# Merits and Drawbacks of the Application of Ultrasonic Power Delivery in Biomedical Implants

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**Abstract:** Wireless power transfer technologies have proven to be a necessary feature for biomedical implants because they reduce medical complications and encourage miniaturization of the implant device. This paper examines the mechanisms behind one of these technologies, ultrasonic power delivery, and discusses its merits and drawbacks. It is found that ultrasonic power delivery has superior power transfer efficiency for scenarios where long transfer distances (decimeter level) and miniaturized receivers (mm-sized) are desired. On the downside, an ultrasonic sound wave is terrible at penetrating stiff materials like bones, which limits its application to soft tissues. The power transfer efficiency is also susceptible to complex factors like acoustic mechanical mismatch. Finally, extended exposure to ultrasonic power delivery may cause health issues like tissue heating and cavitation. Although there are currently insufficient research efforts for the health concerns of ultrasonic power delivery, there have been steady improvements to the power transfer efficiency. As a conclusion to the discussion, this paper points out a future research direction by proposing that an inductive-ultrasonic hybrid link can overcome the challenges faced by ultrasonic power delivery and bring massive improvements to overall power transfer efficiency.

## 1. Introduction

Thanks to the development of material science, integrated circuits, and packaging techniques, implantable electronic devices for medical applications have seen exponential advancements in the past few decades. More mature products like cardiac pacemakers, spinal cord stimulators, and cochlear implants have been used to dramatically improve patients' survival rate and quality of life, while novel technologies like retinal implants promise to benefit a greater part of the population. Accompanying the complex functions of medical implants, however, is the demand for reliable and consistent power supply, which has historically been a challenge. One early approach to this problem is built-in batteries [1]. However, these batteries have short life spans and must be replaced through invasive surgery periodically, causing the patients more pain and increasing the chance of infections [2]. Certain devices can harvest existing energy from the body. Cardiac pacemakers, for example, can harvest kinetic energy from the vibration generated by heartbeats, but the available vibration intensity in the human body is usually too low to be considered as an appropriate method for biomedical implants [3]. All these necessitate the application of wireless power transfer (WPT) in biomedical implants.

In general, there are two main goals that WPT systems for biological implants aim to achieve. The first is miniaturization. Past research has shown that the size of biological implants is closely related to mechanical mismatch, which is responsible for inflammatory responses in the body [4]. Miniaturization helps to reduce mechanical mismatch and in general, improves the biocompatibility of the implant. The second is transfer efficiency, which can be affected by the tissue impedance and transfer distance. Higher transfer efficiency is always desirable since low transfer efficiency necessarily implies higher power consumption, higher heat output, and slower charging rate.

Recent developments in this field are primarily innovations in mid to far fields radiofrequency radiation, inductive coupling, and acoustic power transfer, which operates at ultrasound frequency.

Among these, the acoustic solution draws attention because of its long-range power transfer capability and smaller receiver size [5]. This paper is dedicated to an overview of the mechanism behind ultrasonic power delivery and a close discussion of the merits and drawbacks of the application of ultrasonic power delivery in biomedical implants. Based on these discussions, a solution is proposed to address the problems with ultrasonic power delivery.

## 2. Mechanism and Structure of Ultrasonic Power Delivery

### 2.1 Principles of Ultrasonic Power Delivery

Ultrasonic power delivery uses propagating ultrasound waves to carry energy. A property of ultrasound waves is that, unlike electromagnetic waves, they need a medium to propagate. In the case of a biomedical implant, the medium would be human tissue. The energy of the propagating ultrasonic wave is harvested by a piezoelectric transducer usually made of lead zirconate titanate (PZT) which converts the energy of sound waves to electrical energy [6]. Figure 1 depicts the structure of a typical ultrasonic energy transfer system. TX is an electrically excited oscillator that generates high-frequency acoustic pressure waves through vibrations on the surface. RX is a piezoelectric transducer located inside the main radiation lobe of TX and harvests acoustic energy [7].

