Small Antennas Used in the Vicinity of Human Body

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SUMMARY   Recently, wearable wireless devices or terminals have become hot a topic not only in research but also in business. Implantable wireless devices can temporarily be utilized to monitor a patient's condition in an emergency situation or to identify people in highly secured places. Unlike conventional wireless devices, wearable or implantable devices are used on or in the human body. In this sense, body-centric wireless communications (BCWCs) have become a very active area of research. Radio-frequency or microwave medical devices used for cancer treatment systems and surgical operation have completely different functions, but they are used on or in the human body. In terms of research techniques, such medical devices have a lot of similarities to BCWCs. The antennas to be used in the vicinity of the human body should be safe, small and robust. Also, their interaction with the human body should be well considered. This review paper describes some of the wearable antennas as well as implantable antennas that have been studied in our laboratory.

key words: *wearable antenna, implantable antenna, body-centric wireless communications, RFID, hyperthermia, medical device, human body, phantom*

1.   Introduction

Recently, wearable wireless devices or terminals have become a hot topic not only in research but also in business. They can make our daily life more convenient and safer. Also, they can improve quality of life (QOL) of elderly people or patients in hospitals.

Implantable wireless devices can be utilized temporarily to monitor a patient's condition in an emergency situation or to identify people in highly secured places. Today, they are sometimes used permanently for specific biological monitoring systems.

Unlike conventional wireless devices, wearable or implantable devices are used on or in the human body. In this sense, body-centric wireless communications (BCWCs) have become a very active area of research. There are numerous applications, such as personal health care systems, smart homes, personal entertainment, identification systems, and so on [1], [2].

On the other hand, radio-frequency or microwave medical devices used for cancer treatment systems and surgical operation have completely different functions, and are used on or in the human body [3]–[5]. In terms of research techniques, such medical devices have a lot of similarities to BCWCs. In general, the problem of a small antenna used in

the vicinity of the human body can be treated as "boundary value problem" in which the human body is considered as a lossy medium. By applying Sommerfeld integral, electromagnetic fields around the antenna could be found in principle. However, in reality and simplicity, an individual case is treated appropriately in a specific manner.

The antennas to be used in the vicinity of the human body should be safe, small and robust. Also, their interaction with the human body should be well considered. For experimental evaluation of such interaction, human-body phantoms should be used instead of a real human body [1], [6].

This review paper describes some of the wearable antennas as well as implantable antennas that have been studied in our laboratory. Section 2 introduces two typical examples of wearable antennas: a wearable dual-mode antenna that can transmit various biological information with less power, and a radio frequency identification (RFID) antenna that detects urination for adults. Section 3 introduces three different types of implantable antennas: an implantable RFID tag antenna to monitor biological information, two microwave antennas for thermal therapy (hyperthermia) as well as surgical operation, and a small antenna for a capsule endoscope.

2.   Wearable Antennas

This section introduces two typical examples of wearable antennas. The first one is a wearable dual-mode antenna that can transmit various biological information with less power. The second one is an RFID antenna that detects urination for adults.

2.1   Wearable Dual-Mode Antenna

Recently, BCWCs have become a very active area of research because of their numerous applications, such as personal healthcare systems, smart homes, personal entertainment, identification systems, and so on [1], [2].

The frequency used for most practical applications of BCWCs ranges from a few MHz to 2.45 GHz. In our previous study [7], a conventional top-loaded monopole antenna shown in Fig. 1 is employed. The antenna has low-profile dimension (4-mm thick) and has no matching structure for simplicity.

Figure 2(a) shows a numerical human-body model. The antenna is placed at the navel as a transmitter. Fig-

Fig. 1   Structure of the antenna [7].

(a) Human-body model   (b) 3 MHz   (c) 3 GHz
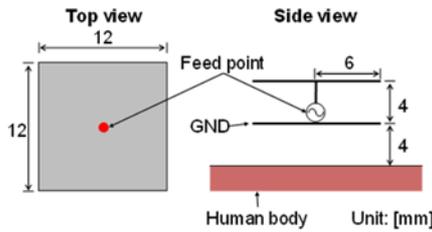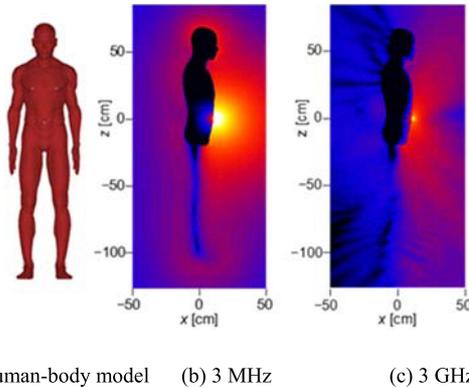
Fig. 2   Human-body model and electric field distributions [7]. A transmitter is placed at the navel and its output power is the same.
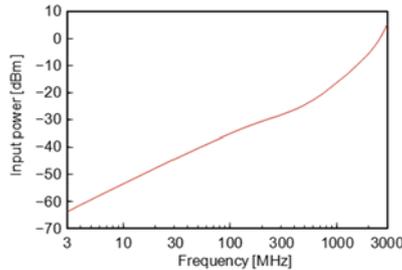

Fig. 3   Estimated input power when 1-V excitation is assumed [7].

