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Exploring the Challenges of Implantable Antennas in Capsule Endoscopy Applications: An Overview

Faishal Adilah Suryanata[1,2], Raimi Dewan[1,2,3,4*], DiviyaDevi Paramasivam[1,2], Man Seng Sim[2], Tan Tian Swee[2,4], Mohamad Rijal bin Hamid[1,2]

[1]Advanced Radio Frequency & Microwave Research Group, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.
[2]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
[3]IJN-UTM Cardiovascular Engineering Centre, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.
[4]Department of Biomedical Engineering and Health Sciences, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.

[*]Corresponding author: raimi.dar@utm.my

Abstract: Antennas play a crucial role in implantable medical devices (IMDs), particularly in applications such as gastric endoscopy. Therefore, this paper reviews recent advancements in antenna design for IMDs, focusing on the benefits and challenges. The findings from recent research will serve as a reference for future studies, emphasizing the need to address existing challenges. Specifically, this paper investigates the miniaturization and signal performance of the antenna when simulated inside the human body and explores the potential solutions for the challenges. Additionally, this paper discusses various gastric diseases, the development of gastric body phantoms, and relevant studies from reputable journals. Finally, the future directions for further improvement of the research are being discussed.

Keywords: antenna, endoscopy, gastric, implantable, miniaturization

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1. INTRODUCTION

Implantable Medical Devices (IMDs) are specialized medical instruments designed for insertion into the human body, either for long-term use or for short-term use like for a duration of 30 days [1]. Wireless implantable medical devices (WIMD) have gained significant attention due to the suitability for home monitoring and diagnostic of various devices, including pacemakers, cardiac defibrillators, insulin pumps, and neurostimulators. WIMD have enabled remote patient monitoring and the delivery of personalized care [2]. Several frequency bands have been authorized for implantable applications, including the Wireless Medical Telemetry System (WMTS) (608 MHz–614 MHz and 1395 MHz–1400 MHz), the Industrial, Scientific, and Medical (ISM) bands (433 MHz–438 MHz, 896 MHz–906 MHz, and 2.4 GHz–2.48 GHz), and the Medical Device Radiocommunication Service (MedRadio) (401 MHz–406 MHz) [3]. A crucial element in WIMD is the implantable antenna, which ensures reliable communication with external devices. Various studies in the literature highlight wideband antenna designs with different technologies, including a wideband folded dipole antenna operating within 700–2194 MHz [4], a circularly polarized patch antenna functioning at 2.45 GHz [4], a dual-band patch antenna covering 400 MHz and 2.45 GHz [4], and a dual-band planar inverted-F antenna (PIFA) designed for MedRadio band operation at 400 MHz and the ISM band at 915 MHz [4].

Wireless biomedical telemetry systems are capable of early disease detection, and diagnosis precise, real-time monitoring and targeted therapeutic interventions. Wireless biomedical telemetry facilitate accurate measurement of physiological signals in ambulatory patients, enabling continuous monitoring and data acquisition while preserving the mobility [5]. Biotelemetry enables the transfer of diagnostic information to the external monitoring systems, supporting well-informed clinical decision-making [6]. For instance, wireless endoscopic systems offer enhanced visualization of the intestinal tract compared to traditional endoscopic methods. As a specialized wireless medical device designed for diagnosing gastrointestinal disorders, a wireless capsule endoscope typically comprises multiple components, including an implantable antenna, a battery unit, a transceiver, an LED illumination system, and a miniature camera [7]. Among the components, the antenna holds a pivotal role in enabling wireless communication, serving as the communication bridge between the capsule and the external receivers [8].

With the continuous development of portable wireless communication devices such as laptops, tablets, and smartphones, implantable medical devices to be miniaturized and capable of operating in multiple bands.

The rapid advancement of modern communication systems necessitates new design criteria for antenna and other microwave devices. Key requirements include miniaturization, bandwidth enhancement, cost efficiency, and multiband functionality, all of which are crucial for optimizing system performance [9]. Additionally, lightweight and cost-efficient design can significantly contribute to minimizing production fabrication while improving patient comfort [10]. The geometry of the antenna plays a crucial role not only in achieving miniaturization but also in optimizing radiation efficiency, polarization characteristics, and performance within biological tissue [11]. Nevertheless, the design must also account for complex radio propagation challenges, including fluctuations in the dielectric properties of biological tissues and external attenuation resulting from human body movement, both of which can substantially degrade the performance of the implantable antenna. Simultaneously, the antenna dimensions must be minimized to ensure compliance with safety requirements and enhance patient comfort [11]. The most common techniques for miniaturizing antennas, to the required specification include, the addition of shorting pins, or the use of high permittivity substrates or the inclusion of meandered lines, the inclusion of open-end slots in ground plane [4].

