Active Video Capsule Endoscopy, A Systematic Review

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Abstract

Diseases affecting the Gastro Intestinal tract are recognized as the second leading cause of mortality on a global scale. The diagnosis of these diseases has consistently been a challenge, due to the unique physiological characteristics of digestive system. Studies support the positive impact of early diagnosis on the treatment and recovery of patients with these diseases. Many significant progresses have been made in the field of diagnosis and treatment of Gastro Intestinal diseases; among them video capsule endoscopy is one of these new emerging technologies. This method entails the patient swallowing a vitamin-sized capsule, containing imaging equipment. The capsule traverses the digestive tract, capturing images that are subsequently transmitted to a recording station. A specialist subsequently examines the transmitted images and renders a diagnosis. The paramount consideration in this technique is the methodology employed for capsule activation. In this context, two principal activation modes have been introduced: passive and active modes. Passive capsules rely on the natural wave-like contractions of the digestive system, known as peristalsis, for propulsion. In contrast, active capsules possess internal mechanisms for independent movement. This review article presents the active video capsules, which are equipped with some kind of activation modules. Furthermore, this paper examines specific clinical and technical tests employed to assess capsule performance. The primary objective of this study is to examine the effectiveness of different capsule video activation modes. Additionally, the study aims to evaluate the device's potential utility in diagnosing gastrointestinal disorders. The most significant result is the absence of clinical trials. It would appear that the principal emphasis of these experiments lies in the examination of the technical specifications of video capsules.
Keywords: video capsule, endoscopy, Active Video-capsule, Clinical tests, technical tests

1. Introduction

Digestive system diseases, including stomach cancer, are known to be the second leading cause of death in the world[1]. Challenges have consistently been associated with the diagnosis of Gastro-Intestinal (GI) tract. The ethology of this challenge lies in the unique anatomical organization of the digestive system. Accessing all parts of the lengthy and complex digestive system presents a significant diagnostic challenge. Despite this difficulty, timely diagnosis is essential for patient recovery[2-4]. Endoscopy plays a crucial role in the diagnosis of digestive conditions by allowing for both the visualization and sampling of targeted areas. Endoscopy, while advantageous, can be a challenging procedure for patients. Discomfort is common, anaesthesia may be required, and the complex structure of the small intestine can limit the scope of the examination[1, 5, 6]. The problems associated with the conventional endoscopy led to the invention of video capsule endoscopy, also called wireless capsule endoscopy. A small, vitamin-sized capsule, equipped with imaging technology, is swallowed by the patient and takes pictures as it moves through the digestive system. Over the 6-8 hour procedure, images are transmitted to a recorder and then to a central computer where a specialist analyses them to determine the patient's diagnosis and treatment plan[1]. The most significant hurdle in capsule endoscopy is managing both the activation and the movement of the capsule. Video capsules are generally classified into two distinct categories: passive and active. In the passive configuration, propulsion of the capsule is achieved through the inherent peristaltic activity of the gastrointestinal tract. The absence of activation modules contributes to the simplified structural design of this capsule. A key limitation of this capsule is the absence of mechanisms for controlling both its cessation and its trajectory. Active capsules are characterized by the inclusion of propelling components, which facilitate both stationary positioning within the desired anatomical region and retrograde movement for enhanced visualization[7, 8]. Magnetic field activation is one such method, but it necessitates the use of substantial extracorporeal equipment, with the magnetically responsive modules integrated within the capsule. In a separate class of active capsules, activation is achieved internally, thus precluding the requirement for external devices. Figure 1 illustrates the categorization of video capsules according to their activation mechanism.

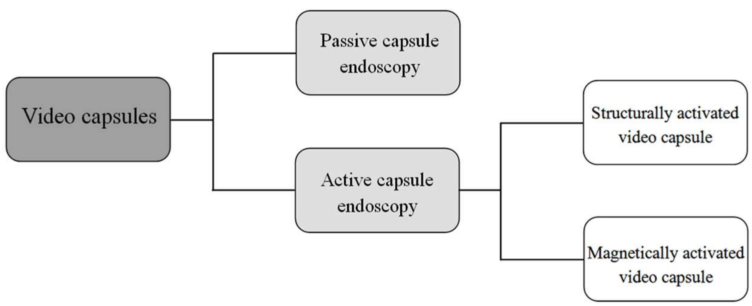

Fig.1. Classification of video capsules, based on activation agent

In this review paper, structurally activated video capsule has been introduced. Besides, clinical and technical tests performed by this kind of video capsules has been of interest. The aim of this review is to evaluate the effectiveness of the active video capsule in the diagnosis of the Gastro-Intestinal disorders. Furthermore, technical features of the capsule have been investigated.

