A Review of Implantable and Ingestible Antenna for Wireless Capsule Endoscopy System

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Abstract. Wireless medical devices are utilized to obtain physiological signals from the human body to an external monitoring device. The in-body antenna plays a crucial role in ensuring the transmission of physiological signals for implantable or ingestible wireless medical devices. One of the wireless medical devices that involve implantable and ingestible antennas is capsule endoscopy. The implantable one is to be implanted surgically into the human body while the ingestible one is swallowed like a multi-vitamin to perform a wide variety of diagnostic and therapeutic functions in the gastrointestinal (GI) tract. A review of both antennas and their application is presented. Besides, the design of such in-body antenna in the wireless capsule endoscopy especially in current technologies (e.g Wi-Fi, WLAN, Bluetooth, IoT) is extremely challenging and intriguing owing to it deals with the challenges related to the selection of operating frequency band, type of antenna design, and antenna miniaturization technique. Most of the antenna is facing the issue with bandwidth, transmission rate, the robustness of the communication links, size constraint, components arrangement in capsule, and others that could directly affect the patient safety and performance of capsule endoscopy in the human body. Nevertheless, the application of such implantable and ingestible antenna in wireless capsule endoscopy is incessant and rapid growth along with the evolution of technology, thus eliminating any concerns related to the aforementioned challenges and their invasive nature. In this paper, comparative reviews on the design consideration of the in-body antennas are discussed.

I. INTRODUCTION

The development of medical devices is rapidly improving along with the rise of technology. Especially those compact and systematic devices are used to detect physiological signals and(or) stimulate the nervous system in the human body (1,2). These physiological signals are acquired using appropriate transducers, then processed before being sent to a monitoring system device through communication technologies. According to a national survey of 1,000 respondents commissioned by The Society for Participatory Medicine and Healthcare technology company, Biotricity Inc, a result of 84% of adults would rely on a health and medical device to obtain their physiological parameters, such as a smartwatch that records the number of steps and heart beeps or a wearables blood pressure monitor that tracks blood pressure level (3). Nevertheless, only a few types of physiological parameters are accessible externally from the human body which becomes the limitation for these medical devices. Along with these approaches, the medical devices that are inserted directly inside the human body are bringing this application to an entirely new realm (4,5). Endoscopy is one of the common medical devices that are being inserted into the human body to obtain physiological signals which becoming increasingly popular nowadays. In the traditional medical field, a long and thin flexible tube that is wire-connected to an external monitoring device was used to insert into a patient's body through the throat or anus to observe an internal organ or tissue in detail (6). This traditional endoscopy technique is very time-consuming and it caused pain and discomfort to patients while diagnosing upper or lower gastrointestinal (GI) disorders (7), but limited by physical reasons, as leaving the remaining 20 feet of the small intestines unreachable as shown in Fig. 1.

FIGURE 1. The Traditional Upper & Lower Endoscopy Procedures Neglecting Small Intestines (8)

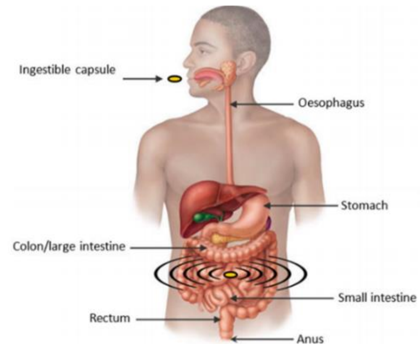


FIGURE 2. The Operation of Wireless Capsule Endoscopy (8)

In this scenario, the wireless capsule endoscopy (WCE) arose as an ideal replacement for the traditional approach and has gained favor among researchers not only it is painless, minimally invasive, and does not require anesthesia, but also by making full use of innovative technologies such as IoT, AI, and Big Data. As known nowadays, wireless systems are available to communicate with the outside world (1) without the need for wires or cables. Eventually, WCE became available in the market in 2001 and many researchers have worked to improve their diagnostic potential since then (9–14). Moreover, it allows the medical professionals to visualize the entire length of the small intestine that cannot be reached by the traditional endoscopy, not just the first one to two feet as shown in Fig. 2. A typical wireless capsule endoscopy system is built up with light-emitting diodes (LED), short focal length lens, lens holder, tiny camera, transmitter, batteries, in-body antenna, and optical dome. The in-body antenna in WCE serves as an 'Electronic eye' of the endoscopic system (15). The challenging demand for wireless capsule endoscopy systems reflects on the difficulties of designing the in-body antenna for those devices since the in-body antenna plays a key role in having an abundance of quality communication links and miniaturization of the device, compared to the other essential components. However, the research and development of in-body antennas offer significant advantages to patients, medical professionals, and the healthcare industry. Worldwide researchers are paying a lot of attention to the design of in-body antenna in the WCE. In this paper, a review of the in-body antenna used in the wireless medical device as well as in WCE is discussed in Section II. There is a variety of criteria to be selective while designing the in-body antenna, such as the frequency band of antenna, the type of antenna design and the miniaturization of antenna. Section III will address the design considerations related to the in-body antenna in WCE.