Multiband antennas are of particular interest, given the ability to operate on two distinct frequency bands. The feature is important for implantable applications, including capsule endoscopy, as it allows simultaneous transmission of data and reception on separate frequency bands. In wireless capsule endoscopy, a dual-band antenna is crucial to enable simultaneous data transmission and wireless power transmission. Designing such an antenna ensures efficient communication and sustained power supply, optimizing the functionality and extended operational lifespan of the capsule within the body [8].

In recent study, microstrip line technology has been documented to exhibit substantial losses at millimetre-wave frequencies, primarily due to significant radiation losses. This phenomenon is a key factor contributing to the degradation of antenna system efficiency [12]. In addition, substrate-integrated waveguide (SIW) technology improves isolation; however, the dielectric losses is critical in mm-wave, exposing the system to significant performance degradation., which incurs additional costs and complexity [13]. In wearable device applications, the existence of the human anatomical structure significantly degrades antenna performance, it will decrease the efficiency and the reading range, detuning the antenna resonant frequency, and deteriorating the radiated electromagnetic far-field. Moreover, the geometrical and electromagnetic parameters of the human body, on which the antenna is attached, may also differ based on the antenna location even on the same person [14].

Wearable antennas are required to maintain consistent performance despite being subjected to continuous flexing and stretching due to body movements. Physical activities such as bending, twisting, and elongation can induce impedance mismatches, leading to efficiency degradation. Moreover, the antennas experience repeated mechanical stress, which may result in material fatigue and reduced long-term durability [15]. The antenna serves as the critical communication link between the external base station and the capsule, enabling wireless data transmission throughout the examination process due to the environment surrounding the human body is so dynamic and complicated [5]. A study also emphasizes that in superficial tissues, the use of an appropriate tissue model is crucial as it directly impacts the reliability of antenna performance [16].

The paper aims to unravel the above-mentioned strategies to study the state-of-the-art implantable antennas specifically for capsule endoscopy applications. This section reviews prior research on compact implantable antennas, focusing on critical factors influencing the performance, including spatial constraints, functional stability, and their interaction with surrounding biological tissues. Finally, the future directions for further improvement of these strategies are discussed.

2. CHALLENGES ASSOCIATED WITH CAPSULE ENDOSCOPY

The design of capsule antennas for wireless capsule endoscopy (WCE) presents unique challenges due to the stringent spatial constraints and complex anatomical environments within the human body. Given the limited internal volume of the capsule, the antenna must be compact enough to integrate seamlessly alongside critical components such as the camera, battery, and transmitter. In addition to miniaturization, the antenna must fulfil essential performance criteria, including wide impedance bandwidth, omnidirectional radiation pattern, and high radiation efficiency to ensure reliable data transmission through the gastrointestinal (GI) [17]. As the demand for increasingly miniaturized biomedical devices grows, the development of efficient implantable antennas becomes more challenging. These antennas must operate effectively within the highly inhomogeneous and lossy biological tissues, where electromagnetic wave propagation is significantly affected by frequency-dependent and dispersive dielectric properties [18].

Such environments often result in signal attenuation, reflection, and detuning effects, which must be carefully addressed to maintain consistent performance. Compared to fixed-location implantable antennas, antennas used in endoscopic systems face additional complexity due to their dynamic position within the body. Capsule antennas must maintain stable radiation and impedance characteristics throughout their journey in the GI tract to prevent bandwidth shifting and to ensure accurate diagnostic imaging and continuous data transmission [7].

To mitigate detuning effects caused by varying tissue permittivity and proximity, wideband antenna designs are often employed. These designs not only support high-resolution imaging but also enhance system robustness against the variability of biological environments [19]. Therefore, the design of capsule endoscopy antennas necessitates a delicate balance between compactness, bandwidth, radiation stability, and resilience to bio-environmental variability, all of which are critical for ensuring the diagnostic effectiveness and reliability of the

WCE system. A comprehensive understanding of the gastrointestinal (GI) tract physiological architecture and functional behaviour discussed in the next section which is critical for enhancing antenna design in wireless capsule endoscopy system.

