Applications of Wireless Power Transfer in Medicine: State-of-the-Art Reviews

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Abstract—Magnetic resonance within the field of wireless power transfer has seen an increase in popularity over the past decades. This rise can be attributed to the technological advances of electronics and the increased efficiency of popular battery technologies. The same principles of electromagnetic theory can be applied to the medical field. Several medical devices intended for use inside the body use batteries and electrical circuits that could be powered wirelessly. Other medical devices limit the mobility or make patients uncomfortable while in use. The fundamental theory of electromagnetics can improve the field by solving some of these problems. This survey paper summarizes the recent uses and discoveries of wireless power in the medical field. A comprehensive search for papers was conducted using engineering search engines and included papers from related conferences. During the initial search, 247 papers were found then non-relevant papers were eliminated to leave only suitable material. Seventeen relevant journal papers and/or conference papers were found, then separated into defined categories: Implants, Pumps, Ultrasound Imaging, and Gastrointestinal (GI) Endoscopy. The approach and methods for each paper were analyzed and compared yielding a comprehensive review of these state of the art technologies.

Keywords—Wireless power transfer, Wireless charging, Implants, Medical devices.

INTRODUCTION

Wireless Power Transfer (WPT) exists in several forms, different in terms of used sources, technologies, frequencies and working ranges. Among these, the one using the principles of magnetic induction to deliver power from a transmitting coil to a receiving coil is getting more and more importance. In the majority of cases, a switching electric current is applied to the transmitting coil which produces a magnetic field at a set frequency. When the receiving coil is placed within the transmitting coil's magnetic field, an electric current is generated in the receiving coil. This switching current can be rectified to produce a DC voltage, which can charge a battery or power a DC circuit.[1,28,46]

The efficiency of the power transfer is directly related to the distance between the coils. The magnetic field becomes exponentially weaker as the distance increases. The most efficient method for WPT, uses the theory of magnetic resonance. In this theory, the resonant frequency is calculated with the total inductance and capacitance of the transmitting coil. When the receiving coil is tuned to the same frequency, the coils will couple and will work at a farther distance.[1,22] Using these electromagnetic principles to power internal medical devices is appealing to doctors and their patients. In this work, the four types of Medical Implantable Microsystems (MIMs) that will be considered are Implants, Pumps, Ultrasound Imaging, and Gastrointestinal (GI) Endoscopy.[2,24]

Active Implantable Medical Devices (AIMDs) are *in vivo* devices that aid in or monitor a bodily function. One of the most common AIMDs is the pacemaker, which monitors cardiac rhythms and sends electronic pulses to the heart to correct its rhythm. The primary disadvantage to most AIMDs is their battery life. Invasive surgery could be required to replace the battery. Applying WPT methods prevents the need for surgery and allows the battery to be charged externally.[8,35,45,50]

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Mechanical Pumps within the medical field move fluids or gasses inside the body. A popular medical pump is the Ventricular Assist Device (VAD) which replaces the function of pumping blood in a defective ventricle.[3] A constant supply of power is needed for the VAD so, instead of using an external battery, these pumps can be powered by electromagnetic induction.

A Doppler Flow meter uses ultrasonic imaging to observe the flow of blood through a vascular graft in order to detect a potential failure.[57] These failures are caused by clotting in the graft and require immediate replacement. A single pacemaker battery in an implantable Doppler flow meter system can only last for 5 years. Then surgery is required to replace the battery. Charging the battery or powering the circuit using fundamentals of induction can prevent the need for invasive surgeries.

Endoscopies are the leading standard to observe and diagnose problems in the Gastrointestinal (GI) tract. Commonly conducted with a camera connected to long wire to that enters through the mouth. Endoscopic Capsules are being created and tested to make the procedure faster and painless.

The aim of this manuscript is to identify innovative papers in the area of wirelessly powered medical devices. In the methods section, a brief overview of the selected papers will be provided, then some analysis and suggestions for further work will be given in the proceeding sections.

METHODS

The research processes consisted of using the leading scientific research search engines in this field: Google Scholar,[16] ScienceDirect,[47] IEEE Xplore,[20] The IEEE Wireless Power Conference, and The IEEE Transportation Electrification Conference and Expo to find the most relevant articles to the scope of this work. These online databases were used to find relevant articles between 2006 and 2017.

Initially, a general search was conducted with each engine to find any articles related to wireless power in medical devices. Then those articles were processed to eliminate any non-relevant research or duplicate papers across the different search engines. The remaining papers were scored with a rating scale of 0 (clearly irrelevant) to 10 (clearly relevant). The authors performed a manual scan of each article to assess the scale. The initial search yielded 247 articles, then were filtered to exclude research pertaining to Magnetic Resonance Imaging (MRI) or Ultrasonic Resonance powered devices. Eliminating the non-relevant papers resulted in a total of 17 papers (Fig. 1). These papers were separated based on the MIM in reference, Im-

plants, Pumps, Ultrasound Imaging, and Gastrointestinal (GI) Endoscopy. The remaining text in this section will be organized into those four categories.

Implants

Campi *et al.* investigated the safety aspects of wireless power transfer (WPT) to active implantable medical devices (AIMDs).[4] There are limitations to AIMDs with WPT functionalities because the strong magnetic fields generated pose health risks to humans. However, at certain frequencies, WPT is safe for humans and has many beneficial applications in the medical space.

Experiments were conducted at four different configurations (Fig. 2) at both 300 kHz and 13.56 MHz. The tests observed different capacitor combinations and coil turns to determine each efficiency. In the first configuration, the transmitting and receiving coils are not separated by biological tissues. The second configuration has the receiving coil in biological tissue. The third configuration places the receiving coil in a titanium pacemaker case in the biological tissues, and the fourth configuration places the receiving coil in the pacemaker case in the tissue, then places a 1 mm ferrite shield within the distance.

The first experiment sought to find the efficiencies when the distance between transmitting and receiving coil was set to 5 mm. The results show that the efficiencies at 13.56 MHz were greater overall than those at 300 kHz. The second experiment determined the efficiencies at each configuration when the distance between coils varied between 10 and 60 mm to account for patients of different sizes. The results from this experiment concluded that the efficiencies rapidly decrease as the distance increases. The series–parallel capacitor configuration at 300 kHz and the series–series capacitor configuration at 13.56 MHz yielded the most efficient results. Further experiments were conducted to address coil misalignment and impedance-matching, effectively testing the realistic use of WPT to power AIMDs.

In this experiment, researchers at Stanford University used a metal plate to control the near field coupling in order to demonstrate milliwatt levels of power transfer to a miniaturized coil in deep heterogeneous tissue.[19] The device consists of a multi-turn coil, rectifier, silicon-on-insulator integrated circuit (IC) for pulse control, and electrodes. Power transfer goes through the multilayer structure, shown in Fig. 3a, with the source positioned a subwavelength above the skin layer.

The physical midfield powering source is metal plate patterned with slot-array structures that are excited at four independent radiofrequency ports, then generates

circular current paths to determine an approximate current density.[13] Their power transfer device simulations, shown in Fig. 3b, are in the left ventricle of the heart and the cortex region of the brain. The measured power transfer to the coil using an initial coupling of 500mW and a separation distance of 5 cm, is 195 μW for the heart and 200 μw for the brain. When the operating depth is increased to 10 cm the received power is about 10 μW. Further tests conducted demonstrated the capabilities of the wireless electro stimulator device by inserting it into the lower epicardium of a rabbit.