II. IN-BODY ANTENNA AND ITS APPLICATIONS

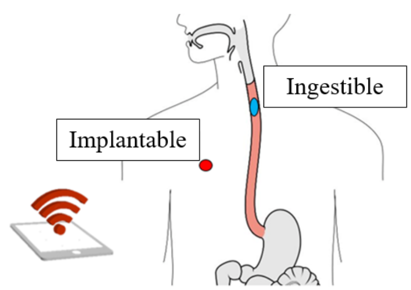
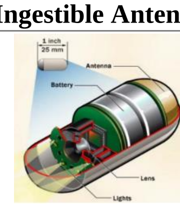


FIGURE 3. Definition of Implantable and Ingestible Antenna in Medical Devices

As shown in Fig. 3, there are two types of in-body antennas based on the way of insertion into a human body, which are implantable and ingestible. These antennas allow the medical device in the human body to transfer physiological signals, images, and real-time videos through electromagnetic waves and radio frequency (RF) to external monitoring devices (e.g. smartphones or pads). A comparison of implantable and ingestible antenna based on their example and application is summarized in Table 1. Basically, an implantable antenna is developed to be small to insert into a medical device, then surgically implanted into a patient's body. Eventually, most implantable medical devices use the implantable antenna. However, the implantation of these devices into the human body is risky as its required surgical operation. Besides, the implanted device will stay inside the human body for a long period, so the safety and sustainable features must be well designed especially the material of the enclosure. For example, the pacemaker is one of the most familiar implantable medical devices that is being miniaturized to place inside the human body to control cardiac arrhythmias (16). The modern pacemaker was improved in its physical size and can communicate with external device to transmit diagnostic information. Medtronic Micra (the world's smallest pacemaker) shown in Fig. 4 was invented to be implanted into a human's heart to perform full-body Magnetic Resonance Imaging (MRI) (17). The sensor system (18) and deep brain neurosensing system (19) was inserted into the human skull by drilling a hole. Hence, a hermetic enclosure is required to ensure the medical device to be safe under human skin. In addition, omnidirectional radiation is optional for implantable antenna as the position is predetermined. On the other hand, ingestible antenna is popular to be used in a capsule device or endoscopy as the patient would ingest a capsule device or endoscopy into the body to perform diagnostic or medical needs. For example, Given Imaging provides pill-sized disposable capsules to patients without pain or intrusive procedures that able to track and visualize the esophagus, small bowel, and colon in 2005 (20). This wireless capsule device or endoscopy is designed to look like a multi-vitamin capsule and taken through the human mouth like a pill, then travels through the GI tract and digestive system and lastly excrete through a bowel movement. Along the traveling period, the WCE is able to capture images, transmit real-time video, and detect several physiological signals. Most of the medical professional make use of WCE for diagnostic needs such as bleeding zone detection, digestive system failure detection, and digestive organ classification. For example, S. Hossain et al. (21) had invented a WCE for ulcer detection (Fig. 5) to capture images with a frame rate of 2 per second and transmit to a small portable recorder for storage via antenna. The design of this ingestible antenna is more challenging as its required continuous and robust communication with external devices in the human body. In fact, the reliable transmission of data of the in-body antenna in WCE enables the medical professional to remotely monitor the GI tract and digestive system effectively. It also required a 360° signal transfer feature as the position of the ingestible antenna is undetermined inside the GI tract. Hence, the ingestible antenna that is capable of mobility along the GI tract which can transmit images and real-time videos in a WCE could be an advantage over an implantable antenna that is unable to provide such these features as the implantable medical device was already been stationary in a particular position in the human body.

TABLE 1. Example and Reported Application of Implantable and Ingestible Antennas used in Wireless Medical Devices

	Implantable Antenna	**Ingestible Antenna**
Example of Antenna used in Wireless Medical Device	 **FIGURE 4.** Medtronic Micra Pacemaker (17)	 **FIGURE 5.** Wireless Capsule Endoscopy (21)
Application	Pacemaker (17)	Imaging of Digestive System (22,23)
	Deep Brain Neuropotential Acquisition (19,24)	Abdominal Ulcer Detection (21,25)
	Intracranial Pressure Monitoring (4,18)	Gastrointestinal Tract Monitoring (26–28)

III. DESIGN CONSIDERATION OF WIRELESS CAPSULE ENDOSCOPY ANTENNA

A. Operating Frequency Bands for Implantable and Ingestible Antenna

Relevant societies have been paying attention to the selection of operating frequency bands for wireless capsule endoscopy (WCE). The operating frequency for WCE should be chosen in accordance with the IEEE 802.15.6 standard (29), which was published by the Institute of Electrical and Electronics Engineers (IEEE) in 2012 to address short-range and wireless communications in the propinquity of or internal of the human body. According to the standard, a WCE shall allow transmission and reception in at least one of the frequency bands as listed: 402.0 MHz to 405.0 MHz, 420.0 MHz to 450.0 MHz, 863.0 MHz to 870.0 MHz, 902.0 MHz to 928.0 MHz, 950.0 MHz to 958.0 MHz, 2360.0 MHz to 2400.0 MHz, and 2400.0 MHz to 2483.5 MHz, 3494.4 MHz to 4492.8 MHz, and 6489.6 MHz to 9984.0 MHz. The frequency bands that have been employed for the implantable and ingestible antenna are summarized in Table 2. Generally, the selection of operating frequency involves a number of trade-offs. Low frequencies could allow for easy wave propagation through human tissues but limit the speed of communication, indicates the use of large antenna and components which lead to an increase in the size of the capsule while high frequency could achieve a higher data transfer rate, better image resolution, and miniaturization but could imply an attenuation. For example, Miah et al. (14) have proposed the antenna operating at 433 MHz with a large bandwidth, but the capsule size is larger than the standard one. Herewith, bandwidth is a crucial criterion for an antenna as it needs to be as wide as possible to pursue a high data transfer rate and a better image resolution.

