Video Capsule Endoscopy Designs for AI-assisted Medical Imaging of the Human Gastrointestinal Tract

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Abstract

Monitoring the gastrointestinal tract in real-time, in a both safe and comfortable manner, is informative for diagnosing and treating various diseases of the gastrointestinal tract. The intricacy of the Gastrointestinal (GI) tract in humans and other animals, along with the potential complications that may arise, necessitates a comprehensive understanding and interaction with its different parts and other systems. By gaining imaging access to the GI tract, we can not only detect physiological and pathophysiological signals from the human body but also utilize ingestible electronics in medical diagnostics and therapy. This allows for direct interaction with the digestive system, enabling a more extensive collection of data and the administration of treatment. In this review, we discuss the gastrointestinal tract and the guidelines set by the Food and Drug Administration (FDA) for wireless telemetric medical devices that can be ingested. We discuss capsule systems that are in medical use and under research development, while mentioning the individual components that are utilized for gastrointestinal health monitoring. We also discuss the ongoing research on biocompatible materials and batteries, edible electronics, and alternative energy sources for powering the ingestible capsule systems. To assess the safety and effectiveness of ingestible capsule procedures, we examine the results from clinical studies and analyze key performance indicators. Finally, we discuss the current challenges and future trends to address the concerns related to health risks, the clinical testing and approval process, and the user acceptance of the technology by both patients and clinicians.

Introduction

Diagnostics in the medical field offer valuable insights into the inner workings of the gastrointestinal (GI) tract. Understanding the biological processes and condition of the GI tract is crucial in both human and veterinary medicine [1-3]. To assess the health of the GI tract, various imaging techniques such as computed tomography, magnetic resonance imaging, endoscopy, and colonoscopy are employed. These tests provide visual representations of different parts of the GI tract [4-7]. In addition to imaging, non-imaging procedures like biopsy and pH sensing devices are used during endoscopy or colonoscopy to gather non-image data. However, there are limitations to these diagnostic methods. Computed tomography and MRI fail to capture images of the walls of the systems they examine. Moreover, CT scans expose patients to radiation, while MRI can be problematic for individuals with metallic devices or objects in or attached to their bodies. Although traditional endoscopes and colonoscopes enable physicians to examine the walls of the GI tract, they have limitations. These devices cannot provide a complete view of the entire GI tract and can cause considerable discomfort to patients. To alleviate this discomfort, sedatives are often administered prior to the procedure. However, these medications can also introduce additional risks to the patients. Consequently, there is a demand for alternative diagnostic tools that can effectively image the entire GI tract without causing significant discomfort or posing risks to the patient [1-4]. Traditional endoscopes and colonoscopes have their drawbacks when it comes to examining the GI tract. They are unable to provide a comprehensive view of the entire tract and can be quite uncomfortable for patients. Sedatives are often needed to ease this discomfort, but they come with their own risks. As a result, there is a need for new diagnostic tools that can provide a complete image of the GI tract without causing any significant discomfort or posing any risks to the patient.

The emerging field of smart GI imaging pills that can be ingested shows great potential for monitoring gastrointestinal health [7-20]. These pills contain electronic devices that can capture important visual and chemical signals in the GI tract [4]. Essentially, they are capsule shells equipped with wireless electronics that are swallowed and move through the digestive system. As transistor sizes continue to decrease, there is more opportunity to incorporate various functions into these ingestible electronic devices. For example, they can collect data on imagery, GI gases, pH levels, temperature, pressure, and even transmit data, deliver drugs to specific locations, and collect energy. However, there are currently some limitations to these devices, including safety, size, power, and the movement of the digestive system. These devices are commonly referred to as passive capsule systems [10-15].

The Gastrointestinal Tract

The human gastrointestinal (GI) tract is situated within the inner lumen and spans approximately eight meters in length [1-4]. It is composed of four main components: the esophagus, stomach, small intestine, and large intestine. The esophagus, resembling a straight tube, measures around 25-30 cm in length. The small intestine, which has a curvy and convoluted shape, averages at 6 meters in length with a diameter of 3-4 cm. On the other hand, the large intestine mirrors an upside "U" character and is about 1.5 meters long with a diameter of 6.5 cm. These distinct structures within the GI tract result in varied effects of peristalsis as objects pass through each subsystem.