Implantable circulatory assist devices require an amount of power that implantable batteries cannot sustain. The current method to receive power is the use of percutaneous leads; however, it can cause infection due to the wires passing through the skin. In transcutaneous energy transfer systems (TET) power is transferred across the skin without direct electrical connectivity using magnetic fields.
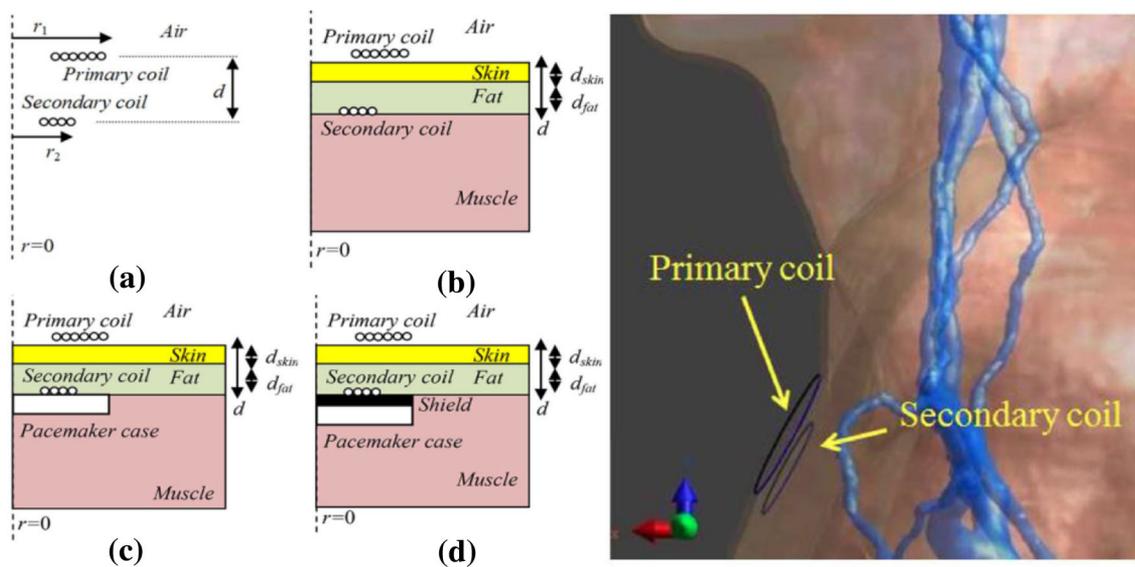
Initial Article Search				
Implants	Pumps	Ultrasound Imaging	GI Endoscopy	Total
103	36	23	58	247

Exclusion of non-relevant research				
7	3	3	4	17

FIGURE 1. The overview of the research process for each category.

FIGURE 2. The left figure shows sketches of the four experimental configurations. In the first experiment: d_{skin} = 3 mm, d_{fat} = 2 mm. In the second experiment, d varied from 10 mm to 60 mm. The right figure shows the coil positions on an anatomical model.[57]
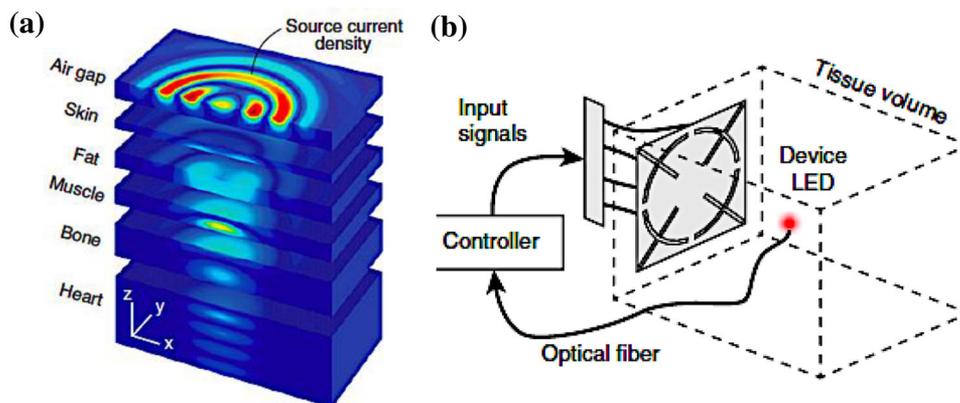

FIGURE 3. (a) Expanded view of the magnetic field in tissue multilayers (b) Experimental setup for measuring the transferred power to a moving device, whose properties mimic muscle tissue.[16]

In their experiment, researchers at The University of Auckland developed a TET system that uses a closed loop frequency, in the primary power, as a base controller that regulates the power being delivered to a load to compensate for variable coupling conditions.[9] The secondary coil was implanted in six sheep to observe a stable 15 W power output over 4 weeks continuously. The experiment's power results ranged from 14.6 to 15 W due to the movement of the sheep which altered the alignment of the primary and secondary coil (Fig. 4).

Lee et al. developed an external digital signal processor (DSP) that transmits encoded data and charging energy to the internal circuit through a set of coils.[31] The data received is then transmitted through the body via the same coils. This bidirectional data transmission is achieved using a closed loop implantable microstimulator system on chip (IMSoC). An IMSoC is powered by radio frequency (RF) coupling and is combined with a battery control in order to be utilized as a rechargeable device.[33] The IMSoC, shown in Fig. 5a, consists of a power interface that has the ability to control charging, digital circuitry that enhances the reliability in communication, and a pacing channel that has a digital to analog converter (DAC) and a pulse generator. The pacing channel generates stimulation pulses in order to protect the heart from the lack of peak pulses (R-waves).

The in vivo experiment inserts a catheter into the artery toward the right ventricle, an electrode, which coiled in a single loop at the site of cannulation, and the IMSoC. The IMSoC is connected to an external electrode placed in the back of the animal. The operation distance of the IMSoC to the animal is 25–45 mm and a R–R beat interval is detected at a rate of 1 kHz within a stimulation period of 400 ms. The stimulation is visually indicated by the LED shown in Fig. 5b.

Researchers at the University of Salento developed a wirelessly powered pacemaker.[39] WPT for a pacemaker is achieved by reaching a good RF-to-RF effi-ciency, shown in Fig. 6a. The primary resonator operates outside of the body with direct skin contact and the secondary resonator is integrated in the silicone header of a pacemaker. The system is both simulated numerically and replicated experimentally using the fabricated resonators, shown in Fig. 6b, and minced pork (to reproduce human tissues). The simulator and the ex vivo experiment undergo an impedance load of 50 Ω and a frequency of 403 MHz in order to produce a 56.8 and 51.4% efficiency, respectively. The system complies with safety regulations by having their specific absorption rate under 2 W/kg per a mass of 10 g with a recorded power input of 118 mW.

Kim et al. developed an ideal wireless power transfer method for miniature implants using electromagnetic waves over ultrasound waves, because the efficiency does not deteriorate with respect to the different acoustic impedances of the tissue layers and the skull.[26] Brain machine interface technologies require miniature implants, to increase longevity, reduce scarring and cell death, and increase the coverage over the cortical surface[18,23,29,37,43] The power is delivered via a magnetic flux shared by the transmitting and receiving coil, which produces an electromotive force (EMF). The EMF is directly proportional to the area of the receiving coil; thus, the system's efficiency is dependent on the size of the coil. In order to keep the implant small, the operating frequency is increased to an optimal range of 100 MHz–1 Ghz, which is still under the SAR regulations.[36,40]

The coil's geometry, separation distance, and on-chip design must all maximize the receiving coil's coupling coefficient and minimize its parasitic resistance. A receiving coil with many turns offers a larger voltage and increases the inductance; however, the quality factor of the system can decrease due to a rise in parasitic resistance. The optimal amount of turns for a mm-sized implant is between 2 and 4 turns at an operating frequency range of 100 MHz–300 MHz. The receiving coil loses energy and introduces noise due to Eddy currents induced by metal planes or loops. In
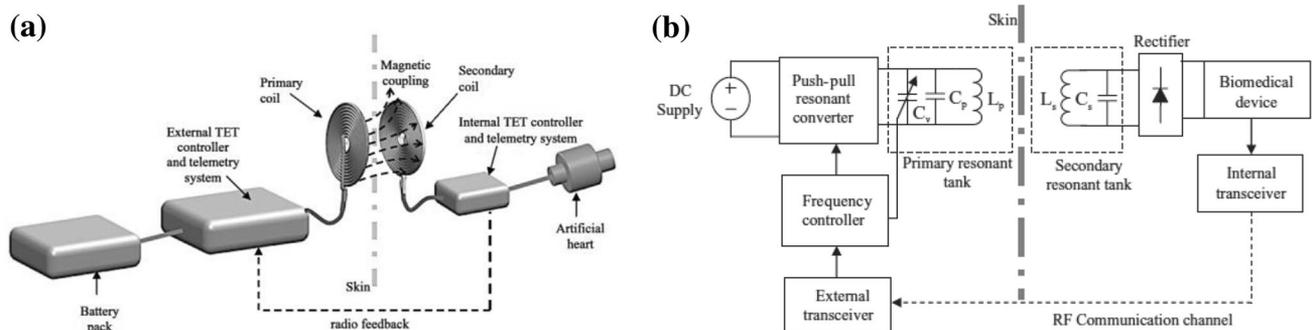