Fig. 4   An example of a personal healthcare system.

Fig. 5   Structure of a dual-mode antenna [8].
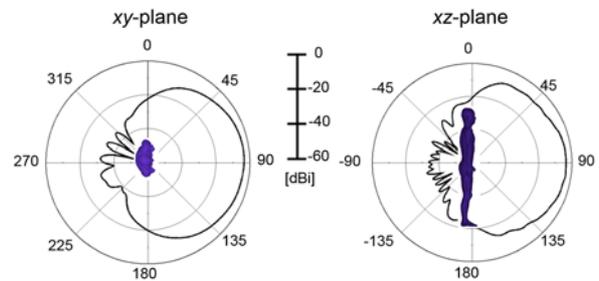
Fig. 6   Simulated radiation patterns at 2.45 GHz [8].

ures 2(b) and (c) illustrate calculated electric field distributions around the human-body model at 3 MHz and 3 GHz [7]. The radiation efficiency at 3 MHz is almost zero because the field around the human body mainly consists of the electrical stored energy. On the contrary, at 3 GHz, the radiation efficiency reaches 48% and strong radiation from the antenna is observed.

Figure 3 shows input power versus frequency for the antenna with 1-V excitation [7]. The use of lower frequency would be more efficient in terms of power consumption.

Figure 4 illustrates an example of a personal healthcare system. Various bio-signals from different bio-sensors are sent to a repeater through on-body communications at 21 MHz, and these bio-signals are transmitted to an external device (access point) in off-body mode at 2.45 GHz. Therefore, significantly low power consumption can be realized [7] for on-body communications.

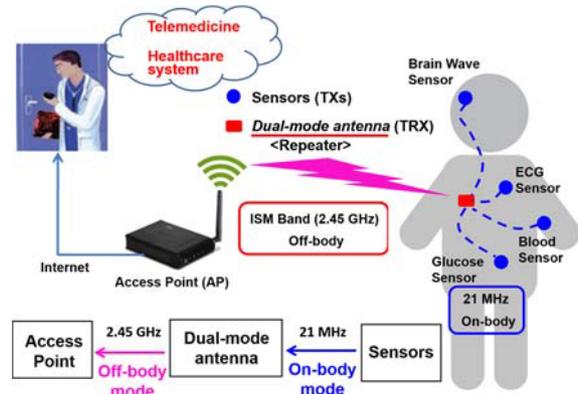Figure 5 shows the structure of a practical dual-mode antenna [8]. It acts as a receiver in on-body mode (21 MHz) and a transmitter in off-body mode (2.45 GHz). Regarding the polarization generated from an antenna, vertical polarization to the human-body surface is suitable for on-body mode and horizontal polarization for off-body mode. The antenna in Fig. 5 is designed to generate such proper polarizations.

Figure 6 shows the simulated radiation patterns with the high-resolution human-body model. From the results, the radiation patterns in both planes are relatively omni-directional with no deep nulls in the half-sphere.

We are planning to take measurements on the antenna with a human torso phantom fabricated in our laboratory, shown in Fig. 7.
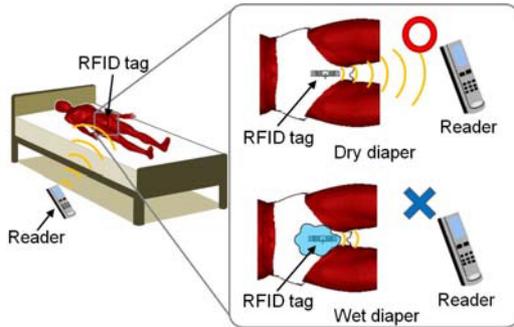
Fig. 7 Torso phantom for measurement.

Fig. 8 Suggested simple urination detection system.

2.2 Urination Detection System Using RFID

Some admitted patients wear diapers. In many hospitals across Japan, the diapers of care-receivers are changed several times a day. The care personnel can only know whether the care-receivers urinated or not by removing their clothes. Thus, in this section, a simple urination detection system using RFID [9]–[11] is presented in order to provide a comfortable healthcare environment for the patients and improve the quality of medical support.

