

WIRELESS CAPSULE ENDOSCOPY: A NON-INVASIVE REVOLUTION IN GI TRACT EXAMINATION

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ABSTRACT

A revolutionary development in gastrointestinal (GI) diagnosis, wireless capsule endoscopy (WCE) provides a painless, non-invasive substitute for conventional endoscopy. The whole GI tract, including previously inaccessible areas like the small intestine, may now be seen in real time thanks to the technology. This essay examines the fundamentals, developments in technology, methods of operation, and clinical uses of WCE. It draws attention to how several kinds of capsules—steerable, magnetic, robotic, and hybrid—have evolved to overcome shortcomings in localisation, imaging, and navigation. With the addition of artificial intelligence, wireless power transfer, and active mobility, WCE is still developing despite obstacles including short battery life, slow picture interpretation, and a lack of therapeutic potential. These innovations aim to enhance diagnostic accuracy, efficiency, and patient comfort, paving the way for intelligent, multifunctional micro-robotic capsules that combine imaging, sensing, and targeted therapy.

KEYWORDS: Wireless Capsule Endoscopy, Gastrointestinal Tract, Non-invasive Diagnosis, Magnetic Capsule, Robotic Capsule, Artificial Intelligence, Biomedical Imaging.

1. INTRODUCTION

In the modern era, a growing number of people are suffering from gastrointestinal illnesses.^[1] as a result of malignant diseases, including gastric cancer, tumours, and bleeding.^[2] to mention a few. The gastrointestinal (GI) or digestive system is responsible for extracting the nutrients of our diet and keeping our body active. For successful prevention and treatment that can stop further problems or illnesses, early detection is crucial. Advanced endoscopy holds a lot of promise for this early detection screening function. More significantly, it enables a comprehensive diagnosis to be

carried out without interfering with the patient's everyday activities. It can also give a patient with a comfortable and painless diagnosis and potentially shorten the length of time the patient must spend in a medical institution. This is made feasible by wireless capsule endoscopes (WCEs), which can enter areas like the small intestinal area that conventional endoscopes cannot.^[3] and can be used without a specialist's full supervision.

WCE is the only method that has been available for more than ten years.^[4] that enables direct vision of the whole GI tract, including the small bowel, for numerous diseases.^[5] For usage in various GI tract regions, several clinical items have been developed thus far.^[6] with varying requirements. The primary concern, however, continues to be the diagnostic yield (DY)^[3] because WCE is currently regarded as an emerging technology with numerous aspects that need to be improved. Enhancements in key aspects such as image resolution, frame rate, working time, and view angle are necessary to achieve a higher diagnostic yield.^[7]

The evaluation of small intestinal lesions has benefited greatly from the use of capsule endoscopy since its introduction in the early 2000s^[8] In cases of unclear gastrointestinal bleeding, capsule endoscopy is advised as the initial test. For small bowel disorders such Crohn's disease, small bowel tumors, celiac disease, unexplained stomach pain, and diarrhea, it is an excellent diagnostic tool.^[9] In contrast to traditional endoscopy, capsule endoscopy is a less invasive examination technique that minimizes patient discomfort and does not require sedation during the examination. It also makes previously difficult-to-reach tissues like the small intestine easily accessible. Since it began to be used in clinical practice, capsule endoscopy has steadily improved.^[10,11] Still, some issues must be resolved. (1) To begin, the examiner is unable to position the capsule endoscope as anticipated. (2) In contrast to traditional endoscopes, the air cannot be sufficiently expanded, which restricts the amount of the gastrointestinal tract that can be observed. (3) The device's small pill size makes it difficult to apply effective optical technology. (4) The state of the intestinal tract, including air bubbles or inadequate bowel preparation, affects the quality of the examination. (5) It is not feasible to do procedures like hemostasis or biopsy. (6) Capsule retention is possible. (7) After the test is conducted, interpretation requires a significant amount of time and work.

Because no single technique can accurately diagnose every kind of gastrointestinal tract pathology (some techniques are better at detecting tumors, while others are better at detecting bleeding, etc.), To get the most out of capsule endoscopy technology, we must combine a number of strategies. In order to describe some of these cutting-edge methods, this study is divided into sections.