FIGURE 4. (a) Basic structure of a TET system (b) Overall schematic of the developed TET system.[20]
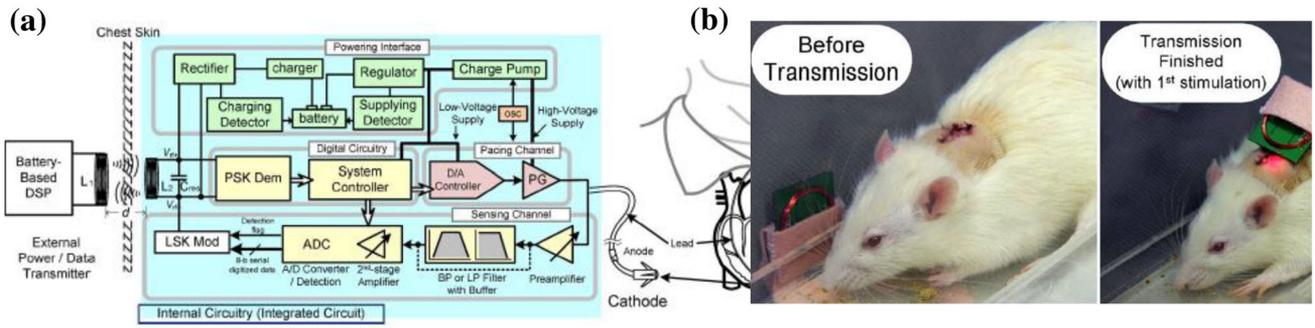
(a)

(b)

FIGURE 5. (a) Schematic of the Implantable Microstimulator. (b) *In vivo* experiment with the LED lighting up at the moment of pulse stimulation.[4]
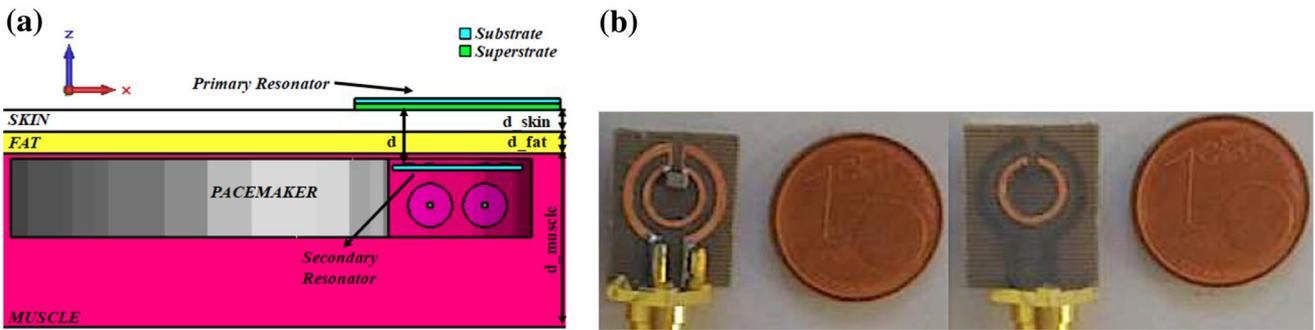
(a)

(b)

FIGURE 6. (a) Proposed WPT system. (b) Fabricated secondary resonator using a specific geometry (front and back), that maximizes its link efficiency.[13]

order to increase the system's efficiency, the on-chip metal loops and planes are removed using an H-tree power network, shown in Fig. 7a.

A complementary metal–oxide–semiconductor (CMOS) fully integrated resonant regulating rectifier uses a pulse-width modulated (PWM) and pulse-frequency modulated (PFM) signal to activate a conductive path between the resonant tank and the load. Another method is to use an adaptive buck-boost resonant regulating rectifier (B^2R^3). The system uses the boost mode to convert low RF voltage to high regulated DC voltage, and the Buck modes convert large RF voltages down. Figure 7b displays a proposed figure of merit of an ideal mm-sized implant that incorporates a 3-turn coil, B^2R^3, and H-tree power and signal distribution.[62]

Monti *et al.* qualified a wireless power transfer technique with the MedRadio band that is intended for
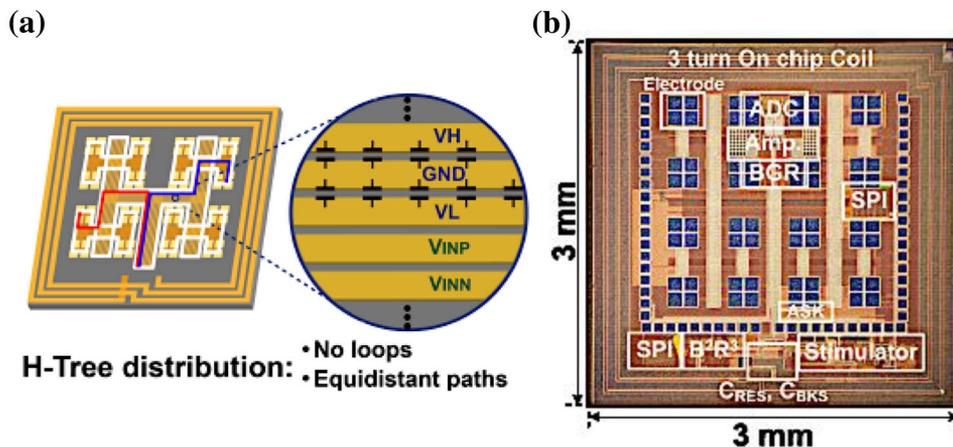
(a)

(b)

FIGURE 7. (a) Schematic of the H tree distribution (b) Zargham's proposed 3 × 3 cm figure of merit m-sized implant.[9]

implantable medical devices.[38] Operating in the MedRadio Band is reserved for medical devices, allowing it to minimize the interference, and can be used for remote monitoring. The wireless power transfer proposed operates within the MedRadio band, at a frequency of 403 MHz, using magnetic coupling. The primary resonator is connected to the power source outside of the body and consists of two planar spirals printed on both sides. This resonator was designed using spiral geometry to optimize parameters using full-wave simulations. The secondary resonator is implanted 5 mm under the muscle in order to connect to the medical device, and has a primary loop using a square SSR, shown in Fig. 8a.[14] The system experiments using minced pork to replicate the electromagnetic parameters of the homogenous medium from the simulation. It also uses scattering parameters from a vector network analyzer to calculate the power delivered to the implanted device.

The efficiency of the wireless power transfer system, shown in Fig. 8b, is sensitive to the resonator distance and misalignment. The efficiency decreased by 3–5% when the receiving resonator was tilted 45° compared to when the resonators are parallel to each other. As the displacement along the x and y axis increases, the efficiency of the system decreases slowly.

Pacemakers have a power consumption range of 10 μW–1 mW. In order to prove this design can produce sufficient power, an AC-to-DC converter is connected to the secondary resonator. The input impedance of the receiver loop and the rectifier is set to 50 Ω, since the input impedance of a pacemaker varies significantly, and the resonators were aligned with the primary resonator's distance at 1.5 mm from the pork. They varied the power delivered to the primary resonator and measured a value of 60 mW, which is sufficient power for a pacemaker. Measurements were also recorded by varying the value of the resistive load in relation to the impedance of the pacemaker, which the maximum load of 330 kΩ resulted in a power output of 1.42 mW.

Pumps

Waters *et al.* evaluated the use of a ventricular assist device (VAD) with a dynamic free-range resonant electrical energy delivery (FREE-D) system.[58] The intended broader impact for this application is to deliver power to a patient's VAD throughout their homes.

The FREE-D system uses the principles of electromagnetic induction to transfer energy from a transmitting coil to a receiving coil. Two experiments were conducted to test the efficiency of the FREE-D system when delivering sufficient power to a VAD. The transmitting resonator was placed 1 m away from the receiving resonator with a relay resonator in between (Fig. 9).

In the first test, the VAD received a constant 8.1 W of rectified power to keep the pump speed at its typical 2400 r/min. The rectified efficiency of the system during this test was 56%, while the resonator efficiency was 85%. In the second test, the pump speed was increased from 1800 to 3000 r/min over two weeks' time, as the VAD power ranged from 4 to 16 W. The results showed that as the pump speed increased, so did the amount of power it demanded. The rectified efficiency of the system during this test was approximately 50%, while the resonator efficiency was greater than 90%. No faults or errors occurred during either of the experiments proving the feasibility of using a WPT to power VADs. Further experiments and a more efficient transmission method are needed for successful implementation.

A MATLAB simulation was conducted to demonstrate how efficiencies can increase when using a π-match filter that matches the impedances of the coils to provide maximum power as the distance between the coils change. In the simulation, the impedances in both coils were matched, which increased the efficiency of the system (Fig. 10).