3. GASTROINTESTINAL TRACT

Although the gastrointestinal (GI) tract functions as a continuous tube, the individual segments are regulated by distinct hierarchical control systems. The peristaltic movement of the exophages is predominantly influenced by vagal regulation, whereas the motor activity of the small and large intestines is primarily controlled by the enteric and autonomic nervous systems. In contrast, gastric peristalsis is largely governed by myogenic mechanisms [20]. The primary mechanism driving gastric peristalsis is the slow wave, a rhythmic oscillation in electrical activity that originates and propagates through specialized cellular networks known as Interstitial Cells of Cajal (ICC). These non-neuronal, non-smooth muscle mesenchymal cells function as intrinsic pacemakers, generating electrical currents while integrating and responding to neuronal, humoral, and mechanical stimuli [21].

Gastric slow waves originate in the corpus, specifically along a region of the greater curvature, and rapidly develop into a band that encircles the stomach circumference [22]. The stomach functions as a natural electrical pacemaker, generating the rhythmic activity at an approximate frequency of 0.05 Hz[23]. While electrical slow waves are continuously present, gastric peristalsis does not consistently occur when the stomach is empty. However, upon food intake, peristaltic waves become prominent and persist at a constant frequency until gastric emptying is complete [22].

Gastrointestinal surgical procedures are widely conducted across the globe, often resulting in notable alterations to both the anatomical structure and physiological conditions of the gastrointestinal tract [24]. Gastric surgery typically leads to significant modifications in the anatomy of the foregut and is linked to various acute and chronic symptoms. While certain postoperative symptoms subside within a few months due to physiological adaptation, some patients experience prolonged symptoms such as nausea, vomiting, abdominal discomfort, early satiety, excessive fullness, reflux, and diarrhoea, indicating an inability to fully adapt [21]. Gastric cancer (GC) continues to be a major global health concern, ranking fifth in incidence and fourth in cancer-related mortality. Although both incidence and mortality rates have declined in recent decades, GC still accounted for over 1 million new cases in 2020, with projections estimating an increase to 1.8 million cases worldwide by 2040 [25].

In-body bioelectronic devices necessitate the integration of multiple components within a confined space to function efficiently. Among these components, the implantable or ingestible antenna plays a vital role, not only in enabling communication but also in enhancing the sensing capabilities of the overall system. A carefully designed antenna sensor capable of multiplexing can substantially optimize both sensing and radiation performance, thereby improving the device's overall functionality [26]. Implantable medical devices are particularly significant for the continuous monitoring and collection of physiological data within the human body. These devices transmit essential health information to external receivers, facilitating improved diagnostic accuracy for healthcare providers. For instance, Wireless Capsule Endoscopy (WCE) was developed to overcome the challenges of conventional wired endoscopes, such as blind spots within the Gastrointestinal (GI) tract, by allowing a thorough examination of the entire GI system [27]. The structural composition of the stomach is examined in the subsequent section.

4. STOMACH ANATOMY

The stomach plays a crucial role as a primary organ within the digestive system and represents its most expanded section. Its lower segment exhibits rhythmic contractions, contributing to mechanical digestion by fragmenting food and blending it with gastric secretions, thereby enabling chemical digestion [28]. This process ensures the progressive breakdown of ingested material, facilitating its subsequent absorption [28]. Structurally, the stomach is a hollow, J-shaped organ situated in the abdominal cavity and constitutes an integral part of the gastrointestinal tract, as illustrated in Figure 1 [29].

Anatomically, the stomach is subdivided into three distinct regions: the fundus (superior section), the corpus (central portion), and the antrum (inferior part) [29]. The autonomic nervous system governs the functional regions of the stomach, regulating essential processes such as food storage, digestion, and propulsion [30]. In terms of dimensions, the human stomach typically measures approximately 211 ± 14 mm in length and 133 ± 11 mm in width, as reported in reference [30]. As shown in Figure 2 both longitudinal and circumferential sections of the stomach wall were excised along the greater curvature, aligning either parallel or perpendicular to the gastric axis [30]. To analyse the mechanical properties of different layers, the gastric wall was divided into left and right sections. In contrast to the right section, where no further separation occurred, the left section underwent a dissection process that isolated the mucosal and muscular layers [30].

