History of the Endoscope

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I. INTRODUCTION

Endoscopy is a technique allowing inspection, manipulation, and treatment of internal organs using devices to enhance visualization from a distance of the target organs without the need of an incision large enough to allow the hand or fingers of the surgeon to enter the surgical field. As can be expected, endoscopy developed in areas where hollow organs were connected to the exterior via natural orifices: the urethra, the vagina, the rectum, the ear canal, and the throat and pharynx. Entry of natural orifices was safe, devoid of wounds, and thus with little risk of infection and death. As also can be expected in the early days without radio, TV, telephone, or internet, numerous physicians and nonphysician scientists invented smaller or larger contributions to the field, sometimes at the same time unaware of the inventions of others. Not all who contributed published their inventions or the application of their inventions, and for others records were lost or destroyed at times of war. As a result the history of the endoscope is not an exact science where each advancement can be placed on a reputable time line and assigned with confidence to a single inventor. The limited space assigned to this summary of the history of the endoscope will not allow any details or nuances; instead it will focus on a number of well-regarded and generally accepted important contributions and its inventors in the early phases of endoscopy and mostly on the technology of the more recent history of endoscopy (Table 1). In addition, rather than focus on the people behind the inventions, this history is aimed mostly at the engineering concepts and subsequent applications in the medical field. For those who desire a more detailed and nuanced history of endoscopy, the reader is referred to books, manuscripts, and websites that cover the entire field or specific subspecialty areas: there are many including cystoscopy, colposcopy, bronchoscopy, thoracoscopy, gastrointestinal endoscopy, laparoscopy, arthroscopy, laryngoscopy, and otoscopy [1]–[10].

This month's article traces the history of endoscopy, with particular focus on the engineering concepts and subsequent applications in the medical field.

If we revisit the definition of endoscopy as given above, we can readily come up with a number of challenges that need to be overcome for endoscopy to be safe and successful. First, there needs to be a safe method of body access: natural orifices and tubes or small incisions into existing cavities at safe locations without significant risk of perforation or infection. Second, natural orifices and tubular structures are relatively safe, but require small diameter and flexibility of instruments. Third, when images are transmitted through instruments, image quality may erode; ideally image quality has to be as good as or better than that obtained with the bare eye and in general wide angle of inspection is preferred. Fourth, because there is very little light inside the human body, a source of external light is required for illumination. Fifth, the equipment and light need to be energy neutral; in particular, a light source cannot excessively heat the internal organs or cause external burns and electricity cannot cause effects other than those intended. Sixth, many human "spaces" are collapsed in their natural state; thus a method to temporarily fill these spaces to allow inspection and more is required. Seventh, although the ability to obtain a diagnosis without invasive surgery is a step forward compared to a diagnosis obtained via open surgery, the holy grail of endoscopy is to perform not only diagnostic but also definitive therapeutic procedures. This requires a much more complicated setup, the ability of many (main operator and assistants) to see the operating field, and a vast array of accessory instruments allowing remote manipulation, cutting, coagulation, injecting, suturing, and retrieval of organs. In the next paragraphs we will discuss the key steps toward resolution of these challenges in the 19th, 20th, and 21st centuries.

II. THE 19TH CENTURY—THE BEGIN OF ENDOSCOPY THROUGH DEVELOPMENT OF BASIC TECHNOLOGY

Most historians name Philip Bozzini, an Italian-German physician, as the inventor of the field of endoscopy [11]. In 1806 he developed a very

Digital Object Identifier: 10.1109/JPROC.2017.2742858

Table 1 Important Milestones in the History of Endoscopy (Adapted From [21])