Current drug delivery devices for *in vivo* experiments may cause stress in the animal, which directly impacts the drug's results. Cobo *et al.* developed an implantable micropump system to administer the drug
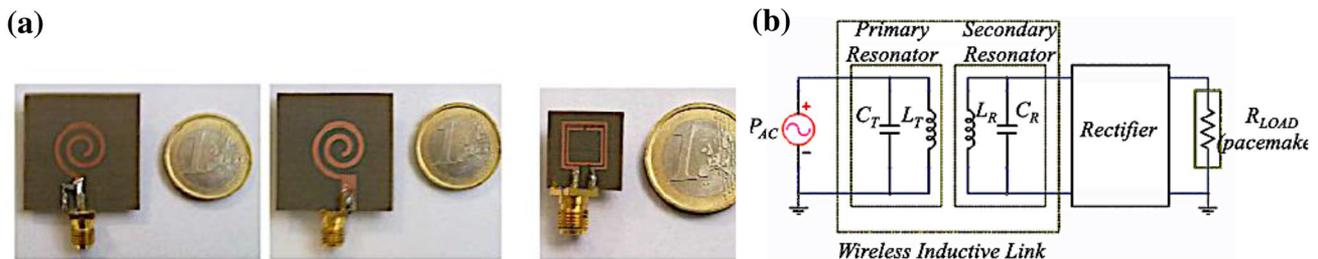
(a)

(b)

FIGURE 8. (a) From left to right: primary resonator front and back, secondary resonator, (b) schematic of the WPT system.[18]
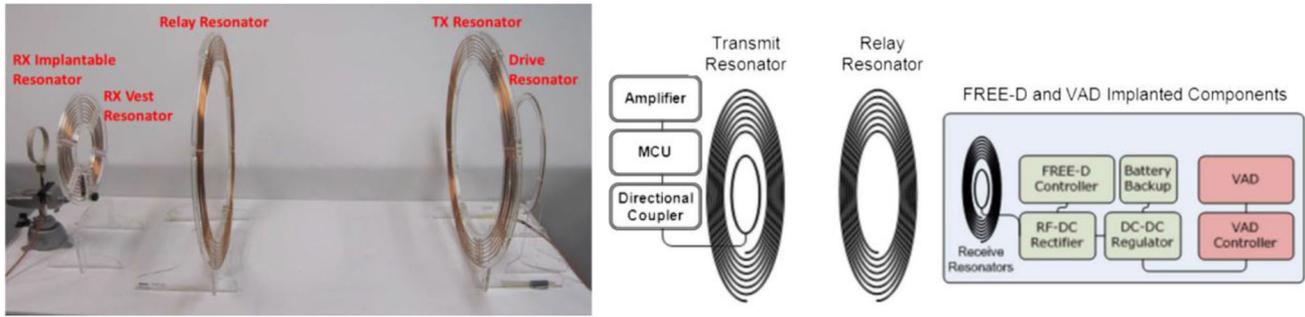
FIGURE 9. The experimental setup. The transmitting and receiving coils are placed 1 m apart from another with a relay resonator in between.[36]
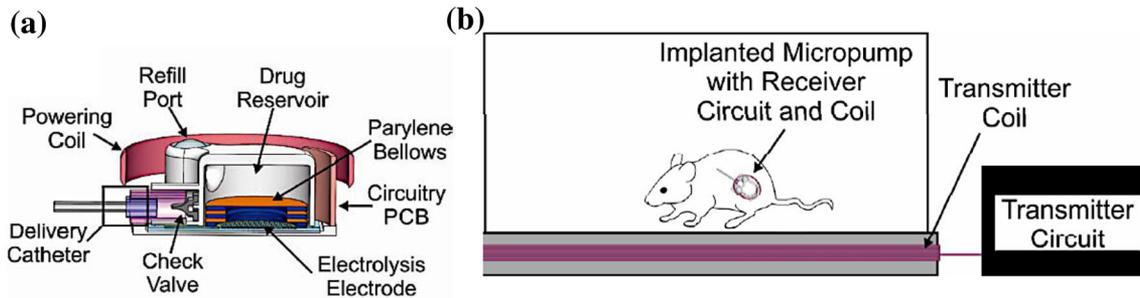

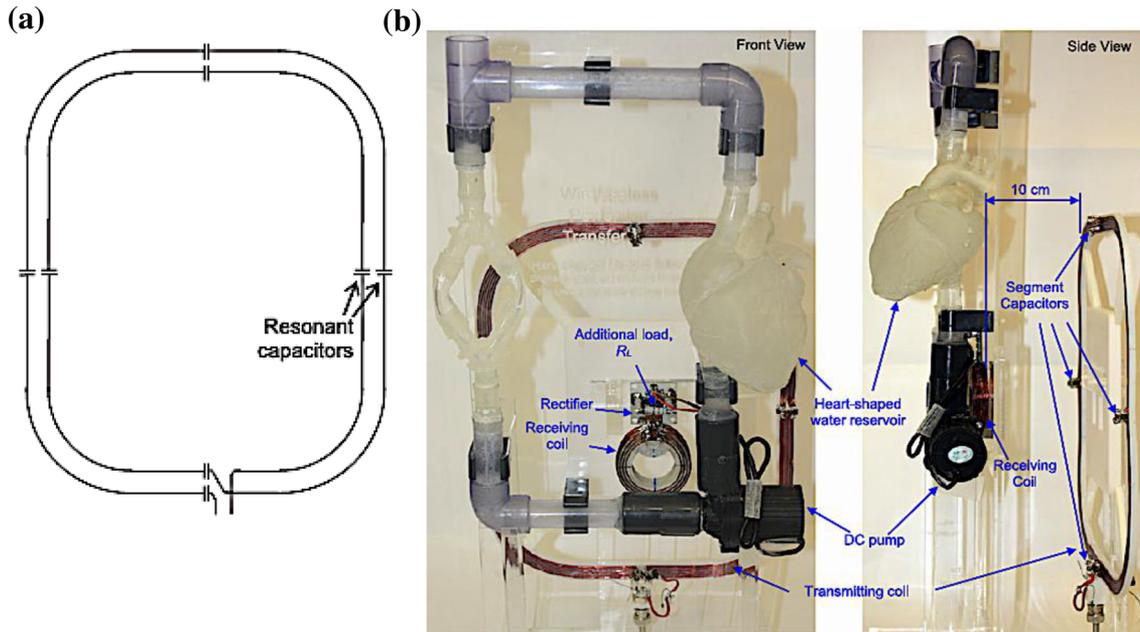**FIGURE 10.** (a) Microimplant schematic (b) In-vivo system.[62]

FIGURE 11. (a) Schematic of a segmented coil. (b) Front and side view of a wirelessly powered circulatory model.[38]

on-demand wirelessly.[6] The system, shown in Fig. 11a, uses electrolysis, because it has large driving forces, low power consumption, low heat generation, and the ability to control the electronic flow rate.

An external transmitting circuit was created under the animal cage, shown in Fig. 11b. It receives an amplified power signal, supplied by a 9 V Class E power system, and transmits it to the implanted micropump. The actuator in the implanted device has

two electrodes that are in contact with an electrolyte and is separated from the drug reservoir by a polymer bellow. The electrodes cause an increase in pressure of hydrogen and oxygen gas when excited by an electric current. The increase in pressure displaces the fluid and activates the check valve, causing the drug to be administered.

The best results occur when the transmitter and receiver coils are parallel at a stationary state; however, an increase in the coil misalignment and distance causes the flow rate and power transmitted to decrease. The device's flow rate drop range is (42.98% and 64.1%) for a separation distance of 2.5 and an angle misalignment of 45°. A 30 μL dosage was administered wirelessly by the micropump with a coil separation of 2 cm, and a constant current of 0.33 mA, in order to ensure the device was functioning properly.

Tang *et al.* created a heart pump that was powered by electromagnetic induction so that the pump can be powered from outside the body.[55] Larger transmitting coils in a mid-range wireless power transfer system have the ability to power a deep-seated implantable device without precise coil alignment.[25,44,52–54,59] Mid-range power transfer requires a higher excitation voltage compared to TET systems, thus it consumes more power, is a health risk for the patient, is higher in cost, and the efficiency can change drastically. The mid-range system can have a low operating voltage by dividing the larger transmitting coil into eight segments, shown in Fig. 12a, and having a capacitor cancel the voltage across each segment. The magnetic field intensity was analyzed in four large transmitting coils to determine the applicable range. A correlation was observed; by increasing the inner and outer diameter, the energy was able to transfer farther into the body.