In Table 2, the frequency bands of 420.0 MHz to 450.0 MHz, 902.0 MHz to 928.0 MHz, and 2400.0 MHz to 2483.5 MHz are commonly used in in-body antenna. The 2400.0 MHz to 2483.5 MHz band has the most potential to become a decent solution to be used for the higher technology of wireless medical devices as it offers a better, larger bandwidth (30) and being well-developed in terms of technology (i.e: Wi-Fi, WLAN, Bluetooth, IoT). Several works (31–37) had proposed 2483.5 MHz (VHF) or higher band in their designs of the antennas. The literatures had stated that the smaller size of antenna and components are available to be used in a higher operating frequency. However, the aforementioned bands are more likely to create an interference issue as most wireless systems are operating at a higher frequency band too. Interference can have negative consequences like false activation of WCE, link failure, and data corruption. Besides, the higher frequency would also affect the human body by the mean of high absorption of electromagnetic energy (38). Since 1997, the 402.0 MHz to 405.0 MHz band has been exclusively reserved for Medical Implant Communications Systems (MICS) and is governed by the European Radiocommunications Committee in Tromso, Norway. This band had become a solution to deal with the interference issue since then. However, the global license-free 402 MHz MICS band has a small bandwidth which is not suitable for WCE applications. On the other hand, the ways to mitigate the interference issue and enhancing the interference tolerance in various bands were being explored by the community follows by the advancing technology such as automatic repeat request (ARQ), forward error correction (FEC), the use of frequency agility and channelization. Similar to bandwidth, bit rate has close relationship to frequency bands. The higher the operating frequency, the higher the bit rate, which could be the reason why most researchers preferred to use a higher frequency band on the antenna for better image or real-time video transmission. According to (30), low bit rates work within a bandwidth lower than 300 kHz in the MISC band, medium bit rates work within a bandwidth between 8.5 kHz to 6.0 MHz in the WMTS band, whereas the UWB bands with bandwidth larger than 500 MHz appeared to be the selection for high bit rates.

TABLE 2. Classification of Antenna Research according to Operating Frequency Bands

Operating Frequency Bands (MHz)	Implantable	Ingestible
<400.0		(28)
402.0 to 405.0	(39), (40), (41), (42)	(43), (44)
420.0 to 450.0	(45), (46), (40)	(14), (45), (47)
863.0 to 870.0	(46), (48), (49), (40)	
902.0 to 928.0	(1), (9), (13), (49), (40), (50)	(10), (43), (51), (52)
1000.0 to 1400.0	(46)	(53)
2400.0 to 2483.5	(39), (54), (55), (56), (40), (57), (50), (42)	(11), (15), (58), (59), (60), (61), (62)
>2483.5		(31), (32), (33), (34), (35), (36), (37)

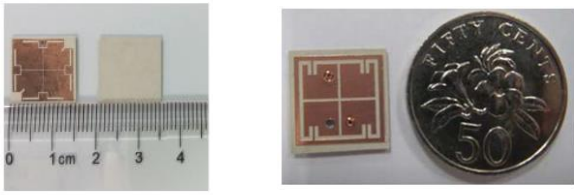
B. Type of Antenna Design in the Literature

One of the important criteria in developing such medical devices which already gaining substantial attention from the researchers is the design of a compact in-body antenna that can work in a complex lossy environment like the human body and at the same time can deal with the human safety. Several ongoing researches on the in-body antenna are proposed in (10,11,14,15,31–33,52,53,58–61) where the types of antennas that being used are dipole, monopole, helical, conformal, patch, and loop antennas which can be found in Table 3. In the event of implantable antennas, the position and orientation are predetermined, patch designs are most commonly chosen because they are highly flexible in design due to the ability to exhibit directive radiation patterns and have a lot of choices of miniaturization techniques and shapes. A circularly slotted radiating patch antenna was designed to obtain a better performance in terms of volume, gain, size, and bandwidth (55). A higher frequency was obtained as a method of microstrip feed was used on the patch antenna such as the ring-shaped microstrip antenna [8] as shown in Fig. 6 (a) and cylinder-conformal microstrip (46). In addition, L. J. Xu et al. (13), V. H. Nguyen et al.(48), R. S. Alrawashdeh et al.(40) had designed the loop antenna for implantable purposes in their biomedical application where the example is shown in Fig. 6 (b). A metamaterial is being utilized to the contribution of the design of loop antenna to improve antenna impedance matching, radiation efficiency, and gain (40).

