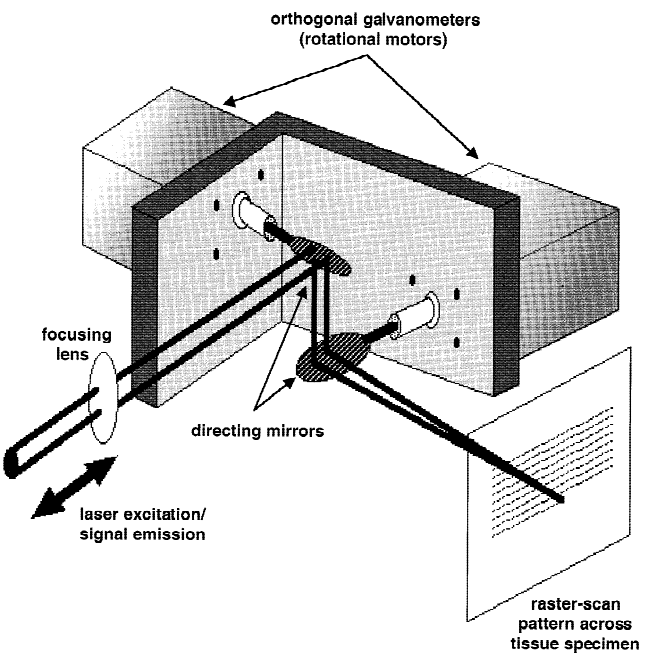

Fig. 3. Optical scanning mechanism. Optical imaging techniques may indirectly acquire an image of tissue microstructure by raster-scanning an optical beam across or through the tissue as shown, or by translating the specimen beneath a fixed optical beam. One example is laser-scanning confocal microscopy, which produces images based on the optical intensity at each pixel.

or more identical stages, each providing unit magnification as the image is transferred [8]. The propagation of light through a relay stage can be diagrammed with two rays (Fig. 1B). The a-ray is collimated as it passes through the aperture stop, while the b-ray is collimated outside of the relay stage. A conventional system of thin biconvex lenses requires that each stage be telecentric in both its object and image spaces. This means that both the entrance and exit pupils of the optical system are at infinity. A single conventional thin-lens stage is shown in Fig. 1B. Notice that the b-ray, which enters and exits with zero slope (parallel to the center optic axis), would pass through pupils (apertures) placed at infinity. In this design, the medium between the field lens and the relay objective lens is air. This free space is replaced with a glass rod in the Hopkins relay system shown in Fig. 1C. The advantages of this design include increased light throughput and reduced vignetting or distortion of the image [17]. Because of these advantages, most modern laparoscopes utilize this design.

Alternatively, it is possible to construct a relay system with a GRadient INdex (GRIN) rod lens (Fig. 1D). The radial gradient index variations within the rod cause the rays of light to bend just as they would through lenses surrounded by air. The ray path, however, is sinusoidal with a period, $p = 2\pi/\alpha$, defined as the pitch. The α is a material parameter specific for each lens. By increasing the length of the GRIN lens, one could use one of a few multiple-pitch

lenses within a laparoscope. The GRIN relay is the easiest rigid relay system to color-correct [17]. However, the manufacturing process of GRIN lenses is somewhat problematic because dopants must be diffused radially into the rod to establish an index gradient. This process is variable, and matching lenses to specifications can be difficult. Although not commonly found in laparoscopes today, GRIN lens relay designs are likely to be incorporated in the next several years as fabrication technology improves. The advantages of the GRIN lens relay include a simple design, fewer optical components, and comparably high optical quality.

The optical properties of the laparoscope require a period of adaptation before the surgeon becomes proficient. The fish-eye objective lens of the laparoscope produces a magnification that depends on the distance of the object from the tip of the laparoscope. Surgeons rely on known anatomical dimensions to provide a sense of scale. However, it is still difficult to quantitatively determine the scale of objects within the laparoscopic view. Since perspective is judged largely on the relative size of objects and the shadowing from light sources, providing a sense of scale or variations in light sources may improve perspective. Current laparoscopes illuminate in the viewing direction. This nearly eliminates the depth cues provided by shadows from off-axis illumination. Providing off-axis illumination with a secondary light source may offer some benefit. Of the 16 cues of depth perception, however, only four are lost by using a two-dimensional video monitor [12]. They include binocular disparity, convergence, accommodation, and eye dominance.