In this experiment, a rectangular shaped transmitting coil divided into segments is within a vest that the patient wears. The coil does not contain ferrite material causing its inductance of 2.72 μH to remain unaltered in respect to frequency; however, the receiving coil is short and radially thick causing the inductance to become dependent on the location of the coils. The output power and efficiency of the coupling coils remained relatively the same as it was measured under different load conditions and at different separation distances. The maximum efficiency of 80% was recorded when the coils are placed parallel and coaxial with a separation distance of 7.7 cm and under a load resistance range of 11–20 Ω. A circulatory model, shown in Fig. 12b, was used to simulate the flow cycling, and it consists of a DC pump, tubing, and a heart-shaped reservoir. The receiving coil is placed next to a DC pump, which represents a left ventricular assist device (LVAD) actuator. The pump is powered *via* the wireless energy coupling and propels water throughout the system. The power efficiency of the energy coupling coils is 75%, but it is reduced to 54% due to the diode rectifier.

Ultrasound Imaging

Tang *et al.* aimed to prove the possibility of using magnetic coupling to power an implanted Doppler Flow meter.[54] Using electromagnetic induction to power the implantable system will decrease the cost of the device as well as eliminate the need for various components required for the large internal battery.

A Doppler Flow meter implant prototype (Fig. 13) was created on a printed circuit board (PCB), equipped with a power receiver, diffraction-grating transducer (DGT), and a small 8 mAh lithium battery. To test the
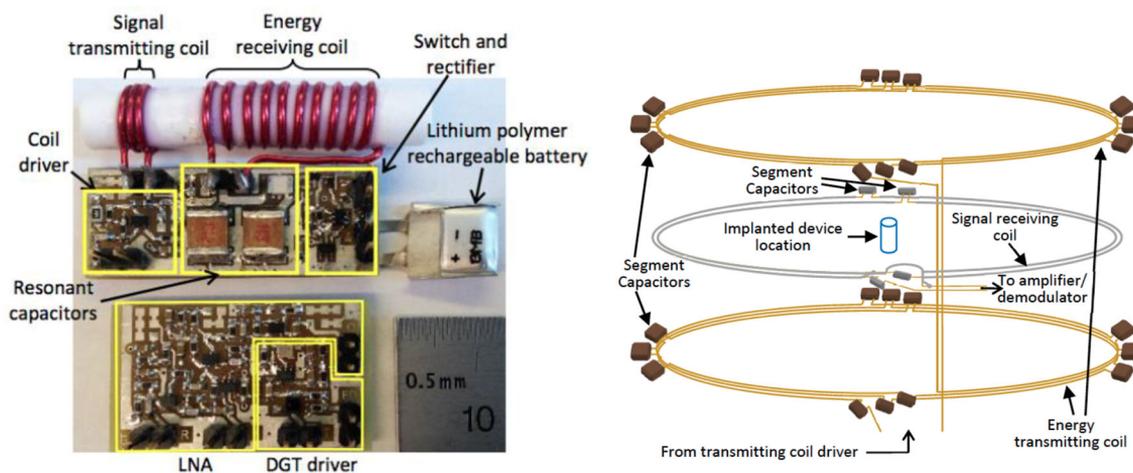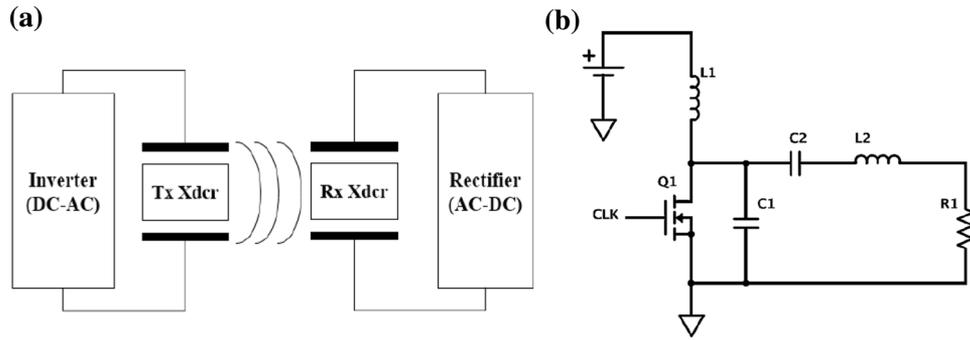

FIGURE 12. The left image shows the prototype of the implantable blood flow meter and the right figure shows the orientation of the transmitting and receiving coils.[44]

(a)   **(b)**

FIGURE 13. (a) An ultrasonic transcutaneous energy transfer system displaying the four energy conversions. (b) Class E amplifier.[53]
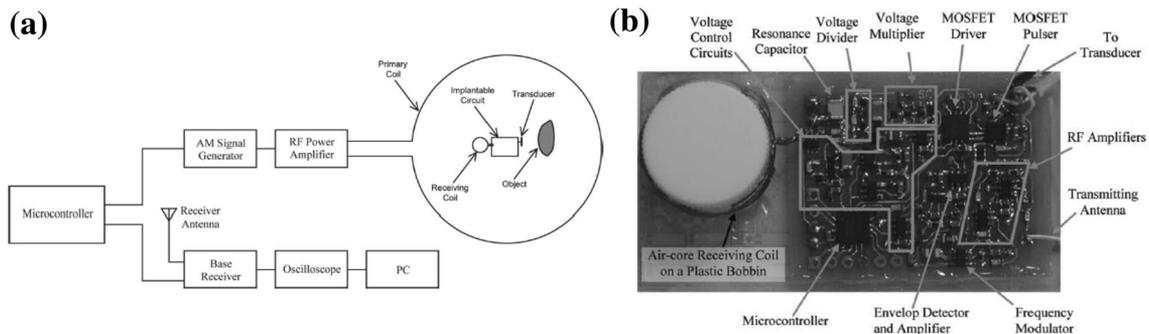
prototype, a fluid with the same conductivity, permittivity, and permeability as human tissue was placed in a cylinder. The meter was connected to the side of the cylinder as the fluid flowed through a graft. The transmitting coil was energized to 2.64 V-rms and 1.6 A-rms at 6.78 MHz, while the receiving circuit saw enough power to charge the battery in approximately 20 s.

The meter recorded the flow through the graft with a high error due to a low signal-to-noise ratio in the Doppler signal. The system still demonstrates the possibility of wirelessly powering implantable Doppler Flow Meters.

Vihvelin *et al.* developed an ultrasonic power transfer system to power implantable devices.[56] Portable ultrasonic power links require device reliability and maximized battery life, which is achieved by an inverter circuit delivering high efficiency to the transmitting piezoelectric transducer. The efficiency for the wireless ultrasonic power link is the product of each energy conversion shown in Fig. 14a. The wireless power transfer process starts when the primary battery sends DC power that is inverted and delivered as AC power to the transmit transducer. The transmit transducer then vibrates and sends a pressure wave that enables the receiving transducer. That transducer converts the pressure waves back into electrical energy. The AC power is converted back into DC *via* a rectifier.

The inverter is developed in this experiment in order to increase the efficiency of the transmit transducer. Many parameters of the system are defined by the transmitting piezoelectric design requirements such as the input voltage, output voltage, frequency, and output power level. There are significant source losses that come from the design frequency range derived from the switch-mode amplifier. Another important factor in design of the amplifier is following the ultrasound safety limits, because there is a maximum power level for the transmitter. Therefore, this experiment uses Class E amplifier, shown in Fig. 14b, since it minimizes the switches by having the only one at the transistor. In a Class E amplifier, the switch current and voltage waveforms are time-shifted so that the power dissipation is minimized, while the power efficiency is maximized. The amplifier's circuit is simulated using the operating parameters and a range of load impedances. Depending on the frequency it obtained, there was a system loss of 4-9% and a direct correlation such that when the system had a small load, their source loss increased.