TABLE 3. Antenna Type Reported in the Literature for Implantable and Ingestible

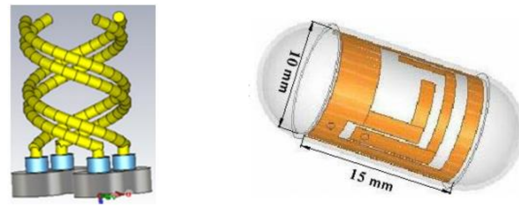
Antenna types	**Implantable**		**Ingestible**	
	Reference	Brief Description	Reference	Brief Description
Patch (Microstrip)	(1)	Scalp-shaped, microstrip feed	(58)	Monopolar wire
	(49)	Open ended slot	(32)	Small size plannar slotted
	(54)	Inset microstrip feed	(10)	Conformal
	(55)	Circular slots	(45)	Slot
	(9)	Ring-shaped microstrip	(33)	Pentagonal shaped fractal microstrip
	(45)	Low profile conformal microstrip	(31)	Compact planar slotted microstrip
	(46)	Cylinder-conformal microstrip	(35)	Compact planar slotted patch
	(57)	Circular	(36)	Microstrip U shaped patch
	(50)	Flower shaped, open ended slot	(37)	Small circular patched microstrip
Loop	(13)	-	(53)	-
	(48)	Small rectangular	(14)	Conformal
	(40)	Elliptic cylindrical		
Dipole			(11)	-
			(59)	Circular
			(60)	-
Slot			(52)	Line fed
Conformal	(41)		(51)	Differentially fed
	(42)	Differentially fed	(15)	Conformal fractal inspired
			(43)	-
			(62)	Rectangular loop, U-shaped strip, protruding L-shaped stub
			(47)	Meandered
Ring	(56)	Annular		
PIFA	(39)	Differentially fed fractal	(61)	In-Package
Helical			(44)	Normal-mode
			(34)	Quadrifilar

On the other hand, an ingestible antenna must have an omnidirectional radiation pattern and circularly polarized while traveling along the GI tract, regardless of its position and orientation. Helical antenna is a promising antenna to use for ingestible WCE because it has the structural design that can achieve a relatively high efficiency and self-resonance in a compact size, in free space (63). For example, T. Nur & F. Samad (34) had proposed a Quadrifillar helical antenna as shown in Fig. 7 (a). However, there are difficulties in modeling a miniaturized helical structures antenna in the presence of anatomical tissue models which have been reported in Koulouridis and Nikita's paper (30) and in the arrangement the helical antenna into the capsule as it is a type of embedded antenna which cannot be flattened or conformed. Furthermore, patch antenna also being a target in ingestible antenna for most researchers due to its flexibility. Recently, an ultra-wideband patch antenna using microstrip in WCE was presented due to its benefits in small, easy to manufacture, and low cost (33). Even has such good advantages, very few works have been done on designing the patch antenna or conformal antenna for the ingestible WCE, especially in the 2.4 GHz ISM band. In addition, the conformal antenna shown in Fig. 7 (b) which utilized the surface area of the capsule able to provide a larger gain and bandwidth (41) and offers better radiation performance, but the arrangement and assembly of all electronic components in the capsule must be well considered to avoid any signal or connection losses. Initially, the flat form antenna possess a directional pattern and eventually, an omnidirectional pattern can be achieved when the antenna is in the conformal form (51). Neither the cylinder radius nor the shell thickness has a major impact on the conformal antenna's properties (41). Furthermore, the loop antenna is one of the magnetic antennas which is preferred over electric antennas as it is insensitive to being close to the surrounding of human tissue. In (14,53), loop antennas were designed without a ground plane to free up space and avoid strong mirror currents. Whereas, this method reduces radiation resistance which leads to reduce in radiation efficiency. In the design of M. Suzan Miah et al. (14), the loop antenna was combined with the conformal method and additional slot in each loop arm to produce an omnidirectional radiation pattern and enhanced bandwidth. As a result, the advantages of the loop antenna have outweighed the disadvantages as this magnetic type antenna would create a less detrimental effect on the human body. Indeed, both antennas become critical to consider their sensitivity to the structure of the surrounding tissue environment (specific anatomical features) and inter-subject variability of the tissue's dielectric permittivity and conductivity since both antennas are intended to operate inside the human body with various tissues (30).



(a) (b)

FIGURE 6. Example of Implantable Antenna Design:
(a) Patch antenna (9) (b) Loop antenna (13)



(a) (b)

FIGURE 7. Example of Ingestible Antenna Design:
(a) Helical antenna (34) (b) Conformal antenna (62)

C. Miniaturization of the Antenna

The major concern of the in-body antenna is the reduction in size. It is required to design an in-body antenna to operate well in such an internal human body environment for a long period and sometimes essential, to make the antenna as small as possible. As the space of the capsule is limited, antenna miniaturization is crucial (11). The implantable device required a physical size which does not exceed 3 cm like the pacemaker while the ingestible WCE needs to be swallowed and the size of the device typically does not exceed the size of a large pill or a vitamin (approximately 11 mm x 30 mm). Therefore, the traditional half-wavelength (λ/2) or quarter-wavelength (λ/4) antennas are useless for the implantable and ingestible applications in the human body, especially at the low-frequency band. The most popular 402 MHz to 405 MHz frequency band resulting in the proper size of the antenna being electrically too small and insufficient radiation efficiency. Hence, attention is being paid to other range of frequency bands. Several structural designs with novel miniaturization techniques have been proposed to mainly focus on the furthest possible to miniaturize the implantable and ingestible antennas. The miniaturization techniques found to be used in the literature include lengthening of the current flow path excited on the radiating patch surface, patch stacking or loading technique, shorting-pin technique, high permittivity dielectric substrate, meandering technique, metamaterials, and others. A comparison of the antenna size of various in-body antennas reported in the literature for implantable and ingestible wireless capsule endoscopy with respect to the applied miniaturization techniques along with the permittivity of dielectric substrates is shown in Table 4 & Table 5, respectively.