The variations in shape and size among different parts of the GI tract require the use of distinct surveying methods for each subsystem. A capsule system that is designed to explore the depths of the small intestine would not be effective in the large intestine, resulting in inaccurate measurements. Therefore, it is crucial to carefully analyze the geometries of each section of the GI tract in order to create a wireless endoscopy capsule that can cover all areas.

Passive capsule systems rely on the natural movements of the digestive system to navigate through the body. As it travels, the system collects important data [14-20]. It is made up of three main parts, including a small capsule that holds electronics, a device for capturing images, and a computer for processing those images. The capsule needs to be small enough to be swallowed, while the image-capturing device should provide clear and detailed images of the gastrointestinal tract to assist doctors in understanding internal conditions and events.

Historical Perspective of Capsule Endoscopy

The original pH monitoring capsule system was created by Heidelberg Medical in Germany [1-4]. This innovative device, measuring 15.4mm in length and 7.1mm in width, resembled a vitamin capsule. It boasted a lifespan of 6 hours and featured a radio transmitter and an electrode. In 1981, the idea of a wireless video capsule was conceived to capture images of the gastrointestinal tract wall. However, it took over a decade for this technology to advance to the prototype stage. The final product consisted of a miniature charge-coupled device (CCD) camera, image processing capabilities, a battery, and a 10-mW microwave transmitter.

In 1997, Dr. Swain and his team made significant progress by successfully testing prototypes of the capsule endoscopy on both live and deceased pigs. These prototypes included various components like a battery, a light, a charge-coupled device camera, a video processor, and a 1.5 cm dipole antenna connected to a 10mW microwave transmitter [15-20]. The SmartPill Company took it further in 2003 and developed the very first FDA approved wireless capsule. While these capsules had sensors to measure pH, temperature, and pressure, they lacked fast imaging or video capabilities. The SmartPill system consisted of different parts, including the capsule itself, a portable receiver for storing sensor data, software to interpret the data, and a docking station for the receiver. In the early 2000s, advancements in CMOS-based image sensors and ASIC allowed for the addition of video capturing to the wireless capsules. The company called Given Imaging was one of the pioneers in this area with their specialized PillCam ESo and PillCam Colon for imaging specific parts of the GI tract. This paved the door for several other companies like Olympus, IntroMedic, and Jihnshan to develop better technologies for these smart capsules.

The initial examinations conducted using wireless endoscopies primarily focused on undiagnosed gastrointestinal bleeding and inflammation of the bowels. In today's era, most capsules have the capability to capture high-quality images, which are then directly assessed by gastroenterologists. This enables a more comprehensive diagnosis of patients who are experiencing conditions like colon cancer and Ulcerative colitis. Despite advancements, there is still skepticism within the medical community regarding the safety of this procedure. The primary concern is the possibility of intestinal obstruction; however, scientific evidence suggests that this is a rare occurrence. In the United States alone, a non-degradable drug delivery system procedure has been performed over 4.4 billion times, with only 85 reported obstructions.

In the 1950s, the first wireless capsules were created that were equipped with sensors that could gather data on temperature, pressure, and pH levels. Nowadays, advancements have been made to endoscopy devices, which now include a camera for viewing the inner wall of the GI tract. Additionally, improvements have been made to the lens view angle and frame rate, as well as a decrease in the number of LEDs used. To conserve battery life, light exposure sensors have been added. The battery used in these capsules is a simple coin-shaped silver-oxide battery that generates 20mW of power. This type of battery is currently the only one approved for medical use. Some companies have developed capsule systems that are specifically designed for different parts of the GI tract, such as the OMOM, Endo Capsule, and MiroCam. These capsules are primarily used for bowel endoscopy. The MiroCam capsule takes a unique approach by using the human body as a means of transmitting the data collected by the system. This is achieved by transmitting the baseband electrical signal through the body at a frequency of 1-3 MHZ. By utilizing the human body as a communication channel, there may be no need for RF components like an oscillator, modulator, or antenna.