Figure 8 shows our proposed simple system. In our proposed urination detection system, a tag is embedded into each diaper worn by a care receiver and the care-personnel brings a reader close to the tag. If the paper diaper is dry, the RFID tag embedded into it can communicate with the reader. On the contrary, if it is wet enough, the urination prevents communication from the tag. Therefore, urination is detected by whether the tag can communicate with the reader or not. This system allows the care personnel to know whether or not a patient has urinated because the urination changes the characteristics of the antenna and makes it unable to communicate to the reader. Thus, the physical and mental strain of both patients and their care personnel can be reduced.

In this section, an antenna that can match the impedance of the integrated circuit (IC) chip for RFID is designed and analyzed. The operating frequency of the antenna is 950 MHz, which is the permitted RFID in Japan.
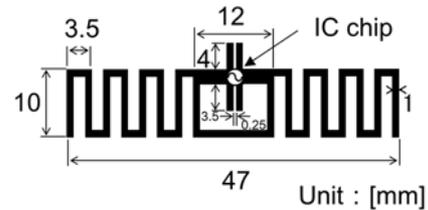
The structure of the proposed RFID antenna is shown

Fig. 9 Antenna structure.

Table 1 Electrical constants of calculation model.

	Relative permittivity	Conductivity [S/m]
Numerical human body (2/3 muscle)	36.6	0.64
Paper diaper (dry)	1.3	0.01
Paper diaper (wet)	61.4	1.54

in Fig. 9. The proposed antenna is embedded into the paper diaper. The thickness of the paper diaper is 6 mm and the depth of the antenna in the diaper is 3 mm. The RFID antenna in each paper diaper must be compact and flat. Due to the size limitation for the RFID tags, the proposed antenna has a meandering structure. For impedance matching, a loop structure is used in our antenna design [12]. Moreover, the capacitance of the antenna can be adjusted by the parallel structure near the IC chip. The impedance of the antenna matches that of the IC chip in each dry paper diaper worn on a human body.

In the calculation, the wet diaper is defined by changing the electrical properties of the diapers. The electrical properties of these models are shown in Table 1. In our research, a two-thirds muscle-equivalent phantom was used for the human model [13].

Figure 10 illustrates a fabricated phantom. This phantom can simulate urination by a tube embedded. Figure 11 shows the manufactured antenna in a paper diaper. For measurement, the urination is defined as an aqueous solution. The aqueous solution has the same electrical properties as urine. The electric properties of urination is derived from [14]. The calculated and measured reflection coefficients of the antenna are shown in Fig. 12. The results are the characteristics of the antenna embedded into a paper diaper on the phantom. The reflection coefficients are converted by the impedance of the IC chip [15]. From the results, the antenna has a good impedance matching at 950 MHz when the paper diaper is dry. On the other hand, the antenna does not resonate when the paper diaper is wet enough. Both the calculated and measured results are in good agreement. Based on those results in the wet diaper, the impedance cannot matched between the antenna and the IC chip, therefore the power is not supplied to the IC chip from the antenna.

The experiments were carried out by using a handy reader (DOTR-920J, Tohoku Systems Support Co., Ltd.). The output power of the handy reader is 250 mW. Five people each wore a diaper and lay down on a bed. Then we

Fig. 10 Phantom between abdomen and femoral.

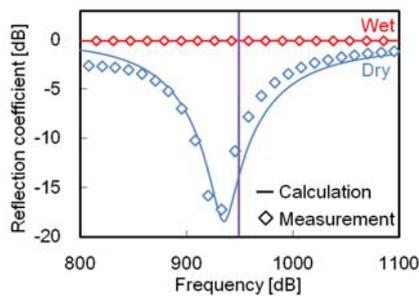
Fig. 11 Manufactured antenna on a paper diaper.

Fig. 12 Reflection coefficient of proposed tag antenna.

held a reader close to the tag and checked whether the tag could communicate with the reader or not. For the study of the wet diaper, the diaper was moistened by 120 milliliters of water solution. From the experimental verification, urination could be detected by the proposed system. In addition, the effect of comforter was very little. This system is very simple and low cost, so it is easy to implement.

3. Implantable Antennas

This section introduces three different types of implantable antennas, namely, an implantable RFID tag antenna to monitor biological information, two microwave antennas for thermal therapy (hyperthermia) as well as surgical operation, and a small antenna for a capsule endoscope.

