Coil-based Wireless Power Transfer for Implanted Pacemakers: A Brief Review

Urfa Khairatun Hisan[1], Liya Yusrina Sabila[2], and Muhammad Miftahul Amri[2*]

[1]*Faculty of Medicine, Universitas Ahmad Dahlan*
Kampus 4 Universitas Ahmad Dahlan, Ringroad Selatan, Banguntapan, Bantul, DIY, 55166, Indonesia
[2]*Department of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan*
Kampus 4 Universitas Ahmad Dahlan, Ringroad Selatan, Banguntapan, Bantul, DIY, 55166, Indonesia
**Corresponding author. Email: Muhammad.amri@te.uad.ac.id*

Abstract— Nowadays, implanted permanent pacemakers (PPM) users need to undergo periodic pacemaker replacement surgery. The surgery is needed since the pacemaker's battery is usually depleted in 5-10 years. This surgery, although poses relatively low health risks, is inconvenient for PPM users. Moreover, the surgery can still be dangerous for PPM users, especially considering that most of the users are elderly. PPM replacement surgery is also costly. In addition to the costs of the surgery itself, the PPM users need to bear the price of the new PPM every time they undergo surgery. Currently, when the PPM's battery runs out, the whole PPM needs to be replaced. This is conducted to prevent the possibility of a leak in the battery seal, which might allow the body fluids to enter the PPM. Typically, once a battery is inserted into the PPM, it will be permanently sealed along with all other electronic components, and thus, battery-only replacement is impossible. Thanks to the recent advancement of wireless power transfer (WPT) technology, a PPM replacement surgery might no longer be necessary in the near future. This article presents a brief review of the current state of coil-based WPT technology and its potential applications in pacemakers. Depending on the load and transmission distance, a recent WPT system for PPM could achieve WPT efficiency as high as 97.91% on air and 78% on pig tissue medium. In terms of output power, recent works that we have summarized showed that they are able to transmit power up to 5W on a WPT system implemented on a human phantom. We also discuss the challenges, limitations, and future prospects for WPT in the medical field, particularly for PPM applications.

Keywords— electromagnetic (EM) radiation; implanted pacemakers; inductive coupling; magnetic coupling; specific absorption rate (SAR); wireless power transfer (WPT)

I. INTRODUCTION

Wireless power transfer (WPT) technology, also known as wireless charging, has been gaining significant attention in recent years due to its potential to revolutionize the way we live and work. WPT technology allows for the transfer of electrical energy from a power source to a user device without the use of physical connectors or wires. This technology has the potential to greatly simplify the way we power our devices, making them more convenient and less prone to damage or wear and tear.

To this date, WPT has been used in various applications [1]–[6]. Among the most well-known applications are toothbrushes [1], electric vehicles [2], and mobile phones [3] and their accessories [4]. The potential use of WPT to power drones [5] or IoT devices such as surveillance cameras [6] has also been investigated. One area of particular interest for WPT technology is the medical field [7]. Of those applications in the medical fields are stimulators for the brain [8], cochlear nerve [9], spinal cord [10], vagus nerve [11], and retinal nerve [12]. WPT utilization to aid drug delivery robots has also been investigated in [13]. In this article, however, we are particularly interested in the potential use of WPT for permanent pacemakers (PPM). Pacemakers are small devices that are implanted in the chest to help regulate the heart's rhythm. They are powered by batteries. Originally, PPM needed to be replaced every couple of years [14]. Nowadays, thanks to the Li-Ion battery technology, the PPM battery can last for 5 to 10 years [15], meaning the PPM replacement does not have to be done every couple of years anymore. Still, this replacement requires a surgical procedure, which can be risky and costly for patients [16].

Although there is no official number of how many pacemakers have been implanted worldwide, previous studies found that the incidence of PPM insertion increase with age, with an approximation of up to 80% of all PPMs being implanted in $\geq$ 65-year-old patients [17]. With the aging populations and the increased overall life expectancy [18], the frequency of PPM insertion has continued to rise in most countries worldwide [19]–[21].

Currently, there is only a little information on the prevalence of PPM insertion in any country. Among that, information is available from the Danish regional population survey in 1990 [22]. It was estimated that the incidence of PPM insertion in the Danish regional population was 160/100,000, with 147 of 100,000 women and 172 of 100,000 men. This number increased with age, with 1102/100,000 for the population aged 75-79 and 2454/100,000 for people aged 90 or older [22]. Moreover, the study [22] predicted that if annual insertion prevalence continued to outnumber the death rate, the incidence figure might double in the next quarter century. Other information was provided by the Medical Device Implant Supplement through the 1988 US National Health Interview Survey [23]. The overall prevalence of the PPM insertion was higher than the Danish one.

Received 7 February 2023, Revised 10 April 2023, Accepted 3 May 2023.
DOI: https://doi.org/10.15294/jte.v15i1.42662

In the survey [23], the figure was estimated to be 260/100,000 for the general population, with 40/100,000 for patients aged between 18 and 65, and 2600/100,000 for those aged ≥75. Unfortunately, over the years, this figure is rapidly increased. Medicare (US) users of PPMs (age ≥65 years) demonstrated this rapid increase, with age-standardized incidence calculated at 325.4, 399.7, and 504.4 for every 100 000 people in 1990, 1995, and 2000, respectively [24]. The study [25] on Western Australian populations found that 9782 PPMs were installed between 1995 and 2009. Over the course of the study, the incidence has increased, reaching more than 1 in 50 among persons aged ≥75 by 2005. Patients aged ≥75 had rates that were more than twice as high as those between 65 and 74. This was supported by the prevalence rate that increased with age and peaked in people who were ≥85 years old, with >500 men per 100,000 people overall and >200 women per 100,000 people.