The size of implantable antenna is ranged between 46.8 mm² and 322.5 mm² in Table 4. A rectangular open-ended slotted patch antenna (49) and circularly slotted patch antenna (55) adopt the size of 49 mm² where both antennas are using the miniaturization technique of shorting pin for better resonant frequency tuning, directivity and efficiency of the antenna. L.J. Xu et al. (13) presented a square patch loop antenna which is fabricated on the Roger 3010 substrate (relative permittivity, ε_r = 10.2) by using the loading patches and shorting pin techniques to form slow wave propagation and achieved 54.4% of miniaturization. Besides, the ring-shaped microstrip patch antenna in (9) is miniaturized by utilizing the loading stubs and meandering slots technique that can push the current to flow along the edge which extensively lengthens the effective current flow path to achieve 65% of miniaturization. In fact, the antenna designers must contend that the antenna miniaturization comes at the sacrifice of the radiation gain and safety performance. For example, the 32% and 65% miniaturization achievement has been found to directly reduces a 21% and 44% of maximum allowable input powers respectively imposed by the IEEEC95.1-1999 safety standard and 5% and 19% of maximum far-field gain values respectively when an implantable antenna was tested in a tissue-simulating cube (30). As a result, the gain and specific absorption rate (SAR) performance had degraded. The meandering technique is also being utilized on microstrip fed patch antenna (1) with a coplanar waveguide construction on a high permittivity dielectric substrate (Roger 6010). However, the coplanar waveguide structure produces a lower bandwidth compared to the coaxial line, substrate integrated waveguide, stripline, and microstrip. Furthermore, G. Samanta and D. Mitra (56) had employed a sectoral patch-based m-CRIS substrate on a 2.45 GHz implantable annular ring antenna as the reactive impedance surface metamaterial has a proper surface characterization and the ability to reduce the size of the antenna as well as to enhance the bandwidth, impedance bandwidth, radiation efficiency, and gain (64).

Most ingestible antenna in WCE have limitations in antenna size, narrow bandwidth, low radiation or coupling performance, difficulties to comply with the maximum specific absorption rate (SAR) set by certain regulators, variety of human body tissue, orientation changing along the gastrointestinal tract, and influences from other components making the ingestible antenna design for capsule devices even more difficult than other implantable antennas. In Table 5, the smallest area of 25 mm² was addressed to the monopolar wire patch antenna in (58) while the circularly polarized conformal antenna (10) owned the largest antenna area (535 mm²). Metamaterials being utilized in the monopolar wire patch antenna embedded with a Double C-shaped Resonant Structure (DCRS) which is able to produce a strong electric response over any desired frequency at the desired split with wide bandwidth due to the negative permittivity of metamaterials. Besides, there are several types of metamaterials such as left-handed media, right-handed media, right/left-handed media, and others available to be used in designing an antenna. Composite right/left-handed transmission lines (CRLH) (65), also referred to as negative refractive index, have unique nonlinear frequency-dependent sub-wavelength impedance or phase electromagnetic wave propagation. Thanks to these properties many compact and multi-band antennas have been realized (66–68), especially at low microwave frequencies, using CRLH. The approach was made to target to produce a significant bandwidth at the same time eliminate the cost of large antenna volume. Not only CRLH configuration has provided more compactness, but also it achieved better matching and lower insertion loss. However, there is no work has been done to introduce such metamaterials in the design of the implantable or ingestible antenna. Besides, the high permittivity dielectric substrate of Roger TMM13i (31) and Roger RO3010 (32) were utilized in miniaturization of UWB ingestible antenna owing to the decreases in the effective wavelength. Furthermore, the current flow path lengthening technique is employed in the design of conformal differentially fed antenna (51) with the aid of the meandering slot (loop slot and T-shaped slot) method to achieve an effective 60% miniaturization. The paper also stated that fabrication jobs and effects on other circuit components can be simplified and performance tuning can be resisted without shorting pin. In addition, fractal geometry is miniaturization technique of using self-similarity and space-filling where the example can be found in (15,33). The self-similarity properties can obtain a wideband antenna by lapping a different amount of resonant frequencies together while space-filling could directly reduce the size of the antenna by the mean of lengthening the effective current flow.

TABLE 4.
Antenna Size and Applied Miniaturization Techniques for Implantable Wireless Capsule Endoscopy Reported in the Literature

Implantable										
		Miniaturization technique								
Ref	In-body antenna type	Metamaterial-based	Meandering	Shorting pin	Loading stubs	Fractal geometry	Current flow path lengthening	High permittivity dielectric substrate	Permittivity of dielectric material	Antenna size (mm)
(49)	Patch			✓					3.14	7 × 7
(55)	Patch			✓					2.9	7 × 7
(9)	Patch		✓		✓		✓	✓	10.2	15 × 15
(54)	Patch		✓					✓	10.2	15 × 21.5
(1)	Patch		✓					✓	10.2	6 × 7.8
(50)	Patch			✓			✓		2.9	7 × 7.2
(48)	Loop + Dipole				✓				2.2	2.4 × 25.4
(13)	Loop			✓	✓			✓	10.2	13 × 13
(56)	Ring	✓						✓	10.2	78.5 mm²
(42)	Conformal							✓	10.2	13.4 × 16
(41)	Conformal		✓						2.55	15 × 15

