Subject-friendly entire gastrointestinal screening with a single capsule endoscope by magnetic navigation and the Internet

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Abstract— **Ever since capsule endoscopy (CE) was introduced into clinical practice, we gastroenterologists have been dreaming of using this less invasive modality to explore the entire gastrointestinal (GI) tract. To realize this dream, we have developed a magnetic navigation system which includes real-time internet streaming of endoscopic video and some useful gadgets (position detection by means of magnetic impedance (MI) sensors and a modified capsule that is "weightless" in water). The design of the weightless capsule made it possible with 0.5T (Tesla) extracorporeal magnets to control the capsule beyond 20cm. A pair of MI sensors on the body surface could detect subtle magnetic flux generated by an intra-capsular magnet in the GI tract by utilizing the space diversity effect which eliminated the interference of terrestrial magnetism. Subjects underwent CE, during which they were free from confinement in the hospital, except for 1 hour when the capsule was manipulated in the stomach and colon. This study had a completion rate of 97.5%. The high completion rate indicates that our system (single capsule endoscopy-SCE) with further improvements could become a viable modality for screening of the entire GI tract.**

I. INTRODUCTION

Capsule endoscopy is less invasive endoscopic modality for the gastrointestinal (GI) tract and is rapidly becoming the gold standard especially for screening of the small intestine. In Eastern Asia, gastric cancer is still one of the major causes of mortality, though the rate of mortality due to colorectal cancer (CRC) is rapidly increasing. As cancer is not limited to one area of the GI tract, screening of the whole of the digestive tract is extremely important to prevent death due to gastrointestinal cancer. To improve the rate of screening of the GI tract, less invasive screening modalities are developing, such as colon capsule endoscopy, CT endoscopy and MR enteroscopy. If CE is become a feasible modality for screening of the entire GI tract, a number of hurdles such as the short battery lifetime and lack of control need to be overcome to make it a reality. The battery lifetime of a conventional CE is not long enough to explore the whole of the GI tract particularly as the movement of the capsule is dependent on gravity and GI motility. Since Paul Swain[1][2] proposed a type of magnetic control for CE five years ago, a small number of different types of magnetic control equipment[3]-[5] for controlling the capsule in the stomach have been proposed, tried and a few of them have undergone clinical trials[6]-[8]. We have also developed a simple, inexpensive and portable magnetic navigation system [9]-[13] which has been presented at past DDW congresses. The strong point of our system is that does not require big changes to the internal parts of the capsule (SB2; Given Imaging Ltd, Israel) nor large electromagnet equipment which is hard to carry. As it is very easy to carry, it does not have to have a designated room. In addition, we have developed some useful devices which enable the capsule to be easily navigated and determine the timing for restarting navigation in the colon.

The aim of this study was twofold. Firstly, to determine whether it was possible with magnetic navigation to complete an exploration of the entire GI tract within the battery's lifetime. Secondly, to compare the sensitivity, specificity and discomfort of our system with that of conventional gastroscopy and colonoscopy.

II. MATERIALS AND METHODS

Our system was composed of 4 subsystems; 1) a modified capsule (Pill Cam SB2) and a magnetic paddle, which consisting of four 0.5T magnetic rods which could concentrate the force in an optimal direction (Fig.1A). The

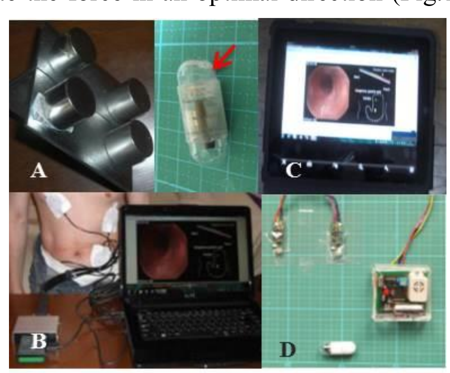

Fig.1 Some newly designed subsystems
A; Extracorporeal controller and modified SB2, B; Real-time dual viewer near the subject for navigation, C; Real-time viewer for checking in the hospital via the internet, D; Ileocecal valve checker

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capsule had its reed switch removed and a tail cap (red arrow) attached, which was contained a magnetic disc (diameter 8mm, depth 1mm, 0.2T (Tesla)) and was designed to increase the buoyancy in water, 2) a real-time dual viewer with remote desktop software and position display software (Fig.1B, C), 3) illeocecal valve checker (ICVC) with beeper (Fig.1D) and 4) a data analysis system consisting of a conventional data recorder and a workstation.

