CHAPTER 3

Energy Solutions for Implantable and Ingestible Electronics

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3.1 Introduction

Implantable and ingestible medical devices provide a convenient and reliable way to diagnose, treat, and monitor a wide range of health conditions in real time. Implantable technologies, such as pacemakers, glucose monitoring sensors, neurostimulators, and drug delivery systems, are designed to be placed inside the body, providing continuous therapeutic monitoring and necessary interventions. Ingestibles, on the other hand, equipped with cameras, sensors, and actuators traverse the gastrointestinal (GI) tract, enabling non-invasive diagnostics, and delivering medication directly to the target site of the GI tract. Both technologies can monitor vital signs, detect abnormalities, apply therapeutic actions, and provide valuable insights into patients' health, paving the way for personalized treatment plans. Over the past decade, this field has advanced significantly, with numerous startups and several FDA-approved devices emerging on the market.[1–3] As of 2024, the global market for implantable and ingestible devices was valued at approximately $93 billion and is expected to exceed $142 billion by 2030.[4–6]

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Pacemakers, along with advancements in neural and gastric stimulation implants, are poised to be major drivers of future growth. In the ingestible devices sector, alongside capsule endoscopy, targeted drug delivery systems are gaining traction and are set to become a key component of the emerging smart pill market.

Depending on the technology and application, the average power consumption of these devices ranges from nanowatts to tens or hundreds of milliwatts (see Table 3.1).[6–8] Existing implantable and ingestible devices employ various powering methods: conventional lithium-ion or silver oxide, flexible, or transient batteries for reliable power supply; acoustic and radiofrequency (RF) power transfer for relatively high-power but battery-free devices; thermal energy harvesting and optical power transfer methods for low-power near-skin implants; and local energy harvesting using galvanic cells, piezoelectric, and triboelectric transducers for ultra-low-power devices.

This chapter examines a range of implantable and ingestible technologies, with a focus on their power requirements and sources. It offers an overview of their operational principles, emphasizing the specific power levels each device requires, and describes various powering methods used to sustain the effective operation of these devices.

3.2 Powering Methods for Implantable and Ingestible Electronics

The power source is one of the most crucial elements determining the operational life of the implantable or ingestible device. Key considerations when selecting a power source include its output power, capacity, size, and safety. As shown in Table 3.1, a wide variety of implantable and ingestible electronic devices exist, with power consumption ranging from nanowatts (nW) to tens of milliwatts (mW), depending on the application. Batteries remain the most common power source for several reasons. First, some sensitive devices such as those involved in therapeutic interventions like electrical stimulation require reliable and stable power. Second, implementing wireless power transfer can be challenging, especially for devices located deep within the body, where signals are significantly attenuated by surrounding tissues. Additionally, dynamic motion, such as in the case of ingestible pills, makes continuous power delivery difficult due to the constant change of the device's location and orientation. When the application allows, a radiofrequency (RF) and acoustic power transfer are increasingly used, particularly for devices positioned closer to the skin or in static locations, where power can be delivered more easily. However, these methods have limitations, including the potential for tissue heating and damage if excessive power is transferred. Power transfer *via* thermal and optical modalities is also emerging as a potential method for near-skin implantable devices. Local energy harvesting through chemical and mechanical means is being actively explored as it enables battery-free, self-sustaining operation.

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Table 3.1 Summary of existing implantable and ingestible devices, their power consumption range, and power source employed for their operation.

Device type	Description	Power range and power source	Some examples of pre-clinically or clinically tested, and commercial devices
Retinal implants	• Device that electrically stimulates neurons in the retina and partially restores sight to people who have lost their photoreceptors due to retinal diseases	• Sub-mW to few mW depending on the number of pixels and stimulation frequency[9–11] • RF power transfer and battery are the most common power sources	• IMIE 256 by Golden Eye Bionic and IntelliMicro Medical • EPI-RET 3 by RWTH Aachen University • NR600 System by Nano Retina • Argus II by Second Sight Medical Products, and more[12]
Cochlear implants	• Device that electrically stimulates the auditory nerve to restore hearing in people with profound hearing loss	• A few to tens of mW depending on the device type, number of channels and stimulation frequency[13–16] • RF power transfer and battery are the most common power sources	• Nucleus, Osia, and Baha Systems by Cochlear • Naida CI M and Sky CI Marvel implants by Advanced Bionics • Sonata, Synchrony, and Concerto implants by MED-EL
Pacemakers	• Device implanted in the chest to regulate a slow heart rate by sending electrical impulses to the heart	• A few hundreds of μW to mW[17,18] • Battery is the most common power source • RF power transfer and mechanical energy harvesting methods are being explored	• Micra, Advisa, and Azure pacemakers by Medtronic • Accolade, Essentio, Ingenio, and Vitalio pacemakers by Boston Scientific • Aveir, Assurity, and Endurity pacemakers by Abbott
Bladder implants	• Device that sends mild electrical pulses to the sacral nerves to help treat bladder control problems, such as overactive bladder and urinary retention	• A few hundreds of μW to several mW[19–22] • Battery and RF power transfer are the most common power sources	• InterStim System by Metronic • eCoin implant by Valencia Technologies • F15 and R20 implants from Axonics