1.1. Endoscopy

A medical treatment called endoscopy includes visually inspecting inside organs with little invasiveness. The market for endoscopes is growing due to the rise in chronic illnesses and the aging population. However, there are certain drawbacks to conventional endoscopy. Through cable actuation, the endoscope's steerable tip can be controlled externally. This mechanism is stiff and extends the entire length of the endoscope, which may have a diameter of up to 13 mm. Patients may therefore experience discomfort, trauma, and pain during the course of treatment.^[12]

2. CAPSULE ENDOSCOPY

A medical technique called capsule endoscopy is used to take interior pictures of the gastrointestinal tract for the purpose of diagnosing illnesses. More recent advancements can even distribute drugs at specified points across the whole gastrointestinal tract and obtain biopsies.^[13] First, The middle part of the small intestine can be seen with capsule

endoscopy, in contrast to the more popular endoscope. Various gastrointestinal malignancies, digestive disorders, ulcers, unexplained bleeding, and general abdominal aches can all be detected with its help. Following ingestion, the capsule travels through the gastrointestinal tract, capturing several pictures per second. These photos are wirelessly sent to a number of receivers that are linked to a portable recording device that the patient is carrying. " Capsule endoscopy has several general advantages over traditional endoscopy, such as a less intrusive process setup, greater visualisation of the gastrointestinal system, and a reduced operation cost.^[14]

2.1. Principle of Wireless Capsule Endoscopy (WCE)

Wireless Capsule Endoscopy (WCE) is based on the principle of capturing real-time images of the gastrointestinal (GI) tract using a miniature, swallowable capsule equipped with electronic components such as a camera, light source, transmitter, and power supply.

Working Principle

1. Ingestion of Capsule

The patient swallows a small capsule (approx. 26×11 mm in size) that contains a miniature camera, LED lights, battery, and radio transmitter.

2. Image Capture

As the capsule moves naturally through the GI tract via peristaltic motion, the built-in camera captures 2–6 images per second illuminated by LEDs.

3. Data Transmission

The captured images are wirelessly transmitted through radiofrequency signals to a data recorder worn on the patient's body.

4. Data Storage and Analysis

After the capsule passes out naturally through feces, the recorded data are downloaded to a computer and analyzed by medical professionals.

5. Diagnostic Visualization

Specialized software reconstructs a video of the GI tract, allowing visualization of abnormalities such as bleeding, ulcers, polyps, or tumors.^[8,15]

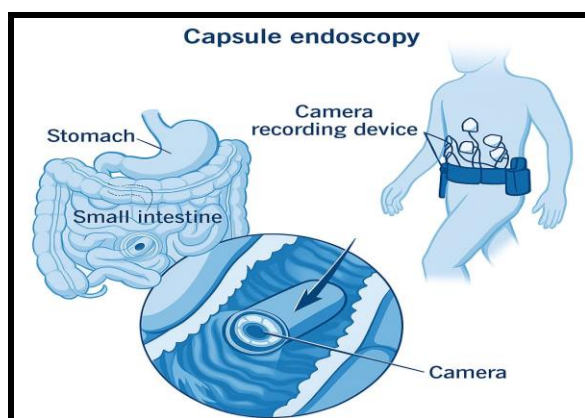


Fig. 1: Capsule Endoscopy.

2.2. Technology of capsule endoscopy

Capsule endoscopy takes pictures of a patient's digestive tract using a small vitamin sized wireless camera. An array of lights, an antenna, and a camera typically make up the capsule. The fifth Because of its small size, the gadget is unable to save photos. Therefore, for the duration of the imaging, a sensor array with a storage unit is applied to the patient's belly. The photos can then be analysed by a medical practitioner by connecting this storage device to a computer later.^[16]

Newer capsule endoscope models have attempted to reduce the amount of medical equipment carried when using the device by adding camera systems on both ends of the pill or even storing images inside the pill itself.^[17] For systems that store images directly in the pill, a separate device must collect the pill after excretion in order to extract the photos.^[18]

The field of view is the primary drawback of capsule endoscopy. Folds in the digestive tract may block images, depending on where the camera system is located within the device. Many businesses and research institutes are developing innovative solutions because of the passive nature of image capturing and the lack of control when moving the device through the digestive tract. The field of view for systems that use the arrangement with the camera system at the end of the capsule is between 140 and 170 degrees.^[19]