A) Design of the weight less capsule in water

In the previous model we adopted magnetic rings over the capsule. They had two functions; to act as a magnetic shield which prevented the reed switch (power switch) from turning off the power and to enhance the maneuverable force between the rings over the capsule and the extracorporeal paddle. However, it was heavier than the original SB2 and did not have enough buoyancy, resulting in the capsule rubbing against the mucosa. The new tail-cap contained a thin magnetic disc and air which improved buoyancy. The length of tail-cap was adjusted to the optimal point to keep a balance between the weight and buoyancy of the capsule and realize a "weightless condition" (Fig.2, black arrow).

Compared to a conventional real-time viewer, our dual real-time dual viewer had two new additional functions:

1. To detect the position of the capsule and display it on a screen.
2. A remote desktop function

The remote desktop function enabled the examiner to use portable devices (smart phone, iPad etc.) in the hospital to control the real-time viewer at the side of the patient and observe images in real time. Recognition of the capsule position in real time was necessary for quick, optimal and skillful maneuvering of the paddle. To minimize the time the doctor spent manipulating the paddle, the capsule was only manipulated during gastric and colonic exploration.

The doctor called the subject back to the hospital after confirming that the capsule had arrived at the ICV by checking images from the real-time viewer via the Internet.

B) Checker for starting the colonic maneuvering

The ICVC had two magnetic impedance (MI) sensors (Aichi Micro Intelligent Ltd. Japan) which were sensitive

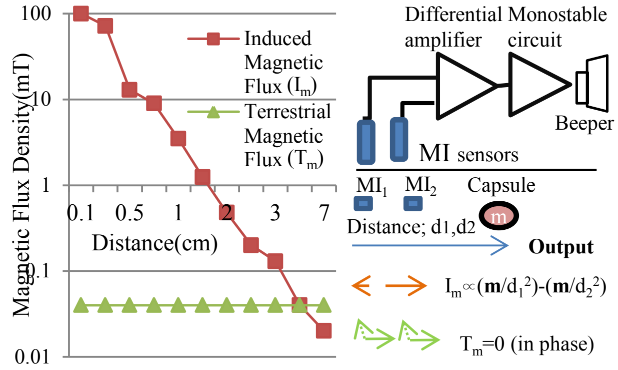
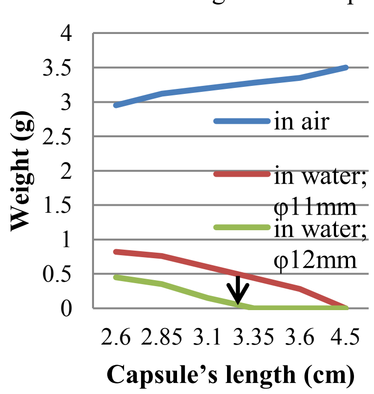


Fig.3 Highly sensitive dual MI sensors

enough to detect the magnetic field induced by the magnetic disc in the capsule. They could detect magnetic fields of about 5000mV/mT (-0.3~+0.3mT zone). A pair of sensors were used in order that the ICVC could distinguish between the local terrestrial magnetism (0.04mT) and magnetic flux of similar intensity generated by the magnetic disc in the GI tract, when it was far from the body surface, and as a result prevent the ICVC from malfunctioning. The ICVC utilized the space diversity effect by comparing the difference between the voltages at both sensors (Fig.3). Fading caused by subjects moving was removed by this effect. The threshold level for detecting the capsule was adjusted to 8 or 9 cm by taking into account the anatomical ICV's location.