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Table 3.1 (*Continued*)

Device type	Description	Power range and power source	Some examples of pre-clinically or clinically tested, and commercial devices
Drug delivery implants	• Device that stores and delivers small, precise doses of therapeutic drugs or medicines into the bloodstream or to specific tissue sites	• A few to tens of mW[23–26] • Battery is the most common power source • RF and acoustic power transfer, and optical excitation are being explored	• Synchromed and MiniMed implants by Medtronic • Prometra implants by Flowonix, and more[27]
Glucose sensing implants	• Device that is inserted under the skin to continuously monitor glucose levels for several months	• A few to hundreds of μW[28–31] • RF power transfer is the most common power source • Acoustic power transfer is being explored	• Eversense E3 CGM implant by Eversense • Subcutaneously implantable device by UNIST[32]
Neural implants	• Device implanted into the brain that records neural activity and stimulates various brain regions	• A few to tens of mW depending on the number of channels[33–36] • Battery is the most common power source • RF and acoustic power transfer, and optical methods are being explored	• N1 implant by Neuralink • Brain–Machine Interfaces by Axoft, Synchron, Blackrock Neurotech, BrainGate, and Precision Neuroscience
Capsule endoscopy	• Ingestible device with multiple cameras used to monitor and diagnose the GI tract in real time	• A few to tens of mW depending on the image acquisition and communication frequency[6,37,38] • Batteries remain the only reliable power source	• PillCam by Medtronic • NaviCam by AnX Robotica • MicroCam by Intro-Medic • EndoCapsule EC-10 by Olympus Medical
Ingestible pills	• Ingestible device with various sensors and actuators used to diagnose and treat GI disorders in real time	• A few μW to tens of mW depending on the application[6,39–42] • Battery is the most common power source	• RaniPill drug delivery system by Rani Therapeutics • Atmo Gas Capsule by Atmo Biosciences

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Table 3.1 (*Continued*)

Device type	Description	Power range and power source	Some examples of pre-clinically or clinically tested, and commercial devices
		• RF and acoustic power transfer for devices with power consumption up to hundreds of μW • Mechanical and chemical energy harvesting for ultra-low-power devices in sub-μW to tens of μW range	• SmartPill for pH, temperature, and pressure sensing by Medtronics • HemoPill for acute bleeding detection by Ovesco • Vibrant Capsule for chronic constipation treatment by Vibrant, and more[6]

However, these approaches are typically limited to ultra-low-power devices, operating in the sub-μW to tens of μW range.

Figure 3.1 offers a summary and comparison of the existing powering methods for implantable and ingestible devices. The following subsections provide a more in-depth analysis of these techniques.

3.2.1 Energy Harvesting

Energy harvesting is one way of powering implantable and ingestible devices. For instance, flexible piezoelectric materials can be used to sense peristaltic movements of the GI tract or expansion of the chest cavity due to breathing, and to convert that mechanical energy into electric power (see Figure 3.1g).[51] Triboelectric energy harvesting is another mechanical method that is used to harvest energy to power the device (see Figure 3.1h).[42,52] Recent *in vivo* experiments of the self-powered intracardiac pacemaker demonstrated that an open circuit voltage and short circuit current of about 6 V and 0.2 μA can be achieved, which paves the way for future development of these devices.[49] Galvanic cells, a type of electrochemical energy harvesting, have also been used to power ingestible capsules using gastric acid as an electrolyte,[53] including clinically approved Proteus Digital[54] (Mg–CuCl couple) and EtectRx[55] (MgCl–AgCl couple) medication adherence capsules. Also, nutrients such as glucose[40] and microorganisms in the gut[56,57] can be exploited for sub-mW-level power generation (see Figure 3.1i). Thermal energy harvesting is another method that utilizes thermoelectric materials to detect the temperature difference across it, and convert it to energy to power the device. This technique is a subject of ongoing research which needs further optimization of thermoelectric