2. Search Strategy

This systematic review was undertaken through an extensive search of the relevant literature within the Scopus, IEEE Transactions, and PubMed databases. The used keywords were capsule endoscopy, video capsule endoscopy, wireless capsule endoscopy, active video-capsule. Using advanced search methods, the databases were searched in all metadata (title, abstract, keywords, case reports and full text). Vast number of papers was available; therefore, some inclusion criteria were implied to reduce the collected papers and extracted the desired studies for this review. The inclusion criteria are listed as below:

- Studies which were published in a journal or conference articles.
- Studies published in English, between the year 2005-2022.

- Studies which introduce an active video capsule.
- Case reports which indicated a clinical test performed by active video capsules
-Studies which report technical teste of active capsule.

The followings were the exclusion criteria:
- Studies which did not contain sufficient information about the device
- Studies which introduced passive video capsules.
- Studies which introduced magnetically activated video capsules
- Universities or companies catalogues and websites that provided a specific model and did not publish any articles in the desired databases.

Figure 2 shows the PRISMA flowchart for shortlisting the articles included in this review.

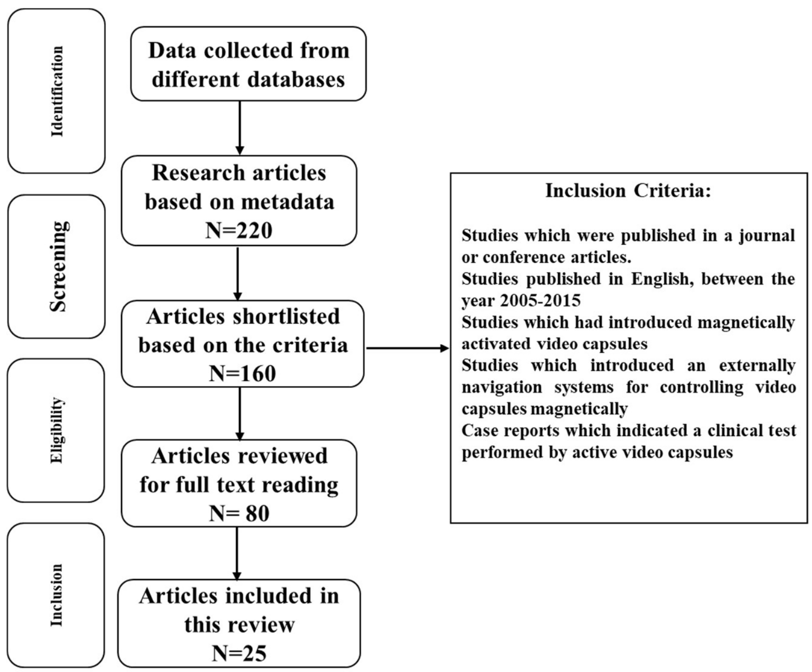

Fig.2. The PRISMA flowchart for active video capsule review

3. Active Video Capsules

3.1. EMILOC Video Capsule

EMILOC (Endoscopic Microcapsule Locomotion and control) project was introduced by *Intelligent Microsystem Center* or *IMC* (Korea) [9-11]. This capsule is activated by a set of bio inspired legs (6 legs with round head to avoid slipping and flexible knees which enable the capsule to pass through GI tract) and made of SMA[1]. Its dimensions are diameter of 12 mm and length of 30 mm. The camera was based on CMOS[2] technology and has a resolution of 320 × 320 pixels.