Choosing capsule endoscopy over regular endoscopy has a number of benefits. The central section of the small intestine cannot be reached by standard endoscopy, which can also cause greater discomfort for the patient and increase the risk of puncturing the walls of the digestive tract. Endoscopes must enter through the rectum or the mouth/nasal cavities. Very crucial areas of the small intestine for diagnosis cannot be reached because of length limitations. Capsule endoscopy cannot be employed as a primary imaging approach above regular endoscope first in the United States at this time. Many patients must therefore first have a normal endoscopy before being recommended for a capsule endoscopy. A lot of work is being done to bring capsule endoscopy up to the current level of care, but more innovation will be needed to make it comparable.^[20]

3. MECHANISM OF WORKING OF CAPSULE ENDOSCOPY

Step 1: Preparation

You will have a pre-assessment appointment with your doctor where you will be asked to follow certain instructions to prepare yourself for the procedure. For instance, there will be some dietary restrictions, like having light meals the day prior to the examination. Also, before the procedure, you will be prescribed to have a solution for bowel cleansing. If you are taking any medications, make sure to inform your doctor. You might have to stop taking them for a while.

Step 2: Swallowing the Capsule

On the day of the procedure, you will be given a small vitamin-sized pill, which you will be asked to swallow. The pill contains a camera, battery, bulb, battery and radio transmitter. You will also be required to wear a recording device around your waist, which will display the images taken by the capsule.

Step 3: Capturing the Images

As the capsule moves through the stomach, esophagus, intestine, colon and rectum, it captures thousands of images of all the internal organs. These pictures are transmitted to the recording device, allowing for real-time data collection.

Step 4: Excretion of the Capsule

The capsule remains in the digestive tract and within 12 hours, it leaves the body naturally through bowel movements. However, it will take more time in exceptional cases like people with intestinal obstruction.

Step 5: Analyzing the Image

The recorded images will then be analysed by the doctor to detect abnormalities such as tumours, bleeding, or inflammation. Based on the results, your doctor will determine the next treatment plans or other further procedures and tests.^[21]

4. TYPES OF ENDOSCOPES

4.1. Steerable Capsule Endoscope

Carta et al. created the steerable capsule endoscope, which has a 3D steerable locomotion system and is 30 cm in length and 15 cm in width, as seen in Figure 1. Active locomotion is not used in the manufacturing of most capsules, but it is enough for small bowel analysis. In order to examine portions of the GI system, especially the stomach, the capsule should be able to steer. The capsule can accelerate, decelerate, and stop with the aid of active locomotion.^[22] A flexible force sensor measures the capsule tissue contact force. Eight force-sensitive components encircled by an internal permanent magnet (IPM) make up the flexible force sensor.^[23]

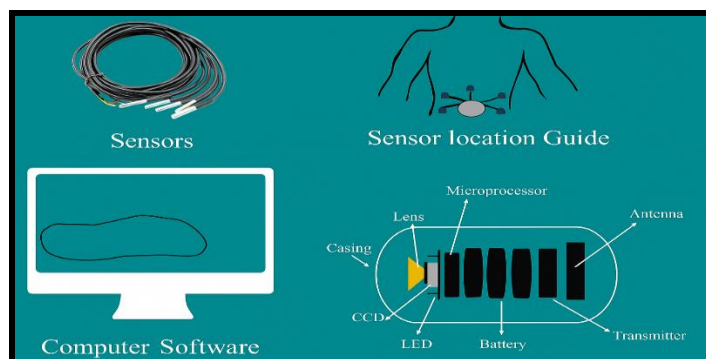


Fig. 2: Working Principle of Steerable Capsule Endoscope.