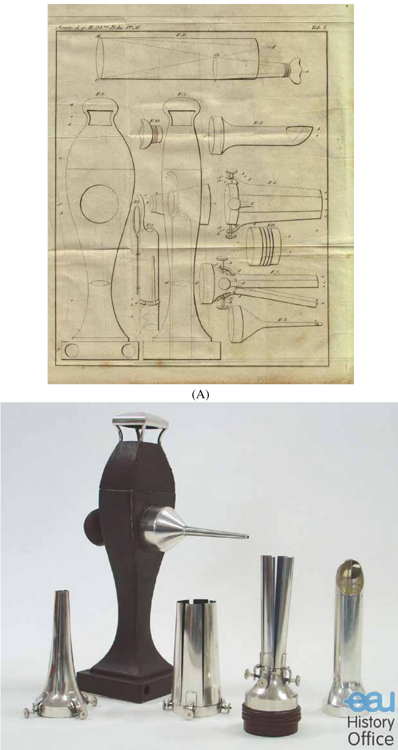
Year	Important person(s) or entity	Contribution
1806	Phillip Bozzini	The "Lichleiter", candle illuminated in a container reflecting light by an angled mirror
1853	Antonin Desmoreaux	First used the term "endoscopy", used kerosene lamp with paraffin flame and 45-degree angled mirror
1858	Nepomuk Czermak	First endoscopic image
1867	Julius Bruck	Platinum filament surrounded by water within a glass cooling system for better illumination
1878	Joseph Swan	Invented lamp produced within a vacuum that was neither hot in temperature nor able to burn out
1879	Max Nitze	Created cystoscope with water-cooled platinum filament lamp and series of lenses in a metal tube
1879	Thomas Edison	Invention of incandescent light bulb
1883	David Newman	Replaced platinum wires with incandescent light bulb on endoscope
1901	Georg Kelling	First laparoscopy in a dog
1910	Hans Christian Jacobaeus	First published laparoscopy in a patient
1924	Richard Zollikofer	First use of CO_2 for insufflation
1948	Harold Hopkins	Developed zoom lens
1953-1954	Harold Hopkins and Narinder Singh Kapany	Created a bundle of glass fibers to transmit images. Named their instrument the fiberscope
1956	Basil Hirschowitz and Larry Curtis	Replaced Hopkins'glass fibers with better flexible optical fiber material and glass coating
1959	Harold Hopkins	Developed rod-lens system
1966	Harold Hopkins and Karl Storz	Designed new rigid endoscope with self-focusing lens
1969	Willard Boyle and George Smith	Invented CCD
1971	Hiromi Shinya and William Wolff	First polypectomy during colonoscopy
1976	Bryce Bayer	Bayer filter to create the color CCD
1985	Erich Muhe	First laparoscopic cholecystectomy
1993	Becker et al.	First report of 3D endoscopic system
1996	Visionsense Corp.	Development of Visionsense 3D endoscopic system
2000	FDA	First systems for general robotic surgery approved for use in humans

simple tubular device he called the "Lichtleiter" (translated: light conductor); it used candle light and mirrors for illumination of the target tissue (Fig. 1) [12]. With his Lichtleiter Bozzini was able to inspect the female urethra and vagina with cervix in actual patients. Therapy however was not really possible with the Lichtleiter. A redesign using a so-called gasogene lamp (a flame produced by a mixture of alcohol and turpentine) invented by Antonio Jean Desormeaux made operative endoscopic procedures a reality for the first time in 1853 [13]. Desormeaux also coined the term "endoscopie" that same year: it is derived from the Greek "endo" meaning "within" and "skopein," "to view or observe." The first endoscopic image likely was taken in 1858 by Czechoslovakian Johan Nepomuk Czermak. The rigid tubular nature of the endoscopes at the time made inspection of esophagus and stomach essentially impossible; Adolf Kussmaul adapted his patient to the task and performed the first direct esophagoscopy in a sword-swallower in 1868 in Freiburg, Germany. Johann Mikulicz is credited with the design of the first successful and practicable esophagoscope in 1881; he did this together with well-known instrument maker Joseph Leiter of Vienna. Together they designed a galvanized wire light source encased in a double barreled glass tube for water cooling inside the patient, decreased the diameter of the endoscope, and introduced a modular design. Mikulicz also used anesthetics during the actual procedure and investigated the best position of the patient using a woman able to swallow instruments—all this to improve the patient experience. At about the same time, in 1873, Trouve in France created a light source from very thin, galvanized platinum wires that did not require water cooling and used an instrument with this light source for endoscopy of the urethra and bladder, rectum, and esophagus.

A major improvement in endoscopy was the use of better optics. The German Maximilian Carl-Friedrich Nitze adapted microscopy optics technology to endoscopy around 1877 and applied this to the field of urology [14]. As Mikulicz he worked with Joseph Leiter and was the first to include as a practical, working solution the electrical light bulb (invented in 1880 by Edison) in a miniaturized format into an endoscope in 1888. He also developed electrocautery devices and reported his personal experience on 150 bladder tumors he removed: 20 recurrences and 1 death, a truly remarkable outcome for those days.

III. THE 20TH CENTURY—THE MATURING OF ENDOSCOPY, AND THE BIRTH AND REBIRTH OF LAPAROSCOPY

By the time endoscopy entered the 20th century, the basics of most of current endoscope technologies were in place: where possible use of natural orifices for endoscope entry, an electrical



(A)

(B)

Fig. 1. ***(a) Original schema of Bozzini's "Lichtleiter." (Reprinted from [11].) (b) Bozzini's original light conductor with specula. In December 1806 Bozzini's light conductor was presented to the professors of the Josephinum, the "Medical-Surgical Joseph's Academy" in Vienna. (Courtesy of the International Nitze-Leiter-Research Society for Endoscopy, Vienna, Austria.)***

light source for illumination, a system of lenses to improve visualization, a small diameter endoscope, the ability to treat and remove tissue, and a rudimentary ability to document findings with images. However, it was clear that many improvements were required before endoscopy will become a general and broadly applied technology. Specifically, the images are still small and will benefit from better magnification, the field of view is narrow and needs to be wider, the amount of light can be enhanced further, the work area inside human cavities requires expansion, and last but not least the ability to document findings and treatment results in the form of images needs vast improvements. All of this will be achieved in the next century and so successful that in the latter part of the 20th century many surgical procedures are being converted from open to laparoscopic or laparoscopic-assisted surgeries.