(a)   **(b)**

FIGURE 14. (a) Schematic of the wireless powering and monitoring system. (b) Implantable ultrasound pulser-receiver prototype.[52]

Ultrasonic implantable devices have the potential to monitor deep-seated tissues due to the proximity to air or bone and can monitor organs after transplant surgery.[42] Implantable devices need to have a reliable long-lasting power source. Tang et al. developed an ultrasonic device (Fig. 15a) that is wirelessly powered and monitored externally.[53] Amplitude modulated sinusoidal currents are generated by a signal generator and amplified in order to excite the primary coil. The system, shown in Fig. 15b, has two coils; the primary is wrapped around the body's waist and the secondary coil is deep-seated in the body at the center. Magnetic field coupling is then produced in the primary coil, and it sends the magnetic energy to the secondary coil. The secondary coil then converts the magnetic energy back into electrical energy via electromagnetic induction. The frequency in this design is low in order to prevent magnetic energy absorption in the body. This device sets itself apart from transcutaneous energy systems, because the receiving coil does not contain ferromagnetic material allowing it to be magnetic resonance compatible.

The device begins operation once sufficient power is received by the secondary coil and the induced voltage is then set by capacitor-diode networks. The desired voltage levels supply power to different parts of the device. An ultrasound transducer converts the electrical energy from the pulser to an acoustic wave and vice versa. The acoustic echo signal is transmitted out of the body through an antenna after it is amplified, detected by an envelope, and is carried via frequency modulation. An external receiver demodulates the FM signal and the waveforms were captured with an oscilloscope.

The prototype was tested at a separation distance of 10 cm, and the envelope of the echo signal received by the ultrasound transducer was excited by a 50 V pulse. The envelope detected at 172 μs after the pulse was sent to the transducer, and then the distance between the tank and the wall was calculated using the speed of sound value and the recorded value. They observed that the voltage supply for the pulser is dependent on the secondary's coil position with respect to the center of the primary coil. An ex vivo experiment placed the primary coil around the animal and measured the same envelope signal and DC signal at the moment the pulser was in the air without implantation.

Gastrointestinal (GI) Endoscopy

Traditional capsule-based endoscopies are relatively small and passively maneuver through the body. This is a non-invasive approach, however there is no control over the direction of the camera or how fast it traverses the GI tract. Several researchers have equipped capsule robots with motors and batteries, in order to have more control over the capsules but are constrained by the size of the capsule. Researchers at The Korea Institute of Technology and Harvard Medical School developed capsule endoscopic robots that work in pairs to perform an endoscopy while powered wirelessly through induction.[25]

The capsule system requires a constant 300 mW to be powered, thus demanding more power than a battery of an allowable size could supply. Instead of a battery, the capsule robots are equipped with a receiving coil, coupled with the frequency of the transmitting coil, located outside of the body (Fig. 16). Their transmitting coil requires a high input voltage up to 32 V at 7 MHz, in order to safely supply the receiver with at least 300 mW at any orientation. Their capsules use a push and pull motion to move through the small intestine. This keeps the capsule stable and allows the operator to adjust the speed and the camera's movement. This prototype proves the feasibility of using WPT to power a capsule based endoscopy, however, the system needs to be miniaturized and further tested.

Witricity is a WPT method that uses resonant coupling from thin film resonant cells. Witricity is non-radiative, has a mid-range field, and is designed to be light and flexible.[28] Liu et al. use the same witricity method and applied it to medical devices inside the
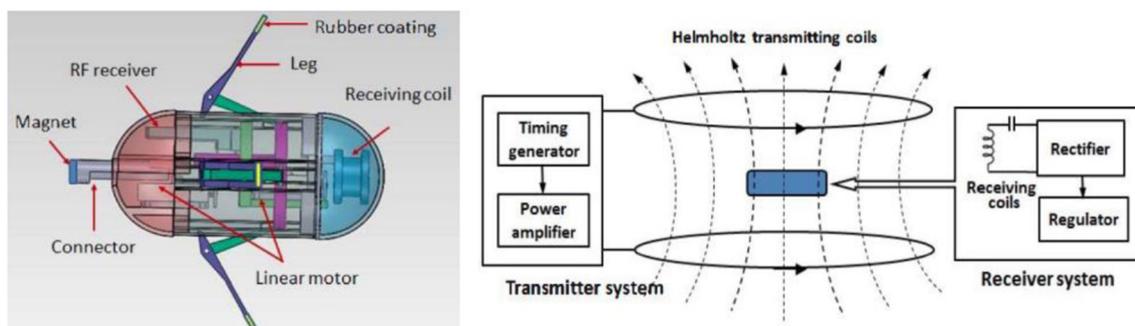

FIGURE 15. The design of the capsule robots. The linear motors are powered electromagnetically by the receiving coil.[59]
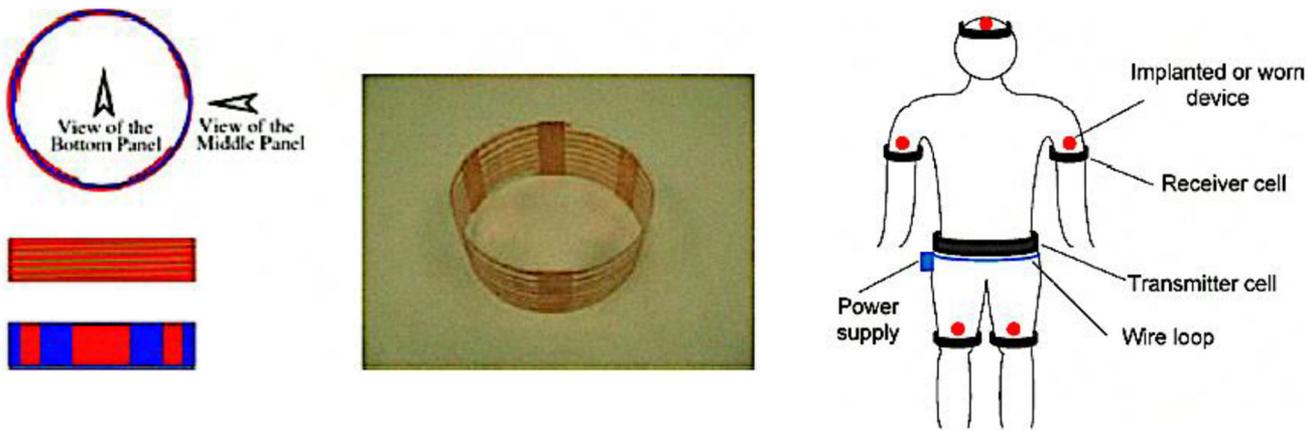
FIGURE 16. (a) Left: three panel view of the cell. Right: actual cell (b) WPT system.[54]
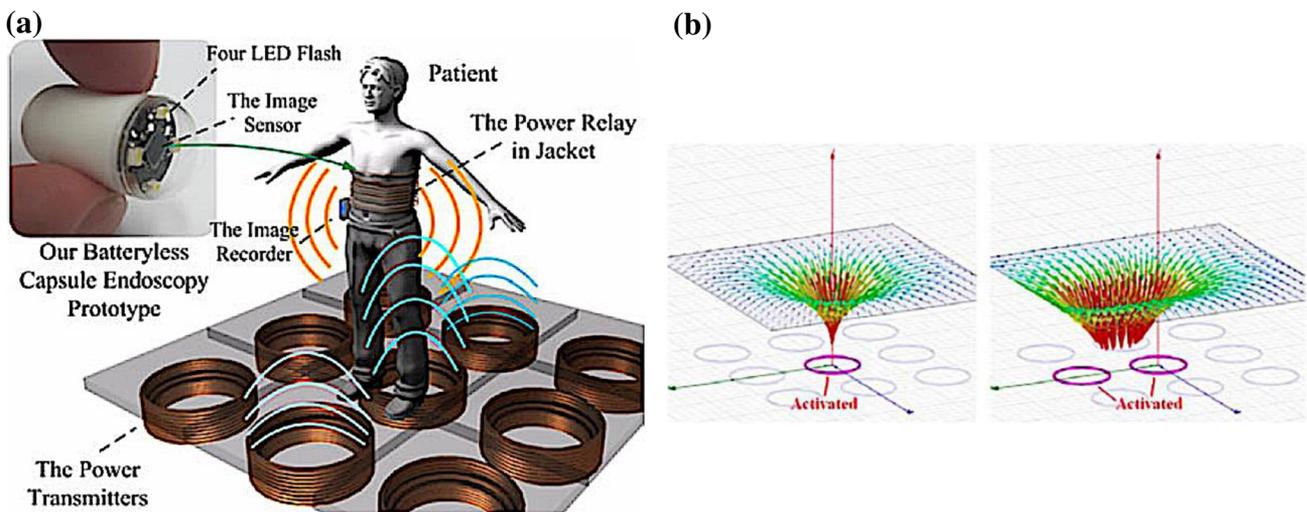

FIGURE 17. (a) Wireless powered capsule endoscope system. (b) Left: magnetic field generated by a single transmitter. Right: magnetic field generated by two transmitters.[34]

body.[34] The thin cell, shown in Fig. 17a, has three layers allowing it to create multiple resonant frequencies. Thus, power transmission and data communication can be used simultaneously. The exterior layer acts as an inductor, allowing it to capture and generate the magnetic field. This layer consists of a helical copper tape coil, which creates the ergonomic design of the cell. The middle layer is made of polymer and acts as an insulator by confining most of the electric field. The interior layer contains conductive strips in parallel that form capacitors and divide the inductor.

