

A capsule endoscopy guide for the practicing clinician: technology and troubleshooting

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The purpose of this article is to discuss the technology of capsule endoscopy (CE) in a manner that would be relevant to the practicing physician. There are inherent difficulties in eliminating bias in an article that describes technology for which only one company's product has been commercially available and when 2 of the investigators work with that company, Given Imaging. Having said that, every attempt was made by us to eliminate bias and commercialization. The reader will note references to specific Given Imaging products and features, which are used to explain the technology. In addition, we acknowledge the input from Olympus Optical Co, Ltd, Japan, for their valuable contributions. In some instances, references are made to the Olympus product. No attempt is made to compare the video capsules. The focus of the article is to explain the technology.

HISTORICAL BACKGROUND

Twenty-six years ago, in 1981, the inventor of the capsule endoscope, Gavriel Iddan, conceived of the idea of a miniature wireless camera device that would image the entire GI tract and, in particular, uncharted territory, such as the small bowel, while passing through it naturally. This region could only be assessed by small-bowel follow-through (SBFT) at this time. Because of technologic limitations then, it was not possible to create a capsule small enough to be swallowed by a human being, with all the necessary components onboard. Independently, experiments were performed on larger capsule prototypes in the mid 1990s by Swain et al¹ from London. In fact, it took almost 20 years from the time that the original idea was conceived until the first small prototype was produced by Given Imaging (Yokneam, Israel) at the end of the last century. By this time, low-power and low-cost image sensors, such as the complementary metal oxide semiconductor (CMOS) type, were small enough to fit into the earliest digital cameras and other similar devices. In addition, application-specific integrated circuit (ASIC) chips and miniature white light-emitting diode (LED) light sources then became available.

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An ASIC chip is a highly compact integrated circuit, with specific functionality designed for a dedicated application only. As such, the chip is very compact and robust, and most suited for CE. Since the late 1990s, more than half a million patients have ingested such a capsule. With thousands of physicians now using CE as part of the primary workup for their patients, hundreds of articles have been written describing its use for indications such as bleeding, iron deficiency anemia, inflammatory bowel disease, celiac disease, nonsteroidal damage, and small-bowel tumors.

Today there are already different types of capsules for specific anatomical regions of the GI tract. In addition to the small-bowel video capsules, innovative capsules with 2 video camera heads were developed by Given Imaging. One such capsule, which was introduced in 2005, is for examination of the esophagus and another one was recently introduced for the colon.²⁻⁴ This latter capsule underwent clinical trials in Europe and the United States, where it is compared with routine colonoscopy. Olympus Medical Systems Corp, Japan, have, in the past few years, produced a single-head, 2 frames per second, small-bowel capsule, based on the same size as the Given capsule but with a charged-coupled device (CCD) rather than a CMOS imager. A Chinese company, Chongqing Jinshan Science and Technology, and the Korean company IntroMedic also developed video capsules for use in the small bowel. Other than with Given Imaging's products, we are not aware of any publications referring to the other capsules.

At the time of writing this article, only the video capsules of Given Imaging have U.S. Food and Drug Administration (FDA) clearance for use. The small-bowel capsule is approved for use in patients 10 years and older, and the esophageal capsule is cleared for use in patients 18 years or older. Because essentially all published clinical data (more than 500 peer-reviewed articles) refer to the Given Imaging capsules, this paper deals primarily with the CE procedure and components of the Given Imaging system.