All of this starts with the German Georg Kelling who, in 1901, performed the first laparoscopy—on a dog. He uses air to insufflate the abdominal cavity to improve visualization and between 1901 and 1910 appears to have used this same method on a few patients. His work is notable for several reasons: he believes endoscopy is safer and cheaper than conventional open surgery. The latter applies specifically to Germany after the war of 1914–1918. He uses a flexible gastroscope, made from vertebrate segments of hollow tubes covered with India rubber. He advocates patient preparation including purging before laparoscopy or gastrointestinal endoscopy in order to reduce complications in case of a perforation. And last, he may be the first to treat hemorrhages in the abdominal cavity caused by tuberculosis. Unfortunately, little more is known about this true innovator as he died and his belongings were destroyed during the war of 1939–1945. At about the same time Hans Christian Jacobaeus, a physician in Stockholm, performed large numbers of laparoscopies on humans and, unlike Kelling, documented this in publications. His first laparoscopy took place in 1910—a man with cirrhosis—and is the first published case of laparoscopy; subsequently, he described a variety of pathology from about 100 laparoscopies in 1912. He also coined the term laparoscopy.

The first arthroscopy is attributed to Severin Nordentoeft of Denmark; he used saline solution for visualization. Nordentoeft is also credited with the first therapeutic thorascopic procedure in 1910. The use of CO_2 for insufflation—with advantage of spontaneous resorption and decreased chance for fire or explosion—was first done by Richard Zollikofer of Switzerland in 1924. The field of vision problem was addressed by German gastroenterologist Heinz Kalk in 1929 when he introduced a forward viewing endoscope with an about 135° field of view that was practical in its use. He used it with considerable success and in 1939 reported a series of 2000 laparoscopies under local anesthesia without a single mortality. The Swedish-born French gynecologist Raoul Palmer did not contribute major technological advances, but was instrumental in developing procedural changes for gynecological laparoscopy during the 1950s that had far reaching effects across all of endoscopy: safety measures including Trendelenburg position to allow organs to fall into the upper abdomen, the routine use of CO_2, monitoring of abdominal pressure during insufflation, and the introduction of an electro-cautery forceps to reduce hemorrhages.

The rigid endoscope proved to be too dangerous for regular gastroscopy due to esophageal and gastric perforations. This stimulated Rudolf Schindler with help of instrument maker Georg Wolf to design a series of semi-rigid instruments; the final, 1932 version consisted of a 34-cm rigid part from mouth to distal esophagus and a 44-cm somewhat flexible part of closely spaced short focus convex lenses in a rubber sleeve with a maximal diameter of 12 mm. The end of the semi-flexible, semi-rigid, large instruments was the gastroscope introduced by the American Edward Benedict in 1948—his operating gastroscope allowed biopsies but this feature required a diameter of 14 mm which was not acceptable to most patients and endoscopists.

In the 1960s, several important developments took place. In the rigid laparoscopy field, the contributions of British scientist Harold Hopkins and German instrument engineer Karl Storz completely transformed the field and created the foundation for modern laparoscopic technology and surgery: the combination in 1967 of the rod-lens optical system (Fig. 2) with a reengineered fiber optics bundle for superb, cold light illumination created the best, most detailed, and true color

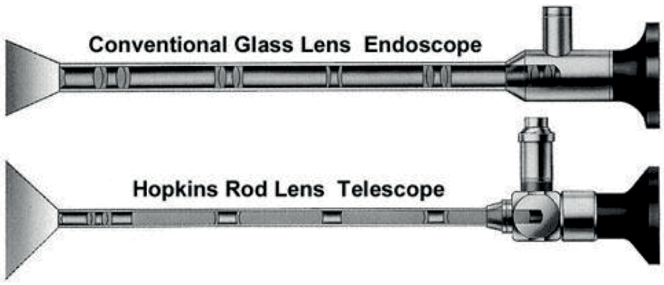


Fig. 2. ***The standard endoscope (above) and Hopkins telescope design (below). The glass rods in the Hopkins telescope provide a larger image, greater light transmission, and improved clarity of vision. (History of the Endoscopy, Max Nitze Museum, Stuttgart.)***

images ever seen, even when using instruments with a diameter of only a few millimeters. Another German, Kurt Semm, was a true pioneer in creating key accessory techniques for laparoscopy, such as intracorporeal knot formation, a loop applicator, and high-volume irrigation and suction equipment. At the same time he advanced the field of operative laparoscopy and was the first to perform a laparoscopic appendectomy in 1980. And yet another German surgeon, Erich Muhe, performed the first laparoscopic cholecystectomy in 1985, although many articles state incorrectly that the French physician Mouret was the first to do so in 1987 [15].