4.2. Magnetic Capsule Endoscopy

A magnetically controlled capsule for monitoring the stomach cavity was developed in a telerobotics lab at the University of Utah and first proposed by Carpi et al. (2006).^[24] This device consists of eight air-cored electromagnetic coils, a control system, and an endoscopic capsule with a permanent magnet placed in the body (Figure 2). Five degrees of freedom (DOF) motion, including two degrees of rotation and three degrees of translation, are built in. This makes it possible to control the capsule using orientation-independent driving (OID).^[25] This development in magnetic capsule endoscopy enhances the effectiveness, precision, and navigation of gastrointestinal tract examinations. The best position for the magnetic capsule endoscope in the upper gastrointestinal tract and the best location for a manual magnet to help it pass through the pylorus are determined using a multiplanar reconstruction CT modeling technique in order to achieve complete visualization of the upper gastrointestinal mucosa.^[26] It serves a number of functions in gastrointestinal tract diagnosis and therapy. To provide precise localization throughout the gastrointestinal tract, it is equipped with cameras, batteries, LEDs, and antennae. It can also identify iron deficiency anemia of uncertain origin, melena, and hematochezia, as well as detect gastrointestinal diseases, including bleeding.^[27] By employing a dual-purpose permanent magnet for both movement and injection activation, it can administer medications to particular

regions of the digestive tract. This capsule is 34.6 mm in length and 12.5 mm in diameter.^[28] Some drawbacks of magnetic capsule endoscopy include poor image quality, insufficient esophageal analysis, and limited control techniques.^[29]

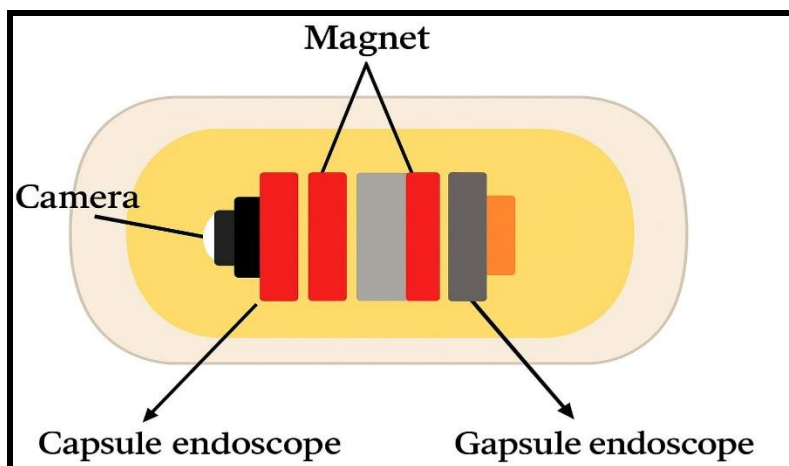


Fig. 3: Working Principle of Magnetic Capsule Endoscopy.

4.3. Robotic Capsule Endoscopy

A magnetic robot capsule endoscopy was proposed by Yim et al.^[30] based on stomach medical operations. The capsule's function and mobility within the gastrointestinal tract are controlled by magnetic fields, as shown in Figure 3.^[31] This method is essential for identifying a number of diseases, including Crohn's disease, celiac disease, gastrointestinal bleeding, and malignancies.^[32] Six elements make up the robotic capsule: (1) movement, (2) telemetry, (3) localization, (4) visualization, (5) powering, and (6) tools for diagnosis and remedy.^[33] Drugs can also be administered to patients via robotic capsules.^[34] These methods work in conjunction with tiny permanent magnets inside the capsule, which are managed by magnetic fields produced by coils or an external magnet.^[35] Without the requirement for anesthesia, robotic capsule endoscopy is used to examine the digestive system, mainly to diagnose gastrointestinal tissue anomalies, especially in the small intestine.^[36] These robots are equipped with wireless communication modules, microcontrollers, micropropellers, and sophisticated sensors.^[37] The robotic wireless capsule endoscopy's inability to identify and treat lesions on its own is one of its primary drawbacks.