Based on the *EMILOC* project, the 6-legged and 12-legged versions were

[1]Shape memory Alloy
[2]Complementary Metal Oxide Semiconductor

produced. Indeed, this approach is based on micro legs which enable capsule to clamp, move, turn and rotate. Besides, drug delivery, biopsy and surgery can be added to capsule applications. The external diameter of legs was 4 mm and the total length was 16.2 mm. Like the *EMILOC*, the legs have round head to reduce friction and maximum output torque of 0.058 is produced[12, 13].

A study was performed in the form of an *ex-vivo* test on the pig's intestine through 12-legged video capsule for evaluating the performance of capsule.

Results: It was observed that increasing the number of legs has some effects; firstly, the radial force would distribute more evenly; secondly, the friction would be reduced, so the slip of capsule would be minimal; finally, the irritation to the tissue would be decreased.

During another study, usability of this capsule was investigated. The 8-legged version was utilized on the GI-tract phantom model made of porcine colon.

Results: The capsule could pass successfully through colon during the *ex-vivo* experiments.

3.2. Paddling-Based Video Capsule

This video capsule is driven by six paddle-like legs [14]. Its components are a micro-brush DC motor, led screw, inner and outer cylinder, an outer ring, 6 long paddles, and an outer body. Its dimensions are as diameter of 15 mm, length of 43 mm and it weighs14 grams. The paddles can make an impact length of 33 mm. Its visual features are resolution of 320 × 320 pixels, imaging rate of 10 frames per second, 125° field of view and 0.62 mm focal length.

At the first moment of movement, the capsule is in initial state. Then the linear actuating system starts to move the inner cylinder backward, here the paddles link to outer cylinder. After that, the capsule advances forward while the actuator moves the inner cylinder farther. The next Phase is the final stage of the impact of the linear actuating mechanism. At this point, when the actuating mechanism is about to move the inner cylinder forward, the paddles fixed to the intestine are released and folded into the capsule body. After this phase, the cylinders and folded paddles return to the phase A without the movement of the capsule body. Finally, the locomotion principle returns to the initial state.

The *in-vivo* and *ex-vivo* experimental tests were done to evaluate the performance of capsule. The *in-vivo* test was done on a silicon tube without elastic deformation [8]. It has length of 50 cm and diameter of 18 mm and was laid on a planar surface, with a maximum slope of 27.5.

Results: The movement of capsule inside the silicon tube was stable and the elapsed time was 50 seconds to move from one end to another. The average velocity was 10 mm/sec or 60 cm/min.

An *ex-vivo* tests were performed on a colon of a pig to evaluate the locomotion system in an elastic and viscous environment. The colon was set in 2 positions: 1) the slope angle of 27.5° and a straight length of 35 cm and 2) the slope of 37.5° and straight length of 62 cm.

Results: Fast and stable movements were observed during experimental tests.

3.3. SPCE Video Capsule

The locomotion mechanism of *SPCE* (Self-Propelling Capsule Endoscope) is based on vibration of a fin due to the vibration of a magnet. When a small magnet is placed in an alternating current magnetic field, it will vibrate. This vibration is transmitted to a fin in capsule and generates the propelling force [15]. The capsule is provided with a micro actuator and a micro machine. The micro-actuator had a urethane float, a fin with a magnet, and a small coil connecting the fin to the covering float. The micro-actuator is in size of 14 × 45 mm^2 and weight of 2.7 gr. The *PillCam SB* was inserted inside the urethane cover. The distance between the magnetic poles is 500 mm and the magnetic field decreases from 12 mT at near the magnetic poles to approximately 5 mT at the center between the two poles.

For evaluating the performance of *SPCE*, a micro-actuator was developed to drive this capsule. This test consisted of some sub-tests:

(1) Operating *SPCE* in the stomach of a dog under sedation.

(2) Placing a haemostatic clip on the gastric mucosa and capturing the images of this clip by SPCE.

(3) Placing two clips at two sites and finding the clips to identify the positions, number and colour of clips.

Results: Obtaining images in the dog's stomach in any desired directions was successful. *SPCE* produced clear images of the clips, as well as, easily identifying of the site, number and color of the clips.