Although a low battery does not always usually result in the complete breakdown of the pacemakers, it is possible that the PPM will malfunction or fail due to power supply depletion [26]. Pacemakers malfunction may result in symptoms associated with the user's heart condition, such as chest pain accompanied by dizziness, nausea, weakness, or vomiting; heart palpitations; heart rate drop; respiratory (breathing) trouble; and even fainting or losing consciousness [27].

As aforementioned, in addition to the initial insertions, surgeries are needed to replace the PPM every about 5-10 years for each patient. Although generally, surgeries required to replace those PPMs are less complicated than those of the initial insertions [28], [29], there are still risks for the patients, especially considering that most of those patients are elderly, which are typically more vulnerable than the adult ones. Moreover, replacing those PPMs incurs significant financial and resources burden [28], [29].

Currently, when the PPM's battery runs out, the whole PPM needs to be replaced. This is conducted to prevent the possibility of a leak in the battery seal, which might lead to the body fluids entering the PPM [14], [30]. When the body fluids enter the PPM, they might break the PPM and ends up threatening the user's life. Therefore, typically, once a battery is inserted into the PPM, it will be permanently sealed along with all the other delicate electronic components, and thus, battery replacement is impossible [31].

Following this situation, many scholars have attempted to develop WPT for PPM applications. The use of WPT in pacemakers could eliminate the need for battery replacement surgeries, making the devices safer and more convenient for patients. There are several different types of WPT technologies currently available, including magnetic induction, electromagnetic radiation, and near-field coupling. Each of these technologies has its own advantages and limitations, and the choice of technology will depend on the specific application. For pacemakers, magnetic induction is arguably the most commonly used WPT technology [32], [33] due to its safety, efficiency, and ease of integration [32].

Magnetic induction WPT uses magnetic fields to transfer energy between a power source and a device. The power source, or transmitter, creates a magnetic field, which is picked up by a receiver coil in the device. The receiver coil then converts the magnetic energy into electrical energy to power the device. One of the key advantages of magnetic induction WPT is that it is relatively safe for human use [34], [35]. The magnetic fields used are non-ionizing and will not cause harm to human tissue. The magnetic fields used are also typically low in frequency, which means that they do not cause any interference with other electronic devices or medical equipment [32]. In the case of pacemakers, the magnetic induction WPT coils are implanted in the body, allowing the energy transfer to happen efficiently with minimal loss of power.

However, there are also some challenges and limitations associated with the use of WPT in pacemakers. One of the main challenges is achieving a sufficient power transfer distance between the transmitter and the receiver [36], [37]. Due to the nature of the magnetic field, the distance between the transmitter and receiver coils is limited by the strength of the magnetic field, and the power transfer efficiency decreases as the distance increases. Therefore, for pacemakers, the distance between the transmitter and receiver coils must be kept as small as possible.

Another limitation is that the WPT efficiency is affected by the coil size, coil design, and the alignment between the transmitter and receiver coils [38]. Despite these challenges, WPT technology is potential to improve the safety and convenience of pacemakers for patients. The use of WPT in pacemakers could eliminate the need for battery replacement surgery, reduce the risk of complications, and improve patient compliance.

In this brief review, we summarized the current state of coil-based WPT technology, specifically its potential applications in pacemakers. We also discussed the challenges and limitations of this technology and its future prospects. The review is derived from the recent high-quality published papers related to the WPT and PPM. Considering the critical need for WPT for implanted PPM, lots of work has been done on that topic in the last decades. Still, WPT systems for implanted pacemakers have not been widely available until this paper was written.

II. METHOD

In this article, we aim to summarize and present the recent development of the WPT, particularly for pacemakers' applications. In addition, we discuss the present challenges and the attempts that have been conducted to overcome those challenges. We also present a comprehensive discussion on the future opportunities of WPT for pacemakers' applications. This review was derived from recent high-quality original research papers, meta-analyses, systematic reviews, and selected literature. We searched major libraries such as Scopus, IEEE, ACM, MDPI, Nature, and Google Scholar for articles related to WPT and PPM for writing this short narrative review. The following keywords were used in the search strategy: wireless power transfer (WPT), wireless charging, resonance, inductive, magnetic, coupling, pacemakers, and permanent pacemakers (PPM). We did not use Boolean operators (e.g., AND, OR, NOT, etc.). Instead, we included all articles which contain one or more of the abovementioned keywords. We limit the language of search to English. There were no limitations on when the study was conducted and was published. The selected studies are summarized in Table I.

When this article was written, there were literally hundreds of previous studies that had been conducted regarding the WPT and PPM. However, this article is intended to be a brief narrative review instead of the comprehensive systematic/scoping one. Therefore, we aim to make the article as short as possible while maintaining the necessary information.