Modern-day Ingestible Capsule Technology

Upgraded battery systems, cameras, motion, and telemetry capabilities are now included in modern capsules [20-34]. The standard battery used in capsules is a basic silver-oxide coin-shaped battery, producing 20mW. This is the only FDA approved battery for medical purposes at present. However, the silver-oxide battery does not have enough capacity or current output to effectively scan the entire GI tract, particularly when used in a capsule with locomotion capabilities. Certain capsules are equipped with either internal or external locomotion features. External locomotion involves a magnet outside the body that attracts and moves the capsule, while internal locomotion entails a micromotor causing vertical vibrations or a compression and extension movement resembling a worm [20-26]. Controlled motion enhances surveillance via cameras. Since the initial installation of cameras on ingestible capsules, continuous improvements have been made to the image quality and video frame rate. Not all capsules have cameras, and some have multiple cameras. Most cameras utilize CMOS and CCD imaging chips. These cameras capture the illuminated interior of the GI tract using external LED lights. Subsequent observations and subsequent sharing of the information with individuals not directly involved in the patient's care [30-34].

ASIC and Data Transmission

ASICs are a suggested approach for enhancing the processing and transmission of image data [20-27]. These ASICs make use of RF channels and respond to command signals, which, if optimized, can greatly reduce power consumption and increase frame rates. Zarlink Semiconductor Inc., an Ottawa-based company, successfully implemented this technology by incorporating a 2.7Mbps, 434 MHz radio transmitter chip with a power consumption of 5.2mW into their capsule. Additionally, compressing image data can further improve overall frame rates. Instead of conventional data transmission methods, transient antennas can be employed to enhance the communication systems of the capsules. These antennas, including coiled, planar, and conformal ones, work together to transmit data effectively. Moreover, they require less space within the capsule and can be flexible enough to fit in various locations. The main objective is to reduce the size of the devices, allowing the antennas to fold during ingestion and when passing through narrow passages, and expand to enable data transmission when needed.

Gas Sensing Applications of Ingestible Capsules

The process of monitoring stomach functions can now be conveniently achieved by analyzing the gases it produces [1-4]. To accomplish this, capsules containing sensors for carbon dioxide, hydrogen, oxygen, and methane have been successfully utilized on animals, with promising results from initial human tests as well. Intestinal gases, such as Hydrogen, Oxygen, and CO2 (and sometimes Methane), arise from various sources like swallowed air and chemical reactions in the body. Changes in these gases can indicate certain disorders in the gastrointestinal tract. By testing for the presence of Oxygen, Hydrogen, and Carbon Dioxide, doctors can diagnose these conditions.

When we digest carbohydrates, they break down into smaller sugars that our body can absorb in the intestine. Any undigested carbohydrates then enter the colon, where bacteria ferment them. This fermentation process can cause excessive gas, bloating, diarrhea, abdominal swelling, and irritable bowel syndrome (IBS). Nowadays, doctors often measure levels of hydrogen or carbon dioxide in breath samples to monitor malabsorption of different carbohydrates (like lactose, fructose, glucose, and lactulose) and small intestine bacterial overgrowth (SIBO) [1-4]. Additionally, higher levels of methane in the gastrointestinal tract may suggest increased colonization of certain microorganisms (like methanogens). The breath of individuals can contain hydrogen and methane, which are linked to higher body mass index and percent body fat. However, hydrogen breath tests can yield inconsistent or inaccurate results due to various factors like oral bacteria, non-hydrogen producing bacteria, gastrointestinal motor disorders, or not following a proper carbohydrate diet.

Enabling the use of capsules to generate real-time gas profiles would enable the identification of the aforementioned gases and pinpoint the source of any unusual spikes. The capsule, measuring 26mm in length and 9.8mm in diameter, features a non-transparent polyethylene casing. It is equipped with coiled antennas, a microcontroller, a 433 MHz transmission system, membranes containing nanomaterials (which prevent liquid permeation but allow gas diffusion), a button-sized battery made of silver oxide, as well as thermal conductive and semiconducting sensors.

The oxygen levels detected by the capsule enable it to pinpoint its location within the digestive system, while the other sensors regulate the functionality of the gut. These sensors are protected by resilient membranes that allow for gas permeability, enabling them to function effectively in both aerobic and anaerobic environments. While enzymatic and chemical reactions in the gut contribute to the production of some of these gases, the majority are generated through bacterial fermentation. Enzymatic reactions, which primarily occur in the stomach, are associated with carbon dioxide and oxygen. On the other hand, bacteria present in the small intestine and the colon work to process the unabsorbed food and produce hydrogen, methane, and a portion of carbon dioxide. By incorporating gas sensors into ingestible electronic devices, the need for breath analysis will be significantly reduced. The level of accuracy in diagnosing gut health can be greatly improved by measuring the pH levels at a higher point in the digestive system, rather than just at the mouth.