3.4. An Inchworm-Like Video Capsule

This capsule consists of a solenoid, steel plunger, cylindrical permanent magnet, baffle plate at one end of the plunger and a cone-shaped silicon polymer at the other end of the plunger [16, 17]. The camera, lightning and wireless transmission circuits are placed in front of the capsule and the driving force is generated by magnet and solenoid. The rigidity of baffle plate prevents plunger from sliding away, while it can create a stroke of few millimetres. The silicon polymer plays the role of clamper for the actuation system. Capsule dimensions are 12 mm × 37 mm, excluding the head. When no current passes through the solenoid, the actuator would be free and no force would be created between the solenoid and the actuator. When an alternating current passes through solenoid, its polarity changes; so, there will be alternating forces created by interacting with the permanent magnet. In combined with operating the cone-shaped polymer, the actuator can linearly propel itself. At first, the magnet and solenoid attract each other and the polymer friction is smaller than that of the solenoid part. Thus, the plunger thrusted forward a longer distance than the solenoid. Then the current direction will change and the repulsion force will separate two parts. During this step, the friction of polymer increases, so the plunger keeps its position while the solenoid moves forward. After that, the current direction will be changed again and a new cycle of actuation will be started. Indeed, during per cycle the actuator makes a displacement.

3.5. Magnetic Shell

This concept can be utilized for all video capsules. It is based on using a magnetic shell for capsule which makes it possible to control the movement, position and orientation through an external magnetic field [18]. Different parts of this video capsule are as follows:

(1) A magnetic shell with following features: interchangeability, disposability ability to run in capsule. A capsule-shell would be created and act as the endoscopic device.

(2) One or more sources and an external magnetic field to run navigation control of capsule-shell.

(3) An imaging system for monitoring the navigation of the capsule and shell *e.g.* ultrasound or X-rays (fluoroscopy).

After covering the capsule with magnetic shell, it will be swallowed by patient and then the magnetic field will be applied. In the following, continuous monitoring along GI tract will be done. An experimental test was conducted to investigate this locomotion mechanism [33]. This experiment was performed on the bovine gastric tissue shaped as a half of a tube. The shell covers an *M2A* video capsule. In the first setup, the set of capsule and shell was moved by a stacked magnet along a piece of bovine tissue. In second time, the set was moved on the surface of a piece of the bovine muscular tissue covered in a plastic cylinder.

Results: The rotation of 180 degrees, in the first set up, and the rotational-displacement movements, in second one, was observed. Also, arbitrary rotational-displacement movements were achieved by employing an external magnetic field.

3.6. Swimming Capsule Endoscope

This capsule can move inside the gastrointestinal tract by generating 5 mN force using three waving tails[19]. The tails can reach speed of 5 mm/sec, without carrying load, and 2 mm/sec with a load which is a standard video capsule. The size of this micro robot is 10 mm in diameter and 20 mm in length, including the three swimming tails.

3.7. The Rotational Micro-Biopsy Device

This capsule was designed so that it can perform tissue sampling, sealing and fixing sequentially in one operation [20]. The initial torque was generated by a torsion spring and a rotating razor with a paraffin block was utilized for cutting tissues. Indeed, when the capsule receives triggering signal, the paraffin block will melt and the rotating razor will be released and collects a tissue sample. The rotation degrees of razor were 120 and it would be sealed after biopsy and a fixing fluid such as alcohol would be supplied to the sampled tissue.

The device was tested on tissue samples prepared from a butchered cow and an etherized rabbit to evaluate its performance.

Results: successfully biopsy was done in the small intestine of the sample tissues.

3.8. Electrical Stimulated Video Capsule

This ovoid-shaped capsule contains electrodes on the tapered part. When a voltage is applied, an electric current will flow thorough the gut wall and lead the adjacent muscles to contract; so, the capsule will move forward. By moving forward, the new muscles will be in contact with the electrodes, thus the capsule can move forward smoothly. This device stimulates the local contraction propagated whenever the electrodes were pushed along the GI tract, not the peristaltic movements.

An experimental test was performed to evaluate the ability of electrical stimulation propel [21].
Results: It was shown that the electrical stimulation causes the capsule to move up or down inside the oesophagus via contracting the regional muscles, with the speed of 6 mm/sec. It was concluded that electrical stimulation could be transferred through small intestine.