TABLE I. SUMMARY OF THE SELECTED STUDIES ON WPT FOR PPM APPLICATIONS

Works	**Output Power**	**Frequency**	**WPT Efficiency**	**Distance (Transmission)**	**Objects**	**Safety Measure**	**WPT System Type**	**Coils**	
								Transmitter	**Receiver**
[39], [40]	1 W	300 kHz	80%	10 mm	Air and saline solution	2 W/kg SAR (IEEE)	Separated	A planar spiral coil: 22 AWG, n = 10 D_{inner} = 36.6 mm	A planar spiral coil: 22 AWG, n = 4 (SP), D_{outer} = 35.4 mm
[39], [40]	1 W	13.56 MHz	80%	10 mm	Air and saline solution	2 W/kg SAR (IEEE)	Separated	A planar spiral coil: 22 AWG, n = 4 (SS), D_{inner} = 36.6 mm	A planar spiral coil: 22 AWG, n = 2 (SS), D_{outer} = 35.4 mm
[41]	5 W	160 kHz	88%	up to 10 cm	Human phantom (male)	2 W/kg SAR (IEEE)	Separated	2 planar spiral coils: n = 25, Δd = 190 mm, D_{outer} = 280 mm, D_{inner} = 190 mm, 16 ferrite bars per coil	2 planar spiral coils: n = 13, Δd = 5 mm, D_{outer} = 50 mm
[42], [43]	3.07 W	300 kHz	78%	8 mm	Pig tissue (skin:fat:lean ratio = 1:2:5 [mm])	2.89 W/kg psSAR (IEEE)	N/A	Planar helix coil: n = 13, size = 58 × 48 mm^2, D = 0.1 mm	Planar helix coil: n = 9, size = 44.5 × 30.5 mm^2
[44]	1 mW	403 MHz	5.24%	1 cm	Minced pork	2 W/kg SAR (IEEE)	Separated	Circular (spiral) resonator: Size = 30 × 30 mm^3	Square Split ring resonator: Size = 14.9 × 14.9 mm^3
[45]	13.26 W (50 Ω load) 23.5 W (100 Ω load)	6.78 MHz	91.86% (50 Ω load) 97.91% (100 Ω load)	1-2 cm	Air	N/A	Separated	Spider web coil: n = 4, D_{outer} = 122 mm, D_{inner} = 105 mm	Spider web coil: n = 3, D_{outer} = 115 mm, D_{inner} = 105 mm
[46]	N/A	6.78 MHz	24%	1 cm	Euthanized rat	N/A	Combined	PCB coil: n = 10, Coil size = 27 × 27 × 0.5 mm^3	PCB coil: n = 36, Coil size = 17 × 19 × 1 mm^3
[47]	200 uW	13.56 MHz	6%	20 - 30 mm (estimated value, by the diameters of the coils)	Euthanized pig	2 W/kg SAR (IEEE)	Combined	A planar spiral coil: n = 18, 23 AWG, D_{outer} = 40 mm, D_{inner} = 10 mm	A planar spiral coil: n = 4, 30 AWG, D_{outer} = 5 mm, D_{inner} = 1 mm
[48]	300 mW	198 MHz	N/A	200 - 300 mm (estimated value, by the diameters of the coils)	Ex vivo Langendorff heart models	N/A	Combined	2 octagonal coils fabricated on PCB: n = 4, n = 3, D_{outer} = 160 mm	A planar square coil: n = 6, 22 AWG, L = 4.9 mm
[49]	500 mW	20 kHz	77%	8 mm	Pig tissue (air:skin:fat ratio = 3:3:2 [mm])	2.7 V/m (ICNIRP)	Combined	A planar spiral coil: n = 29, 18 AWG, D_{outer} = 70 mm	A planar spiral coil: n = 39, 24 AWG, D_{outer} = 46 mm

To achieve the mentioned objective, we manually choose the most appropriate articles which describe the recent advancement of WPT, especially for charging the pacemakers. As a result, 11 published articles were gathered. Published research studies of any type were considered in this paper. However, unpublished data, commentary, personal communications, opinion articles, and technical notes were excluded.

In choosing the selected articles, we consider the following factors: Practical/experiment approach (instead of simulation-only approach), containing coil design information, presenting adequate performance metrics (e.g., output power, frequency range, WPT efficiency, transmission distance), and considering human safety measure (preferred). Due to these factors (particularly due to the first factor), the number of suitable works was significantly reduced. Indeed, there have been numerous studies regarding WPT and pacemakers. However, not many of them consider practicality (experiment approach) and presenting the above factors in their studies. We decided to include only WPT works with an experiment approach not only to present a fair apple-to-apple comparison between the selected articles but also to present more practical works. It is well known that in the WPT research area, simulation results can often differ significantly from the experiment results. Moreover, some works with simulation-only consideration often used unrealistic and ideal assumptions (e.g., zero noise, zero insertion/transmission loss, perfect electric conductor (PEC), etc.)

Note that in this article, the review is not conducted by following any protocol (e.g., PRISMA, etc.), nor using any quality assessment tools (e.g., Cochrane, CASP, etc.). Instead, the review is conducted simply based on the discussion between the authors (i.e., during the article selection process) considering the abovementioned factors.

III. RESULTS AND DISCUSSION

A. Recent Development in WPT for Pacemakers

Pacemakers are normally implanted below the collarbone of the user. An implanted pacemaker will then deliver appropriate electrical pulses to support the user in maintaining stable heart rates [50]. To achieve this function, pacemakers are usually comprised of two main components: a lead system and a pulse generator. As illustrated in Figure 1, pacemaker case typically contains a pulse generator, a battery, and other delicate circuits. A pacemaker is usually implanted not far from the skin surface, and due to this reason, near-field magnetic resonant WPT is preferred for PPMs. One important consideration in WPT design for PPM is that the coil should be designed to be as flexible as possible because the human body will stretch and flex most of the time.

