Technical feasibility of patient-friendly screening and treatment of digestive disease by remote control robotic capsule endoscopes via the Internet

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Abstract—A few types of steerable capsule endoscopes have been proposed but disappointingly their systems were not applicable to common endoscopic treatment or pathological diagnosis. This study validates the possibility of treatment and biopsy by using an internet-linked (wireless control via the internet) robotic capsule endoscope (iRoboCap). iRoboCap consisted of three parts: an imaging unit, a movement control unit and a therapeutic tool unit. Two types of iRoboCaps were designed, one was a submarine type (iRoboCap-S) and the other was an amphibious type (iRoboCap-A). They were remotely and wirelessly steered by a portable tablet device using Bluetooth and via the internet. The success rates of biopsy or clipping were evaluated in a phantom. Although the two prototypes have various problems that need improving, we hope that our robotic and wireless innovations have opened the door to new endoscopic procedures and will pioneer various new applications in medicine.

I. INTRODUCTION

Capsule endoscopy (CE) has been approved as one of less invasive modalities for gastrointestinal screening. Nevertheless, it is restricted only to screening because the capsule cannot move by itself, fix its position or treat lesions that it finds. Innovations in internet, wireless and robotic technology are making it possible to introduce therapeutic tools into CE. Since the introduction of the capsule endoscope, suggestions for controlling capsule endoscopes have mainly focused on steering by extracorporeal magnets[1]-[4]. Though they were simple, they had a number of drawbacks. For example, the equipment was not portable, the method lacked precise control, the equipment was expensive or operators needed a long time to master sophisticated maneuvers. To overcome these drawbacks, the capsule must be fully 3-D steerable, have a simple system for remote control and have low power consumption.

We estimated that the most feasible and cheapest way to realize our purpose might be the introduction of a wireless motor-control system into a CE which is very common in radio-controlled toys. To the best of our knowledge, there are very few reports that have depicted an advanced experimental capsule equipped with a motor that was wirelessly driven, but they did not have an imaging unit [5], network tools or therapeutic devices [6]. We presented a preliminary type of capsule (iRoboCap) at DDW2013 which had an imaging unit and could be controlled three- dimensionally and more precisely and via the internet [7].

Furthermore, to realize treatment by capsule endoscopy, it is inevitable to make use of wireless technology (for remote control) and robotic technology (intelligent procedures controlled by microprocessors and software). There have been a few preliminary experimental reports [8]-[9] on CE applied to therapy. We also have been developing a motor-driven capsule endoscope equipped with either a clipping tool or forceps for biopsy. The capsule has an internet-supported capsule endoscopic system and it can be remotely controlled from a hospital [10]. It is becoming more and more common to use the Internet for remote monitoring of cardio-vascular and metabolic internal medicine, as well as in robotic surgery, and is being introduced rapidly into the area of telemedicine. However, to our disappointment, there are few reports on the utilization of the Internet in endoscopy, even though endoscopic innovation has pioneered various types of endoscopic modality for diagnosis or treatment.

Our goal is to establish entire GI screening and therapy by a CE at home which can be remotely controlled from the patient's hospital, by using ubiquitous networks, wireless control and robotic technology. This report suggests that an ultimate patient friendly remote capsule endoscopic system which can provide endoscopic diagnosis and treatment wherever patients are, and without too much disruption to their daily lives, may not be too far away.

II. MATERIALS AND METHODS

A. Structure of the iRoboCap

Our internet-linked and robotic capsule endoscope

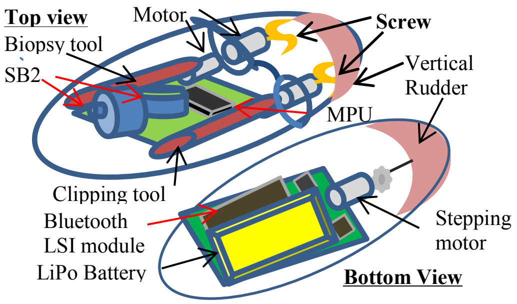

Fig.1 shows the fundamental structure of the iRoboCap composed of three units; imaging unit, movement control unit, and thrapeutic tool unit.