TABLE 5.
Antenna Size and Applied Miniaturization Techniques for Ingestible Wireless Capsule Endoscopy Reported in the Literature

Ingestible										
		Miniaturization technique								
Ref	In-body antenna type	Metamaterial-based	Meandering	Shorting pin	Loading stubs	Fractal geometry	Current flow path lengthening	High permittivity dielectric substrate	Permittivity of dielectric material	Antenna size (mm)
(58)	Patch	✓							-	5 × 5
(10)	Patch		✓						3.14	53.5 ×10
(31)	Patch				✓			✓	12.85	10 × 10
(33)	Patch					✓	✓		4.3	10 × 10
(32)	Patch				✓		✓	✓	10.2	10 × 9
(36)	Patch		✓						2.33	28 × 24
(43)	Conformal		✓	✓					2.9	19 × 15
(51)	Conformal		✓				✓		3.5	34.5 × 5.8
(15)	Conformal					✓	✓		2.9	20 × 13
(59)	Dipole		✓						2.2	78.5 mm²
(53)	Loop						✓		4.3	6.5 × 6.5

IV. CONCLUSION

Significant scientific efforts have been carried out to deal with the challenges of ingestible antenna design for IoT purposes which is related to the selection of operation frequency, type of antenna design, and miniaturization technique of the antenna. Many of the research literature chosen a high band of 2400.0 MHz to 2483.5 MHz as the operation frequency as this band potentially works in the technology of Wi-Fi, WLAN, Bluetooth. Following the advancing of technologies nowadays, more complicated requirements other than bandwidth and data transmission rate for such wireless capsule endoscopy antenna need to be considered. A lot of works need to be carried out to improve and enhance the antenna, especially the miniaturization of the antenna in wireless capsule endoscopy. The combination of antenna design and additional miniaturization techniques is being used by researchers based on the requirements and creativity of researchers themselves while still maintaining the adequate performance of the antenna.

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REFERENCES

1. Kumar SA, Shanmuganantham T. Scalp-Implantable Antenna for Biomedical Applications. 2020 URSI Reg Conf Radio Sci URSI-RCRS 2020 - Proc. 2020;(June).
2. Guarin G, Hofmann M, Nehring J, Weigel R, Fischer G. Biosensors. IEEE Microw Mag. 16:71–86.
3. HITC Staff. 71% of Consumers Would Use Health Monitoring Devices If Data Was Clinically Accurate [Internet]. Healthcare IT News. 2016 [cited 2021 Apr 20]. Available from: https://hitconsultant.net/2016/02/03/31696/
4. Tena G. Too much pressure. Nat Plants. 2020;6(7):731.
5. Bell G. Body electric. Commun ACM. 1997;40(2):30–2.
6. Tim Newman. Endoscopy: Types, preparation, procedure, and risks [Internet]. Medilexicon International. 2017 [cited 2021 May 15]. Available from: https://www.medicalnewstoday.com/articles/153737#:~:text=Endoscopy is the insertion of,as the mouth or anus.
7. S. Lewis B. Small Intestinal Bleeding. Gastroenterol Clin. 2000;29(1):67–95.
8. M. Phillip M. GI Bleeding - series [Internet]. HIE Multimedia. 2021 [cited 2021 May 28]. Available from: http://slu.adam.com/content.aspx?productId=117&pid=3&gid=100162
9. Zhang K, Liu C, Liu X, Guo H, Yang X. Miniaturized Circularly Polarized Implantable Antenna for ISM-Band Biomedical Devices. Int J Antennas Propag. 2017;2017.
10. Das R, Yoo H. A wideband circularly polarized conformal endoscopic antenna system for high-speed data transfer. IEEE Trans Antennas Propag. 2017;65(6):2816–26.
11. Li Y, Guo YX, Xiao S. Orientation Insensitive Antenna with Polarization Diversity for Wireless Capsule Endoscope System. IEEE Trans Antennas Propag. 2017;65(7):3738–43.
12. Guardiola M, Djafri K, Challal M, Gonzalez Ballester MA, Fernandez-Esparrach G, Camara O, et al. Design and evaluation of an antenna applicator for a microwave colonoscopy system. IEEE Trans Antennas Propag. 2019;67(8):4968–77.
13. Xu LJ, Guo YX, Wu W. Miniaturized circularly polarized loop antenna for biomedical applications. IEEE Trans Antennas Propag. 2015;63(3):922–30.
14. Suzan Miah M, Khan AN, Icheln C, Haneda K, Takizawa KI. Antenna system design for improved wireless capsule endoscope links at 433 MHz. IEEE Trans Antennas Propag. 2019;67(4):2687–99.
15. Biswas B, Karmakar A, Chandra V. Fractal inspired miniaturized wideband ingestible antenna for wireless capsule endoscopy. AEU - Int J Electron Commun. 2020;120(June).
16. Plummer CJ, Henderson S, Gardener L, McComb JM. The use of permanent pacemakers in the detection of cardiac arrhythmias. Europace. 2001;3(3):229–32.
17. Reynolds D, Duray GZ, Omar R, Soejima K, Neuzil P, Zhang S, et al. A Leadless Intracardiac Transcatheter Pacing System. N Engl J Med. 2016;374(6):533–41.