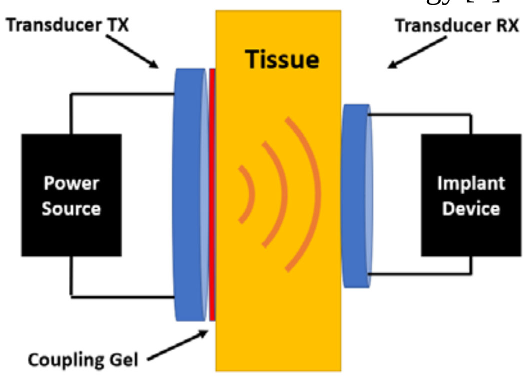


Figure 1. Structure of an ultrasonic power delivery system

The Huygens principle aids in the process of finding the field pattern of the sound wave. Since each point on the transducer can be regarded as an independent source, the wave pattern can be calculated as the vector sum of the contributions from all independent sources. The pressure field at an observation point is thus given by the following:

$$P(x,y,z:t) = \frac{jk\rho_0 c_0 u_0}{2\pi} e^{iwt} \int_S \frac{e^{-jkR}}{R} dS \tag{1}$$

Where R is the distance from the infinitesimal point source to the point of observation; $u_0$ is the vibration velocity amplitude; λ is the wavelength of pressure wave; $c_0$ is the wave's phase velocity; $\rho_0$ is the medium density; ω is the angular frequency; and k is the wave number [8].

### 2.2 Ultrasonic Power Transfer Efficiency

Three factors, transfer distance, wave frequency, reflection loss play important roles in the power transfer efficiency of an acoustic power delivery system. Each will be addressed below.

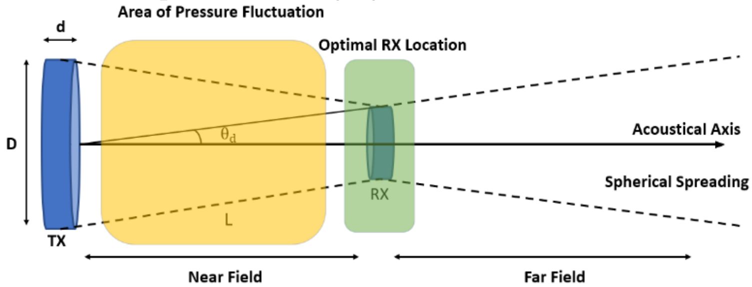


Figure 2. Ultrasonic wave behavior and optimal receiver location

Acoustic power transfer for implanted medical devices depends on the propagation of ultrasonic waves through the biological tissue, and the density and elastic properties of the medium determine the wave speed. The near field wave is close to TX, and the oscillation of the pressure field envelope in this field results in great fluctuations in power. The far field is characterized by a wave that spreads spherically and decays as it travels further from the source. The preferred location (colored in green in figure 2) for the receiver corresponds to the region where near field to far field transition happens, which is known as the natural focus zone. Here the wave's beam waist reaches a minimum. The distance between TX and this transition region is defined as the Rayleigh distance [2]:

$$L = \frac{(D^2-\lambda^2)}{4\lambda} \approx \frac{D^2}{4\lambda}, D^2 \gg \lambda^2 \tag{2}$$

Where D is the aperture width of TX; λ is the wavelength of the acoustic wave. At the Rayleigh distance, the divergence angle at which the acoustic beam spreads is:

$$\theta_d = sin^{-1}(\frac{1.22\lambda}{D}) \tag{3}$$

The Rayleigh distance is where the theoretical maximum power occurs. The acoustic pressure reaches a maximum and is relatively stable. Eq. 1 approximates the location of the pressure maxima in the near field region along the acoustic axis

$$X_{max}(m) = \frac{D^2-\lambda^2(2m+1)^2}{4\lambda(2m+1)} \tag{4}$$

Where m (=1, 2, 3…) is the order of the pressure peaks.

The transmission frequency is also crucial for transfer efficiency, as it affects Rayleigh distance, tissue attenuation, and the size of the transducers. The maximum transfer power is achieved at the transducer's resonant frequency, which can be determined by its material and geometric properties

$$f_r = \frac{c}{2d} \tag{5}$$

Where c is the acoustic velocity in the piezoelectric transducer and d the transducer's thickness. Increasing resonant frequency leads to smaller transducer size and longer Rayleigh distance; however, it comes at the cost of increased tissue absorption [9].