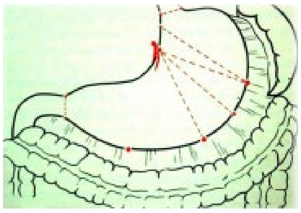


Figure 1. Gastric Anatomy [29]

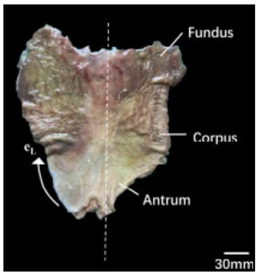


Figure 2. Segments of the gastric wall [30]

Endocrine cells located within the mucosal lining of both the stomach and small intestine play a critical role in digestion by secreting hormones in response to food intake [31]. Gastrin, a peptide hormone produced by gastric cells in reaction to stomach distension, serves to stimulate the secretion of hydrochloric acid. Additionally, secretin, another peptide hormone synthesized by the small intestine upon exposure to acidic chyme from the stomach, triggers the pancreas to release bicarbonate [31]. The mucosa, which constitutes the innermost layer of the gastrointestinal tract, comprises the lamina propria, muscularis mucosae, and gastric glands. Furthermore, it features specialized folds known as rugae, which undergo flattening as digestion progresses and food is ingested [32].

The mucosa maintains independent movement from the underlying muscular layer due to the presence of the submucosa, a dense yet flexible collagenous network that provides structural support. This layer also contains an intricate system of blood and lymphatic vessels. The muscular layer itself consists of at least two interconnected muscle layers and is encased within an extracellular matrix predominantly composed of collagen [32]. Gastric juice, secreted by specialized glandular cells within the gastric mucosa, is a complex mixture containing hydrochloric acid, enzymes, and mineral salts. It is enveloped in a protective mucus layer that counteracts acidity, thereby safeguarding the mucosal lining from potential damage and assisting in food absorption [33].

In addition to its enzymatic components, mucus, hydrochloric acid, and various organic and inorganic substances, gastric juice also contains an essential biochemical known as the Castle factor. This factor is crucial for vitamin B12 absorption within the small intestine, a process integral to the production of red blood cells in the bone marrow [33]. A gastric anatomical body phantom is frequently employed to analyse the interaction between the stomach and the performance of an antenna. A comprehensive analysis of the gastric body phantom is presented in the subsequent section.

5. GASTRIC BODY PHANTOM

Gastric emptying analysis was conducted using two-dimensional (2D) planar imaging, where regions of interest were outlined around the entire stomach. Adjustments were applied to account for tissue attenuation and isotope decay. The assessment of the proximal stomach was performed by determining the proportion of radioactive counts within this region, which was defined as the upper 50% of the stomach longitudinal axis [34]. In a recent study, the gastric body phantom includes patient-specific morphology which is important for assessing the effectiveness of the Intragastric Balloon (IGB) when placed in the patient's gastrointestinal tract. The gastrointestinal phantom employed to evaluate IGB performance must be crafted from durable and flexible materials to enable the simulation of gastric motility. Figure 3 shows the design of the gastric body phantom. It is made entirely of rubber-like material and coated with silicone to increase its strength and flexibility [35].

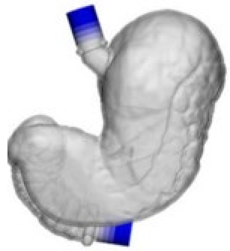


Figure 3. Gastric body phantom design [35]

To conduct the study, standard materials are required, which serve as the primary components for constructing a body phantom [36]. A variety of phantom materials are available in the university laboratory, including agar, distilled water, gelatine, Triton X-100, and Polyvinyl Alcohol (PVA) (lab grade polyvinyl alcohol) and sodium chloride. In the recent study, typical materials employed for constructing the body phantom include oils and fats, 3D-printed resins or plastics, silicone, PVA, Polyvinyl Chloride (PVC), along with additional components such as acetone, sodium chloride, gypsum plaster, and carbomer 980 [36], [37]. Each material needs to follow the specific quantity and processes during the preparation of body phantoms such as Table 1. The following section provides an analysis of gastric endoscopy, a technique used for monitoring gastrointestinal activity.

Table 1. Components of gastric body phantom formula [37]

No.	Material	Quality		
		Skin	Fat	Muscle
1.	Gelatine	3.01 g	2 g	6.02 g
2.	Distilled water	10 mL	3 g	20 mL
3.	Sunflower oil	1.68 mL	-	3.36 mL
No.	Material	Quality		
		Skin	Fat	Muscle
4.	Dish-washing liquid	0.83 mL	0.5 mL	1.67 mL

6. WIRELESS CAPSULE ENDOSCOPY

Capsule endoscopy represents a widely utilized clinical technique that facilitates a detailed visual examination of the upper gastrointestinal tract using a flexible endoscope

[38]. Wireless endoscopic systems enable the transmission of diagnostic data from patients to medical facilities, which can then make informed treatment decisions. Wireless endoscopic systems provide superior visualization of the intestinal tract compared to conventional endoscopic methods [7]. Traditional endoscopy involves inserting a lengthy cable into the patient body cavity to capture images of critical areas, enabling diagnostic and therapeutic interventions. However, this approach often causes discomfort and pain due to the extensive contact area of the wired endoscope. Wireless Capsule Endoscopy (WCE) has emerged as a globally acknowledged, patient-centred, and minimally invasive alternative, effectively addressing the challenges posed by traditional methods [39].