Hopkins also contributed to a breakthrough in gastrointestinal endoscopy: the creation of coherent fiber bundle to allow visualization. Improvements to prevent signal leakage by Larry Curtis and Wilbur Peters were incorporated in the first truly functional flexible endoscope created by Basil Hirschowitz and commercially made available in the fall of 1960 by ACMI [16]. By the end of the 1960s, Japanese instrument manufacturers Olympus and Machida started producing endoscopes as well [17]. In early 1971 instrument length exceeded 100 cm, four-way tip control was introduced, tip deflection up to 180° was possible (allowing retroflexion), and channels for suction and air/water infusion as well as lens cleaning were present. The greater length of gastroscopes allowed visualization of the duodenum; a side-viewing lens and an instrument lever made cannulation of the duodenal papilla possible and the technique of endoscopic retrograde cholangio-pancreaticography (ERCP) was born with first case series reported from Japan in 1970 and the United States in 1972. Around the same time, the same companies started producing endoscopes specifically targeted for inspection of the colon. The first snare polypectomies using colonoscopes were done by Hiromi Shinya and William Wolff in 1971. The fiber optic endoscope was also used to inspect and treat the airways: in 1967 Machida introduced the first bronchoscope.

IV. THE INVENTION OF THE CCD—VIDEO ENDOSCOPY AND LAPAROSCOPIC SURGERY

Probably the most important breakthrough for endoscopy using flexible instruments was the invention of the charge-coupled device (CCD) in 1969 at AT&T Bell Labs. The CCD was used for the first time for image capture in a Kodak 100 × 100 pixel, still image camera in 1975. The American medical instrument manufacturer Welch Allyn introduced the first CCD-based video endoscope in 1983; in Japan Fujinon, Olympus, and Pentax soon followed. A CCD sensor at the tip of the endoscope converts the optical image into a digital signal that can be transferred via the shaft of the endoscope to an image processor where a standard format video signal is generated that is displayed on a monitor. The benefits of such a system are obvious: all issues related to a coherent bundle of fibers (poor image, progressive loss of fibers due to breakage over time from usage, volume of fiber bundle within endoscope shaft, etc.) are gone, there is more room for other functions within the endoscope shaft, more extreme tip deflections are possible, and the already developed tip control mechanisms do not require essential modifications. Multiple people—the endoscopist, assistants, and trainees—can see the same high-quality image. The ergonomics of watching a monitor with both eyes rather than peering with one eye into a lens coupled to a coherent fiber bundle favored use of the video endoscope. Since the initial video endoscope, CCD technology has greatly improved and so has the quality of the video endoscope signal. CCD image sensors are getting smaller, and the number of pixels and the image capture rates are steadily increasing. The result is that all currently available endoscope manufacturers provide high-definition images [most offer at least a high-definition multimedia interface (HDMI) version 1.0 output signal that allows 1920 × 1200 pixels at 60 Hz]. CCD sensors do not generate a color signal: color has to be generated by combining red, green, and blue (RGB) signals. This in general is achieved using one of two methods. The first one is RGB sequential imaging: using a rotating filter RGB light is alternatively used to illuminate the tissue, and the resulting signal captured by the CCD sensor [Fig. 3(a)]. With a 60-Hz image, a filter wheel with RGB filters rotates 20 times per second which some endoscopists experience as a distracting flickering signal with color separation, especially during tip movement. The second method uses a color CCD chip, where the separation of RGB occurs by use of a mosaic pattern filter between the lens and the CCD [Fig. 3(b) and (c)]. The advantage of this method is that a nonstroboscopic, more natural appearing Xenon light source can be used and that the capture frequency for the entire image