3.1 Implantable RFID Tag Antenna

RFID systems have also been introduced for the management of medical instruments to improve the quality of medical services. In recent years, the combination of such a
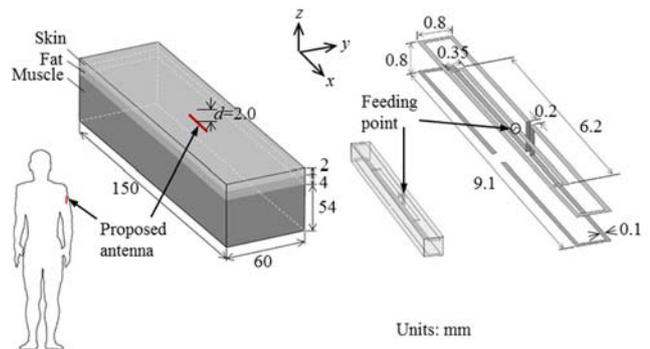

Fig. 13 Antenna geometry and three-layered phantom.

system with a biological monitoring system through permanent implantation in the human body has been suggested to reduce malpractice events and lessen patient suffering [16], [17]. The complex human body causes an extreme reduction of the antenna's performance; therefore, some of the essentials of antenna design should be completely reconsidered: (a) the physical antenna size should be miniaturized such that the antenna can be injected into the human body via a syringe in order to reduce pain during injection, and (b) the antenna should be coated with a biocompatible material to avoid direct contact with the human tissues and reduce attenuation from the human body.

This section presents an implantable RFID tag antenna design that can match the conjugate impedance of most IC chips at 2.45 GHz [18]. The proposed antenna can be injected into the human body through a biological syringe, owing to its compact size. The proposed antenna has a folded structure [19]. The performance of the proposed antenna is investigated by simulating its impedance characteristic, transmission coefficient, and received power using a finite element method. Furthermore, a three-layered phantom is introduced into the simulation and measurement as a substitute for a real human arm [20].

The geometry of the proposed antenna is shown in Fig. 13. The antenna is fabricated by bending a narrow strip of 0.1 mm into a folded structure to reduce the physical size. The total size of the proposed antenna is 9.1 mm × 0.8 mm × 0.8 mm. Moreover, the loop structure is placed near the feeding point to match the aforementioned conjugate impedance of the IC chip. Finally, the proposed antenna is 9.3 mm × 1.0 mm × 1.0 mm after coating with glass (ε_r = 5.0). We evaluated the antenna performance by a three-layered human phantom as a substitute for the human arm. The human phantom was constructed with skin (ε_r = 38.0, σ = 1.5 S/m), fat (ε_r = 5.3σ = 0.1 S/m), and muscle (ε_r = 52.7, σ = 1.7 S/m) at the desired frequency of 2.45 GHz [21] with thicknesses of 2 mm, 4 mm, and 54 mm, respectively. The size of the phantom was 150 mm × 60 mm × 60 mm. In addition, we have embedded the proposed antenna in the fat layer at a depth of 2 mm because the loss in fat is less than that in skin and muscle.

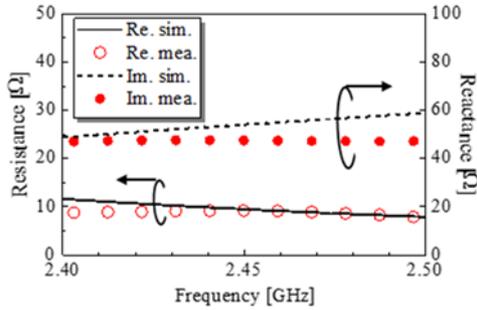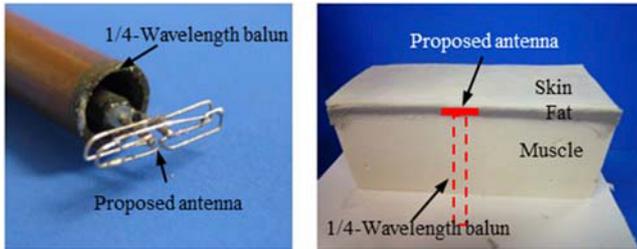In this section, we discuss the impedance character-

Fig. 14　Impedance characteristics of the proposed antenna.

(a) Fabricated antenna　　　　(b) Three-layered phantom

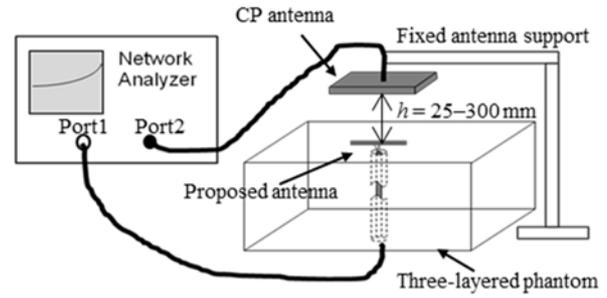**Fig. 15**　Measurement of the impedance characteristics.