Wireless Capsule Endoscopy systems comprise various components, including imaging and sensor devices, engineered to interact with luminal environment and record physiological parameters. Measurement devices may include optical (camera), thermal, pH, and pressure sensors [40]. The device necessitates a battery-powered energy source with sufficient capacity to support the microelectronic circuits and specialized detection components, ensuring an adequate operational lifespan to complete the diagnostic process [40]. Microcontrollers are integral to the device, managing all operational aspects by processing sensor signals. Finally, the capsule's housing serves as an enclosure for its components, protecting and ensuring functionality [40].

One of the critical design factors for achieving reliable wireless communication involves ensuring proper impedance matching between the antenna and associated electronic circuits. Changes in the dielectric properties of biological tissues across different frequencies can cause shifts in the antenna's resonant frequency. For mitigating this effect, an adaptive broadband impedance matching network is employed, which helps to counteract detuning caused by the absorptive characteristics of body tissues [21]. The pacing electrodes are strategically positioned to align with the longitudinal and circumferential muscle fibres of the stomach [41]. Four surface-contact pacing electrodes are arranged in a 2 x 2 grid at the centre of the electrode array and can enables the selection of two leads for bipolar pacing along either the longitudinal or circumferential axis without necessitating repositioning of the electrode array. The pacing leads are specifically positioned in the corpus region of the stomach [41]. PillCam SB 3 is an example of recent gastric endoscopy,

The PillCam SB 3 capsule enables direct visualization of the small intestine, enhancing diagnostic reliability in lesion monitoring. Equipped with advanced optical and imaging technology, the system provides high-quality mucosal images and adjusts the capture rate between two and six frames per second (fps) depending on the capsule's transit speed through the small bowel. The PillCam SB 3 specifications include an antenna dimension corresponding to a capsule diameter of 11.4 mm and a total device weight of 3.0 g. The device has an operational duration of up to 8 hours and exhibits resistance to dissolution within a pH range of 2 to 8. The device can operate in 13.6 mHz operating frequency [42]. The following section presents a discussion on the circularly polarized antenna, which can be employed as the antenna for gastric endoscopy.

7. CIRCULAR POLARIZED ANTENNA

Circularly polarized (CP) antennas are a reliable choice for stable communication, as they effectively resist multipath interference and reduce polarization mismatch between the transmitting and receiving antennas [43]. The circular polarized antenna also can prevent the polarization mismatch regardless of the device's positioning [44]. Due to their applicability, CP antennas are widely utilized in satellite communications, radio-frequency identification (RFID) systems, and next-generation 5G base stations and mobile communication technologies [43]. A straightforward approach to achieving circular polarization is by utilizing a single feed microstrip antenna. Another commonly employed technique in microstrip antennas is coplanar waveguide feeding, which offers a simple and effective method for signal transmission [45]. Circularly polarized antennas offer several significant advantages over linearly polarized counterparts, including enhanced resistance to multipath interference and signal fading, minimized Faraday rotation effects, and the ability to operate effectively without requiring precise alignment between the transmitting and receiving antennas [46].

Implantable and ingestible antennas operate within the human body, where strong electromagnetic coupling between the antenna and biological tissues significantly influences the antenna performance. Linearly polarized antennas exhibit limited resistance to interference in the human body, whereas circularly polarized antennas effectively mitigate multipath interference, enable transmission and reception independent of orientation, enhance information transmission efficiency, and compensate for the adaptability challenges of linearly polarized antennas in biological environments [47].

For applications within the human body, the antenna must be designed to be flexible and biocompatible with human tissue to prevent potential damage. Additionally, it should possess a wide bandwidth to ensure coverage of the required frequency spectrum when tested in biological environments. The radiation characteristics of a CP antenna often vary due to the multilayered composition of the human body, which consists of skin, fat, bone, muscle, and blood. Designing a biocompatible CP antenna for use in the human body presents challenges due to the differing dielectric properties of these tissues. Many in-body CP antennas are developed to support wireless communication within the frequency ranges of 402–405 MHz and 2.4–2.48 GHz [48].