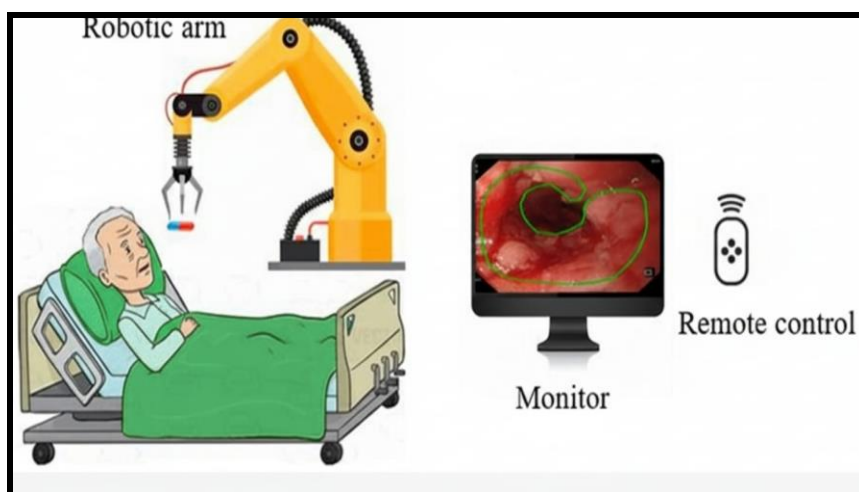


Fig.4: Working Principle of Robotic Capsule Endoscopy.

4.4. Hybrid Capsule Endoscopy

To assess the digestive tract, Simi et al. created a hybrid wireless capsule (Figure 4). They used an internal actuation system in conjunction with external magnetic dragging to produce a capsule-shaped micro robot with active hybrid mobility. A magnet inside the capsule is used in conjunction with an external magnetic field produced by coils or permanent magnets to enable external movement. Small permanent magnets that interact with an external magnetic field are used by the internal actuator.^[38] A magnetic capsule that combines spiral motion and fish-like mobility was developed in collaboration with Tianjin University of Technology and Kagawa University. It makes use of the gravity approach and an axial magnet to create a fin movement. Additionally, it uses a radial magnet to regulate the spiral body's spin. The capsule robot has a diameter of 10 mm and a length of 90 mm.

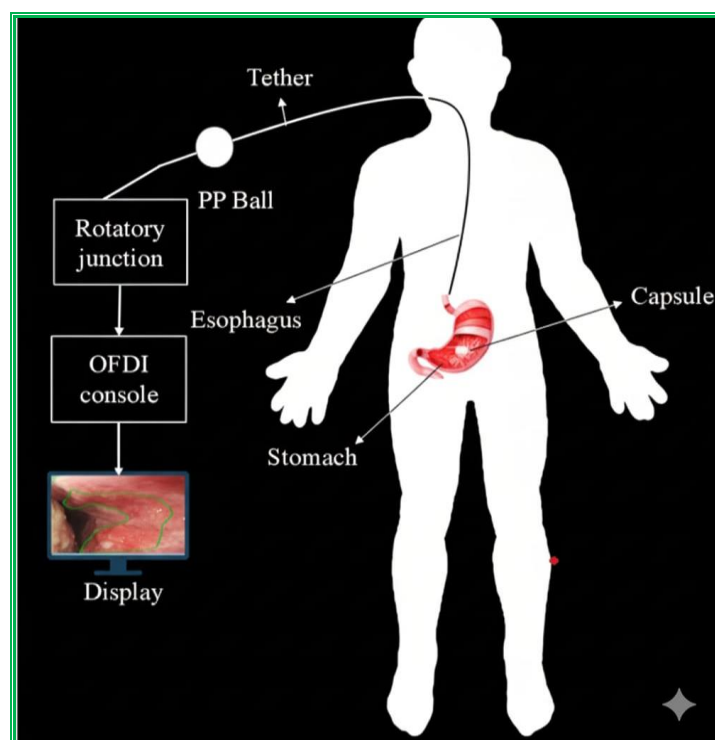


Fig. 5: Working Principle of Hybrid Capsule Endoscopy.

5. INDICATION OF CAPSULE INDOSCOPY

5.1 Indications of Esophageal Capsules

A) Screening for Barrett's Esophagus

Barrett's oesophagus is characterised by a metaplastic alteration of the lining of the esophageal mucosa, where the squamous epithelium that typically covers the distal oesophagus is replaced by columnar epithelium.^[39] According to multiple studies, the incidence of Barrett's oesophagus has quickly increased over time, making it a significant risk factor for the development of esophageal cancer.^[40] According to studies comparing the diagnostic yield of CE and traditional EGD, CE was practical, secure, and well-tolerated by patients. Furthermore, CE was consistently preferred by the patients over unsedated EGD. However, the sensitivity of the esophageal capsule varied between 60 and 100 percent for BE and 50 and 89 percent for another esophageal condition.^[41] Although the results in terms of sensitivity are promising, studies have suggested that EGD is more cost-effective than CE for BE screening.^[42]

B) Screening for Esophageal Varices

The use of CE for detecting esophageal varices is not well defined due to the fact that all the studies present considerable heterogeneity between their findings.