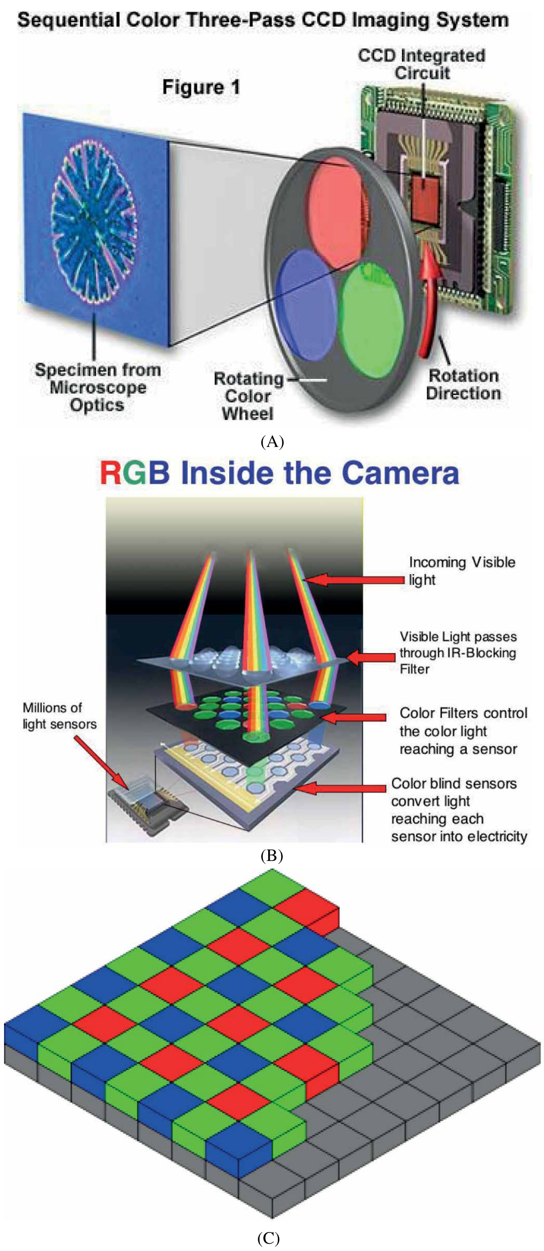


Fig. 3. ***(a) Three-pass sequential color CCD imaging systems employ a rotating color wheel to capture three successive exposures in order to obtain the desired RGB color characteristics of a digital image. The major advantage of this technique is the ability to fully utilize the entire pixel array of a CCD imaging chip, by using one pass for each color. The primary advantage of this technique is the ability to achieve the highest resolution capable of the device, which equals the size of the CCD array. The major disadvantage of this system is the relatively long exposure times necessary to accumulate three individual color arrays, which requires an almost stationary subject and vibration-free operation of the rotating color wheel mechanical components. (b) A color CCD chip camera utilizes a Bayer filter to only project RGB light from incoming visible light onto specific sensor elements. The major advantage of this technique is short exposure times required to accumulate all three colors. The major disadvantage of this technique is that the highest resolution capable of the device is about one quarter of the size of the CCD array. (c) A Bayer filter mosaic is a color filter array for arranging RGB color filters on a square grid of photosensors. Its particular arrangement of color filters is used in most single-chip digital image sensors used in digital cameras, camcorders, and scanners to create a color image. The filter pattern is 50% green, 25% red, and 25% blue. It is named after its inventor, Bryce Bayer of Eastman Kodak. He used twice as many green elements as red or blue to mimic the physiology of the human eye.***

is a true 60 Hz, but an obvious disadvantage is that not all pixels are used for a given light frequency. Therefore, color CCD chips have a lower resolution. However, when taken in all considerations into account, the color chip may be a better solution for endoscopy than RGB sequential imaging given the use of more natural light, the absence of flicker and color-trailing during rapid endoscope tip motion, and the higher image capture frequency.

Despite the major changes in width of view and image quality, and the proof of principle by Semm and Muhe showing that true minimal invasive or laparoscopic surgery was possible, laparoscopic surgery was mainly a gynecological procedure for inspection of the female organs and tubal ligation until the last decade of the 20th century. That all changed in 1990 with the introduction of a laparoscopic clip applier with automatically advancing clips. This device allowed surgeons to place all required clips during cholecystectomy in a single session instead of repeated removal, loading, and reinsertion of a clip applier or the even slower method of manual suturing and tying of knots. Laparoscopic surgery really took off and new devices such as staplers allowing one or two rows of linear, curved or circular placed staples, with or without a dividing cut, facilitated more complex laparoscopic surgeries. Nearly all types of organ resections for benign or malignant diseases now can be performed using laparascopic techniques, including gastric bypass surgery, total colectomy, and pancreaticoduodenectomy. Indeed, laparascopic surgery has replaced many commonly performed open surgical procedures with equal or better long-term outcome, lower patient morbidity due to smaller incisions, shorter hospital admission duration, and shorter patient recovery times. At present laparoscopic techniques are applied to nearly every field of surgery, sometimes completely replacing open procedures, sometimes replacing part of the conventional open procedure.

Current instruments used in laparoscopic surgery are rigid: a telescopic rod lens system as developed by Hopkins and Storz that is connected to a digital video camera. Rigidness is required in clinical practice as it allows very easy and accurate laparoscope manipulation. Although there are digital laparoscopes with a CCD placed at its tip, the rod-lens-based laparoscopes have a better optical resolution and overall image quality, and therefore make up the majority of currently used instruments. Cold light now is a standard feature, as is the use of CO_2 for luminal distension; the latter because it is nonflammable, easily absorbed by tissue, and exhaled via the lungs.