A study conducted by Arslan [48], The measured gain of the antenna was recorded at -15.8 dB, while its bandwidth within skin tissue was reported to be 47.7%. Additionally, the 3 dB axial ratio (AR) bandwidth was experimentally determined to be 53.8% when tested in a skin-mimicking gel. The advancement of medical applications is closely associated with concerns regarding biocompatibility and safety. Due to its compact size, this antenna is well-suited for in-body biomedical applications, making it a promising candidate for such uses [48]. In another study by Rania [49], the simulated performance of the antenna was assessed using a three-layer numerical human body model with an implantation depth of 15 mm. Despite the small size, the antenna demonstrated effective performance, achieving a wide axial ratio (AR) of 23%, a beamwidth of 37.56°, an -10 dB impedance bandwidth of 5.66%, and a satisfactory gain of -26.25 dB [49]. Furthermore, the maximum Specific Absorption Rate (SAR) value, with a peak power of 3 mW, complies with IEEE regulations, ensuring patient safety. According to the latest study, achieving both axial ratio and impedance bandwidths that are closely matched requires further investigation into improving impedance bandwidth in the future [49]. The design simulation is evident in reported studies that have analysed the compact implantable antenna for gastric pacemakers, as detailed in the following subsection.

8. STATE OF THE ART OF COMPACT IMPLANTABLE ANTENNA FOR GASTRIC ENDOSCOPY

In the research conducted by Song (2024), a miniaturized circularly polarized implantable antenna was designed for integration into capsule endoscopy systems. The antenna structure consists of a radiating patch, a ground plane, a circular dielectric substrate, and a superstrate, both fabricated using Rogers RO 6010 material [7]. The configuration of the proposed antenna is illustrated in Figure 4. The radiating patch has a circular shape with a 4 mm radius and includes a square cutout. Additionally, triangular sections are removed from the upper left and lower right corners, positioned at the centre of the circular patch [7]. The overall antenna dimensions are 44.7 mm³ [7]. To activate the antenna and enhance its impedance properties, feedlines with a 0.3 mm radius are placed on the left side of the ground plane. The circular configuration of the radiation patch fulfils multiple roles, including elongating the effective current path, minimizing the antenna's overall dimensions, and producing a 90-degree phase shift between the two orthogonal radiation components, thereby achieving circular polarization [7]. The antenna system is embedded within a multi-layer human tissue model for simulation and analytical evaluation.

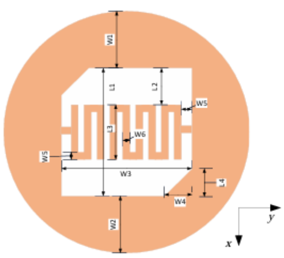
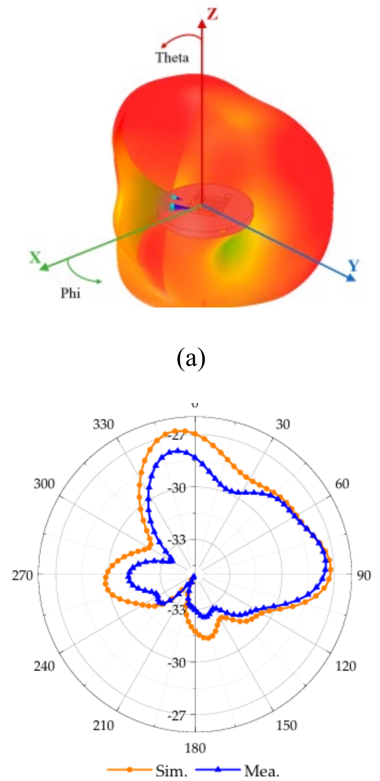


Figure 4. Circular patch antenna design [7]

The incorporation of slotting and a shorting post in the circular radiation patch enhances the effective current path, thereby reducing the antenna's overall dimensions and generating a 90-degree phase shift between its two orthogonal radiation components. The three-dimensional radiation pattern of the antenna is simulated within a multilayer human body model, as illustrated in Figure 5 [7]. The far-field gain pattern at 2.45 GHz is measured at -26.7 dBi and -27.8 dBi as shown in Figure 5(b) where the peak gains were observed at , ensuring consistent performance within the test environment and fulfilling the operational requirements for implantable medical monitoring devices [7].