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Fig.2 Two prototypes of iRoboCap (therapeutic version). A. screw-driven submarine type, B. wheel-driven amphibious type, C. Smartphone for steering.

(iRoboCap) was used for this study. IRoboCap consisted of three parts: an imaging unit, a movement control unit and a therapeutic tool unit (Fig.1). The imaging unit came from a PillCam SB2 (Given Imaging, Yoquium Israel). Two ways of moving the iRobocap were investigated. One was a submarine type (screw-driven; iRoboCap-S) and the other was an amphibious type (wheel-driven; iRoboCap-A) (Fig.2 a,b). The iRoboCap-S was equipped with three motors for movement and a driver integrated circuit, so that it could be steered three-dimensionally in water and remotely. On the other hand, iRoboCap-A was equipped with two motors and a driver integrated circuit which meant it could only move two-dimensionally. IRobocap's therapeutic tool unit consisted of biopsy forceps or a clipping device and a motor. The motor was used to release a mini-hemoclip or operate the forceps. Each tool had its own motor. The tools were promptly controlled by signals generated from a single microprocessor chip on the same circuit according to sequences which were previously programmed. For each model, the power for locomotion and driving the therapeutic tools came from a rechargeable LiPo battery (3.7V, 150mAh; S.T.L. JAPAN) and for imaging from silver oxide button batteries respectively. The mobility of each prototype and their success rates with the two tools were evaluated in a phantom.

B. Architecture of the iRoboCap system

Figure 3 shows the architecture of the iRoboCap system. Both the S and A versions of iRobocap used two different frequency bands and tranceiver LSIs. 430MHz was used for images and 2.4GHz (Bluetooth specification) for control signal transmission. For security of the wireless signal, WEP encryption was used to pair Bluetooth devices. On the other hand, image signals from the capsule were unilaterally received by antennas on the surface of the phantom and stored in a conventional data recorder. In addition, they were sometimes simultaneously transmitted wirelessly back to the hospital via a real-time viewer linked to the Internet. A tablet device in our hospital was used to control the prototypes remotely by using application software installed on a smartphone (Galaxy; Samsung Co. or iPhone, Apple Co.) which was next to the phantom. The smartphone was used as a repeater for the control signals between the tablet and each prototype. When each prototype was controlled wirelessly via the Internet, it was done in a different room in our hospital which was beyond the range of communication by Bluetooth. Each prototype's microprocessor was equipped with a Bluetooth transceiver which allowed signals to be securely transferred between each prototype and the smartphone

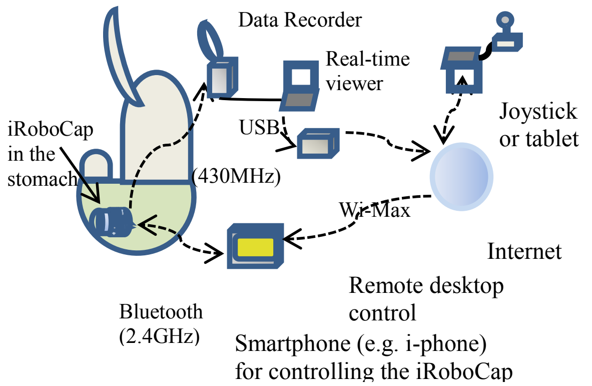

Fig.3 iRoboCap was controlled remotely by a doctor in the hospital

III. MEASUREMENT OF 2.4GHZ LOSS IN THE BODY

The 2.4 GHz frequency band is very useful for utilizing Bluetooth and/or Wi-Fi enabled devices and connecting them with personal computers or microprocessors via USBs. However, the band's suitability for transmitting data between the inside of the body and the body surface has not been clarified. Fig.4 shows results of endoscopic experiment we did to try and assess it suitability. The transmission loss between several points in the digestive tract and a smartphone on the surface of the body was measured in human volunteers. We simply measured Wi-Fi signal power levels by the Wi-Fi analyzer (Softnic, Japan) installed on the smartphone from Wi-Fi Rooter equipped with an original antenna through the forceps channel. This data indicated the availability of 2.4GHz for our purpose. In addition, figure 4 indicates that BMI (Body Mass Index) does not affected 2.4GHz communication.