V. THE 21ST CENTURY—VIDEO CAPSULE ENDOSCOPY, ROBOTICS, NOTES, AND MORE

By 2000 most hollow, not blood-filled human organs were routinely inspected using endoscopes: nose, pharynx, larynx, esophagus, stomach, duodenum, colon, bladder, abdominal cavity, pleural space, bronchi, external ear canal, and joint cavities. Notably absent was the small bowel. Although very long endoscopes had been developed, their use was cumbersome, required many hours of scope advancement, and did not readily allow treatment. A team of scientists from Israel and the United Kingdom devised a miniature endoscope in the shape of a large capsule: it consisted of a lens, a CCD image sensor, a set of miniature LEDs for illumination, the hardware to wirelessly transmit the images to an external receiver, and a battery to power the device [18]. Once the video capsule is activated, the LEDs start flashing at a rate of twice per second, and at the same time the CCD captures an image that is wirelessly transmitted. The patient swallows the capsule, and an antenna equipped device located over the abdomen of the patient receives and records the images. The battery of a video capsule lasts about 8 h; therefore there is about 8 h of capsule movement through the esophagus, stomach, duodenum, small bowel and colon available, enough to see images of the entire small bowel in most patients. The results are gratifying: video capsule endoscopy, now offered by several manufacturers, has become a vital technique for inspection of the small bowel, in particular for patients with chronic gastrointestinal blood loss without findings on upper (esophagus, stomach, and duodenum) or lower (colon) endoscopy. As can be expected, video capsule endoscopy is evolving: forward and rearward viewing CCD cameras on a single capsule, 360° image creation from multiple CCDs arranged circumferentially on a capsule and complete capture of all images within the memory of the capsule without the need for a receiving device, but instead requiring capsule retrieval after anal passage.

With laparoscopic surgery, the hands and fingers of the surgical team no longer are inside the patient but still are handling the surgical equipment. That means that all instrument motions are a direct result of hand motions of the surgical team. In 1994 the first robotic surgical equipment was approved by the FDA: the Automated Endoscopic System for Optimal Positioning (AESOP) [19]. AESOP's function was to maneuver an endoscope inside the patient's body during the surgery based on voice commands given by the surgeon. By 2000 the first systems for general robotic surgery became FDA approved. With the current robotics systems, surgeons operate through a few small incisions, watch a magnified 3-D high-definition vision system and use tiny wristed instruments that bend and rotate far greater than the human hand allowing enhanced vision, precision, and control (Fig. 4) [20]. Robotic surgery has been applied to many surgical areas: cardiac, colorectal, general, gynecologic, head & neck, brain, thoracic and urologic surgery [21].

As for rigid laparoscopic equipment, numerous improvements and new accessory technologies have fueled the growth of procedures that are now possible using flexible endoscopes (Fig. 5). The main challenge for the most frequently used devices is the diameter of the working channel of a flexible endoscope. In general the maximal diameter is between 3 and 3.7 mm. Physicians and engineers have been inventive, and essentially every technique possible has been scaled down or modified to allow delivery via this physical constraint: numerous

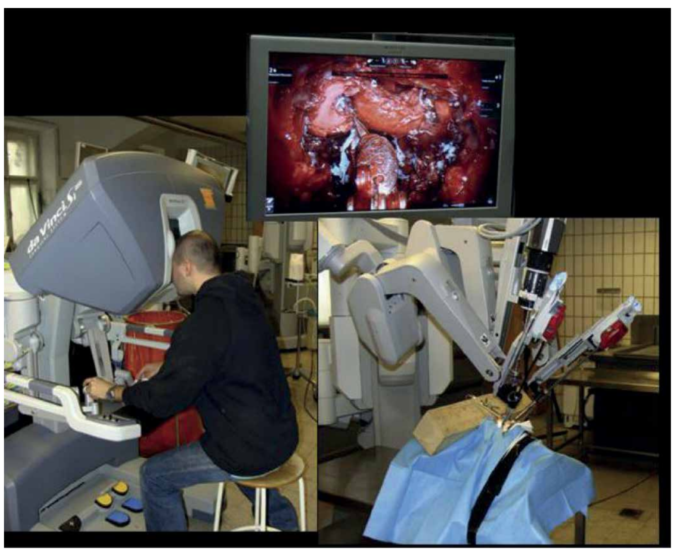


Fig. 4. ***Exemplary application of robotics and endoscopy. A surgeon is shown using the da Vinci Surgical System for pituitary surgery in a cadaver specimen at the Centre for Anatomy and Cell Biology, Medical University of Vienna, Vienna, Austria.***