Pena et al. found that an esophageal capsule could be used in the assessment of esophageal varices (EV). The sensitivity calculated in this study was 68.4% in detecting EV using CE against 95% using EGD. However, due to the minimal discomfort, lack of sedation, and low risk offered by CE, this technology is a possible substitute for EGD.^[43] Groce's study showed a sensitivity of CE in detecting EV around 78% and that CE may be superior to EGD for identification of small EV.^[44] On the other hand, Einsen's and Smith's study indicated a better perspective on CE tests, with sensitivity reaching up to 100%.^[45] The same results were found in Ragunath's study [46]. The lowest sensitivity was showed in Jensen's study, where it was only 8.3%, with modest accuracy of the CE in the identification of EV.^[47]

5.2. Indications of Intestinal Capsules

A) Intestinal Tumors

Small bowel (SB) tumours account for 5% of all GI tract tumours and 2% of cancer cases, while the estimative accuracy is quite poor because the existing approaches have been shown to be insufficient.^[48] However, in 2004, CE was developed as a useful diagnostic tool for small bowel tumours, and SB tumours were identified in 8.9% of patients who had the operation. The physicians hoped that CE would improve outcomes for patients with neoplasms by resulting in earlier SB tumour diagnosis and treatment.^[49]

B) Obscure GI Bleeding

A positive faecal occult blood test, episodes of digestive bleeding, or persistent iron-deficiency anaemia can all be indicators of obscure GI bleeding.^[50] The fact that bleeding can originate from several lesions at various locations along the GI tract adds to the intricacy of GI bleeding. Although the patient can see this pathology, it may have a source that is difficult to identify with standard upper or lower endoscopy.^[51] As a result, according to meta-analysis studies, intestinal capsule diagnostic yields range from 55% to 81%, confirming the superiority of CE diagnosis over other traditional endoscopic modalities.^[52] The small bowel results of cryptic GI bleeding obtained with intestinal CE are displayed in Figure 5.

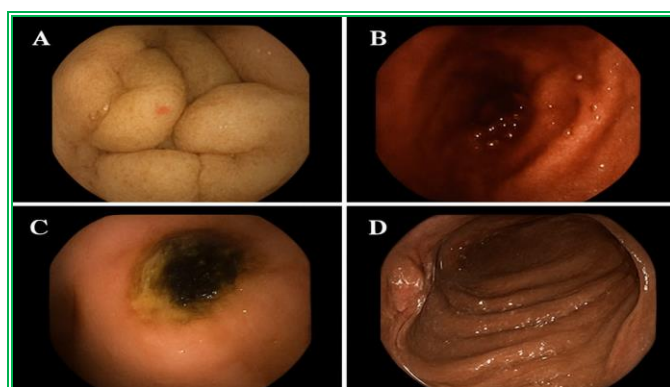


Figure 6: Spectrum of small bowel findings identified via capsule endoscopy (CE) in patients with obscure gastrointestinal bleeding (OGIB). (A) Nonbleeding angioectasia, (B) active bleeding, (C) ulcer with stenosis, (D) small bowel erosion.

6. CHALLENGES IN WIRELESS CAPSULE ENDOSCOPY

Although there have been significant improvements in wireless capsule endoscopy (WCE) technology, various challenges still exist that restrict its broad application in clinical settings and affect its diagnostic precision.

6.1. Limited Battery Life

The small size of the capsule limits the space for batteries. The ongoing processes of capturing images, transmitting data, and operating sensors quickly consume power, usually restricting the operational duration to 8 to 12 hours. This may lead to an incomplete view of the gastrointestinal (GI) tract.^[53]

6.2. Data Transmission and Signal Loss

Transmitting data wirelessly through body tissues is difficult because signals weaken and can be disrupted. Real-time imaging requires high data rates; however, there are constraints on bandwidth and transmission power.^[54]

6.3. Localization and Tracking

It is challenging to accurately identify the capsule's location in the gastrointestinal tract. Magnetic, radiofrequency, and image-based tracking systems are being developed; however, none have yet demonstrated consistent reliability in clinical settings.^[55]