(a)

(b)

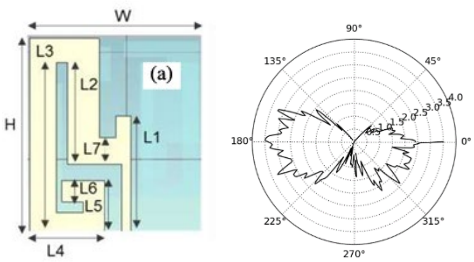
Figure 5. (a) 3D radiation antenna distribution and (b) the radiation pattern results [7]

Figure 6(a) illustrates the antenna was embedded at a depth of 3 cm, aligning with the simulation configuration that employed a container with a diameter of 30 cm and a height of 15 cm [7]. In general, errors are inevitable and potentially arising due to discrepancies between the enclosed measurement environment and the simulated conditions, particularly the absence of the outer tissue layer. Additionally, inaccuracies may be introduced during the fabrication process, including variations in implantation depth, the presence of air gaps, and the detachment of the antenna from the protective layer. The size of antenna. Nonetheless, improvements in the antenna design are recommended, particularly in implementing techniques for miniaturization are employed to enhance bandwidth while further decreasing the overall dimensions of the antenna [7]. Table 2 presents a comprehensive overview of the design parameters associated with the circular patch antenna.

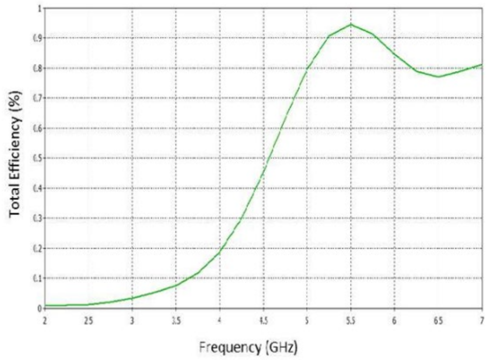
Figure 6. Experimental implanted antenna using bowl [7]

Mimouni (2024) proposed a gastric endoscopy antenna, as illustrated in Figure 7 (a) that features a height of 25 mm, a 5.5 mm curvature radius, and a 2 mm conductive line width. To achieve the compatibility with the standard dimensions of a gastric endoscopy device (26 × 11 mm²), further miniaturization of the antenna is necessary [50]. Figure 7 (b) presents the two-dimensional gain radiation patterns of the antenna across different frequencies, specifically illustrating the azimuthal perspectives at Phi = 0 and Phi = 90. At 5800 MHz, the antenna achieved its maximum gain of 3.6 dBi, demonstrating its ability to enhance power distribution in a specific direction. The results demonstrate that the antenna achieves an approximately omnidirectional radiation pattern, indicating uniform signal radiation and reception strength in various directions around the axis [50, 51].

Figure 7 (c) demonstrates the overall efficiency of the antenna design, corresponding to a frequency of 5800 MHz within the intended operational band of 5750–5850 MHz and the antenna exhibits an overall efficiency within the range of 85% to 90%. The results highlight that optimal performance is attained within the designated frequency band, with the antenna achieving a remarkable total efficiency of 90%. The efficiency assessment demonstrates the antenna's capability to effectively convert input power into radiated electromagnetic energy within the specified operational range. Nevertheless, investigating the impact of antenna positioning is essential to enhance the accuracy and reliability of localization within biomedical environments [50]. In Table 3, the planar antenna specification is described.



(a) (b)



(c)

Figure 7. (a) Gastric endoscopy antenna design, (b) 2D gain radiation pattern of the antenna, and (c) total efficiency of the antenna over the frequency [50]

In a study conducted by Abbas (2022), A compact antenna for wireless capsule endoscopy is developed, featuring a surface area of 6.0 × 6.5 mm² and a thickness of 0.2 mm, as illustrated in Figure 8. The antenna efficiency is enhanced by introducing rectangular slots into both the ground plane and the radiating patch. Furthermore, the integration of a shorting pin and open-ended slots within these components contributes to the overall miniaturization of the antenna [52]. The simulation setup presented in Figure 9 (a) is placed within a homogeneous muscle phantom model measuring 100 mm × 100 mm in volume. The S_{11} value of the antenna, displayed in Figure 9 (b), verifies that the antenna successfully operates within the 2.45 GHz ISM band across all four tissue types with the simulated gain at -16.5 dBi. However, both the electrical conductivity of surrounding tissues and the depth at which the antenna is implanted significantly influence the gain performance. As conductivity and implantation depth increase, the antenna gain tends to decrease. The high-water content in the stomach also increases the permittivity, resulting in a decrease in the resonant frequency. However, when the antenna was positioned in various orientations to assess its impact on performance, no significant effects were noted in the study [52]. Below, Table 2 shows the design specification for stated wireless endoscopy antenna while Table 3 presents a comparative analysis of the strengths and limitations associated with recent advancements in wireless endoscopic antenna designs.