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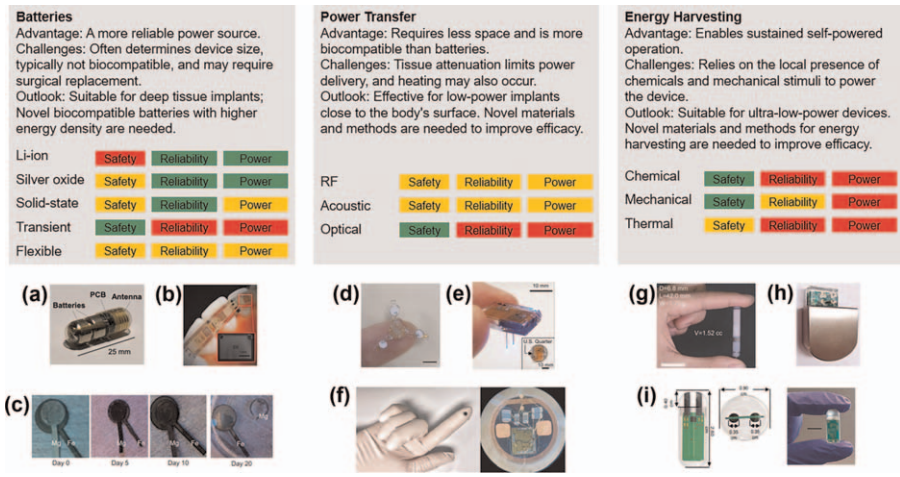


Figure 3.1 Summary of powering methods and existing technologies. (a) Battery-powered ingestible pill for monitoring vital signs. Reproduced from ref. 43 with permission from Elsevier, Copyright 2023. (b) Flexible and biocompatible solid-state micro-battery for implantable orthodontic system. Reproduced from ref. 44, https://doi.org/10.1038/s41528-017-0008-7, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (c) Biodegradable magnesium/iron battery for transient implantable devices. Reproduced from ref. 45, https://doi.org/10.1038/micronano.2015.24, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (d) Ultrasonically powered, wireless battery-free eye modulation patch for high myopia therapy. Reproduced from ref. 46, https://doi.org/10.1038/s41467-024-46049-6, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (e) RF-powered, wirelessly rechargeable, fully implantable, soft optoelectronic system for optogenetics. Reproduced from ref. 47, https://doi.org/10.1038/s41467-020-20803-y, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (f) RF-powered, implantable, wireless, battery-free system for tactile pressure sensing. Reproduced from ref. 48, https://doi.org/10.1038/s41378-023-00602-3, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (g) Mechanically self-powered intracardiac pacemaker. Reproduced from ref. 49, https://doi.org/10.1038/s41467-023-44510-6, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (h) Mechanically self-rechargeable cardiac pacemaker system. Reproduced from ref. 50, https://doi.org/10.1038/s41467-021-24417-w, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/. (i) Galvanically self-powered ingestible wireless biosensing system for real-time *in situ* monitoring of gastrointestinal tract metabolites. Reproduced from ref. 40, https://doi.org/10.1038/s41467-022-35074-y, under the terms of the CC BY 4.0 license, http://creativecommons.org/licenses/by/4.0/.

materials, and is suitable only for ultra-low-power devices operating in the μW or sub-μW range.[58] The transducers for these energy harvesting methods are typically custom designed and optimized for the target device specifications.

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The disadvantage of these energy harvesting techniques is their unreliability as they may not be able to generate power continuously for long measurements due to a lack of chemicals such as gastric juice or glucose, movements such as GI or body muscle contractions, and temperature difference necessary for generating sufficient power.