Drug Absorption Applications of Ingestible Capsules

Another important application of gas measurement is in the assessment of drug absorption and utilization [1-4]. While most individuals prefer oral drug administration, it can be challenging to deliver drugs with low solubility or stability to specific regions of the gastrointestinal (GI) tract through this route. To overcome this, a current approach involves the use of ingestible capsules to deliver these drugs. These capsules target specific areas of absorption, ensuring accurate dosage delivery to patients. In addition to drug delivery, these capsules can also administer electrical pulses to assess neurological disorders or mobility issues in the GI tract. By stimulating neurons, these pulses provide insights into their functionality and potential diagnostic information. Furthermore, if ingestible capsules can successfully deliver drugs to targeted GI areas, the gas-sensing capsules mentioned earlier can detect desired levels of methane, hydrogen, and carbon dioxide, ensuring optimal gut health.

The microcontroller contained within these capsules has the ability to deactivate the main electronics, increasing the lifespan to 30 days. This is feasible because the only components in operation would be the temperature sensor and transmission circuits, both of which require minimal current. A small receiver, conveniently located near the individual, collects all the data from the capsule and transfers it every 5 minutes to a Bluetooth-enabled device (such as a mobile phone with the necessary app). This enables real-time monitoring of the individual's vital signs, allowing for the estimation of their current location based on this information. The use of capsules offers several advantages over other commonly used tests. Capsules not only provide clearer and more precise data compared to pH sensor capsules, but they also offer a reliable point of origin. Gastric examinations utilizing O2 sensors are more accurate than those using pH sensors. This is due to the linear nature of Oxygen sensors, as opposed to the logarithmic nature of pH sensors, resulting in cleaner and more reliable data.

Potential Limitations

Although capsule endoscopy is considered an improvement over traditional endoscopy, there are still areas that need improvement before it becomes the standard procedure [1-4]. Many of the prototypes available prioritize cutting-edge sensors and image capturing, but there is a need to balance this with power efficiency. In other words, there is often a trade-off between power and advanced technology [31-34]. When looking at capsules from a few years ago, it is clear that there were basic limitations in terms of hardware. The image resolution was not high enough and the frame rates were lackluster, which could greatly hinder a doctor's ability to make a diagnosis. Additionally, power efficiency quickly became a concern for proponents of this technology. Basar et al. suggested using a "highly efficient transceiver chip" to improve data transmission and maintain optimized power efficiency. However, they also noted one of the most important limitations of wireless capsules: their movement and steering. Currently, they rely heavily on natural bowel movements to navigate the gastrointestinal tract.

Wireless communication presents interesting challenges in ingestible capsules. The commercially available capsule is equipped with numerous sensors and cameras, resulting in a significant amount of data being generated. To avoid the inconvenience of retrieving the capsule's data later, it is essential to transmit it wirelessly in real-time. Far-field radiofrequency communication is commonly used for this purpose, but it necessitates the use of an antenna that is at least one-fourth the wavelength for effective communication. Additionally, longer wavelengths are more compatible with body tissues, which further emphasizes the need for larger antennas. The safety aspect of ingestible electronics is an important consideration. With multiple systems operating within a capsule, there is a risk of retention in certain users, which can result in gastrointestinal obstruction. In patients with suspected bowel disease, the retention rate of a typical endoscopic capsule is 1.4%. However, individuals with Crohn's disease may experience even higher retention rates, reaching up to 13%.

The provision of power to the capsule is a crucial aspect of its design, as it determines not only the lifespan and communication capabilities of the capsule, but also contributes significantly to its size. As mentioned before, the possibility of obstruction is a genuine concern for medical professionals, which is why there is a need for new battery technology. Lithium-Ion batteries are known to pose risks such as toxicity and spontaneous ignition, which is why Silver oxide batteries are currently being used. However, there is a growing interest in making the capsules even smaller for safer usage, which is why it is important to explore alternative options to the current Silver oxide batteries.