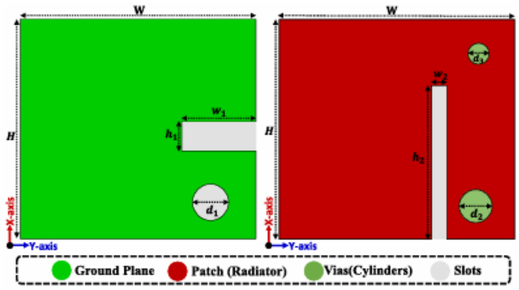
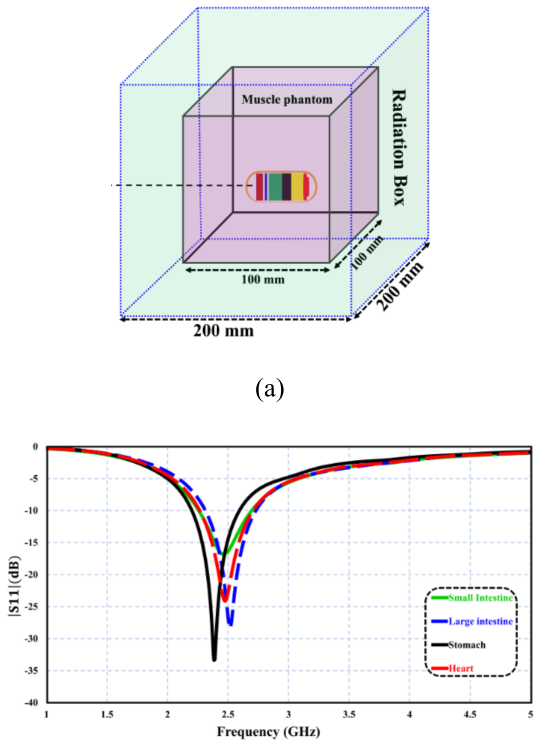


Figure 8. A small antenna for wireless capsule gastric endoscopy [52]



(a)

(b)

Figure 9. Antenna was placed in homogenous muscle phantom (a), S_{11} values of the antenna simulation (b) [52]

Table 2. Wireless endoscopy antenna specification

No.	Antenna	Parameters	Spec.	Ref.
1.	Circular polarized antenna	Operating frequency	2.45 GHz	[7]
		Antenna dimension	44.7 mm³	
		Gain pattern	26.7 and -27.8 dBi	
2.	Planar Antenna	Operating frequency	5750-5850 MHz	[50]
		Antenna dimension	26 × 11 mm²	
		Gain pattern	3.6 dBi	
3.	Planar inverted-F (PIFA) antenna	Operating frequency	2.45 GHz	[52]
		Antenna dimension	6.0 × 6.5 mm²	
		Gain pattern	-16.5 dBi	

Table 3. Wireless endoscopy antenna comparison

No.	Antenna	Advantages	Disadvantages	Ref.
1.	Circular polarized antenna	- Compact size - Stable peak gain antenna performance	- Measurement errors due to mismatch between test setup and simulation conditions - Fabrication inaccuracy.	[7]
2.	Planar Antenna	- Compact size - Focused power in one direction - Uniform signal coverage	The localization of antenna is not discussed	[50]
3.	Planar inverted-F (PIFA) antenna	- Compact design -Improved efficiency using rectangular slots	Performance in different orientations not clearly addressed	[52]

9. CONCLUSION

Many researchers have worked for decades in implementing implantable antennas to stomach for gastric endoscopy applications and investigated a variety of design strategies aimed at overcoming key challenges such as limited space, operational reliability, and interaction with biological tissues. To overcome the shortcomings, various methods are explored on antenna miniaturization and study the operational effectiveness of the antenna within human tissue referring to the antenna performance. The review paper begins with the brief of implantable antenna, the description of gastric, gastric disease related to gastric endoscopy, and the recent studies about the gastric endoscopy antenna simulation. Although the improvement of gastric endoscopy antenna has been made in recent studies, there are several issues that remain unresolved which include inconsistencies between simulated outcomes and experimental measurements, fabrication inaccuracy which affect the antenna performance measurement, as well as a lack of investigation into antenna behaviour under varying orientations. Future studies need to be conducted to study antenna performances in more detail about the effects of the various antenna movements and develop antenna capable of maintaining stable performance regardless of orientation which are essential for the functionality of implantable gastric endoscopy.

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