18. Khan MWA, Member S, Björninen T, Sydänheimo L, Ukkonen L. Remotely Powered Piezoresistive Pressure Sensor : Toward Wireless Monitoring of Intracranial Pressure. 2016;26(7):549–51.
19. Lee CWL, Member S, Kiourti A, Volakis JL. Miniaturized Fully Passive Brain Implant for Wireless Neuropotential Acquisition. 2017;16:645–8.
20. Panescu D. An imaging pill for gastrointestinal endoscopy. IEEE Eng Med Biol Mag. 2005;24(4):12–4.
21. Hossain S. Easy Scheme for Ulcer Detection in Wireless Capsule Endoscopy Images. 2019;2019(Icasert):2–6.
22. Zou Y, Li L, Wang Y, Yu J, Li Y, Deng WJ. Classifying Digestive Organs in Wireless Capsule Endoscopy Images Based on Deep Convolutional Neural Network. 2015;1274–8.
23. Hajabdollahi M, Esfandiarpoor R, Najarian K, Karimi N, Samavi S, Soroushmehr SMR. Low Complexity CNN Structure for Automatic Bleeding Zone Detection in Wireless Capsule Endoscopy Imaging. 2019;7227–30.
24. Kiourti A, Lee CWL, Member S, Chae J, Member S, Volakis JL. A Wireless Fully-Passive Neural Recording Device for Unobtrusive Neuropotential Monitoring. 2016;63(1):131–7.
25. Mamun A Al. Ulcer Detection in Image Converted from Video Footage of Wireless Capsule Endoscopy. 2019;2019(Icasert):2019–22.
26. Leung BHK, Poon CCY, Member S, Zhang R, Zheng Y, Chan CKW, et al. A Therapeutic Wireless Capsule for Treatment of Gastrointestinal Haemorrhage by Balloon Tamponade Effect. 2017;64(5):1106–14.
27. Athavale ON, Paskaranandavadivel N, Angeli TR, Avci R, Cheng LK. Design of Pressure Sensor Arrays to Assess Electrode Contact Pressure During In Vivo Recordings in the Gut *. 2020;4204–7.
28. Liao CH, Cheng CT, Chen CC, Jow UM, Chen CH, Lai YL, et al. An ingestible electronics for continuous and real-time intraabdominal pressure monitoring. J Pers Med. 2021;11(1):1–10.
29. Man LAN, Committee S, Computer I. IEEE Standard for Local and metropolitan area networks - Wireless Body Area Networks. 2012.
30. Kiourti A, Psathas KA, Nikita KS. Implantable and ingestible medical devices with wireless telemetry functionalities: A review of current status and challenges. Bioelectromagnetics. 2014;35(1):1–15.
31. Islam S, Samad F. Design and analysis of a miniaturized UWB antenna for wireless capsule endoscopy. ICECE 2018 - 10th Int Conf Electr Comput Eng. 2019;369–72.
32. Arifin F, Saha PK. Design of a miniaturized UWB ingestible antenna for Wireless Capsule Endoscopy. Proc 2015 3rd Int Conf Adv Electr Eng ICAEE 2015. 2016;51–4.
33. Nizar Hammed MA, Fayadh RA, Farhan HM. UWB Pentagonal Shaped Fractal Patch Antenna for Wireless Capsule Endoscopy. IOP Conf Ser Mater Sci Eng. 2020;745(1).
34. Nur T, Samad F. Design and Simulation of a Quadrifilar Helical Antenna for Wireless Capsule Endoscopy. 2019 4th Int Conf Electr Inf Commun Technol EICT 2019. 2019;(December):20–2.
35. Arifin F, Saha PK. Bandwidth enhancement of a compact planar antenna for wireless capsule endoscopy. Proc 9th Int Conf Electr Comput Eng ICECE 2016. 2017;411–4.
36. Tajin MAS, Ahmed M, Saha PK. Performance analysis of an Ultra Wideband Antenna for Wireless Capsule Endoscopy. 1st Int Conf Med Eng Heal Informatics Technol MediTec 2016. 2017;85–8.
37. Kaffa M, Nugroho BS, Sudjai M. Design of microstrip antenna for wireless capsule endoscopy in wireless body area network. APWiMob 2017 - IEEE Asia Pacific Conf Wirel Mobile, Proc. 2018;2017-Novem:134–7.
38. Chatterjee I, Gu Y, Ghadhi OP. Quantification of electromagnetic absorption in humans from body mounted communication transceivers. IEEE Trans Veh Technol. 1985;VT-34(2):55–62.
39. Fan Y, Liu H, Liu X, Cao Y, Li Z, Tentzeris MM. Novel coated differentially fed dual-band fractal antenna for implantable medical devices. IET Microwaves, Antennas Propag. 2020;14(2):199–208.
40. Alrawashdeh RS, Huang Y, Member S, Kod M, Abu A, Sajak B. A Broadband Flexible Implantable Loop Antenna With Complementary Split Ring Resonators. 2015;14:1506–9.
41. Wang J, Leach M, Lim EG, Wang Z, Pei R, Huang Y. An Implantable and Conformal Antenna for Wireless Capsule Endoscopy. 2018;17(7):1153–7.
42. Duan Z, Guo YX, Je M, Kwong DL. Design and in vitro test of a differentially fed dual-band implantable antenna operating at MICS and ISM Bands. IEEE Trans Antennas Propag. 2014;62(5):2430–9.
43. Alamgir Y, Mabrouk I Ben, Faisal F, Zada M, Bashir Z, Akram A, et al. Compacted Conformal Implantable Antenna with Multitasking Capabilities for Ingestible Capsule Endoscope. IEEE Access. 2020;8:157617–27.
44. Baharin RHM, Uno T, Arima T, Yamada Y. Input resistance and radiation efficiency of normal-mode helical antenna inside human body. 2019 Int Symp Antennas Propagation, ISAP 2019 - Proc. 2019;2:1–3.