C) Procedure for the entire GI exploration

The procedure for total GI screening is shown in Fig.4. After the initial preparation, co-medical staff set up the equipment and the subject ingested the capsule followed by exploration of the stomach and proximal duodenum under magnetic navigation which was supported by observing the real-time dual viewer. After the booster preparation, the ICVC was attached to the patient on the body surface closest to the ileocecal area and switched on. The real-time viewer was detached from the subject and carried by the subject. From then onwards, the subject became free and could go anywhere, home, office and so on. When the capsule arrived at the cecum, it set off the ICVC's beeper. On hearing the



<u>Buoyancy calculation</u>

Breakdown of the capusule's weight (g)

circuit	0.70
battery	1.65
housing	0.59
magnet	0.20
total	2.94

Buoyancy $=\pi\varphi^3/6 + \pi\varphi^2 \cdot (L-\varphi)/4$

L ; length (cm)
φ ; diameter
specific gravity: 1.0

Fig.2 Capsule's weight in water owed to the buoyancy

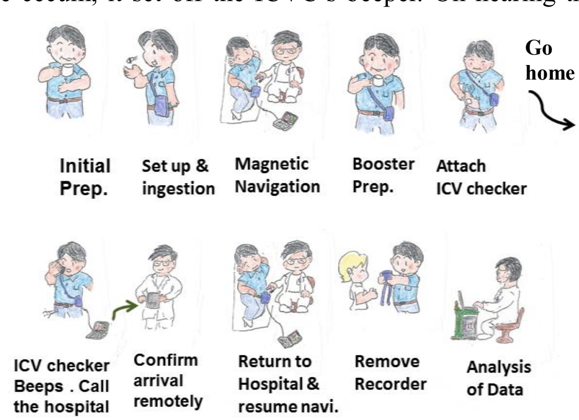


Fig.4 Procedure for the entire GI exploration

beeper, the subject phoned the hospital, turned on the real-time viewer and connected it to the data recorder again. Then using remote desktop control software, the doctor at the hospital confirmed via the Internet that the capsule had passed through the ICV. After the subject returned to hospital, the doctor resumed navigation of the capsule in the colon and rectum. After confirming the capsule's arrival at the anus, the data recorder was detached and then the image data was analyzed on the workstation.

D) Clinical Study

Forty fecal occult blood test positive patients were enrolled into this study. Before CE screening, all of them underwent gastroscopy and colonoscopy. Exclusion criteria were subjects with magnetic materials in their bodies, BMI>35, strictures in the GI tract that were too narrow for the capsule to pass through or the GI tract had previously been operated on. Preparation was PEG-4l split regimen based on the guidelines by Oka [14]. Detection criteria for sensitivity and specificity were major and minor findings as used by Rey [7]. Acceptability was assessed by a 4-point scale in the questionnaire and compared to colonoscopy sedated by midazolam. Written informed consent was obtained from all the participants and the study was approved by the ethics committees of the collaborating hospitals.

III. RESULTS

A) Observed Stomach

Skillful manipulation and appropriate postural changes enabled the capsule to observe every part of stomach perfectly. In term of postural changes, our system did not have any problems, even with changes that other magnetic control systems find difficult such as the subject bending over to observe the cardia. The worst disturbances were due to bubbles and mucus. Even though, the Japanese subjects managed to drink a large volume of solution including 5 ml dimethicone (bubble reducer)), there were still some bubbles and mucus floating over the horizon zone (the boundary between the air and preparation liquid). During ingestion of the capsule it was difficult for the subjects to avoid swallowing saliva (including mucus) and air (as bubbles).

B) Transit time

Table 1 shows transit times. The examination time for navigation was much shorter than that for conventional CE. Compared to conventional CE, gastric transit time (GTT) and small bowel transit time (SBTT) were reduced by half and a quarter respectively. The booster preparation was

Table 1 Transit time (min.)

	SB2	CE-Navi
GTT	40.3	18.8
SBTT	246	188
CRTT	>720	48
CR(%)	87 (only in SB)	97.5

Table 2 Accuracy (%)

	Stomach	colon
Sensitivity	96	91
Specificity	91	85

*Cleanliness: 29/40 over fair in 4-point scale

Fig.5 Image of real-time viewer and scene of navigating a capsule by a magnetic paddle

responsible for shortening the SBTT. The capsule's arrival at the ICV was checked remotely via the Internet and the results showed the ICVC had a false detection rate of 12/40.