In their WPT system they use thin film cells as the transmitter and receivers. The system contains one transmitter and multiple receivers, shown in Fig. 17b, that are placed on the waist and anywhere near the implanted/worn devices, respectively. The transmitter is coupled with a power driving loop and the load's driving circuit is inductively coupled with a receiver.

The coupling of the receiver is achieved with a single coil and multiple turns. The voltage and power are directly associated with the number of turns.

This experiment lacked accuracy because they used convenient measurements for the load, which directly affected the measured voltage and the calculated power values. The article does not provide values for their voltage and power; however, their experiment yielded a 40% efficiency at a distance of 20 cm. The other applications in Table 1. have higher efficiencies and larger frequencies. The insulation layer of the thin cell should be researched in this WPT system, since it has lower frequencies that are beneficial.

Wireless capsule endoscopes (WCE) require patients to wear a jacket with antennas and a power transmitter that is connected to an external power source *via* a long power cable.[11,32] The patient's mobility is restricted making it uncomfortable for them both psychologi-

TABLE 1. Summary of wireless power transfer medical implantable microsystems reviewed in this work.

Application	Frequency	Transmitting voltage	Receiving power	Distance	Receiving coil size	Transmitting coil size	Efficiency	Topology
Implants								
Charging AIMDS and pacemakers[4]	300 kHz, 13.56 MHz	0.2–5.15 V	1 W	5 mm, 10–60 mm	17.65 mm	18.3 mm	Varies, up to 95%	Circular planar coils, 1-10 turns
Deep-tissue microimplants[19]	1.6 GHz	2 V	1.7–2.2 mW	5.5 cm	2 mm diameter	N/A	N/A	Multi-turn 1-15 turns
Transcutaneous energy transfer implant[9]	156.5–185.4 kHz	12 V	15 W	10–20 mm	50 mm diameter	50 mm diameter	Varies, up to 80%	2 coils
Endocardial stimulation for cardiac pacemaker[31]	256 kHz	1 V	48 μW	25–45 mm	~ 1.5×1.6 mm^2	N/A	N/A	Small multi-turn coils
Rechargeable pacemakers[39]	403 MHz	N/A	110 mW–118 mW	5 mm	~4.94 mm	~ 7.53 mm	~ 51%	PCB spiral
Miniaturized implants[26]	Up to 100 MHz	4.5 V	Up to 100 μW	5–15 mm	1–8 mm	N/A	68%	Three-turn on-chip Rx
Remote powering of pacemakers[38]	403 MHz	N/A	80 mW	5 mm	9.5×9.5 mm^2	9.5×9.5 mm^2	5.24%	PCB coils
Pumps								
Powering ventricle assist devices[58]	13.56 MHz	N/A	4–16 W	1 m	9.3 cm	9.3 cm	> 85%, rectified: 45% to 50%	PCB coils
Infusion micropump[6]	2 MHz	9 V	N./A	2–4 cm	17 mm diameter	310 × 140 mm	N/A	Transmitter: 8 turns Receiver: 6 turns
Implantable heart pump[55]	6.78 MHz	8.57 Vrms	19.7 W	10 cm	5.3 cm diameter, 1.24 cm height	1.2 mm diameter	54%	Transmitter: 2 turns Receiver: 1 turn, 4 layers
Ultrasound imaging								
Doppler system for vascular grafts[54]	6.78 MHz	2.64 V-rms	60 mA	~ 10 cm	20 cm diameter, 10 turns	N/A	N/A	Helmholtz configuration
Class E RF amplifier in ultrasonic links[56]	1.275 MHz	3.3 V or 5 V	293 mW	N/A	N/A	N/A	90%	N/A
Deep-seaed impantable ultrasonic pulser-reciever[42]	5.7 MHz	12.5–50 V	12 mW	14 cm	2 cm diameter	30 cm diameter	N/A	Primary coil-1 turn Secondary coil-5 turns
GI endoscopy								
Modular capsule endoscopes[25]	7 MHz	32 V	300–700 mW	> 50 m	2 cm diameter, 1 cm height	N/A	varies	Helmholtz transmitting coils, Rx: 14 turns

TABLE 1. continued

Application	Frequency	Transmitting voltage	Receiving power	Distance	Receiving coil size	Transmitting coil size	Efficiency	Topology
Witricity[34] 2 coils Transmitter: 4 turns Receiver: 7 turns	7.02–	7.04 MHz	N/A	N/A	10 cm	16.26 cm diameter, 6.71 cm height	35.2 cm diameter, 29 mm height	Varies, up to 75%
Two-hop wireless capsule endoscopy[49]	13.56 MHz	0–10 V	24–90 mW	1 m	11 mm diameter	48 cm diameter	Varies, up to 39.8%	First hop: 4 coils Second hop: 2 coils
Magnetic resonance WCE[10]	8.2 MHz	N/A	Varies, up to 51.6 mW	Varies, up to 4 cm	0.6 cm diameter	15 cm diameter	Varies, up to 26.14%	4 coils turns A coil: 1 S coil: 3 D coil: 10 L coil: 3

cally and physically. Sun *et al.* proposed a WCE system (Fig. 18a) to increase mobility using a wireless power transmitter array installed under the floor.[49] This allows the patient to wear a jacket that has a resonant antenna and still be able to move around the room unrestricted. Pressure sensors are able to identify the position of the patient by activating the nearest transmitter to generate wireless power. The power is delivered to the jacket and the capsule inside the patient picks up energy from the power relay. The distance of the system is 5-30 times greater than other current WCE systems.[10,48]

The floor consists of pressure sensors that determine the patient's position, shown in Fig. 18b, and only one transmitter is activated at a time. When a patient is walking between two transmitters, the first transmitter is turned off once the second transmitter is turned on by a switching operation. There are nine transmitters in an array, and stability is ensured by using the strong-coupling technique and Schmitt triggers for all the switches.

In this WPT system the first hop consists of a strong-coupling mechanism with high resonators, while the second hop has loose coupling with small antennas. The dropout voltage and switch timing of rectifiers can determine the efficiency in the wirelessly powered implant.[15,30,41,60,61] The experiment shows that the patient's lateral alignments determine the transfer efficiency. When the patient is directly above the transmitter and the capsule is positioned near the power relay, the efficiency is at its peak. The reason for the shift in efficiency is the loose coupling in the two-hop step.

Ingestible wireless capsules have restricted locomotion, battery power, ability to stop, and can only be used for one organ. However, wireless capsule endoscopy (WCE) is a solution that can be tolerated by the patients, does not require sedation, and does not entail radiation absorption. WCE can also be used on patients that have portable electric cardiac devices.[27] The first ingestible capsule is the M2A, which has the capability to take more than 55 thousand 140° images during the 8-h process, and also have its position located. The M2A sent images *via* radiofrequency to an antenna array that is taped to the abdomen, and its position was determined by a triangulation process of the signal strength received.[7,51] The EndoCapsule was developed after as a self-disintegrating pill that is located by radiofrequency and has a sensor camera allowing physicians to view real-time images.[12] The SmartPill is another advanced WCE containing three sensors to monitor the pH, temperature, and pressure inside the GI tract.