6.4. Limited Control and Navigation

Current capsules travel through the digestive system by peristalsis, resulting in inconsistent coverage and extended retention in the stomach. The optimization of active locomotion through magnetic or mechanical systems is ongoing, focusing on safety and energy efficiency.^[56]

6.5. Image Quality and Diagnostic Accuracy

The small size of the sensor and low light conditions in the gastrointestinal tract decrease the quality of the images. Motion blur and incomplete coverage can lead to overlooked lesions or incorrect diagnoses.^[57]

6.6. Data Overload and Interpretation

One capsule produces between 50,000 and 100,000 images, which results in extended reading times and can cause fatigue for those reviewing the images. AI-assisted image analysis is developing but still needs thorough validation.^[58]

6.7. Safety and Biocompatibility

Capsule retention can happen in cases of strictures or blockages, although it is uncommon. It is important to ensure biocompatibility and safe passage, particularly for patients with known gastrointestinal diseases.^[59]

6.8. Cost and Accessibility

The high costs of devices and analysis restrict their use, particularly in areas with limited resources. Using reusable capsules and automated analysis could lower costs over time.^[60,63]

7. FUTURE PROSPECTIVE OF WIRELESS CAPSULE ENDOSCOPY

Wireless capsule endoscopy (WCE) is rapidly evolving from a purely diagnostic imaging tool to a multifunctional platform integrating imaging, sensing, and therapeutic capabilities. Future developments are expected to overcome current limitations and significantly expand its clinical applications.

Wireless power transfer and energy management represent a significant area of progress. Incorporating energy harvesting methods with wireless charging via magnetic or inductive coupling may increase the capsule's operational duration and enable more sophisticated features like active locomotion and real-time video transmission.^[43]

By automating lesion detection, classification, and localisation, artificial intelligence (AI) will revolutionise capsule endoscopy. Through objective picture interpretation, deep learning-based systems can significantly lessen the effort for physicians while increasing diagnostic accuracy.^[48] Real-time decision support is anticipated to be made possible by future AI systems, which will enable physicians to quickly detect diseases as the capsule moves through the gastrointestinal (GI) tract.

The creation of active or magnetically controlled capsules is another exciting avenue. Under external magnetic direction, these next-generation devices can transit the GI system, enabling precision drug delivery or biopsy collection, focused imaging, and extended monitoring of questionable.^[56] The capsule could become a comprehensive diagnostic tool that can correlate physiological and visual data by integrating multimodal sensing, such as pH, temperature, pressure, and biochemical sensors. Furthermore, advancements in micro-robotics and biocompatible materials will enhance patient comfort, capsule safety, and miniaturisation.

Clinically speaking, WCE's future is in preventive and personalised medicine, where capsules are utilised for ongoing health monitoring, early GI problem detection, and diagnosis. WCE in conjunction with cloud-based data storage and telemedicine platforms will enable worldwide data exchange and remote diagnosis, particularly in healthcare settings with limited resources.^[55] All things considered, wireless capsule endoscopy is moving towards intelligent, controllable, and multipurpose micro-devices that combine therapeutic, sensing, and imaging capabilities, aided by artificial intelligence and wireless power technologies. These developments will revolutionise non-invasive diagnostics and represent a major advancement in intelligent gastrointestinal medicine.

8. CONCLUSION

A revolutionary development in gastrointestinal diagnostics, wireless capsule endoscopy (WCE) provides a non-invasive, patient-friendly substitute for conventional endoscopic techniques. With little discomfort and without the need for sedation, it enables full visualisation of the gastrointestinal tract, including the small intestine. WCE is still developing thanks to developments in artificial intelligence, wireless power transmission, and active locomotion technologies, despite obstacles including short battery life, limited navigation control, and time-consuming picture interpretation.

Future advancements suggest that intelligent, multipurpose capsules will be able to do focused therapy, real-time sensing, precise localisation, and imaging. The accuracy, accessibility, and efficiency of diagnosis will be further improved by integration with cloud-based telemedicine platforms and AI-based diagnostic systems. Ultimately, WCE is set to transform gastrointestinal healthcare by enabling early disease detection, personalized diagnostics, and continuous patient monitoring — marking a major step toward the future of smart, non-invasive medical technology.

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