CE TECHNOLOGY: THE CAPSULE SYSTEM

A capsule system comprises 4 primary components: (1) an ingestible video capsule, (2) a recording device, (3) a workstation, with (4) physician review/reporting

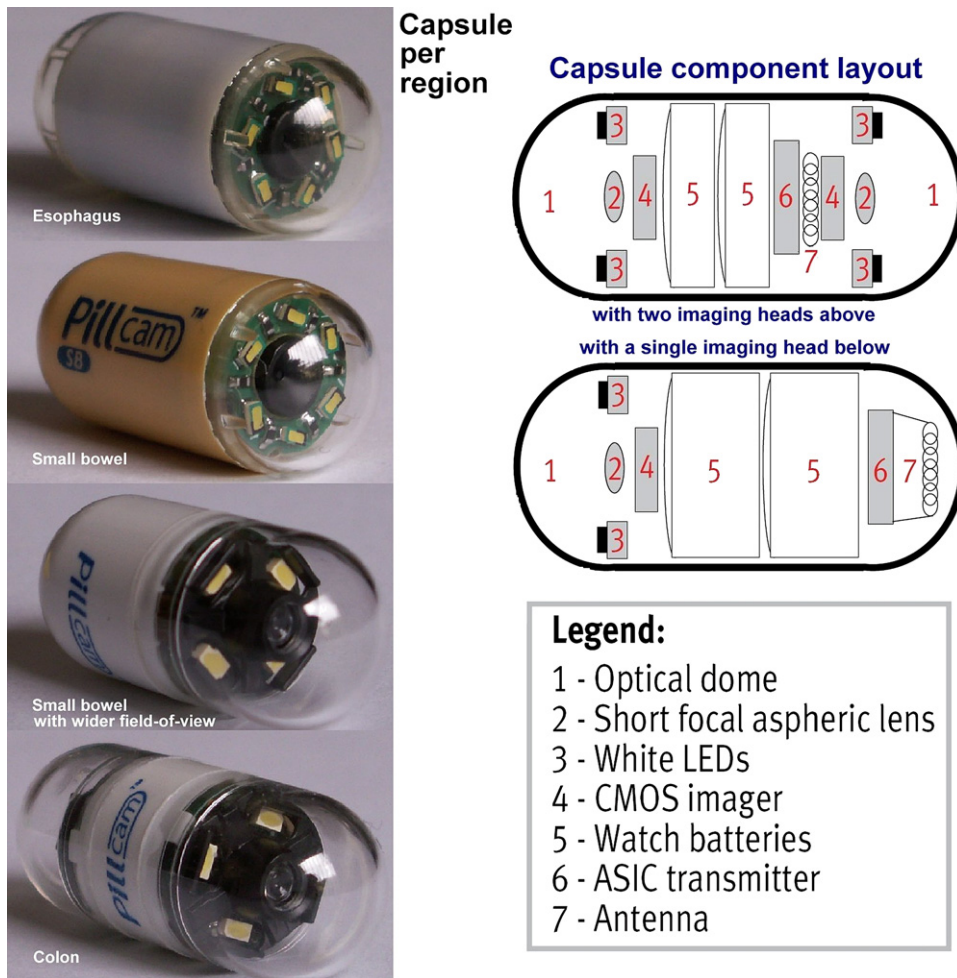


Figure 1. Range of Given Imaging capsules and typical component layout.

software. The capsule as a single-use device is not recovered for reuse. Hence, the images it captures are transmitted immediately to an external recorder worn by the patient. This recording device is designed to be compact, easily used and handled, and remains with the patient as part of an ambulatory examination throughout the day. The images received and stored by the recording device are transferred, after the examination, to the workstation, which has software that supports the recorder, transfers its data to local memory, compiles data into a video, and review/reporting functions for the physician.

Capsule

Given Imaging’s PillCam SB capsule is the size of a large vitamin pill (26-mm long, 11-mm wide). It weighs 3.4 g, has a field of view of 140°, uses 6 white LEDs, and has a battery life of 8 hours. The esophageal capsule is also 26 × 11 mm. The colon capsule is a little longer (31-mm long × 11-mm wide), with a field of view of 156°. All small-bowel video capsules have 1 video camera head, whereas Given Imaging’s esophagus and colon capsules have 2. The idea to add a second head to the latter

capsules was based on maximizing the surface area coverage for larger organs (those wider than the width of the capsule, such as in the colon) and in regions where the capsule is expected to travel through the tract very quickly, which minimizes image capture (such as in the esophagus). Each video capsule contains a tiny pair of batteries, an ASIC transmitter with antenna, and a set of LEDs with each video camera head, all encapsulated in a bio-compatible plastic casing. The range of Given Imaging capsules is shown in Figure 1.