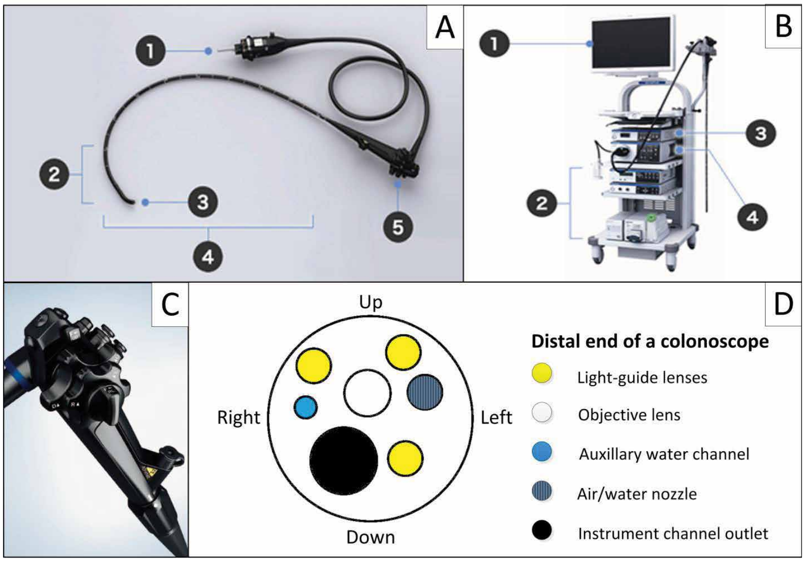


Fig. 5. ***Components and functions of a video endoscope system. (a) The actual endoscope components: 1) connector; 2) bending section; 3) distal end; 4) insertion section (shaft); and 5) control section. (b) The components of an endoscope system: 1) LCD monitor to display the image; 2) image management hub and other accessories such as waterpump, CO_2 pump, etc.; 3) video system center (the video processor converts electrical signals from the endoscope into video signals and displays them on the monitor); 4) light source (the light source uses a xenon lamp to produce light similar to natural light, which is transmitted to the scope's distal end, and also incorporates a pump for supplying water and air to the scope). (c) A closeup of the handle bars of an endoscope. Two large control wheels allow up/down (large wheel) and left/right (small wheel) movement of the distal end of the endoscope. Two buttons are used for air/water insufflation and suction. Other buttons are for image capture, and special functions. The rubber cap on the right covers the working channel. (d) A schematic example of the distal end of a colonoscope showing the typical components of current endoscopes. The air/water nozzle is used to clean the lens of debris. The maximal outer diameter of the distal end of this colonoscope is 13.2 mm and the inner diameter of the instrument channel is 3.7 mm.***

types of cutting instruments, graspers or forceps, snares, ligatures, ultrasound probes, thermal devices, cold spray applicators, laser beams for tissue destruction, rubber band ligation controls, ionized argon plasma for tissue ablation, and dilation and radiofrequency ablation balloons. More complex or larger devices for specific applications have also been designed and are being used in hands of experts: suturing devices that can be attached to the tip of an endoscope, submucosal dissection instrumentation, clip-on additional side-viewing cameras and over the endoscope clips for closure of perforations. In colonoscopy, the use of water instead of air or CO_2 during insertion has been found to have several advantages [22]. Indeed, the growth in the number and complexity of endoscopic procedures during the last decade is mostly the result of new accessory technologies rather than new features of the core endoscopic instruments. Yet new endoscopes continue to be developed: endoscopes with more than one camera (side viewing or 360° vision around the longitudinal axis), a self-propelled, self-navigating endoscopes that use gas pressure to advance, and an endoscope based on inverted sleeve technology eliminating friction between endoscope and mucosa. Disposable endoscopes are being developed to prevent the risk of patient-to-patient infection; this is a known risk during both upper and lower endoscopic procedures with reuse of complex flexible instruments that are disinfected in between procedures but cannot be sterilized [23], [24].

The superb vision possible with the latest CCD-based flexible endoscopes, and the steadily growing number of accessory devices able to inject, cut, dilate, coagulate, stitch, clip, connect and image, allowed gastroenterologists to increasingly perform procedures that formally were done by surgeons and radiologists. Indeed, endoscopic ultrasound now is used to drain intra-abdominal abscesses, sample cysts, biopsy suspected mass lesions and perform celiac plexus blockade. Esophageal varices can be obliterated endoscopically by injection with sclerosing agents or band ligation. And large polyps or mucosal malignancies are now removed endoscopically using endoscopic mucosal resection or endoscopic submucosal dissection. Aberrant esophageal mucosa can be resected or destroyed using radio-frequency ablation; strictures can be dilated or temporarily or permanently stented. Gastric fundoplication for reflux can now be done endoscopically, and endoscopic methods to reduce gastric volume as treatment for obesity have been developed. All of this more or less naturally led to the question whether surgery outside the gastrointestinal tract using natural orifices is possible: Natural Orifice Translumenal Endoscopic Surgery (NOTES). NOTES by surgeons is mostly done via the vagina, where a small incision allows entry into the pelvic cavity. The most common NOTES procedure by gastroenterologists is peroral endoscopic myotomy (POEM) to relieve obstruction of the lower esophagus due to achalasia. Many traditional surgical procedures have been performed using NOTES, including appendectomy via upper endoscopy, yet at present NOTES is mostly confined to research studies.