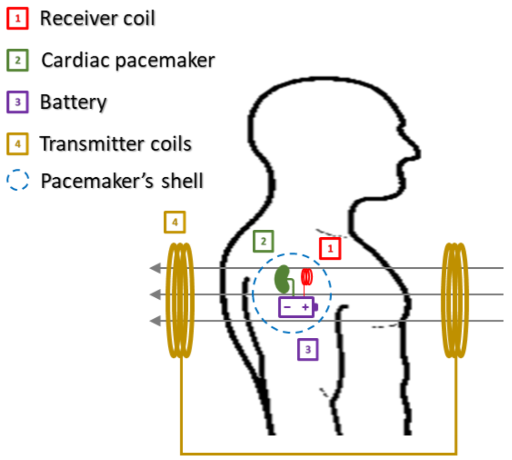

Figure 1. Typical magnetic coils-based WPT for PPM Applications

In Table I, we present several selected studies on WPT for pacemaker applications. When this paper was written, there were numerous studies on the WPT system for powering the PPM. Various media have been considered in previous studies. For instance, studies [39], [40] consider air and saline solution, while study [45] considers only air media. Pig tissue and pork become the most used media in Table I [42], [43], [47], [49], arguably due to their similarity with human tissue. The utilization of animal models has also been demonstrated in [46], where the authors conducted experiments on euthanized rats. The authors in [41] consider male human mannequins, while the authors in [48] employed Ex vivo Langendorff heart models. Figure 1 depicts the typical WPT system for PPM using magnetic coils. In [44], a resonant inductive link at 403 MHz is proposed to wirelessly power pacemakers with a power delivery of only 1 mW. In [43], the authors analyzed the eddy current's effect in the pacemaker's case without ferrite shielding at various positions. Then, with the EM radiation safety consideration in mind, a two-coil topology was employed with the resonant frequencies of 300 kHz and 13.56 MHz in the analysis of the EM field problem [39]. The proposed system is able to achieve power transfer efficiency as high as 80%. In [45], the authors managed to achieve a very high WPT efficiency (i.e., 97.91%). Attempts have also been made to design battery-less pacemakers which can be powered through the wireless link. However, this approach has quickly lost researcher's interest as it might be impractical for mobile patients [51], [52].

In [40], [53], magnetic resonant coupling-based WPT systems at 300 kHz and 13.56 MHz have been proposed to charge active implantable medical devices (AIMD). Possible coil misalignment and EMF safety standards have been taken into consideration. In that study, it was found that skin and proximity effects have induced notable losses [40], [53]. It was also found that the proposed WPT systems do not introduce significant safety concerns. The authors in [41] proposed a sandwiched WPT system to charge implantable cardiac pacemakers. A sandwich structure with a bilateral coil design approach is used to design a WPT system in a low-frequency band (i.e., 160 kHz). Thanks to the sandwich transmitting coil architecture, high feasibility and flexibility of the controllable distance for different devices can be achieved. In the study [41], the transmitter side is comprised of two coils that are wrapped with 165 0.1 mm Litz wires to minimize proximity and skin effects. The transmitting coils have 16 ferrite cores each to ensure that optimal power transfer efficiency can be achieved. Both coils have an outer diameter (D_{outer}) of 280 mm and an inner diameter (D_{inner}) of 190 mm. Those coils are co-located with a 190 mm gap between them. The gap is made such that it is enough for an adult patient to lie down or stand between those two coils. Likewise, the two receiver coils are wrapped with 100 0.07 mm Litz wire. In that study, two symmetrical coils are used to increase the WPT efficiency. As a result, a relatively decent WPT efficiency of 88% can be achieved in the in vitro test. However, coils misalignment (i.e., rotation and position shift) might deteriorate the power transfer efficiency, thus, needs to be anticipated.

The feasibility of splitting the wireless transmission link and the pacer is illustrated by previous studies (see Table I). The integration of operational and power components may produce a relatively poor efficiency because the magnetic flux may readily reach the reception coil with a closer transmission length. Additionally, different research studies showed different output power values. These parameters represent the period of the charging phase. However, a quick charging duration could have unfavorable consequences. Due to its excellent metal shell ductility, titanium is often used as the encapsulating material for pacemakers, as indicated by almost all of the studies mentioned in Table I. However, it shall be noted that metallic shielding causes the eddy current effect to be stimulated. This will cause a drop in power transfer efficiency (PTE) and a rise in specific absorption rate (SAR) with heat generation. Typically, there is no additional coating analysis for the implanted coil because the receiving coil is already built inside the cardiac case. Using various criteria, each study on the list complies with the safety requirements for SAR. Since the majority of study papers extensively examined the SAR or thermal impacts, the safety metric is also included in Table I. The focus on safety issues is a sign that the study has reached the commercialization and optimization stages.

B. Specific Absorption Rate (SAR)

SAR can be defined as a time derivative of incremental energy dissipated in or absorbed by an incremental mass within a given density in a known volume [54]. Generally, the SAR value can be estimated as [55]:

$$\mathrm{SAR} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\rho \mathrm{d}V}\right) \qquad (1)$$

In relation to the electric fields at a certain point (i.e., human tissue), (1) can be rewritten as:

$$\mathrm{SAR} = \frac{\sigma}{\rho} \times E^2 \left[\frac{W}{kg}\right] \qquad (2)$$

where σ is the tissue conductivity [S/m], ρ is the tissue mass density [kg/m3], and E is the electric field strength of the RMS [V/m].

As in Table I, Studies [45], [46], and study [48] did not specify the SAR standard in their study analysis. However, the majority of the selected studies (i.e., 7 studies) adopted the IEEE standard as their SAR constraint, while the study [49] adopted the ICNIRP standard for the SAR analysis. Regardless, the proposed WPT systems in those eight studies managed to satisfy the SAR safety requirements.