The EndoCapsule (Olympus) for the small bowel has undergone preliminary testing in the United States, Japan, and Europe. It uses CCD technology for the imager. CCD technology is well known by endoscope manufacturers who use the technology in video endoscopes. The Olympus capsule is 26 × 11 mm, weighs 3.8 g, has a field of view of 145°, uses 6 white LEDs, and has a battery life of 8 hours. The EndoCapsule is shown in Figure 2.

CCD and CMOS imagers are 2 different technologies for digital capture of images. CMOS technology is most suited for small devices because of its high integration capability and low-power consumption. CCD imagers are



Figure 2. EndoCapsule (Olympus).

traditionally of higher image depth but require larger packaging. CMOS imagers use less power than CCDs, making them appealing for small devices. Both imagers use pixilated metal oxide semiconductors; they accumulate a signal charge in each pixel, proportional to the local illumination intensity. The CCD imager transfers the charge from the pixel, created by photoelectric conversion, through a “bucket relay” transfer to the imager output stage. The charge transfer is almost complete, which means that noise is rare, but a high voltage differential is required to improve transfer efficiency, which increases power consumption. A CMOS imager converts the charge to voltage within each pixel. This difference in readout technique implies significant differences in architecture, capabilities, and limitations. CMOS imagers use an array of pixels to convert light into electronic signals. The electronic charge that is generated by the pixel is weak and needs amplifying to a usable level. For this purpose, each pixel in a CMOS sensor has its own amplifier circuit. CMOS imagers often contain additional image processing circuitry on the chip itself, making it easier and faster to retrieve and process picture information. This results in a lower chip count, increased reliability, reduced power consumption, and a more compact design.

Those that argue in favor of a CCD technology say that it produces the greatest level of signal and the least amount of signal noise. They argue that CMOS imagers require a much more uniform illumination to get good images. Those that argue in favor of CMOS technology say that it requires less power and provides the capability of adding all of the electronic circuitry into a single microchip. They also suggest that CCDs have higher power and space requirements. In addition, newer ASIC imager chips, together with special power management algorithms, enable CMOS-based capsules to produce higher frame rates, have a longer duration, and use multiple head capsules. From a clinical point of view, both technologies provide excellent images of the GI tract.

The video capsule is provided ready for ingestion in a hermetically sealed blister. The proximity of the video

capsule to a magnet in the blister keeps its magnetic switch open and, therefore, inactive. Once removed from the blister, the switch closes and the capsule is operational.

After ingestion, the video capsule is propelled by peristalsis through the GI tract. The video camera located behind a transparent plastic dome acquires images while the capsule travels along the patient’s GI tract. Because it is unlike an endoscope device in which air insufflation is used, the capsule travels through turbid media and may often meet undigested food particles. Nonetheless, the transparent dome remains clean, because the capsule relies on peristalsis to progress it forward while it is brushed against the mucosal wall as part of its natural progression through the GI tract. With a standard endoscope or colonoscope, any fluid or turbid media is evacuated so that, with air insufflation, the optics look at a flattened mucosal wall at a distance of several centimeters away. The capsule, however, moves primarily through GI fluid, and the images of the mucosa are acquired through this fluid with the small bowel in its natural state. This capsule interface with fluid causes the reflected light to refract into the dome. The result is that the lens picks up the signal from a larger surface area than the optics would ordinarily have acquired through air. So the capsule not only looks at the mucosa straight on, but captures images from zero to just a few millimeters away from the outer surface of the dome.