45. Nikolayev D, Zhadobov M, Le Coq L, Karban P, Sauleau R. Robust Ultraminiature Capsule Antenna for Ingestible and Implantable Applications. IEEE Trans Antennas Propag. 2017;65(11):6107–19.
46. Nikolayev D, Joseph W, Zhadobov M, Martens L, Sauleau R, Skrivervik AK. Application of Fundamental In-Body Radiation Limitations to Practical Design of Antennas for Implantable Bioelectronics. 2020 IEEE MTT-S Int Microw Biomed Conf IMBioC 2020. 2020;23–5.
47. Arefin MS, Redoute JM, Yuce MR. Meandered conformai antenna for ISM-band ingestible capsule communication systems. Proc Annu Int Conf IEEE Eng Med Biol Soc EMBS. 2016;2016-Octob:3031–4.
48. Nguyen VH, Diallo A, Le Thuc P, Staraj R, Lanteri S, Carle GF. A miniature implanted antenna for UHF RFID applications. Prog Electromagn Res C. 2020;99(January):221–38.
49. Yousaf M, Bashir Z, Amin Y, Akram A. A Miniaturized Wideband Implantable Antenna for Telemetry Applications. 1st Int Conf Electr Commun Comput Eng ICECCE 2019. 2019;(June 2020).
50. Faisal F, Yoo H. A miniaturized novel-shape dual-band antenna for implantable applications. IEEE Trans Antennas Propag. 2019;67(2):774–83.
51. Zhang K, Liu C, Liu X, Cao H, Zhang Y, Yang X, et al. A Conformal Differentially Fed Antenna for Ingestible Capsule System. IEEE Trans Antennas Propag. 2018;66(4):1695–703.
52. Biswas B, Karmakar A, Chandra V. Miniaturised wideband ingestible antenna for wireless capsule endoscopy. IET Microwaves, Antennas Propag. 2020;14(4):293–301.
53. Abubakar Abid. Ingestible Electronics Without Batteries: Wireless Power and Communication for Gastroresident Devices. MASSACHUSETTS Inst Technol. 2016;(2000):1–195.
54. Loktongbam P, Pal D, Koley C. Design of an implantable antenna for biotelemetry applications. Microsyst Technol. 2020;26(7):2217–26.
55. Abbas N, Manzoor B, Yousaf M, Zahid M, Bashir Z, Akram A, et al. A compact wide band implantable antenna for biotelemetry. 2019 2nd Int Conf Latest Trends Electr Eng Comput Technol INTELLECT 2019. 2019;(November).
56. Samanta G, Mitra D. Miniaturised and radiation efficient implantable antenna using reactive impedance surface for biotelemetry. IET Microwaves, Antennas Propag. 2020;14(2):177–84.
57. Bhattacharjee S, Maity S, Chaudhuri SRB, Mitra M. Metamaterial-inspired wideband biocompatible antenna for implantable applications. IET Microwaves, Antennas Propag. 2018;12(11):1799–805.
58. Mary Neebha T, Nesasudha M. Analysis of an ultra miniature capsule antenna for gastrointestinal endoscopy. Eng Sci Technol an Int J [Internet]. 2018;21(5):938–44. Available from: https://doi.org/10.1016/j.jestch.2018.06.017
59. Bao Z, Guo YX. Novel Miniaturized Antenna With a Highly-Tunable Complex Input Impedance for Capsules. IEEE Trans Antennas Propag. 2020;(November).
60. Preethiba S, Brindha S. Design of conformal antenna for wireless capsule. Proc 2018 Int Conf Commun Comput Internet Things, IC3IoT 2018. 2019;(March):77–80.
61. Guo Y, Chu H. Capsule. 2017;56–7.
62. Li R, Guo Y, Du G. Communication A Conformal Circularly Polarized Antenna for Wireless. 2018;66(4):2119–24.
63. Dung DT, Nguyen QD, Trinh DQ, Yamada Y. Investigating equations used to design a very small normal-mode helical antenna in free space. Int J Antennas Propag. 2018;2018.
64. Mosallaei H, Sarabandi K. Antenna Miniaturization and Bandwidth Enhancement Using a Reactive. 2004;52(9):2403–14.
65. Caloz C, Itoh T. Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications. New Jersey: John Wiley & Sons; 2006.
66. Lee CJ, Huang W, Gummalla A, Achour M. Small antennas based on CRLH structures: Concept, design, and applications. IEEE Antennas Propag Mag. 2011;53(2):10–25.
67. Abdalla MA, Ibrahim AA, El-Azeem MHA. Phase enhancement for multi-resonance compact metamaterial antennas. Prog Electromagn Res C. 2015;60(November):83–93.
68. Abdalla MA, Fouad MA. CPW dual-band antenna based on asymmetric generalized metamaterial π NRI transmission line for ultra compact applications. Prog Electromagn Res C. 2016;62(February):99–107.