As the pressure wave propagates from TX to RX, it encounters a phenomenon known as acoustic impedance mismatch. This causes a part of the pressure wave to reflect to the transducer-tissue boundary. The pressure reflection coefficient for normal incidence is given by the following equation.

$$|\tau| = \left|\frac{Z_{tissue}-Z_{transducer}}{Z_{tissue}+Z_{transducer}}\right| \tag{6}$$

An intuitive interpretation for $\tau$ is the ratio of the amplitude of the reflected wave to that of the incident wave. Thus, $P_t = (1-\tau)P_i$ is the transferred pressure, where $P_i$ is the pressure of the incident wave. Since the power intensity depends on $P_t^2$, an acoustically unmatched transducer will cause a drastic drop in the transferred power. An unmatched transducer usually has a high mechanical Q factor, so it will also narrow the range of operating frequencies around the resonance frequency. Last but not least, mismatched impedance can cause the generation of pressure standing waves with peak pressure levels possibly exceeding the safety limit of the tissue. Consequently, matching the transducer impedance to the tissue impedance is essential to creating a successful ultrasonic power delivery system.

Ultimately, when many different factors are taken into consideration together, the power transfer efficiency can be expressed by the following equation [9]:

$$\eta = \left|\frac{P_{OUT}}{P_{IN}}\right| = \frac{(\mu TNR_L)^2}{C_{TX}C_{RX}V_{IN}^2(R_L+Z_{OUT})^2} \tag{7}$$

Where $C_{RX}$ is the receiver capacitance, $Z_{out} = 1/j\omega C_{RX}$ is the output impedance, $\mu = e^{-2\alpha x}$ is the tissue attenuation factor ($\alpha$ is the attenuation coefficient and x is the implant depth), N is the turn ratio of the electrically equivalent model of a piezoelectric transducer and $T \approx 2|Z_{receiver}| \times c$ ($Z_{receiver}$ is the acoustic impedance of the receiver defined as the product of its density and the speed of sound in the material).

## 3. Merits of Ultrasonic Power Delivery

### 3.1 Ultrasound Waves Decays Slowly in Soft Tissue

Compared to traditional WPT solutions utilizing electromagnetic waves, ultrasonic energy has less attenuation in human tissue. This increases penetration depth and reduces the introduction of excessive power into the tissue, which is usually caused by absorption and scattering.

Alexey Denisov and Eric Yeatman conducted a simulation to compare the power transfer efficiency in human tissue of acoustic solutions and inductive coupling solutions on various transfer distances [10]. As expected, both solutions saw drops in transfer efficiency as the source-receiver distance increased. However, the efficiency drop of the acoustic solution decays is less significant. For a 5 mm receiver, the acoustic solution achieved higher efficiency when the distance was longer than 1.5 cm; for a 10 mm receiver, the acoustic solution achieved higher efficiency when the distance was longer than 3 cm.

Tzu-Chieh Chou et al. designed a miniaturized ultrasonic power delivery system and tested it on pork muscle [5]. They also included an electromagnetic coupling power delivery system as a comparison. The results indicate that the acoustic solution offers superior results compared to electromagnetic coupling when the source-receiver distance exceeds 9.5-15.5mm.

In 2015, Leon Radziemski et al. demonstrated the power transfer efficiency of an Ultrasound Electrical Recharging System (USER) [11]. In vitro experiments with 25 mm diameter PZT (Lead zirconate titanate) transmitter-receiver pair showed 15% efficiency for 10mm porcine tissue and 1.1% efficiency for 50 mm tissue. They were able to show that the idea of using transducers bonded to titanium, as is used in many biomedical implants, is feasible. The 25 mm diameter Ti and PZT composite transducer-receiver pair achieved 10% efficiency for 6-10 mm porcine tissue. These results bring ultrasonic power delivery closer to actual applications in medical implants, especially those embedded deep in the human body.

### 3.2 Ultrasound Waves Enables Miniaturized Receivers

The Friis propagation equation spells out another advantage of ultrasonic power delivery [12]:

$$\frac{P_R}{P_T} = \frac{A_T A_R}{R^2 \lambda^2} \tag{8}$$

Where PR and PT are the received and transmitted powers; AR and AT are the receiver and transmitter aperture; R is the transmitter-receiver distance; λ is the wavelength in the medium. Leaving aside interfering factors like loss during propagation and circuit implementation, it is easy to conclude that smaller wavelengths are more efficient for fixed-size miniaturized transmitters and receivers. However, it should be noted that radiation and matching efficiency also have an impact on efficient energy coupling: for example, if the receiver antenna is smaller than the operating wavelength, it exhibits low radiation resistance and high quality factors, which result in poor energy conversion efficiency. This necessarily means that sound waves, which travel much slower than electromagnetic waves and thus have shorter wavelengths at similar frequencies, have lower requirements for the size of receivers.