The capsules are designed to acquire images at a prefixed frame rate, 2 frames per second (fps) for the small-bowel capsules, 14 fps for Given Imaging’s esophagus capsule (because of its quick passage time), and up to 4 fps for its colon capsule. These frame rates were determined to optimize the data collection while maximizing the diagnostic yield.^{5,6} Once activated, the capsule ASIC chip controls the rate at which images are acquired and transmitted to the recorder outside the patient. During each image acquisition, the LEDs are lit and the scenery is exposed to light, which reflects back into the capsule dome. This is picked up by the lens and focused onto the imager. With the Given Imaging capsules, the imager builds up a sufficient signal for display by using an on-board algorithm feature called automatic light control, which adjusts, in real time, the exposure time required. This is a function of the brightness of the scenery in front of the capsule transparent dome. In practice, this lights up distant regions and provides a view over a large depth of view within the GI tract. For most of the available capsules, after the image is acquired, the ASIC chip transmits the image matrix of data via its radiofrequency (RF) antenna to the recording device attached to the patient. This is repeated at the frame rate specific to each type of capsule. With a twin-head capsule, the images are acquired alternately from each imaging head. After a designated amount of time, 20 minutes for the esophageal capsule, and up to 9 hours for a small bowel or colon capsule, the capsule stops imaging.

Typically, the capsule can spend from several minutes up to an hour in the stomach^{7,8} before entering the pylorus and progressing into the small bowel. Because gastric-emptying times are a function of the patient's condition and these should be as low as possible so as not to consume capsule operating time within the small bowel, the physician can now monitor the capsule image transmission in real time, with an optional device connected to the recording device. With Given Imaging, this is in the form of a small notebook that allows a real-time view of the images currently being received by the recorder, without any processing or review functionality. The Olympus product also has a real-time viewer. Some physicians like to release their patients for the day only after the capsule has entered the small bowel. The real-time viewing feature can also be used to determine whether the capsule has entered the cecum when the patient returns. It is also useful for monitoring the progress of the esophageal capsule as it passes the Z-line and enters the stomach.

Dependent on patient physiology and possible pathologic condition, it may take between several hours to several days before the capsule exits the body. There are some cases of the capsule being retained in patients with asymptomatic conditions for several years.^{9,10} Because of the special glue bonding now used, the capsules stay intact and are not affected by the pH environment. In the unlikely event of a capsule breakage, the individual nontoxic components do not present any health risk because even silver oxide batteries are encased in a special hermetic seal.¹¹

As with any new or developing product, the FDA has applied a series of technical contraindications and warnings when using the capsule endoscope. These include as contraindications, patients with pacemakers or other implanted devices that may be affected by the capsule and, as warnings, not to be in the vicinity of a magnetic resonance imaging (MRI) scanner because of its powerful magnetic field if the capsule has not been excreted. Pacemakers are used by 2.4 million Americans, and 460,000 have intracardiac defibrillators (ICD). Although pacemakers and ICDs have been tested,¹²⁻¹⁵ there are many different devices, and it is impossible to test all of them. Although CE remains contraindicated in any patient with an implanted electromedical device, there have not been any reports of interference either from the device to the capsule or the recorder, nor have there been any reports of interference from the capsule to the implanted device.

Technology advances will allow new features in future capsules. Given Imaging's latest version of the small-bowel capsule, the PillCam SB 2, as shown in Figure 1, has a special multilens optical head, which provides a wider field of view, of 156°, of the mucosa. In the future, image streaming with very high image frame rates will be possible. Researchers also speculate that future technology will allow the integration of biosensors, biopsy devices, drug delivery, and other interesting imaging concepts.