Ingestible electronics have always faced a limitation in their inability to move on their own. This constraint hampers the potential of capsule endoscopy to effectively target specific areas of the GI tract, resulting in incomplete diagnoses. Researchers have made initial efforts to address this issue by harnessing the muscles present in the tract and using electrical stimulation to propel the capsules. However, these experiments have only been conducted on live animals and have not yet undergone clinical testing. This is due to concerns about the safety and power requirements of such a method.

Possible Solutions in Maneuvering Ingestible Capsules

Currently, the movement of ingestible technology in the body relies solely on the natural rhythm of the digestive tract. This means that doctors cannot control the movement of the capsules and are limited in their ability to closely examine certain sections of the digestive tract. To address this limitation, researchers are developing three different designs for a maneuverable ingestible capsule system. The first design involves using legs to move the capsule. These legs could be rigid, adhesive (similar to a gecko's legs), or paddle-like. In contrast to the leg-based models, researchers are also exploring the possibility of inducing muscular contraction in the intestinal wall using electricity. This contraction would propel the endoscopic capsule through the GI system and could also be used to stop the capsule at specific locations. Clinical trials have not been conducted with the system of pig models due to safety concerns. Another method for movement, which shows promise, is the utilization of magnetic shells that enclose the components of the ingestible endoscope. By combining these magnetic shells with magnetic actuators, it becomes possible to control the movement of the endoscope capsules using external magnets. The initial clinical trials for manually guided capsule endoscopes have already taken place.

Future Trends in Powering Ingestible Capsules

The current research in the field is focused on increasing the power capacity of endoscope systems. A specific area of interest is finding ways for the capsule system to generate energy from the body. Scientists at the Massachusetts Institute of Technology are currently working on a bio-galvanic energy-harvesting cell that can continuously measure and transmit internal body temperature. This technology would eliminate the need for primary cell devices, which often have harmful substances, by using the body's own resources to power in vivo devices.

The biocompatible materials in the small intestine, stomach, and large intestine are activated by the GI fluid. After collecting energy for 6 days, these specific devices become self-sustaining. The harvested energy is then combined with a boost converter, enabling the use of intricate electronics to transmit data inside the body. These energy harvesting techniques can be utilized in more advanced devices in the future. One valuable application could be a drug delivery or testing system for individuals living with Alzheimer's. The autonomous delivery of medication through a capsule system would greatly benefit those who are unable to administer it themselves. This is just one advantage of a bioenergy-powered device.

The wireless power telemetry (WPT) system utilizes electromagnetism instead of batteries to supply power to the device. To achieve this, a Helmholtz transmitting coil is attached to the patient, while a ferrite-core receiving coil is placed inside the capsule. By manipulating electromagnetic fields, the capsule can be positioned to receive power. Test results indicate that the WPT can deliver up to 500mW of power to the capsule, surpassing the necessary amount for most functions. It is theorized that the system's effectiveness is linked to the intensity of the electromagnetic waves. However, exposure to higher levels of electromagnetic waves may pose a potential risk to body tissue. Humans can tolerate frequencies of around 266.5 kHz at 25W. Additionally, the performance of WPT-powered devices relies on the alignment of the transmitting and receiving coils, which may unexpectedly vary during use. Researchers are also focused on developing smaller power sources for implantable medical devices. The primary objective here is to reduce the size of batteries while maintaining or enhancing their efficiency.

Energy Harvesting Techniques for Ingestible Capsules

There is a strong demand for capsules that employ energy harvesting or alternative forms of energy production and storage. The need for power efficient CMOS technology coupled with fully passive gastric devices for ultra-long drug delivery, could lead to bio-compatible galvanic/voltaic cells. In vitro trials with prototype cells have concluded that Zn-Cu cells outlasted their Mg counterparts and therefore were the chosen system for actual capsule implementation. Two different capsules were fitted with these cells: one containing a temperature sensor, the other a drug-delivery system. Both were fully powered by the Zn-Cu cell for all functions, including wireless transmission, with a receiver present 2m away from the host. The Zn-Cu cells are able to harvest enough power in conjunction with the gastric fluids present in the GI tract in order to power already existing capsules. The corrosion that these cells produced lead to zinc ion dissolution into the host, with the highest possible rate of 27 mg/day, way below the US Food and Nutrition Board upper limit of 40 mg/day. The continued development in ultra-low-power electronics with the implementation of ASIC chips and further development in the voltage and power of these cells (taking in consideration the unavoidable corrosion) could lead to widely available capsules with energy harvesting properties: eliminating the need for silver oxide batteries.