C. Power Transfer Level and Efficiency

The output power level (power delivery) P_L of WPT, in general, and particularly for pacemaker applications, can be calculated simply by multiplying the load voltage V_L and the load current I_L of the WPT system as in (3) [56], [57]:

$$\mathrm{P_L} = V_L \times I_L \qquad (3)$$

whereas the power transfer efficiency can be calculated as [56], [57]:

$$\mathrm{Efficiency} = \frac{\mathrm{P_{out}}}{\mathrm{Pin}} \times 100\% \qquad (4)$$

where $\mathrm{P_{out}}$ represents the delivered power and $\mathrm{P_{in}}$ represents the input power.

D. Challenges in WPT Research for Pacemakers

Following previous studies, the challenges and difficulties of WPT research and implementation for pacemakers can be summarized as follows. First, due to the variations in the muscles and tissues of the chests among individuals, the transmission distances among WPT users can be different. Thus, it may affect the performance of the implanted WPT system (e.g., efficiency, power level, etc.). Second, it is quite challenging to balance the requirements between the power transfer level and the resonant frequency. Ideally, a PPM needs an adequately high WPT level to be able to charge and operate normally. Indeed, a higher resonant frequency might enable a better capability of WPT under identical distances [58], [59]. However, a sufficiently high resonant frequency might introduce a higher risk of safety hazards for PPM users.

Although previous studies have considered safety measurements (i.e., SAR, EMF safety standard), there is no guarantee that long-term exposure to radiation (even at the 'safe' level) will not introduce impacts on human health. Previous studies showed that radiation might affect the human body on genes, proteins, and even DNA levels [60]. In the context of WPT implementations for PPM, the risk of a potentially higher probability of heart attack due to the reduced protein level [61] shall be taken into account. Then, as additional wires might need to be employed to transfer the power to the pacers [62], the additional safety risks need due to those extra wires need to be taken into account. Lastly, a rechargeable PPM requires additional delicate circuits, ferrite beads, and coil that need to be packed into the PPM case, not to mention that some rechargeable PPM might need multiple coils to minimize the probability of coils misalignments and increase the power transfer efficiency. Due to space constraints, the design complexity of the already complex PPM might increase exponentially. With this design consideration in mind, the WPT efficiency and eddy current effect shall also be considered [63].

E. Future Directions for WPT Research for Pacemakers

The ultimate goal for WPT implementations is to deliver a sufficiently high power level via high-efficiency wireless links in a safe and pleasant manner. To achieve this, innovation in WPT compensation topologies (e.g., LCC-C [42] and LCL [42]) can be explored. To increase the power transfer efficiency, multiple coils and ferrite cores can be utilized. Previous studies [64]–[66] have indicated that employing ferrite cores in wireless links, although increasing the production costs and complexities, intensifies the electromagnetic field for a higher power transfer efficiency.

An adequately high power transfer level is preferred such that the users do not need to stay nearby the charging station for a long time. However, accurate numerical evaluation of SAR and thermal effects should be conducted to ensure the safety of the users.

Coil misalignment is another challenge for WPT implementations. As aforementioned, multiple coils, configured in an appropriate manner, can prevent the probability of WPT outage due to the coils' misalignment. However, this approach increases the complexity and the PPM size requirements. Another method to avoid coil misalignment in WPT for implantable pacemakers is by completely removing it. In the future, radio frequency-based WPT will be preferred for power delivery for implantable devices [67]–[69]. This is because radio frequency-based WPT offers a longer distance (i.e., in the order of meters, tens of meters, hundreds of meters, and even hundreds of kilometers [70]). To enable this, the PPM should be equipped with receiving antenna, rectifier, and WPT circuits. However, rf-based WPT, at least in its current state, is notorious for its low power transfer level and low efficiency. While a low power transfer level is not a problem (as long as it is adequate), low efficiency can be improved through various methods. Beamforming [71], efficient rectifiers [72], and multi-antennas [73] are among the techniques that can be used to increase the efficiency of the RF-based WPT.

IV. CONCLUSION

WPT technology has the potential to revolutionize pacemakers by eliminating the need for battery replacement surgeries, making them safer and more convenient for patients. Magnetic induction, among various WPT technologies available (e.g., magnetic induction, electromagnetic radiation, and near-field coupling), is commonly used in pacemakers due to its safety, efficiency, and ease of integration. This technology uses magnetic fields to transfer energy, ensuring non-ionizing and interference-free operation with other electronic devices and medical equipment. This article briefly reviews the current state of coil-based WPT technology and its potential applications in pacemakers. Recent research has demonstrated that the WPT system for PPM can achieve high efficiency of up to 97.91% over the air and 78% over pig tissue, depending on the transmission distance and load. Furthermore, recent studies have shown that WPT system can transmit up to 5W of output power when implemented on a human phantom. Despite challenges such as distance limitations and coil size alignment affecting power transfer efficiency, further research and development might overcome these obstacles. With the benefits of WPT technology, such as improved patient safety and avoiding battery replacement surgeries, outweighing the drawbacks, it is crucial to continue exploring its potential applications in pacemakers.

REFERENCES

[1] N. Shinohara, "History, present and future of wpt," *Wireless Power Transfer via Radiowaves*, pp. 1–20, 2013.

[2] D. M. Vilathgamuwa and J. P. K. Sampath, "Wireless power transfer (WPT) for electric vehicles (EVS)—Present and future trends," *Plug In Electric Vehicles in Smart Grids: Integration Techniques*, pp. 33–60, 2015.

[3] M. Fareq *et al.*, "Solar wireless power transfer using inductive coupling for mobile phone charger," in *2014 IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014)*, 2014, pp. 473–476.

[4] H. Yang, L. Yang, L. Jia, and R. Shone, "Motorized Wireless-Charging Pad that Uses Magnetic Field Detection," *Technical Disclosure Commons: Defensive Publications Series, Art. 2397*, p. 1-12, 2019.