VI. THE FUTURE OF ENDOSCOPY—MORE COMPLEX, QUALITY CONTROL, AUTOMATION, MINIATURIZATION, SIMULATION, AND ARTIFICIAL INTELLIGENCE

The field of endoscopy is still expanding, in particular in gastroenterology and surgery. We now have general endoscopists, those specialized in ERCP, those specialized in endoscopic ultrasound, and soon those specialized in NOTES and other advanced endoscopic procedures. It is becoming impossible for a single endoscopist to master all aspects of flexible endoscopy. Accessories will continue to grow in number and variety with accessories specific for a single type of procedure and specific indication; for instance, a device to flatten colon folds may only be used for those who undergo colonoscopy for colorectal cancer prevention. New endoscopes will be designed to allow easier performance of existing procedures, or to enable altogether new procedures developed within NOTES. Three-dimensional vision with natural depth of view may be introduced into the general endoscopy practice [25], [26]. In laparascopic surgery, single port systems are being developed with the goal of reducing the number of small scars from three or four to only one, ideally in a location where it is barely or not at all noticed such as the navel [27]. Single port instruments come in three configurations—standard rigid instruments as have been used in the past 30 years, and instruments that allow better triangulation by either an articulating or a prebent, rigid design. For both flexible and rigid endoscopic systems, the future likely will include stereoscopic high-definition video presented via a wearable head-up display to all members of the operating team.

Several groups are studying ways to help the gastrointestinal endoscopist to achieve the best possible outcome by providing information about time spent during specific phases of the procedure, clarity of vision, speed of endoscope movement, the nature of a polypoid lesion, and configuration of the intestine. Most of this work is done for colonoscopy [28]. Others are developing tools that make inspection easier such as plastic clip-on devices or balloons that flatten haustral folds and allow inspection of a large part of the mucosal surface.

Yet another way to improve quality of endoscopy is to train endoscopists in all aspects of procedures, including preprocedure planning, interprocedural communications, and management of complications, using a simulated environment [29]. Indeed, given the increasing complexity of endoscopic equipment, the invasive nature of newer endoscopic techniques, the endoscopy team rather than single endoscopist approach and the aging patient population with multiple co-morbidities, training and retraining using simulation are becoming an essential component of endoscopy. Initially, simulation meant a small simulator for a specific purpose; however, complex endoscopic procedures performed by teams require a formal simulation infrastructure. Numerous academic medical centers as well as professional organizations, such as the ASGE, have realized this and in response have created simulations centers that allow simulation of a growing number of simple and complex endoscopic procedures.

Endoscopy is still mostly an operator-dependent technology. In some ways handling an endoscope is similar to driving a car: you can go forward and backward, slow and fast, and ideally you look all around you for looming dangers. Indeed, quality of colonoscopy, the most frequently performed and evaluated endoscopic procedure, is directly related to the attitude and "driving" skills of the endocopist; is the endoscopist not in a rush and has the right skill set, than removal of all polyps is highly likely. Yet, soon driving a car may be something of the past as autonomous vehicles are in advanced stages of development; similarly, it can be expected that driving of the endoscope will become automated as well.

There is no doubt that artificial intelligence systems will gradually be introduced in endoscopy and the small bowel may be the first area where this will happen. Indeed, automation, miniaturization, self-propelling mechanisms, stabilization and tissue targeting systems, and tissue cutting or destroying capabilities in theory can all be combined in a longer, flexible, multicompartment disposable capsule or "snake" that can enter a patient via a natural orifice and move itself through the intestines while scanning the mucosal surface and removing, or destroying lesions that are readily recognized as abnormal. All the mechanisms in the handle of current flexible endoscopes (e.g., navigation, lens cleaning, instrument manipulation) need to be electronically controlled, instruments need to be packed within the body of the device but the artificial intelligence driving the "scope" may reside outside the body where it controls the scope and instruments using wireless communication.

VII. SUMMARY

Endoscopy has replaced open methods in virtually all aspects of procedural medicine and surgery in a time span of a few decades. The benefits of smaller or no scars, superb closeup visualization, less morbidity, and quicker patient recovery are universally accepted. The glass rod lens and the CCD chip combined with creation of intuitive tools that can traverse orifices of small diameter are the key discoveries that made endoscopy a viable and eventually a better alternative to many open surgical methods. There is no doubt that the field of endoscopy—using as much as possible natural orifices—will continue to grow and expand, in particular due to incorporation of miniaturization, integral driving and stabilization systems, wireless control, automation, and artificial intelligence. Looking to the future of procedural medicine and surgery basically comes down to looking (and working) inside the human (and animal) body using "scopes": endoscopy. ■

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