Heart Rate and Respiratory Rate Sensors

The implementation of real-time heart rate and respiratory rates sensors into ingestible electronics could be beneficial for the technology field [4-10]. The current methods of electrocardiograms, photoplethysmography and ballistocardiographs mostly rely on tethered sensors. These, despite being useful for some evaluations, provide limitations for the patient in regard to movement and comfort, namely they are compromised when heavy physical activity is present and can induce significant skin irritation at the points of contact. Research into incorporating heart rate (HR) sensors and respiratory rate (RR) sensors into ingestible sensors have shown promising results in regard to fidelity and practicality. Traverso et al. utilized an electret microphone to capture waveforms within the GI tract of pigs. Running the raw data through a modified phonocardiogram HR estimation algorithm and traditional means of measuring both HR and RR for a control data. The research concluded that HR was detected within 5 bpm on average 96.66% of the trials, and RR within 5 breaths per minute an average of 84.66%. As noted by the paper, a specialized microphone with a lower frequency range could easily be implemented to increase accuracy. Furthermore, the technology from the experiment proved to be smaller than the typical capsule size, 000, used in regular ingestible electronics. However, one speculated limitation would be the transit time between individuals, specifically healthy ones. The best results came from the upper section of the GI tract (esophagus to small intestine), and the transit time in these sections may vary drastically. Another problem could stem from the fact that waveforms were used for data gathering. Potential interference and ambient noise pollution (in the upper dB brackets) could skew the data retrieved. However, this challenge could be circumvented with more robust filtering and signal processing after the data is acquired.

Future Industry Trends in Smart Capsules

The future of ingestible capsules involves addressing current challenges and testing strategies for technology improvements and patient acceptance [30-34]. This technology is moving towards a single, all-in-one chip that includes CMOS image sensors, physiochemical sensors, ASICs, memory units, transceivers, and antenna-in-package. Researchers are exploring new materials with properties that can encapsulate electronic components, harvest energy, provide structural support for faster movement through the body, and possess chemical properties for bio-absorption and biodegradability. In the next few years, it will be crucial to implement closed-loop feedback systems to continuously monitor target parameters for gastrointestinal disorders in almost real-time and automatically adjust external control as needed. The applications of small bowel capsule endoscopy could also be expanded and validated for therapeutic purposes, such as treating obscure gastrointestinal bleeding or detecting damage to the mucosal lining caused by drugs and NSAIDS. Furthermore, the probiotics industry is also becoming a lucrative market for assessing, exploiting, and restoring the balance of gut microbiota and commensal organisms. The ingestible capsules could be developed to identify inflammatory proteins, hormones, or metabolites that indicate viral infections or alterations in the gut microbiome. The potential of bioelectric neuromodulation and gastric electrical stimulation could be used to treat gut inflammation, obesity, gastroparesis, and fecal incontinence. As time goes on, the performance measures for endoscopic procedures will evolve, impacting various aspects such as organization, leadership, staffing, quality and safety, and patient involvement. The future of endoscopic therapeutics and diagnosis will be shaped by the integration of artificial intelligence and personalized treatments. Additionally, video capsule endoscopy has the potential to complement existing surgical and radiological procedures by providing safe and high-quality outpatient procedures, reducing medical complications, and enabling quicker and more cost-effective diagnostics.

Conclusion

The field of ingestible electronics has developed substantially in the last 30 years to the benefit of medical diagnostics pertaining to the GI system. These capsules collect data on GI physical manifestations, GI gases, pH levels, temperature, pressure, while transmitting data and delivering drugs to specific locations. These ingestible devices allow for increased accuracy and volumes of data collected, while considering the comfort and safety of patients. Yet, the potential within the realms of ingestible technology remains still to be fully explored. The power available to the capsule is a crucial aspect of its design, as it determines the lifespan, communication capabilities, and physical size. The technology field is steadily progressing towards a single, all-in-one chip that incorporates various components including CMOS image sensors, physiochemical sensors, ASICs, memory units, transceivers, and antenna-in-package. There are physical limits on the size of the electronic devices and the amount of power available for advancing the technology and complexity. Research to overcome these limitations is currently being conducted and will open up the way for the promising future of ingestible electronic devices.

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