Navigation resulted in completion of total GI screening within the battery's lifetime (CR=97.5%), mainly because the colorectal transit time (CRTT) was only 48 minutes compared with 720 minutes for conventional CE. To realize this high CR, postural changes were also useful during colon navigation. The magnetic force was not strong enough for the capsule to overcome peristalsis or sphincter contraction.

C) Accuracy and cleansing level

The results for accuracy in the stomach and colon are shown in table 2. Sensitivity and specificity were above 84%. To our disappointment, evaluation of the preparation indicated that the amount of conventional PEG preparation used in Japan or the timing of the booster preparation was not enough to observe all parts of the colorectal region. In the colorectal region, poor cleanliness directly led to poor quality in accuracy.

D) Evaluation of discomfort and adverse reactions

Eighty percent of the subjects preferred SCE to conventional colonoscopy. However, 8 subjects felt discomfort and 2 subjects complained of nausea due to the amount of preparation. After completing a clinical trial, we are planning to submit clinical results to a medical journal.

IV. DISCUSSION

These days, telecommunication technology and nano-technology are developing extremely rapidly. With new technological developments, it may be possible in the near future to realize the dream of diagnosis and treatment by a capsule endoscope which has multi- functions such as wireless remote control, computer assisted control and minute robotic technology.

One of our aims is to make CE as subject-friendly as possible. Our CE system introduced the ICVC and the Internet which allowed the subjects more freedom. This study has clarified that the design of the weightless capsule and space diversity detection of the capsule's position were useful for improving the controllability of the capsule.

SCE is another step towards that goal. As our system is composed of simple inexpensive and portable parts it would be relatively easy to introduce it into daily practice at small clinics or large hospitals. The 97.5% completion rate indicated that magnetic navigation was an extremely useful tool for enabling the capsule to explore the entire GI tract within the lifetime of the battery. Practically any reduction in examination time is looked upon very favorably by both doctors and patients. By using smooth muscle relaxant to reduce sphincter contractions and colonic spasms, it may be possible to reduce the examination time even more.

Evaluating the accuracy of a capsule endoscopy is important in determining if it meets the standards required for a screening modality. To the best of our knowledge, the clinical trial by Dr. Rey et al on stomach exploration using their MGCE system is the only study to have reported accuracy findings for the upper GI tract. For the lower GI tract, Spada et al.[13] have recently reported accuracy results for the PillCam Colon, for polyps ≧ 6mm and ≧10mm. In our study, accuracy was measured in a similar way to Rey's study by comparing the results with current endoscopy.

Accuracy of GI screening is mostly related to the cleansing level, especially in the case of CE during which an endoscopist cannot wash the mucosa, aspirate mucus or erase bubbles by a bubble reducer injection. Bubbles and mucus affected the view in the upper GI tract and residual feces in the lower GI tract. The colonic cleansing level was a significant problem for colon screening by SCE. Unlike a conventional endoscope, a capsule endoscope cannot irrigate or cleanse the colon appropriately, therefore preparations for the colorectal region need to be improved to increase accuracy, especially for colonic exploration.

Limitations of SCE

A number of limitations should be taken into account. Firstly, the force from the magnetic paddle reached only 20cm in from the surface of the body. Sophisticated postural changes helped to improve capsule control. In larger individuals over BMI35, control may be more difficult. Control of the capsule could be improved by using stronger magnets. A second limitation is cost. Today MR enterography and CT enterography are improving rapidly, though they still have various difficulties regarding quality to become tough competitors for CE. However, from the point of view of cost, except for the initial equipment investment, the cost of each capsule endoscopic examination is disappointingly no match for them. Capsules are disposable devices and that leads to the higher cost for this screening modality. In order to reduce costs and from an environmental standpoint, future studies should investigate the feasibility of reusing the capsule's internal hardware. A third limitation is the security of personal data on internet networks. Security software that prevents leakage of personal data should be investigated.

V. CONCLUSION

This single capsule system has the possibility to become a more subject friendly and more accurate modality than conventional endoscopy, though it will be necessary to reduce costs and improve security.

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