IV. MOTILITY OF THE IROBOCAP-S AND –A PROTOTYPES AND BATTERY LIFETIME

The dimensions of the two prototypes were nearly the same; width 22mm, length 52mm, height 28mm. Both versions of the iRobocap were equipped with a PIC24 series LSI microprocessor which worked promptly and executed the procedure perfectly according to the program installed. iRoboCap-S was equipped with three brush DC motors (diameter 4mm, length 10mm), so it could be moved three-dimensionally (one motor for forward and backward, one for right and left and one for submerging and surfacing). Though they generated electrical noise, they did not interfere with the transmission of signals or the microprocessor's performance. Moreover, iRoboCap-S was equipped with two

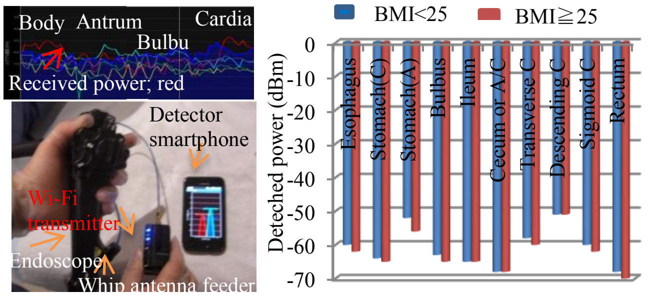

Fig.4 Transmission loss measurement system and results

more brush DC motors (diameter 3mm, length 8mm) for working the therapeutic tools and again no interference was observed between the motor drive circuits and the imaging circuit.

On the other hand, the amphibious type had two motors for two-dimensional movement and like the iRoboCap-S it had two smaller motors for the therapeutic devices. The fundamental movement characteristics of the two prototypes are shown in table 1. The amphibious type could travel at a speed of 120cm/sec. maximally which was too quick for the operators to control it, in real time via the Internet. The amphibious type could not move up and down, and as it was heavier than water, it consequently was always on the bottom. The iRoboCap-S had a merit in that it had the ability to move three- dimensionally so it could be made to hover and keep its position. The therapeutic devices consumed a small amount of power for a short duration (5sec.) on demand whereas locomotive power was 53 minutes for each iRoboCap.

EXPPERIMENTAL RESULTS OF THE THERAPEUTIC DEVICES

The microprocessor's software was operated by commands sent from a smartphone. A touch panel on the smartphone worked as switches which controlled functions such as biopsy and clipping. Table 2 shows the specifications of the therapeutic tools and how well each prototype did with the different tools. The two tools had the same mechanism. However, to our disappointment, both tools had the limitation of not being reusable. As the iRoboCap-S was nearly in a weightless condition in water, it was pushed back from the lesion by opposing forces while attempting biopsies (with the biopsy tool) and was therefore unable to obtain any tissue. The iRoboCap-S was inferior to the iRoboCap-A at keeping the same position on the surface of the phantom. On the other hand, the clip's blade had jaw-like teeth enabling it to stick into the tissue, which was why clipping had higher success rates than biopsy.

Controlling both prototypes via the Internet was difficult, because there was about a one second time lag for both prototypes, between the video appearing on the real-time viewer next to the phantom and the same video appearing on the remote tablet. The delay occurred between the real-time viewer and the tablet. However, the delay was more noticeable with the iRoboCap-A, because it moved at a much faster speed than the iRoboCap-S. In addition, it was difficult to determine the orientation of the iRoboCap-A at the conventional frame rate of two frames per second. The time lag via the Internet and the fast speed at which iRoboCap-A moved, made it difficult to control via the Internet, resulting in wild steering and the missing of lesions. Neither the conventional frame rate nor the transmission speed was adequate for real-time control.