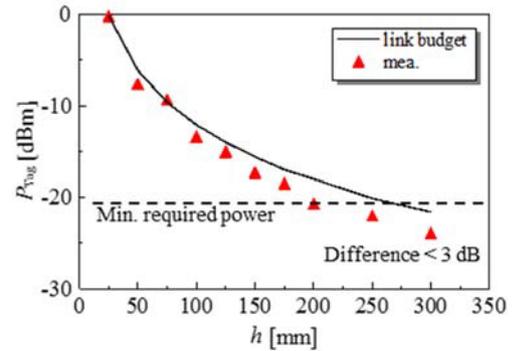**Fig. 16**　Measurement setup for the received power.

Fig. 17　Received power comparison between the link budget and the measurement result when the CP antenna is placed above the three-layered phantom at $h = 25 - 300$ mm.

istics when the dipole antenna is bent into a folded structure. The loop structure near the feeding point can apparently improve the input impedance of the proposed antenna $9.5 + j54.1 \, \Omega$, which approaches the conjugate impedance of $9.3 - j55.2 \, \Omega$. Figure 14 shows a comparison of the simulated and measured input impedances. As a result, the measured impedance of $9.1 + j47.4 \, \Omega$ shows good agreement with the simulation. Figures 15(a) and (b) show the fabricated antenna, which is connected by a one quarter-wavelength balun (with a length of 30.6 mm at 2.45 GHz) and a three-layered human phantom, respectively. In our experiment, a hole is dug into the phantom to connect the balun to the antenna and fix the antenna in the fat layer of the three-layered phantom.

Estimation of the path loss between an external reader/writer (R/W) and a tag is essential because the tag is embedded in the human body, which is a complex environment. Therefore, the transmission coefficient and received power are analyzed and discussed.

The proposed antenna is in the fat layer of the three-layered phantom, and the circular polarized (CP) antenna is set above the phantom at a specific height (h). A patch antenna with perturbation elements is used as a CP antenna [22]. The maximum CP antenna gain and bandwidth (< 3-dB axial ratio) are 2.9 dBi and 28 MHz, respectively.

In the RFID system, the link budget generally is used for estimating the amount of power that is actually received by a tag placed at a distance r from the isotropic antenna, which is denoted as the power required for R/W. A minimum RF input power of $10 \, \mu$W to $50 \, \mu$W (-20 dBm to -13 dBm) is required to power up the chip [23].

Figure 16 shows the measurement setup for the received power. Port 1 and Port 2 of the network analyzer connect to the proposed antenna and CP antenna, respectively; a fixed antenna support is used to change the height of the CP antenna. The measured gains of the proposed antenna and CP antenna are -19.3 and 2.2 dBi, respectively.

Figure 17 shows the comparison of the calculated received power by using the link budget and the measured received power when the CP antenna is located at $h = 25 - 300$ mm. The received power is obtained by using a transmission coefficient S_{21} and the input power to the CP antenna of 30 dBm (1 W). As a result, it is found that when the CP antenna is placed at $h = 25 - 195$ mm, the measured received power can satisfy the minimum required power of -20 dBm. Moreover, the measured results agree with the calculations because the difference is less than 3 dB.

3.2　Therapeutic Techniques of Microwave Energy

(a) Microwave hyperthermia

In recent years, various types of medical applications of microwave antennas have been widely investigated. Typical recent applications include medical information transmission, diagnosis, and treatment. This section introduces, microwave techniques for treatments, that employ the thermal effect of the electromagnetic wave, such as a thermal treatment of cancer called hyperthermia and surgical devices

using high power microwave energy.

There are several different treatments for cancer, including surgical operation, radiation therapy, chemotherapy, gene therapy, immunotherapy, ablation, and hyperthermia. Two or more different ways are sometimes combined for clinical use. Hyperthermia is one of the promising modalities for cancer treatment, utilizing the difference of thermal sensitivity between tumor and normal tissue and is one of the most effective medical applications of microwave techniques. In this treatment, the tumor is heated up to the therapeutic temperature between 42 and 45°C without overheating the surrounding normal tissues [24]. In addition, the effect of other cancer treatments such as radiotherapy and chemotherapy can be enhanced by using them together with hyperthermia.