Given Imaging also produces a dissolvable capsule to prove GI-tract patency without any electronics or imaging head as a possible prerequisite before ingestion of a small-bowel video capsule for patients with suspected strictures.¹⁶ It is the same size as the small bowel and esophageal capsules, and contains a lactose-based center, with an RF identification tag inside it. At either end of this capsule are plugs that are designed to dissolve once exposed to GI fluid. Should the capsule be retained for extended periods, these ends dissolve, causing the contents to leak out and break-up the capsule into several small parts, which then easily pass through obstructions in the tract. If the capsule is excreted, then it is expected that the small-bowel video capsule will pass uneventfully through the GI tract.¹⁷ A separate scanner is available, which is used to detect the presence of the RF identification tag inside the patient.

Recording device

The recording device is an external RF receiver and recording unit that receives and stores into memory the image data transmitted by the video capsule. It is a portable CD-player-size battery-operated unit attached to a belt worn by the patient during the entire examination. It is part of the overall equipment that is used for a CE examination. The belt not only supports the recording device but is also used to attenuate the RF signal away from the patient.

A set of 8 small RF sensors are positioned over the patient's abdomen for a small-bowel or colon examination, used for receiving the images transmitted by the capsule and for displaying the capsule location to within a fist-size accuracy by the workstation software.^{18,19} Each sensor is placed inside a disposable sticky sleeve that keeps it in position during the CE examination. Only 3 sensors are required for an esophagus examination by using a reduced version of the sensors. Placement of the sensors normally occurs while the patient is supine on a bed, although for the patient who is larger or obese, this is best placed while the patient is in an upright position. An alternative set of sensors may be developed, which can be worn around the body and will not require sticking any sensor sleeves onto the patient. This innovation will be more user friendly for patients and clinical staff.

The recording device is ready for operation once it is initialized by the workstation with patient details, has a fully charged battery, and the sensors are connected between it and the patient's abdomen. It starts recording as soon as a signal is received from the video capsule. A blinking LED indicates the recording device is receiving data. The LED does not blink when the signal from the video capsule is too weak.

Recorders have been improved over the past few years to accommodate an increasing number of different capsules. Their capacity, battery performance, and reliability have also increased with technologic advances in different types of memory, batteries, and RF systems. They are now

easy to use, with simple LED indications for capsule reception, correct operation, and battery-charge level.

Workstation with physician review/reporting software

The workstation is a dedicated computer designed for processing and storing the acquired capsule images and generating the videos. The physician review/reporting application software is designed to support all the capsules and the CE examination in all of its phases: patient check-in and recorder initialization before the examination; data transfer; and compilation from the recorder, including multiple downloads after the examination; viewing of the video and generation of a CE report. The software handles all these capsule support features, including reviewing and reporting functions.

Compilation by the application software on the workstation of the raw data of images stored in the recorder creates a video. This video is built-up frame by frame on the workstation, while activating many algorithms that are used to highlight to the user interesting images and features when the video is reviewed afterward. Compilation times vary, typically between 10 minutes to 2 hours, depending on the capsule used and the strength of the workstation platform. The length of the video depends on the CE examination duration, the frame rate used by the capsule, and the effect of frame compression in pooling together similar images. Typically, an examination from an esophageal capsule generates 840 frames per minute of video and, from a small-bowel capsule, several thousand frames per hour of video. An esophageal video can take up to a few hundred megabytes of space on the workstation, whereas, today, a small-bowel video requires several times this space. For this reason, the standard media for long-term storage is a digital video disc rather than a compact disc today. A universal serial bus (USB) mass storage disk is often used for this purpose. A smaller 1 or 2 GB USB key is often used for transfer of the complete video to a physician's laptop for review by using a preinstalled physician review/reporting application. The latter is similar to the software on the workstation but is specially adapted for use with a standard laptop personal computer.

With the video ready, the physician can review it by using all the available features and functions provided with the application software. Images of interest throughout the video are captured into thumbnails, which may be annotated and used for the final report or exported as images or small video clips for demonstration.