Alexey Denisov et al. conducted a simulation to study the power transfer efficiency of ultrasonic power delivery by comparing its efficiency to that of traditional inductive coupling solutions [10]. At 10 cm transfer distance, the acoustic solution constantly outperforms the inductive coupling solution with receiver sizes ranging from 2mm to 10mm. This supports the theory stated above, proving that ultrasonic power delivery is indeed a perfect candidate for miniaturized biomedical implants.

In 2010, Francesco Mazzilli et al. developed an in-vitro platform to study ultrasonic power delivery, and, with a 50 mm water medium, the $0.3cm^2$ receiver achieved 10% transfer efficiency [13]. In 2015, Jayant Charthad et al. developed an mm-sized implantable medical device with ultrasonic power transfer [14]. Their 1 mm * 1mm * 1.4 mm and 0.7mm * 0.7mm *1mm piezoelectric receivers both achieved an acoustic-to-electrical conversion efficiency of greater than 50%, with an average power of 0.36 and 0.176 mW respectively. These successes prove the feasibility of the application of ultrasonic power delivery in mm-sized systems.

## 4. Drawbacks of Ultrasonic Power Delivery

### 4.1 Ultrasound Waves Decays Quickly in Stiff Materials

What makes ultrasonic power delivery so useful for powering deeply implanted biomedical implants is the small acoustic attenuation coefficient of the human body, which can be as low as 0.6dB/MHz*cm. However, this is only true for soft tissue instead of stiff materials like bones. In their studies, Adler and Cook measured the attenuation of longitudinal waves in wet canine (Haversian) tibial bone at 22” C to be 13 dB/cm at 3 MHz and 19 dB/cm at 5 MHz (0.14 nepers/mm and 0.22 nepers/mm), which is significant [15]. Later, Roderic Lakes et al. studied the propagation and attenuation of ultrasonic waves in human bones. The attenuation was 0.23 nepers/mm at 5 MHz [16]. They concluded that large values of ultrasonic attenuation were observed in human bones, and, most notably, the attenuation in wet human bones in the radial direction was large enough to limit the penetration depth to at most 2mm, making it unlikely to be of use in a clinical setting.

This limits the possible scope of applications of ultrasonic power delivery. For example, neural implants that are installed in the human brain like automatic drug delivery devices require wireless power delivery through the human skull, which has an average thickness of 6.5 millimeters. At this depth, the loss of energy carried by ultrasonic waves would be so significant that wireless power delivery becomes unviable.

It is also worth mentioning that the attenuation of the pressure field by the soft tissue layers where the acoustic impedance falls in the acceptable range exponentially decreases the field intensity as the frequency and distance increase. This problem can be partially solved by picking the optimal operating frequency for different parts of the human body and the proper location for installing the implant.

### 4.2 Safety Concerns of Prolonged Exposure

The nature of wireless power delivery technologies for biological implants dictates that the part of the human body serving as the medium for transmission would be under prolonged exposure to ultrasonic waves, and the effects of such exposures can be complicated.

One concern is the amount of ultrasound-induced temperature increase. As ultrasound waves propagate through the tissue, some of its energy inevitably becomes absorbed and then transformed into the thermal energy of the tissue. The heating of human man tissue is mainly affected by the dynamic equilibrium of heat absorption and dissipation. It is well understood that heat absorption increases as the amount of protein in the organ increase [17]. The problem of dissipation, on the other hand, is very complicated and difficult to model. The behavior of conduction to neighboring organs might be accurately modeled, but the contribution of perfusion is hard to estimate. The empirical result obtained from past experiments is that bones, brains, spinal cord, and human fetus are most susceptible to ultrasound-induced heating [17]. This could limit the use of ultrasonic power delivery in biomedical implants like spinal cord stimulators, and pregnant women in general should avoid this technology.