When the imaging instrument must be passed through tortuous lumens of the body, a rigid device is impractical. Flexible bronchoscopes and colonoscopes that are fiber-optic–based also permit the relay of an image from the distal to the proximal end of the instrument. By utilizing a coherent fiber bundle composed of thousands of fibers, each $\approx$ μm in diameter, an image can be relayed (Fig. 2A). Although this technology provides an adequate view, there still exists a degree of graininess resulting from the pixelation by the individual fibers. New colonscope designs now utilize advances in CCD camera miniaturization and place a single chip at the distal end (Fig. 2B). Rather than relaying the optical image, the image is converted to electrical signals, which are then passed to the display terminal and suffer minimal loss, interference, and distortion in the process. One interesting design uses a single monochrome CCD chip with alternating red, green, and blue illumination to form a color image rather than using three chips and three separate color filters. This reduces space requirements and takes advantage of established high-resolution monochrome CCD chip technology. The use of particular wavelengths of illumination may be used to enhance contrast during viewing. For example, illumination with green light would improve contrast of blood vessels due to the absorption of green light by blood relative to the more highly reflecting adjacent tissue. It may be possible to replace the current illumination lamp with three light-emitting or laser diodes. These could be located at the tip of the colonoscope as well and eliminate the need for a large heat-generating lamp. Currently, the primary limitation is the power and reliability of diodes that emit blue light. Once available, however, a diode-based illumination method will be a likely alternative.

In contrast to the direct visualization of tissue that most MIS optical instruments provide, some optical imaging technologies may indirectly acquire an image of tissue by scanning it pixel by pixel. This introduces some additional technical challenges in adapting these approaches to MIS. The prime example of this approach is laser-scanning confocal microscopy. The advantages of confocal microscopy include resolution at the level of histology (0.5–5 μm) and the ability to selectively image cells and subcellular constituents with the use of florescent markers. In order to acquire images corresponding to a particular depth plane in the tissue, the optics of confocal microscopy are based on acquiring information from each pixel sequentially, removing out-of-plane light, and assembling the image from an array of individual pixels. Each pixel contains intensity information based on the optical properties of the tissue from a single point. In the simplest embodiment, the specimen is translated beneath a fixed optical beam.

In the case of in vivo applications where the tissue is stationary, the optical beam must be moved in a 2-D or 3-D scan across the tissue to collect the intensity information (Fig. 3). Scanning may be performed with mirrors mounted orthogonally on galvanometers (rotational motors) or with other mechanical displacement mechanisms. Although confocal microscopy has shown promising clinical results in dermatology [14] and endoscopes with optical sectioning capabilities have been investigated [6], the integration of confocal and other optical imaging technologies requiring mechanical scanning in MIS instruments is difficult, largely due to size constraints. Significant engineering advancements are required to enable high-resolution sectioning using miniaturized raster-scanning mechanisms at acquisition rates that are fast enough to eliminate motion artifacts.

Future directions in optical imaging technology

The field of minimally invasive surgery is evolving rapidly. However, a number of technical limitations still exist in areas such as visualization and display, tissue imaging, and instrumentation. These are summarized in Table 1. In the future, complex MIS procedures will take advantage of synergistic benefits of combined technologies [5], and a new generation of devices may incorporate multiple imaging modalities into a single instrument. Ultrasound has already been integrated into endoscope instruments, and efforts are under way to incorporate MRI technology into MIS devices [3]. There is no doubt that optics and laser-based techniques will be integrated as well. Modern computing power will also be applied to the image-based world of MIS to transform the methods of retrieving, displaying, and analyzing images and data. Expert-assisted computer diagnostics for object identification in images will be applied to MIS for the intelligent, automated segmentation and recognition of pathology at the organ, tissue, and cellular levels. Improvements in three-dimensional imaging, viewing, and display will make diagnosis, tissue manipulation, and overall operability more feasible.

The use of an in situ optical technique capable of identifying tissue components and pathology as well as obtaining microstructural images may eliminate several of the current limitations in MIS today. In the optical engineering

Table 1. MIS procedures: technical obstacles and possible solutions

Depth perception	Implement 3-D cameras, polarized light detection, and other systems
	Provide binocular viewing in a simple instrument
Color CCD technology	Improve accuracy and reproducibility of color representation of tissue
	Provide spectral analysis and single wavelength imaging
Illumination	Provide off-axis illumination for shadowing and depth perception
	Filter wavelengths to improve contrast
Magnification	Reduce fish-eye magnification and distortion
	Increase magnification and resolution to sub-cellular level
	Provide variable magnification and zoom capability
	Implement measurement-scale within field
Mechanical problems	Miniaturize scan mechanisms for raster-scanning
	Increase degrees of freedom of instruments
Guidance	Stereotactically register instrument to patient for image-guided surgery
	Provide assisted placement of laparoscope/endoscope tip
	Assist endoscope tip advancement through lumens
Instruments	Integrate multiple mechanical and imaging modalities into single instruments
	Combine/coordinate control and display of multi-modality imaging systems
Tissue imaging	Provide subsurface imaging
	Improve identification and differentiation between normal/pathologic tissue
	Provide reliable detection of tumor margins
	Perform “optical biopsies” without resection
	Locate and avoid vessels and nerves