Video images can be viewed in single, dual (2×1) and quad (2×2) formats. The suggested format to use depends on the experience of the physician. Each format has a range of view speeds from, typically, 5 up to 40 fps, even up to 80 with a colon video, where the physician again will select the most suitable speed, depending on his/her experience. Typically, this is 12 to 15 fps for the beginner and 20 to 24 fps for a more experienced user.²⁰

Users with a lot of experience will often use an even higher fps. As a result, the typical review times for a complete small-bowel video vary between 30 to 60 minutes.

Among the provided assisting tools for the physician with the Given Imaging software is the Suspected Blood Indicator (SBI), which identifies images with red content. It may display a relatively high number of false positives, but is useful for catching regions of active bleeding.^{21,22} This tool does not replace a review of the complete video but is useful for targeting potential sites.

The video time bar, enabling the physician to get quickly to any image within the video, also has a color bar that reflects the average color of the images in each region. This provides a quick way of landmarking key anatomical features within the GI tract, such as the first gastric, duodenal, and cecal images. Identifying these and other landmarks provides the physician with passage times and color coding of each region in the time bar and displayed capsule location trace.

A QuickView tool provided with the Given Imaging workstation software allows a fast-forward review of interesting sites within the video, often used as a 2- to 3-minute preview before a thorough review of the complete video. Even though it may highlight regions that may have pathology, this tool does not substitute a complete review, because it only highlights sample images within each region of the video.

CE PROCEDURE

CE of the small bowel requires fasting after dinner the night beforehand, without any medication. An esophageal study requires fasting only 4 hours before the examination, and a study of the colon involves a 24-hour preparation period similar to that used before a colonoscopy.

On the morning of the examination, the patient is provided with the equipment (recording device, belt, and sensor pads) at the clinic. The ingestion procedure depends on the capsule in use. With the esophageal capsule, a 20-minute examination is required in which the patient swallows the capsule while lying on his/her right side down and takes small sips of water; with the small-bowel and colon capsules, the patient would normally swallow while standing upright and leave immediately afterward. Normally the capsule is swallowed with a small amount of water.

The patient returns to the clinic in the afternoon, has the equipment removed, and is discharged. The recording device is connected to the workstation, where the capsule images acquired during the examination are transferred and a video is created. The physician then reviews this video with the application software. The video is typically read while using the available tools, including identifying landmarks by using the time bar, highlighting key areas by using the quick preview mode, reading the video in one of several formats, referencing the image

atlas (if available), and then annotating images and preparing a report.

CE TROUBLESHOOTING

One of the principal concerns of clinicians who use CE is the possibility of retention of the capsule and the need for surgery to remove it. Capsule retention is uncommon and is reported to occur in fewer than 10 patients in 1000. Capsule retention is less common now than when the capsule was first released, because of an awareness that capsule retention is more frequent in those patients with Crohn's disease and those at higher risk of strictures, such as users of nonsteroidal anti-inflammatory agents. Patients who have undergone radiation therapy to the GI tract or intestinal surgery may also be more likely to have a capsule become retained. Recent reports, however, suggested that postsurgical patients may safely undergo CE.^{23,24} Although capsule retention may indicate the presence of a pathologic lesion adjacent to that site, recent evidence suggests that the capsule itself does not pose a significant risk to the patient. Because the capsule contains metal, it is recommended that patients should not undergo an MRI until it can be demonstrated that the capsule has been excreted.

A consensus statement on capsule retention concluded that "there are no reported cases of capsule impaction in an area of stenosis, and no sequelae of capsule retention have been reported other than identifying an area of narrowing."¹⁰ In fact, the CE video resulting from a case of retention often leads to a valuable diagnosis.²⁵ Even in cases where surgery is performed, a clear benefit for the patient was demonstrated in 4 of 5 patients in 1 retrospective review.²⁶ Cheifetz et al²⁵ concluded that, in most patients in whom retention occurs, "non-emergent surgery can remove the capsule, resect the responsible stricture, and lead to improvement in the patient's preexisting symptoms." An example of such a situation is demonstrated in Figure 3. A patient with suspected Crohn's disease had negative diagnostic studies, including a normal SBFT. A subsequent CE was performed, and the capsule was retained. The CE revealed a small-intestinal stricture, diffuse edema, and ulcerations, consistent with Crohn's disease. Medical therapy was instituted successfully for Crohn's disease. The capsule remained in the small bowel for 2 years before finally being excreted uneventfully.