There are several energy sources for heating tumors such as hot water, ultrasound, electromagnetic wave, etc. Microwave energy is one of the heating sources used for localized hyperthermia [25]. The frequency for microwave hyperthermia ranges from several hundred to several thousand MHz (i.e., up to several GHz). For hyperthermia treatments, heating devices using 430 MHz, 915 MHz, and 2.45 GHz have been commercially developed.

In addition, several different types of microwave heating schemes have been reported. Among them, interstitial microwave heating can be applied for localized tumors [26]. With this technique, an array of thin microwave antennas is inserted into the tumor and radiate microwave energy directly into the target [25], [27], permitting effective and reliable heating of the tumor.

The authors have developed coaxial-slot antennas [28], which are used for interstitial microwave heating, and have many experiences of actual clinical treatments in collaboration with medical doctors. Figure 18 shows the basic structure of a typical coaxial-slot antenna. Before a clinical treatment, many types of heating patterns around the antenna were calculated to deal with various shapes of tumors. For example, Fig. 19 shows a calculated temperature distribution around the array applicator composed of four coaxial-slot antennas under some practical assumptions, with an operating frequency of the antenna at 2.45 GHz, which is one of the industrial, scientific and medical (ISM) frequencies.

Figure 20 shows one of the photographs during the treatment taken by our developed antennas. Detailed information of the treatment is described in [29].

(b) Microwave surgical device

Generally, electrical scalpels have been used for surgical operation. Conventional electrical scalpels utilize an RF current (from several hundred kHz to several MHz) and can realize both tissue coagulation and dissection. However, these devices have some problems. First, the device requires an external electrode, which sometimes causes burn injury around it. Moreover, the RF current may go through an unexpected part of the human body and cause involuntary muscle movement. In addition, since the device generates an excessively high temperature, biological tissue is carbonized, and fog will be generated. This is one of the most serious
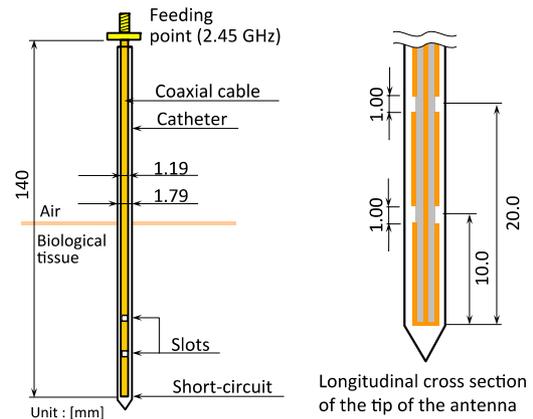

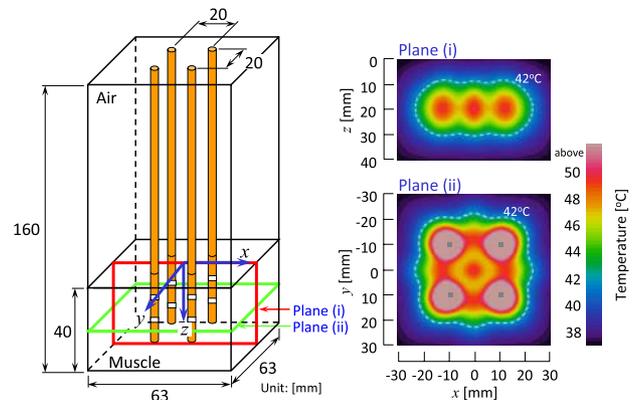**Fig. 18** Basic structure of typical coaxial-slot antenna.

Fig. 19 Calculated temperature distributions around the array applicator composed of four coaxial-slot antennas. (Total radiation power: 20 W, Blood flow rate: $8.33 \times 10 - 6\,\mathrm{m^3/kg \cdot s}$ [30], Initial temperature: 37.0°C, Heating time: 300 s.)
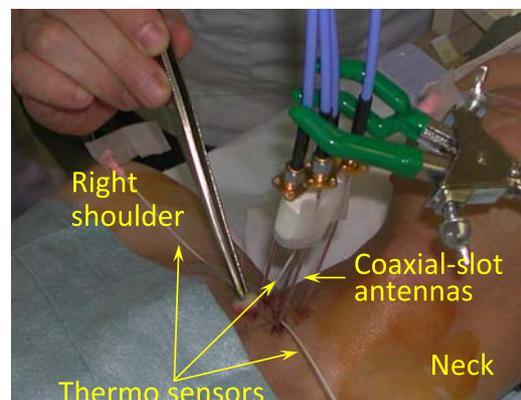

Fig. 20 Actual clinical treatment by our developed antenna.

problems, especially in laparoscopic surgery.