3.2.2 Energy Storage

Batteries are the most widely used power sources as the majority of implantable and ingestible devices require a continuous and stable supply of electrical power for reliable operation. This is particularly important for critical devices that perform therapeutic actions such as electrical stimulation and drug delivery. Capsule endoscopy pills are another example as they must continuously transmit images from the GI tract to an external reader. However, batteries tend to occupy significant space and often determine the overall size of the device. This can be particularly problematic for ingestibles because a larger pill size increases the risk of its retention in the GI tract. There are various types of batteries available for implantable and ingestible devices: some are commercially available off-the-shelf, while others are still under research and development. Standard lithium-ion batteries offer high electrical capacity and can output up to several hundred mW of power (see Figure 3.1a). However, they are vulnerable to issues such as thermal runaway, explosions, and toxic electrolyte leakage.[59] Silver-oxide batteries, which are not prone to thermal runaway but still contain toxic metals and caustic electrolytes, are preferred as an on-board power source and the only type of battery approved for clinical use to power capsule endoscopes.[60–62] They typically generate up to 100 mW of power, which, while less than standard lithium-ion batteries, is generally sufficient for most applications. Solid-state batteries are also attractive due to their reduced risk of thermal runaway, flammability, and leakages (see Figure 3.1b).[63,64] Transient batteries made from biodegradable materials may eliminate the risks associated with toxicity and minimize GI obstruction through partial or complete decomposition, which also makes them attractive for implants and ingestibles designed to self-degrade over time (see Figure 3.1c). However, they have much lower capacity than traditional batteries, typically thousands of times smaller, which could only be suitable for devices operating in the μW-level power range.[65–67] Similarly, flexible batteries made from biocompatible materials provide another option to minimize the device's volume.[44,68] Implantable and ingestible devices can also benefit from new technologies such as fully 3D-printed batteries made from disposable papers[69] and gel-based micro-batteries consisting of organic and organometallic molecules.[70] Most regular coin cells, and some solid-state and flexible batteries, can be purchased off-the-shelf. However, transient, and most solid-state and flexible batteries remain part of ongoing research studies.

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3.2.3 Power Transfer

Remote powering of implantable and ingestible devices is also possible using acoustic,[10,71–73] RF,[74,75] and optical[76] power transfer. Due to the low propagation loss of sound waves, the first method can deliver several mWs of power with the implant placed under 6 cm of animal tissue. Typically, acoustic power transfer relies on transmitting an ultrasonic wave at sub- or MHz-level frequency, which is picked up by a piezoelectric material on the device and further converted to a stable voltage by power management circuits (see Figure 3.1d). Similarly, RF power transfer is implemented by transmitting electromagnetic waves at one of the industrial, scientific, and medical (ISM) frequency bands, which is detected by coils on the implant or ingestible device, and converted to a stable direct current (DC) voltage (see Figure 3.1e and f). *In vivo* experiments in pigs showed the feasibility of this method delivering hundreds of μW to the implanted device. These numbers may be affected by frequency-dependent path loss, antenna size, and orientation of the device in the body. When utilizing this power delivery method, it is essential to ensure that the specific absorption rate (SAR) values are lower than the standard provided by the Institute of Electrical and Electronics Engineers (IEEE) (the standard limit for 1-g tissue is 1.6 $W\,kg^{-1}$ for an input power of 1 W).[77] Optical power transfer is an emerging technology used in wearable and implantable devices.[76,78] It uses an LED as a light source, and miniature solar cells or photodiodes on the device as optical receivers. It has been demonstrated that a few hundred of μW can be delivered to a device positioned beneath 3 mm of chicken skin.[79] This method remains as the least studied power delivery technique and is highly sensitive to misalignments between the external light source and the onboard photodiodes. Typically, the piezoelectric materials used in acoustic power transfer, LEDs, and photodiodes employed in optical power transfer, and circuits that convert an AC signal from the external transmitter to the stable DC voltage rail are available off-the-shelf, and they can be integrated into an implantable or ingestible device.

3.3 Summary

This chapter provides an overview of existing implantable and ingestible devices, focusing on the various powering methods used to sustain their operation. The goal of this chapter is not to delve deeply into each method, but rather to offer readers a broad understanding of the available approaches. Some methods such as utilizing batteries and certain applications of wireless power transfer are well-established with certain limitations. Others, such as optical power transfer and most of the energy harvesting techniques, are still the subjects of ongoing research. Generally, energy harvesting is the most appealing method for powering implantable and ingestible devices, as it offers a seamless and safe solution that is not constrained by batteries or external power delivery systems. However, due to its

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inherently unstable nature of relying on the presence of local chemicals or mechanical stimuli, this approach remains largely limited to specific applications such as pacemakers, where continuous heartbeats and breathing can drive piezoelectric or triboelectric generators, or ingestible devices designed for short-term monitoring of biomarkers using chemical modality for self-powering. If a more reliable and long-term powering solution is required for a near-skin device, wireless power transfer serves as a middle ground that enables consistent energy delivery. However, to ensure safe operation, it is essential that the device is designed to operate with minimal power consumption, thereby allowing lower power transfer and reducing heat generation. To further mitigate heating concerns, further development of acoustic and optical power transfer methods may offer safer alternatives. For devices located deeper within the body, the development of transient batteries becomes critical as they may provide a safe and reliable means of powering the implant over extended periods of time. More detailed descriptions of these methods will be provided in the following chapters of this book.

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