Radiologic imaging performed before CE has not been perfect at predicting which patients will have retention of the capsule. Although it is unusual, patients without any stricture evident of small-bowel series, have had capsules retained. In addition, intestinal strictures have been demonstrated on imaging studies, whereas subsequent capsules were ingested and excreted normally. A specially constructed patency capsule noted above has been designed to assess whether the intestinal tract is patent for

a capsule with the same dimensions as the small-bowel capsule. An improved version of this capsule includes 2 timer plugs, with 1 at each end, which allows digestive enzymes to dissolve the capsule's lactose body should it become impacted in a stricture. The original patency capsule includes only 1 timer plug, and it was believed that this earlier version of the capsule could lead to bowel obstruction if the single timer plug was on the end of the capsule that was within the stricture where the enzymes necessary to dissolve the capsule were not present. A recent, international multicenter trial demonstrated the safety of this updated patency capsule even when used in a patient with known strictures.²⁶

Peroral CE is contraindicated in those with a known swallowing disorder. Aspiration of the capsule is extremely rare but has been reported.²⁷ Rondonotti et al⁹ reported a patient with aspiration who spontaneously coughed and expelled the capsule without the need for a bronchoscopy. In addition, 5 additional reports of aspirated capsules were received by the manufacturer, and these events seem to be predominantly in elderly residents of long-term care facilities. In addition to those patients with dysphagia, other people may be unable to ingest the capsule. These include young children and adults who suffer from anxiety when attempting to swallow the device.

In patients who cannot swallow the capsule, it may be inserted during a gastroscopy. Different tools have been used to grasp and release the capsule in such cases. These included a net-retrieval catheter, a stone-retrieval basket, a polypectomy snare, or a specially designed capsule deployment device. The latter, manufactured by US Endoscopy (Mentor, Ohio) uses a catheter inserted through the endoscopy with a fitted cup to hold the capsule until it is placed in the duodenum. The cup can be opened to propel the capsule forward into the small bowel. Another unique delivery system was proposed by using a combination of a net-retrieval device and a band-ligator device.²⁸ This technique was reported to allow greater visibility upon insertion of the endoscope and deployment of the capsule.

Even in cases where the capsule is swallowed normally, CE may be hampered by incomplete visualization of the small bowel. A retrospective review of over 700 small-bowel CE studies showed that, in nearly 15% of cases, the capsule did not reach the ileocecal valve.⁹ Although no explanation for this result could be found in about half of these cases, it was observed that the delayed gastric emptying was frequently responsible.

The manufacturer does not recommend any special preparation before CE of the small bowel. Investigators have tried different purgatives, such as 2 to 4 L polyethylene glycol and prokinetics, including erythromycin and metoclopramide. No regimen has been definitely shown to be superior to another, and informal surveys of participants in a CE meeting have consistently failed to show