Massive bleeding during a surgical operation could be dangerous for a patient. Laparoscopic surgery cannot be continued under such massive bleeding, because the view of the laparoscope is reduced. Therefore, hemostasis is one of the most important treatments. The authors have been
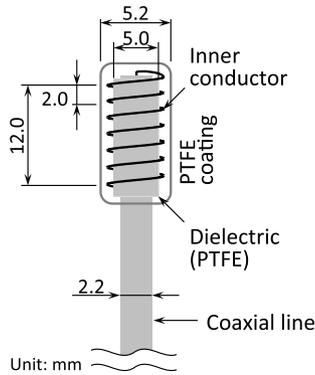
Fig. 21   Basic structure of stick-type hemostasis device.

Fig. 23   Antenna for capsular endoscope.
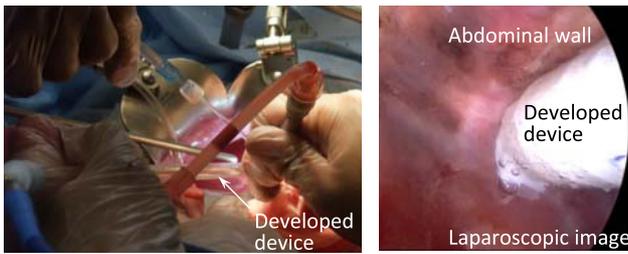

Fig. 22   Animal experiment.

studying tissue coagulation devices for hemostasis by using microwave energy.

The authors have developed several microwave surgical devices, such as forceps-type, scissor-type, knife-type and stick-type devices. A stick-type device based on helical structure for tissue coagulation and hemostasis is introduced. Figure 21 shows the basic configuration of the device tip. Whole helical part shows covered with polytetrafluoroethylene (PTFE) material for prevention of tissue adhesion. The operating frequency of the antenna is 2.45 GHz.

With the help of medical doctors, the authors have done several animal experiments using swine. The effectiveness of the device could be confirmed in the living tissue with blood flow. Figure 22 is one of the photographs taken during the animal experiment using our developed device.

3.3   Antenna for Capsular Endoscope

Wireless power transmission (WPT) has been investigated for many applications, for example, the Space Solar Power Satellite/station (SPS) plan [31] and wireless charging for electronic products. It is an attractive charging system candidate for capsular endoscopes. Capsular endoscopes are noninvasive diagnosing devices for digestive organs. They can diagnose the small intestine, which conventional endoscopes cannot reach, and are less uncomfortable to patients. However, current capsular endoscopes can take only a limited number of photographs because of their small battery capacity. The authors have been developing a capsular endoscope with a WPT system that uses microwaves for constant charging; no batteries are needed. In this capsular
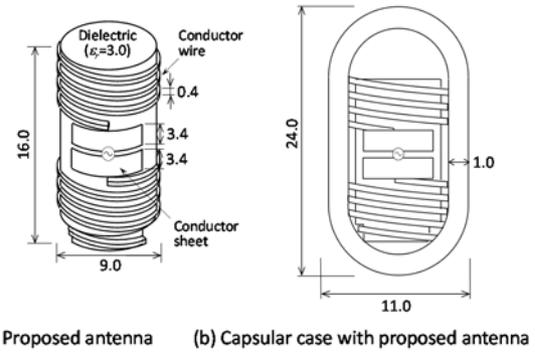
endoscope with the WPT system, because the battery can be eliminated and the WPT and RF transmission antennas can be merged, a significant space saving is possible. According to [32], 315–600 MHz band is a suitable operating frequency due to its transmission characteristics and safety for the human body. Therefore, in our study, 433.92 MHz, which is one of the ISM frequencies, is employed for the operation. Previously, a small receiving antenna in the capsular endoscope for the WPT was proposed in [33]. However, the bandwidth of the receiving antenna was not enough because of shifting of the resonance frequency. Therefore, in this study, an antenna, that can improve the bandwidth and the transmitting efficiency, is proposed.

Figure 23(a) shows the structure of the proposed receiving antenna, which is designed to coil around the dielectric case, in order to effectively receive power radiated from the transmitting antenna. Here, a helical antenna with a diameter of 9 mm and a height of 16 mm is proposed based on the size of commercially available products. In addition, the input impedance of a normal helical antenna is too low to match 50 Ω, so two conductor sheets are set near the feeding point to improve impedance matching. The width and length of the sheet are 3.4 mm and 8.6 mm, respectively. Figure 23(b) shows the proposed receiving antenna inside a capsular case. The length and diameter of the case are 24 and 11 mm, respectively.