Fang *et al.* developed another wireless capsule endoscope system that uses electromagnetic induc-
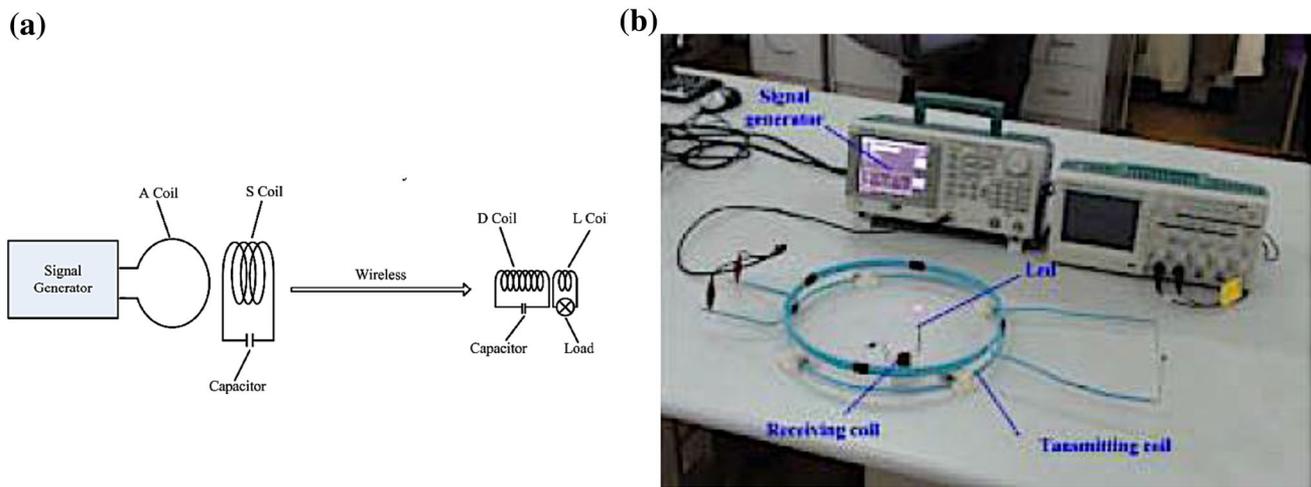
(a) **(b)**

FIGURE 18. (a) Diagram of the wireless power transfer system. (b) Experiment WPT system.[32]

tion.[10] To implement this in capsule endoscopy, the size of the receiving coils must be limited, while maintaining a high system efficiency. The WPT system, shown in Fig. 18a, has two large coils for energy emission and two small coils for energy receiving. The coil parameters influence the frequency, and the quality factor affects the power loss of coils. For this experiment, they used silver-plater copper wire to increase the surface conductivity of the conductor and prevent additional dielectric loss. The quality factor of coil is improved by the number of turns and radius of the coil; however, the capsule endoscopy limits the experiment to hollow single coils.

The experiment system, shown in Fig. 18b, is comprised of two coils as the receiver, a signal generator for the transmitter, and a light-emitting diode as the final load. The purpose of this experiment was to measure the transmission and received power using an oscilloscope in order to calculate the efficiency. The results yielded a correlation between the efficiency of the system and the distance between the transmission coils. The best performance of the system is when the transmission coil distance is at the focal length.

REVIEW ANALYSIS

From the initial article search, 17 were found to be relevant research to the scope of this work. Most of the non-relevant material focused on the applications of the specific technology and did not introduce a new medical device hardware that incorporated the use of electromagnetic wireless power transfer. The selected papers all aimed to improve the field of medical implantable microsystems (MIMs) with electromagnetic wireless power transfer. The majority of the relevant papers were classified as implant-related where
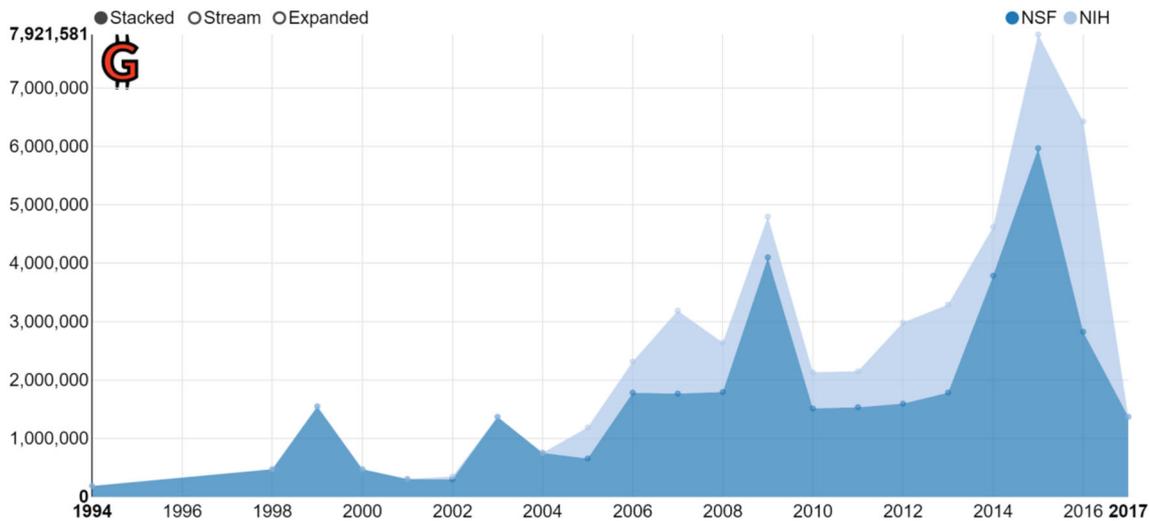
the ultrasound imaging and pump categories contained the least amount of papers. Table 1 consolidates the methods from each paper reviewed and allows easy comparison between different technologies and applications.

When comparing the four categories, we find that each system was different and no strong correlation was found between the system parameters and general application. However, the frequencies of the WPT systems highlighted in this review were mostly in the low megahertz range (1–14 MHz) and the power was less than 500 mW with a few exceptions for some implants and heart pumps. WPT systems in the GI endoscopy category were more likely to have a complex coil topology in order to increase transfer efficiency as the endoscope maneuvers through the body. A summary of future challenges and hurdles to implementation are presented below.

Directions for Future Work

Due to the recent introduction of these devices, most of the devices were in the early prototype phase and intended to prove their concept before the researchers move on to clinical testing. Further work is needed to increase the efficiency of the wireless power transmission.

Many of the reviewed articles contained prototypes with size limitations. The coil geometry constrained the overall size of the prototypes. The relationship between the diameter of the receiving and transmitting coils must be maintained to ensure an efficient transfer of energy. The motor size for some of the endoscopes reviewed also contributed to the size limitation. These researchers need to either re-arrange the components in their prototype or find smaller motors that will work

FIGURE 19. Total grant funding from the National Science Foundation (NSF) and the National Institutes of Health (NIH) for research in wireless medical devices.[17]

in their design. Other potential risks are centered around heating. The electronics both on the transmitting and receiving side can produce high levels of heat that can be harmful for patients or equipment operators. Special measures should be taken in order to dissipate the heat in a safe way for the people involved.

Regulation

In order for these state of the art technologies to be adopted and used on human patients, they must be approved by clinical regulatory agencies. The U.S. Food and Drug Administration (FDA) and European Medicines Agency (EMA) are two organizations in place to ensure the reliability, user safety, and ease of use for new medical technologies. The technologies reviewed in this paper can be adopted to medical practice only when they follow regulations and improve the medical field.

Lack of clinical trials can be partially attributed to the safety risk WPT poses. WPT can induce heating caused by radio frequency (RF) absorption in the body. Therefore, the maximum specific absorption rate (SAR) is set to be 2 W/kg per 10 g human body according to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) regulation.[21] There are certain transmitting frequencies that are prohibited by most countries. These frequencies are either unsafe for human interaction or they pose electromagnetic compatibility (EMC) risks.[5]

Funding

The field of wireless medical devices have been receiving attention because of its potential to shape the future of the medical field. The total amount of money awarded to those researching wireless medical devices has been on the rise. Figure 19 shows the total award amount from the National Science Foundation (NSF) and National Institutes of Health (NIH) per year for grants involving wireless medical devices.[17] The funding for this field is steadily increasing and progress is assumed to continue.

CONCLUSION

Wireless Power Transfer has several possible applications within the medical field. Each technology reviewed in this work aims to solve a unique problem with the current method or technology on the market. Some devices make powering implanted electronics easier, or even prevent surgeries to change a battery.

This work located seventeen journal or conference articles that pertain to this specific topic. After determining the most common medical implantable microsystems (MIMs), the papers were categorized into four groups: Implants, Pumps, Ultrasonic Imaging, and GI Endoscopy.

The transmission profiles from the experiments in each paper were analyzed and presented in Table 1. The results of each paper discussed their transmission efficiencies. The frequency, power, and coil distance were used to quantify and compare the efficiencies. Other quantifying criteria included coil size, topography and efficiency. With the results, it can be concluded that the theory of electromagnetic induction has feasible applications with medical implantable microsystems. Additional efforts to increase efficiency to the receiving coils are needed for further implementa-

tion. Also, more government regulation is needed to keep the consumers safe and to provide uniform guidance to researchers and inventors.

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