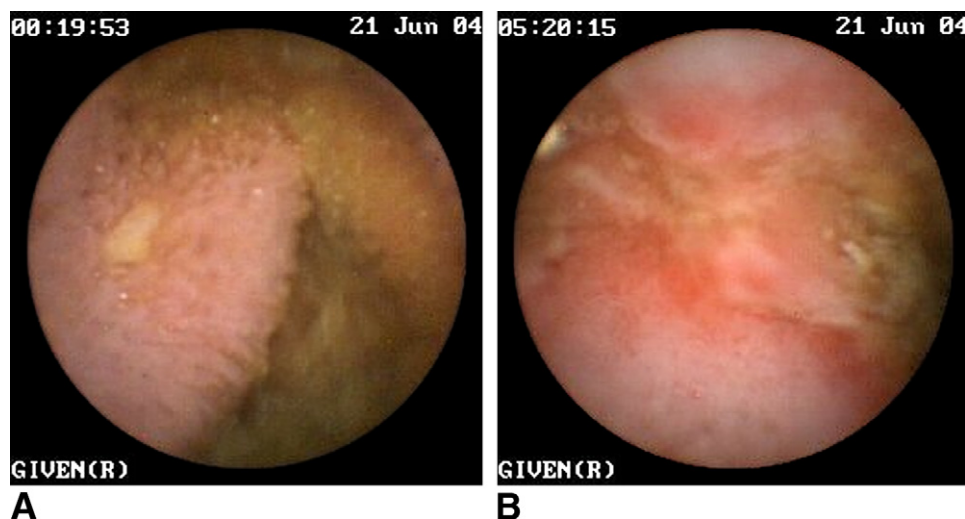


Figure 3. Diagnostic value of a retained capsule. Ulcer in small bowel is consistent with Crohn's disease (A) and stricture seen at site of retention (B). The capsule was excreted after 2 years. (Courtesy of S. N. Adler, Bikur Holim Hospital, Jerusalem, Israel.)

any agreement on this issue. In a multicenter review of CE videos performed mainly for the investigation of obscure GI bleeding, there was no impact of the use of PEG on the diagnostic outcome.⁹

Preparation is very important in the use of CE to visualize the colon. Preliminary studies used preparation techniques similar to that used for conventional colonoscopy, including PEG and sodium phosphate solutions. In addition, prokinetic agents have been used to help ensure bowel cleanliness and promote propulsion of the capsule into and through the colon.^{3,4,29}

For the esophagus, ingestion of the capsule was tailored to slow down the capsule as it descends to ensure adequate visualization of the mucosa. In 1 approach, patients ingest the capsule while supine, but then move up into a seated position.⁶ A relatively newer technique puts the patient in the right lateral decubitus position. This has been reported to affect progression of the capsule and improve visualization at the gastroesophageal junction.³⁰

Technical malfunction of equipment associated with the CE procedure has been reported but is rarely clinically significant.⁹ With increasing experience with this relatively new technology, reports of technical problems are steadily being reduced. Concerns regarding capsule-battery life, recorder failures, and gaps or prematurely short videos were addressed with the introduction of more advanced hardware components together with an increase in quality of the components used, and more efficient testing by manufacturers. Before 2005, Given Imaging's small-bowel capsule delivered 7 ± 1 hours of imaging time because of the variability in the energy management system. Since then, the small-bowel capsule has used improved energy management, which reliably delivers 8 hours of imaging time in each procedure, allowing the capsule to consistently view the entire small bowel until the cecum.

CONCLUSIONS

The capsule endoscope has been an extremely valuable addition to the diagnostic armamentarium available for the evaluation and management of GI diseases. This article was designed to review the current and evolving technology for the practicing clinician so that CE could best be applied to clinical practice.

DISCLOSURE

Jeremy Gerber and Ari Bergwerk are both employees of Given Imaging Ltd. Dr Fleischer has participated in research supported by both Given Imaging Ltd and Olympus Medical Systems Corp.

Abbreviations: ASIC, application-specific integrated circuit; CCD, charged coupled device; CE, capsule endoscopy; CMOS, complementary metal oxide semiconductor; FDA, U.S. Food and Drug Administration; fps, frames per second; ICD, intracardiac defibrillators; LED, light-emitting diode; MRI, magnetic resonance imaging; PEG, polyethylene glycol; RF, radiofrequency; SBFT, small-bowel follow-through; SBI, Suspected Blood Indicator; USB, universal serial bus.

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