Some results of the performance evaluations by the numerical calculations are described in [34]. In order to evaluate some performances of the antenna, a realistic abdomen phantom has been developed (Fig. 24). This phantom consists of muscle, lung, heart, liver, stomach, large intestine, and small intestine. The electrical properties of each part are listed in Table 2. Figure 25 shows a setup of experimental evaluation for antenna performances using the developed phantom. The receiving antenna shown in Fig. 23 is placed in the small intestine and a half-wavelength dipole antenna is employed as a transmitting antenna. Figure 26 shows the results of the measurement. In calculations and measurements of the transmission coefficient, two directions of transmitting dipole antenna are considered. From the results, good agreements between calculation and measurement are observed. Moreover, minimum value of the re-
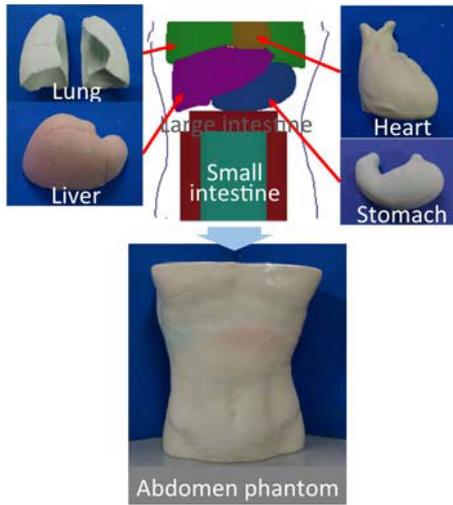
Fig. 24   Abdomen phantom.

Table 2   Electrical properties of phantom (target value).

	Relative permittivity	Conductivity [S/m]
Muscle	57.7	0.83
Lung	Same as muscle	
Heart	Same as muscle	
Liver	50.7	0.67
Stomach	67.2	1.01
Large intestine	62.0	0.87
Small intestine	65.3	1.92

Fig. 25   Experimental setup.

(a) Reflection coefficients

(b) Transmission coefficients

Fig. 26   Calculated and measured results.
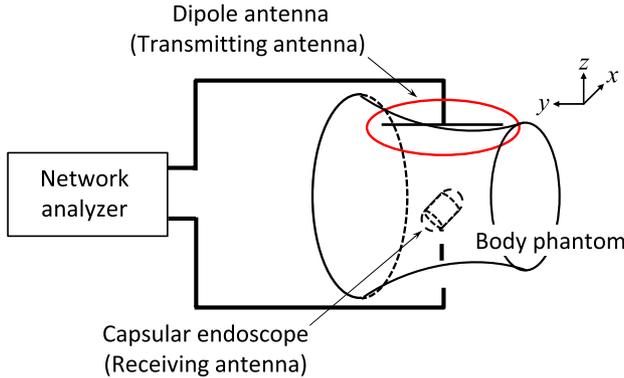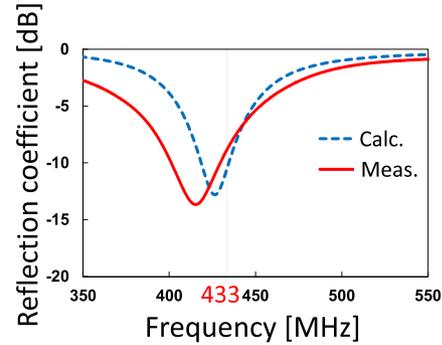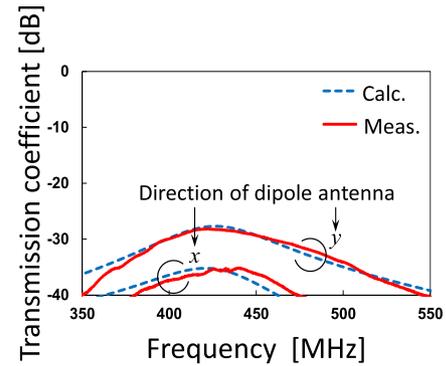
flection coefficient and maximum value of the transmission coefficient are observed around the operating frequency.

4.   Conclusion

This paper has reviewed some of the wearable antennas and implantable antennas that have been studied in our laboratory. Section 2 introduced a small wearable dual-mode antenna that can transmit various biological information with less power, and an RFID antenna that detects urination by adults. Section 3 introduced an implantable RFID tag antenna to monitor biological information, two microwave thin antennas for thermal therapy (hyperthermia) as well as surgical operation, and a small antenna for a capsule endoscope.

Different types of human-body phantoms have also been introduced for experimental evaluation of antenna performance.

The authors hope this review paper will serve as a reference for relevant research fields and will stimulate particularly younger researchers and students to study these topics further.

Acknowledgments

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