3.9. Electrical Stimuli for Controlling a Wireless Capsule

The electrical stimulation can be utilized for controlling the speed of movements of video capsules in GI tract [22]. For this purpose, a video capsule capable of producing electrical stimulation was designed and tested on a pig's intestine.
Results: The contraction intensity was closely related with the amount of electrical stimulation voltage. Its speed can be controlled through external setting of the amplitude of pulse of stimulation signal.

3.10. Inchworm-Based Locomotive Video Capsule

An inchworm-like capsule with two different actuators, clamper and extensor, was designed [23]. While the clamper adheres to the GI wall, the extensor makes displacement. In the simplest prototype, two clampers and one extensor were considered. The clampers stay on the ends of capsule and the extensor is at the middle. Theoretically, an inchworm device advances a distance equal to its stroke length during a cycle of the locomotive sequence, but in practice this will not be occurred.

The efficiency of this mechanism was evaluated on a pig's colon, with the length of 150 cm constrained at both ends, and in the form of an *in-vitro* experimental test Also, an *in-vivo* experimental test was performed on a pig's bowel through colonoscopy. Indeed, conventional colonoscopy was performed first and then capsule endoscopy was done.
Results: These experimental tests led to create new parameter named locomotion efficacy which can be utilized in analytically predicting and comparing the performance of video capsules.

3.11. SMA-Actuated Video Capsule

This video capsule is propelled by an *SMA* wire actuator. This actuator shows different characteristics which depends on diameter of wire [24]. The *SMA* wires in various diameters ranging from 25 µm to 375 µm were utilized in this video capsule. The forces exerted by them varied from 7 to 2000 grams depending on diameter. To provide bi-linear motion, a pulling force should be externally applied by wires. So, the difference between *SMA* recovery force and external pulling force was the maximum producible force by *SMA* wire. Since the *SMA*-wire actuators can produce a small displacement, it is difficult to provide an appropriate pulling force. Accordingly, a different type of *SMA* actuator was fabricated as an alternative actuator which have capability of making a quite large strain and making it easy to provide an appropriate pulling force when they are used in pairs.

4. Results

In this review paper, active video capsule endoscopes were examined. Model-specific review results are available. This review identified a deficiency in the number of clinical trials conducted with these capsules. The primary objective of these tests appears to be the evaluation of the technical characteristics of the video capsule. These experiments measured the average capsule velocity, degree of rotation, and transit time through a specific digestive tract, as shown in the results.

5. CONCLUSION

While digestive diseases pose a significant health threat, early diagnosis improves outcomes. Video capsule endoscopy offers a promising new approach to gastrointestinal screening. Capsule endoscopy represents a significant advancement in gastrointestinal disorder diagnostics. This method offers comprehensive visualization of the digestive tract. This review explores video capsules enhanced with activation modules. A key advantage of this video capsule activation model compared to magnetic activation is the elimination of the need for large magnetic devices and equipment. A drawback of this method is the increased weight and design complexity of the capsules. The increased weight of the capsule negatively impacts its movement, resulting in slower speeds, longer travel times, and greater energy consumption.

As can be seen in the results, most of the tests performed are technical tests related to the performance of the device, while the tests described in [1] identified diseases of the digestive system. While a biopsy was conducted in case [19], the focus of the other cases was on evaluating capsule function. In addition, the amount of displacement and rotation of the capsules was also tested in [12], [16] and [19]. These results indicate that it is possible to obtain 3-D images for more accurate diagnosis of diseases.

Despite the usefulness of video capsule endoscopy, it has not yet been widely used clinically and has only been technically tested. Therefore, it is not possible to say with certainty whether the numbers obtained for speed or rate of movement and rotation can provide useful images. Therefore, it is better to conduct clinical trials on this model of capsules so that, if appropriate, they can provide significant assistance in the timely diagnosis and treatment of diseases. On the other hand, the capsule can be designed in such a way that, in addition to the diagnostic process, it can also be used in therapeutic processes such as drug delivery, sampling, and cutting of tissue or tumours. In addition to the above, the quality of the received images is also of particular importance. High image quality helps in more accurate diagnosis of diseases. Therefore, processing of images received from video capsule endoscopes is another area for research in this field.

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