[5] T. Campi, F. Dionisi, S. Cruciani, V. de Santis, M. Feliziani, and F. Maradei, "Magnetic field levels in drones equipped with wireless power transfer technology," in *2016 Asia-Pacific international symposium on electromagnetic compatibility (APEMC)*, 2016, vol. 1, pp. 544–547.

[6] S. Naderiparizi, A. N. Parks, Z. Kapetanovic, B. Ransford, and J. R. Smith, "WISPCam: A battery-free RFID camera," in *2015 IEEE International Conference on RFID (RFID)*, 2015, pp. 166–173.

[7] Y. Zhou, C. Liu, and Y. Huang, "Wireless power transfer for implanted medical application: A review," *Energies (Basel)*, vol. 13, no. 11, p. 2837, 2020.

[8] C.-L. Yang, C.-K. Chang, S.-Y. Lee, S.-J. Chang, and L.-Y. Chiou, "Efficient four-coil wireless power transfer for deep brain stimulation," *IEEE Trans Microw Theory Tech*, vol. 65, no. 7, pp. 2496–2507, 2017.

[9] S. Rao and J.-C. Chiao, "Body electric: Wireless power transfer for implant applications," *IEEE Microw Mag*, vol. 16, no. 2, pp. 54–64, 2015.

[10] Q. Xu, D. Hu, B. Duan, and J. He, "A fully implantable stimulator with wireless power and data transmission for experimental investigation of epidural spinal cord stimulation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 23, no. 4, pp. 683–692, 2015.

[11] I. Habibagahi *et al.*, "Vagus nerve stimulation using a miniaturized wirelessly powered stimulator in pigs," *Sci Rep*, vol. 12, no. 1, pp. 1–12, 2022.

[12] G. Wang, W. Liu, M. Sivaprakasam, M. Zhou, J. D. Weiland, and M. S. Humayun, "A dual band wireless power and data telemetry for retinal prosthesis," in *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, 2006, pp. 4392–4395.

[13] J. Gao *et al.*, "Design and testing of a motor-based capsule robot powered by wireless power transmission," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 2, pp. 683–693, 2015.

[14] V. S. Mallela, V. Ilankumaran, and N. S. Rao, "Trends in cardiac pacemaker batteries," *Indian Pacing Electrophysiol J*, vol. 4, no. 4, p. 201, 2004.

[15] W. F. DeForge, "Cardiac pacemakers: a basic review of the history and current technology," *Journal of Veterinary Cardiology*, vol. 22, pp. 40–50, 2019.

[16] O. Merin *et al.*, "Permanent pacemaker implantation following cardiac surgery: indications and long-term follow-up," *Pacing and clinical electrophysiology*, vol. 32, no. 1, pp. 7–12, 2009.

[17] W. S. Aronow and G. Gregoratos, "Management of atrial fibrillation, ventricular arrhythmias and pacemakers in older persons: Permanent pacemakers in older persons," *J Am Geriatr Soc*, vol. 47, no. 9, pp. 1125–1135, 1999.

[18] G. McNicoll, "World Population Ageing 1950-2050.," *Popul Dev Rev*, vol. 28, no. 4, pp. 814–816, 2002.

[19] H. G. Mond and A. Proclemer, "The 11th world survey of cardiac pacing and implantable cardioverter-defibrillators: calendar year 2009–a World Society of Arrhythmia's project," *Pacing and clinical electrophysiology*, vol. 34, no. 8, pp. 1013–1027, 2011.

[20] H. Ector and P. Vardas, "Current use of pacemakers, implantable cardioverter defibrillators, and resynchronization devices: data from the registry of the European Heart Rhythm Association," *European Heart Journal Supplements*, vol. 9, no. suppl_I, pp. I44–I49, 2007.

[21] H. G. Mond, M. Irwin, C. Morillo, and H. Ector, "The world survey of cardiac pacing and cardioverter defibrillators: calendar year 2001," *Pacing and clinical electrophysiology*, vol. 27, no. 7, pp. 955–964, 2004.

[22] G. Andersen, A. Green, G. M. Madsen, and P. E. R. Arnsbo, "The epidemiology of pacemaker implantations in Fyn county, Denmark," *Pacing and Clinical Electrophysiology*, vol. 14, no. 11, pp. 1614–1621, 1991.

[23] B. G. Silverman, T. P. Gross, R. G. Kaczmarek, P. Hamilton, and S. Hamburger, "The epidemiology of pacemaker implantation in the United States.," *Public Health Reports*, vol. 110, no. 1, p. 42, 1995.

[24] D. W. Brown, J. B. Croft, W. H. Giles, R. F. Anda, and G. A. Mensah, "Epidemiology of pacemaker procedures among Medicare enrollees in 1990, 1995, and 2000," *Am J Cardiol*, vol. 95, no. 3, pp. 409–411, 2005.

[25] P. J. Bradshaw, P. Stobie, M. W. Knuiman, T. G. Briffa, and M. S. T. Hobbs, "Trends in the incidence and prevalence of cardiac pacemaker insertions in an ageing population," *Open Heart*, vol. 1, no. 1, p. e000177, 2014.

[26] H. G. Mond and G. Freitag, "The cardiac implantable electronic device power source: evolution and revolution," *Pacing and Clinical Electrophysiology*, vol. 37, no. 12, pp. 1728–1745, 2014.

[27] R. Lampert, "Managing with pacemakers and implantable cardioverter defibrillators," *Circulation*, vol. 128, no. 14, pp. 1576–1585, 2013.