Table 1 Fundamental locomotive and electrical characteristics of the two types of iRoboCap

	Submarine	amphibious
Forward	8mm/sec.	120mm/sec.(max.)
Backward	4mm/sec.	120mm/sec.(max.)
Right or left	10deg./sec.	90deg./sec.
Diving	8mm/sec.	always bottom
Surfacing	4mm/sec	impossible
Working time	53 min.	53min

(Continuously 2 motors working).

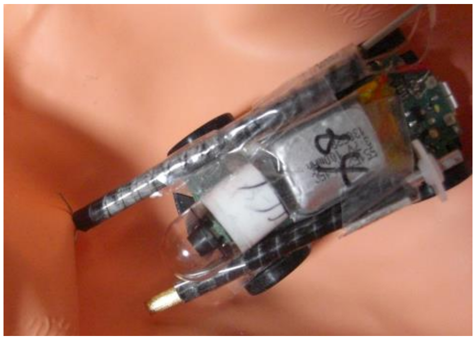

Fig.5 Clipping scene in the phantom

Table 2 Specifications and success rates for the iRoboCaps

Specification	Success rate Tool	 iRoboCap-S	 iRoboCap-A
Biopsy; electromotor size φ4mm x 25mm specimen number 1p	Biopsy	4/18	14/18
Clip ; clip size w 1mm x l 5mm electromotor single use size φ4mm x 25mm	Clip	8//10	10/10

V. DISCUSSION

Most gastroenterologists believe that CE is a tool only for diagnosis. It has become a kind of paradigm of CE. A few of researchers have tried to make a paradigm shift in this field. The VECTOR project is one of those studies, but to our disappointment, it has not yet developed a capsule sophisticated enough to apply it to clinical use. Furthermore, there has been no report about remotely controlling a capsule inside a patient after they had left their hospital. Control via the Internet is a common technology in the video games industry or home electronics, though it has not yet become a common technology in medicine. Some doctors might be planning to introduce remote robotic control systems into remote surgery or telemedicine because they are convenient, cost effective and the technology is more patient-friendly. A few years ago they had several difficulties due to the immaturity of robotic technology or wireless technology. However, it is now possible to remotely control a capsule over the Internet due to rapid developments in wireless technology (high speed LTE), the Internet and peripheral devices.

Wireless peripheral devices and portable devices (included smartphone or tablet devices) are developing rapidly, though they are limited to certain frequencies (800MHz, 2.4GHz, 5.6GHz etc.) Devices for internet technology contain various kinds of cheap small LSIs and antennas which are suitable for miniaturizing equipment and establishing various functions on one circuit. Unfortunately, those frequencies mentioned earlier have large dielectric losses in the human body (so called electronic oven frequency) and therefore it was believed that transmission in human body was impossible. But the quality of those frequency bands have been improving rapidly and their sensitivity levels have come into the target range for realizing communication between intra and extracorporeal transmitters and receivers. Valdastri [8] and De Falco[6] indicated the possibility of 2.4GHz communication in vivo. Our simple in vivo test and by controlling the capsule's movement and the therapeutic tools inside the phantom have provided further evidence that the 2.4GHz frequency band could be used in vivo. The 2.4 GHz frequency band is very useful for connecting to the Internet via wireless HUBs. Fortunately, most smartphones or tablets support 2.4 GHz Wi-Fi connectivity and/or Bluetooth connectivity. Moreover, smartphones and tablets have become very common electronic devices. If such portable devices can detect a 2.4 GHz high baud rate signal such as image signals from a capsule in the GI tract, we only need to install an application on the portable devices to store data locally or transmit it via the Internet, and this would mean the conventional data recorder would no longer be needed. Hopefully, our quite simple system will pave the way for futuristic, impeccable and advanced remote medicine that is not only for capsule endoscopy, but also for interventional medicine including gastroenterology or surgery.

By building and trialing two prototypes, we have identified several areas that need to be improved in order to realize a practical version. They include the following four points, miniaturization, battery lifetime, internet security, frame rate and high-speed transfer of video data for real-time control.