MIS, minimally invasive surgery; CCD, charge-coupled device

community, this concept has been termed an “optical biopsy,” but the term may be a misnomer for the medical community, given that a biopsy has traditionally been defined as the physical resection of tissue. The concept, however, is important because tissue removal can often become a significant issue in MIS. This technique would enable information on tissue composition or microstructure for the diagnosis of disease to be obtained without having to physically remove the tissue. For sensitive tissues of the nervous and cardiovascular systems where the physical resection of tissue could prove detrimental to the patient, an optical biopsy would offer the surgeon a nondestructive means of diagnosing tissue pathology.

Most efforts to develop the optical biopsy technique involve some form of tissue spectroscopy—the study of light absorbed, scattered, or emitted by tissue upon illumination by light. Spectral information from tissue fluorescence is one means of optically differentiating between normal and abnormal tissue, often when differences cannot be observed with the naked eye. Fluorescent dyes may be administered to improve contrast, but tissue autofluorescence following excitation by certain wavelengths of light can be sufficient. Excitation light can be delivered and emitted fluorescence collected using only a few otpical fibers—far fewer than required for imaging fiber bundles. Small instrument probes have been used to collect spectral information from the cervix for the early detection of premalignant states [13]. Fibers can be readily inserted into the working channels of flexible MIS instruments. Catheter designs are being developed to detect early atherosclerotic lipid deposits and calcification in coronary arteries using Raman spectroscopy [2]. Many of the autofluorescence studies to date have involved point measurements using optical fibers; clinical use will probably require intensified CCD cameras to detect the relatively weak autofluorescence signals. Spectral information can also be overlaid with CCD camera-acquired images from a colonoscope to provide real-time detection of nonpolypoid as well as polypoid adenomas [18].

Optical transillumination of tissue to obtain images of internal tissue structure is hindered by the fact that tissue is highly scattering at optical wavelengths. Most photons do not propagate straight through tissue but rather diffuse through. Studies of diffusing photons can provide information on tissue inhomogeneities that interfere with the diffusion process. One of the original goals of such studies was the detection of breast tumors [4]. A more modest goal is the detection of brain oxygenation states [9]. Although images are generated, poor millimeter-scale image resolution and long acquisition times are the major limitations. Integration with MIS instruments does not appear practical.

A relatively new optical imaging technology called “optical coherence tomography” (OCT) [10] may prove useful at providing more information on tissue morphology during MIS endoscopic and laparoscopic procedures. OCT is a laser-based optical imaging technology that is somewhat analogous to ultrasound B-mode imaging. Instead of detecting back-scattered acoustic waves with electronics, OCT detects back-scattered light using a technique called “low-coherence interferometry.” The technology is fiber-optic based, resulting in devices that are compact and readily transportable. Beam delivery to the tissue is accomplished via optical fibers, and the technology can be readily integrated into existing optical instruments such as surgical microscopes, hand-held surgical probes, colonoscopes, catheters [15], and laparoscopes [1]. Fast-scanning mechanisms permit cross-sectional images to be acquired with minimal motion artifacts—an essential factor for in vivo imaging [16]. The imaging penetration depth of OCT is limited to 2–3 mm, depending on the optical properties of the tissue. However, the advantage of the OCT technology for MIS procedures rests in the ability to image subsurface morphology at high acquisition rates and at high resolution through existing instrument designs. In contrast to ultrasound, tissue

contact or an index-matching gel is not needed in order for images to be acquired, and scanning can be performed over large areas of tissues.

Diagnosing endometriosis may be one application for a high-resolution subsurface imaging technology such as OCT. Presently, intraoperative identification of possible endometriosis lesions is based primarily on visual color differences. Subsurface lesions can at times be recognized by slight elevations in the tissue, but diagnosis is not certain. Integrated with a laparoscope, OCT may identify morphological variations consistent with endometriosis and guide the ablation of lesions.

An engineering assessment of optical imaging technology indicates that these two seemingly disparate fields—surgery and engineering—will become increasingly integrated in the future. A better understanding of principles and advances in optical imaging technology is essential if MIS is to provide more refined diagnoses and less morbid therapies in the future. As the field of MIS advances, imaging technologies will be at the forefront, providing the view ahead.

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