[28] Y. Hao, Y. Li, D. Liao, and L. Yang, "Seven times replacement of permanent cardiac pacemaker in 33 years to maintain adequate heart rate: a case report," *Ann Transl Med*, vol. 3, no. 21, p. 1-5, 2015.

[29] X. Liu, L. Ren, and H. Ye, "Reasons and complications of pacemaker replacement operation: clinical analysis of 69 case-times," *Zhonghua Yi Xue Za Zhi*, vol. 88, no. 28, pp. 1989–1991, 2008.

[30] T. Mittal, "Pacemakers—A journey through the years," *Indian J Thorac Cardiovasc Surg*, vol. 21, pp. 236–249, 2005.

[31] J. Dean and N. Sulke, "Pacemaker battery scandal," *BMJ Editorial: British Medical Journal Publishing Group*, vol. 352., p. 1-2, 2016.

[32] M. Haerinia and R. Shadid, "Wireless power transfer approaches for medical implants: A review," *Signals*, vol. 1, no. 2, pp. 209–229, 2020.

[33] P. Nordbeck, G. Ertl, and O. Ritter, "Magnetic resonance imaging safety in pacemaker and implantable cardioverter defibrillator patients: how far have we come?," *Eur Heart J*, vol. 36, no. 24, pp. 1505–1511, 2015.

[34] D. B. Ahire, V. J. Gond, and J. J. Chopade, "Compensation topologies for wireless power transmission system in medical implant applications: A review," *Biosens Bioelectron X*, vol. 11, p. 1-10, 2022.

[35] I. A. Shah, A. Basir, Y. Cho, and H. Yoo, "Safety analysis of medical implants in the human head exposed to a wireless power transfer system," *IEEE Trans Electromagn Compat*, vol. 64, no. 3, pp. 640–649, 2022.

[36] J. Chen and J. Xu, "A new coil structure for implantable wireless charging system," *Biomed Signal Process Control*, vol. 68, p. 102693, 2021.

[37] R. Das and H. Yoo, "Biotelemetry and wireless powering for leadless pacemaker systems," *IEEE Microwave and Wireless Components Letters*, vol. 25, no. 4, pp. 262–264, 2015.

[38] U. Uthayakumar and Y. Jayaweera, "Wireless Power Transfer for Cardiac Pacemaker," in *2022 IEEE Symposium on Wireless Technology & Applications (ISWTA)*, 2022, pp. 62–67.

[39] T. Campi, S. Cruciani, F. Palandrani, V. de Santis, A. Hirata, and M. Feliziani, "Wireless power transfer charging system for AIMDs and pacemakers," *IEEE Trans Microw Theory Tech*, vol. 64, no. 2, pp. 633–642, 2016.

[40] T. Campi, S. Cruciani, V. de Santis, F. Palandrani, F. Maradei, and M. Feliziani, "Induced effects in a pacemaker equipped with a wireless power transfer charging system," *IEEE Trans Magn*, vol. 53, no. 6, pp. 1–4, 2017.

[41] C. Liu, C. Jiang, J. Song, and K. T. Chau, "An effective sandwiched wireless power transfer system for charging implantable cardiac pacemaker," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 4108–4117, 2018.

[42] C. Xiao, D. Cheng, and K. Wei, "An LCC-C compensated wireless charging system for implantable cardiac pacemakers: Theory, experiment, and safety evaluation," *IEEE Trans Power Electron*, vol. 33, no. 6, pp. 4894–4905, 2017.

[43] C. Xiao, K. Wei, D. Cheng, and Y. Liu, "Wireless charging system considering eddy current in cardiac pacemaker shell: Theoretical modeling, experiments, and safety simulations," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 3978–3988, 2016.

[44] G. Monti, P. Arcuti, and L. Tarricone, "Resonant inductive link for remote powering of pacemakers," *IEEE Trans Microw Theory Tech*, vol. 63, no. 11, pp. 3814–3822, 2015.

[45] A. I. Mahmood, S. K. Gharghan, M. A. A. Eldosoky, M. F. Mahmood, and A. M. Soliman, "Wireless power transfer based on spider web–coil for biomedical implants," *IEEE Access*, vol. 9, pp. 167674–167686, 2021.

[46] D. Kim *et al.*, "Design and implementation of a wireless charging-based cardiac monitoring system focused on temperature reduction and robust power transfer efficiency," *Energies (Basel)*, vol. 13, no. 4, p. 1008, 2020.

[47] P. Abiri *et al.*, "Inductively powered wireless pacing via a miniature pacemaker and remote stimulation control system," *Sci Rep*, vol. 7, no. 1, p. 6180, 2017.

[48] H. Lyu *et al.*, "Leadless multisite pacing: A feasibility study using wireless power transfer based on Langendorff rodent heart models," *J Cardiovasc Electrophysiol*, vol. 29, no. 11, pp. 1588–1593, 2018.

[49] T. Campi, S. Cruciani, V. de Santis, and M. Feliziani, "EMF safety and thermal aspects in a pacemaker equipped with a wireless power transfer system working at low frequency," *IEEE Trans Microw Theory Tech*, vol. 64, no. 2, pp. 375–382, 2016.

[50] V. S. Mallela, V. Ilankumaran, and N. S. Rao, "Trends in cardiac pacemaker batteries," *Indian Pacing Electrophysiol J*, vol. 4, no. 4, p. 201, 2004.

[51] H. Wieneke, T. Konorza, R. Erbel, and E. Kisker, "Leadless pacing of the heart using induction technology: a feasibility study," *Pacing and Clinical Electrophysiology*, vol. 32, no. 2, pp. 177–183, 2009.