The second concern is tissue cavitation. Inertial cavitation, which is normally seen in the respiratory and bowls, may develop from gaseous inclusions at moderate acoustic pressure amplitudes. At high pressures, inertial cavitation can cause cavities to exceed the speed of sound in the gas, producing sufficient energy to disrupt chemical bonds and thus create chemically reactive free radicals, which may interfere with DNA [18]. Ultrasound-induced cavitation in the human body is still a postulation, but it should be noted that this concern is not unfounded. Many evidence is based on data from lithotripters, and cavitation-related bioeffects have been reported at gas/tissue interfaces at low-level exposures with pulsed ultrasound [19]. The effect of long-term exposure is still not well understood and deserves more attention.

## 5. The Dilemma of Ultrasonic Power Delivery and a Potential Solution

There is no denying that ultrasonic power delivery is fundamentally more efficient for smaller receivers and longer transfer distances. However, it should be noted that the efficiency is still far from satisfactory. Table 1 documents the power transfer efficiency in some major publications about ultrasonic power delivery.

Table.1. A list of some major publications on ultrasonic power delivery

| Author | Transfer Efficiency | Medium | Receiver size ($cm^3$) | Depth (mm) |
|---|---|---|---|---|
| Arra [20] | 25% | Water | 1.19 | 100 |
| Shigeta [21] | 0.35% | Water | 0.467 | 70 |
| Sanni [22] | 1% | Water | 0.078 | 70 |
| Christensen [23] | 1.95% | Water | 0.24 | 40 |
| Chou [5] | 1% | Oil | 0.046 | 25 |
| Lee [24] | 0.01% | Pork tissue | 0.031 | 25 |
| Shih [25] | 0.015% | Pork tissue | 0.031 | 60 |
| Ozeri [7] | 27% | Prok tissue | 0.53 | 5 |
| Kim [26] | $1.4 \times 10^{-4}\%$ | Pork tissue | 0.0152 | 100 |
| Vihvelin [27] | 25% | Porcine tissue | 0.06 | 5 |

There is an obvious pattern: some of the best efficiencies are obtained by using water as the transfer medium. Water, however, is very different from human tissue, and these experiments do not directly verify the feasibility of ultrasonic power delivery in humans. The results of experiments based on pork tissue, porcine tissue and oil may transfer to humans, but they must sacrifice either receiver size or transfer distance in order to achieve decent efficiencies. When the author attempts to shrink the size of the receiver and extend transfer distance, which is what is expected from ultrasonic power delivery, the transfer efficiency is poor, as is in Kim's case [26]. When implanted in the human body, the wireless power transfer system would face even more problems like bone penetration, impedance mismatch, etc. It should be stressed here that using traditional WPT solutions like RF radiation and inductive coupling in these extreme scenarios would have resulted in worse efficiencies. Ultrasonic power delivery is indeed more efficient than traditional solutions, but it needs to be more efficient.

At this moment, a hybrid solution taking advantage of the strength of both solutions is very promising. In 2016, Miao Meng and Mehdi Kiani developed a hybrid inductive-ultrasonic link for wireless power transmission in mm-sized biomedical implants [28]. Using a 3-cm air-tissue medium, they achieved $1.4 \times 10^{-5}\%$ efficiency with only the ultrasonic link. The low efficiency resulted from the air-tissue impedance mismatch. Under the same conditions, the inductive-ultrasonic hybrid system achieved 0.16% efficiency, which is a significant improvement. The inductive part compensates for the problem of acoustic impedance mismatching and sound wave attenuation, improving efficiency by several orders of magnitudes. This study is a perfect proof of concept for a hybrid WPT system and reveals even more potential of ultrasonic power delivery.

## 6. Conclusion

Ultrasonic power delivery is a promising technology as a wireless power transfer solution for biomedical implants. It benefits from the nature of sound waves and boasts incredible efficiencies when sending power to miniaturized implants located deep inside the human body. However, accompanying this novel technology are safety concerns regarding tissue heating and tissue cavitation, which demand long-term experimentations and clinical data. The power transfer efficiency of ultrasonic power delivery is also extremely sensitive to transfer medium and impedance mismatch, limiting the range of application for ultrasonic power delivery. Completing a holistic review of the merits and drawbacks of ultrasonic power delivery, this paper proposes that an inductive-ultrasonic hybrid WPT system is a promising solution to the problems of ultrasonic power delivery and deserves attention from future research efforts.

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