To miniaturize an iRoboCap to half of the size of the present prototypes, we have to look at every part. We are focusing our attention on 1) integrating the transceiver LSI with the conventional image transmitter or motor driver IC, 2) acquiring a smaller battery with a longer lifetime and 3) acquiring smaller motors with low power consumption. We hope that the first problem will be overcome by introduction of a Bluetooth or ZigBee IC working at higher clock rates in the very near future. Our results indicate that the current LiPo battery would have enough power for navigation in the stomach and colon and for simple treatments, however it would not have enough power for treatments that required more power and a longer operation time such as a polypectomy, an endoscopic mucosal resection (EMR) or a submucosal dissection (ESD). This type of battery is rapidly developing and has been introduced into various fields such as electric cars, personal computers and portable device. Unfortunately, at the moment they have safety issues and bio-batteries are still in their infancy and need years to develop. If we did not need to worry about the price of the iRoboCap or think about reducing costs by reusing it, the third problem could be solved quite easily by buying expensive small low power brushless motors (φ1.5mm). They should help to prolong the battery's lifetime as well as aiding miniaturization.

The most crucial problem might be internet security including secure access to cloud services. Various coding technology might be one solution as well as various new encryption techniques that are currently under development. Another approach is a fail-safe mechanism that may be also one of the better options to surmount any difficulties due to jamming of wireless communication.

The last problem concerns real-time control which was difficult via the Internet due to a delay in the video reaching the remote tablet, the slow frame rate of two frames per second and in the case of the iRoboCap-A, it was exacerbated by the high speed at which iRoboCap-A traveled. Generally speaking, the length of the time lag depended on the speed of at which images were compressed and decompressed, and the transmission rate over the internet network. Using a 4G/LTE smartphone connected to a 4G network should rectify the time lag problem, allow for faster frame rates (adaptive frame rate) and it may be fast enough to do without special software for compressing and decompressing the video images. We intend to test a 4G network connection in the very near future.

VI. CONCLUSION

Our results show that it is possible to remotely control a robotic capsule and operate therapeutic tools via the Internet by using equipment that is fairly cheap and readily available. Though our system is a long way from the finished article, this robotic and wireless innovation has opened the door to new endoscopic procedures and will hopefully pioneer various new applications in gastroenterology. Further developments should focus on building a swallowable version ofthe iRoboCap that can be used to realize patient-friendly remote medicine.

REFERENCES

[1] Swain P, Toor A, Volke F et al. Remote magnetic manipulation of a wireless capsule endoscope in the esophagus and stomach of humans. Gastrointest Endosc 2010;71:1290-1293

[2] Rey JF, Ogata H, Hosoe N et al. Feasibility of stomach exploration with a guided endoscopic capsule endoscope. Endoscopy 2010;42:541-545

[3] Morita E, Ohtsuka N, Shindo Y et al. In vivo trial a driving system for a self-propelling capsule endoscope using a magnetic field. Gastrointest Endosc 2010;72:836-840

[4] Keller J, Fibbe C, Gerber J et al. Inspection of human stomach using remote-controlled capsule endoscopy: a feasibility study in healthy volunteers. Gstrointest Endosc 2011;73:22-28

[5] Carta R, Tortora G, Lenaerts B et al. Wireless powering for a self-propelled and steerable endoscopic capsule for stomach inspection. Biosensors and Bioelectronics 2009;25:845-851

[6] De Falco I, Tortora G, Dario P et al.A integrated system for Wireless capsule Endoscopy in a liquid-distended Stomach Biomedical Engineering IEEE trans.2014;.61, 794-804,

[7] .Ohta H The Dawn of Internet linked Robotic Capsule Endoscopy; a Radio-controlled and motor-driven Capsule Endoscope that can be controlled via the Internet. Gastrointest Endosc 2013;77:AB465-466

[8] Valdastri P, Quaglla C, Susilo E et al. Wireless therapeutic endoscopic capsule: in vivo experiment. Endoscopy 2008;40:979-982

[9] Quirini M, Menciassi A, Scapellato S et al Feasibility proof of a legged locomotion capsule for the GI tract. 2008;67:1153-1158

[10] Ohta H, Katsuki,S Fujita T et al. First trial of a wireless robotic capsule endoscope equipped with therapeutic tools Endoscopy 2013;45:A83