[52] S. Kim, J. S. Ho, and A. S. Y. Poon, "Wireless power transfer to miniature implants: Transmitter optimization," *IEEE Trans Antennas Propag*, vol. 60, no. 10, pp. 4838–4845, 2012.

[53] S. Cruciani, T. Campi, F. Palandrani, V. de Santis, F. Maradei, and M. Feliziani, "Induced effects in a pacemaker equipped with wireless power transfer charging system," in *2016 IEEE Conference on Electromagnetic Field Computation (CEFC)*, 2016, p. 1.

[54] D. Seabury, "An update on SAR standards and the basic requirements for SAR assessment," *Conformity: Feature Article*, pp. 1–8, 2005.

[55] S. Kovar, I. Spano, G. Gatto, J. Valouch, and M. Adamek, "SAR evaluation of wireless antenna on implanted cardiac pacemaker," *J Electromagn Waves Appl*, vol. 31, no. 6, pp. 627–635, 2017.

[56] M. F. Mahmood, S. L. Mohammed, and S. K. Gharghan, "Free battery-based energy harvesting techniques for medical devices," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 745, no. 1, p. 012094.

[57] M. F. Mahmood, S. K. Gharghan, S. L. Mohammed, A. Al-Naji, and J. Chahl, "Design of powering wireless medical sensor based on spiral-spider coils," *Designs (Basel)*, vol. 5, no. 4, p. 59, 2021.

[58] D. Kim, J. Park, K. Kim, H. H. Park, and S. Ahn, "Propulsion and control of implantable micro-robot based on wireless power transfer," in *2015 IEEE Wireless Power Transfer Conference (WPTC)*, 2015, pp. 1–4.

[59] B. Lee, M. Kiani, and M. Ghovanloo, "A triple-loop inductive power transmission system for biomedical applications," *IEEE Trans Biomed Circuits Syst*, vol. 10, no. 1, pp. 138–148, 2015.

[60] S. Ivancsits, E. Diem, A. Pilger, H. W. Rüdiger, and O. Jahn, "Induction of DNA strand breaks by intermittent exposure to extremely-low-frequency electromagnetic fields in human diploid fibroblasts," *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, vol. 519, no. 1–2, pp. 1–13, 2002.

[61] J. Wang, S. Koyama, Y. Komatsubara, Y. Suzuki, M. Taki, and J. Miyakoshi, "Effects of a 2450 MHz high-frequency electromagnetic field with a wide range of SARs on the induction of heat-shock proteins in A172 cells," *Bioelectromagnetics: Journal of the Bioelectromagnetics Society, The Society for Physical Regulation in Biology and Medicine, The European Bioelectromagnetics Association*, vol. 27, no. 6, pp. 479–486, 2006.

[62] S. Giannantonio, W. di Nardo, L. Schinaia, and G. Paludetti, "Adaptation of cochlear implant fitting to various telecommunication systems: a proposal for a 'telephone map'," *Acta Otolaryngol*, vol. 134, no. 8, pp. 802–812, 2014.

[63] C. Xiao, K. Wei, D. Cheng, and Y. Liu, "Wireless charging system considering eddy current in cardiac pacemaker shell: Theoretical modeling, experiments, and safety simulations," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 3978–3988, 2016.

[64] H. Miura, S. Arai, Y. Kakubari, F. Sato, H. Matsuki, and T. Sato, "Improvement of the transcutaneous energy transmission system utilizing ferrite cored coils for artificial hearts," *IEEE Trans Magn*, vol. 42, no. 10, pp. 3578–3580, 2006.

[65] M. Wang, J. Feng, Y. Shi, and M. Shen, "Demagnetization weakening and magnetic field concentration with ferrite core characterization for efficient wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1842–1851, 2018.

[66] S. Santalunai, C. Thongsopa, and T. Thosdeekoraphat, "An increasing the power transmission efficiency of flat spiral coils by using ferrite materials for wireless power transfer applications," in *2014 11th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 2014, pp. 1–4.

[67] A. Basir and H. Yoo, "Efficient wireless power transfer system with a miniaturized quad-band implantable antenna for deep-body multitasking implants," *IEEE Trans Microw Theory Tech*, vol. 68, no. 5, pp. 1943–1953, 2020.

[68] A. Khaleghi, A. Hasanvand, and I. Balasingham, "Radio frequency backscatter communication for high data rate deep implants," *IEEE Trans Microw Theory Tech*, vol. 67, no. 3, pp. 1093–1106, 2018.

[69] P. Abiri, A. Yousefi, H. Cao, J.-C. Chiao, and T. K. Hsiai, "Wirelessly Powered Medical Implants via Radio Frequency," *Interfacing Bioelectronics and Biomedical Sensing*, pp. 101–116, 2020.

[70] L. H. Whitesides, "Researchers beam'space'solar power in Hawaii," *Wired Magazine*, p. 1, 2008.

[71] T. Liu, X. Qu, F. Yin, and Y. Chen, "Energy efficiency maximization for wirelessly powered sensor networks with energy beamforming," *IEEE Communications Letters*, vol. 23, no. 12, pp. 2311–2315, 2019.

[72] B. R. Franciscatto, V. Freitas, J.-M. Duchamp, C. Defay, and T. P. Vuong, "High-efficiency rectifier circuit at 2.45 GHz for low-input-power RF energy harvesting," in *2013 European Microwave Conference*, 2013, pp. 507–510.

[73] X. Chen, Z. Zhang, H.-H. Chen, and H. Zhang, "Enhancing wireless information and power transfer by exploiting multi-antenna techniques," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 133–141, 2015.