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REVIEW ARTICLE

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Power sources and electrical recharging strategies for implantable medical devices

Abstract Implantable medical devices (IMDs) are critically requested for the survival of patients subject to certain serious diseases such as bradycardia, fibrillation, diabetes, and disability, etc. Appropriate working of an active implantable medical device (IMD) heavily relies on the continuous supply of electricity. In this sense, long-term powering and recharging of an IMD via a highly safe, efficient and convenient way is, therefore, extremely important in clinics. Several conventional batteries, such as lithium cell, nuclear cell and bio-fuel cell, etc., have been developed to power IMDs. Meanwhile, the recharge of IMD from outside of the human body is also under investigation. In this paper, some of the most typical IMD batteries are reviewed. Their advantages and disadvantages are compared. In addition, several emerging innovations to recharge or directly drive the implanted batteries, including electromagnetic energy transmission, piezoelectric power generation, thermoelectric devices, ultrasonic power motors, radio frequency recharging and optical recharging methods, etc., are also discussed. Some fundamental and practical issues thus involved are summarized, and future prospects in this area are made.

Keywords implantable medical device, power source, rechargeable battery, micro/nano device, lithium cell, bio-fuel cell, nuclear cell, electromagnetic power, piezoelectric power, thermoelectric device, ultrasound motor, radio frequency technique

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1 Introduction

Among the many diseases that may seriously impair health, some are extremely hard to cure and only by means of medicines or the self recovery mechanisms of the human body. Medical devices are thus of great necessity. Some of the devices work in the inner body to help or replace the function of certain organs. Such products are generally called IMDs.

As illustrated in Fig. 1, the concept of IMDs is in fact pretty wide, which covers various assistances throughout the whole human body. Classification of an IMD can be done by following the rule whether it needs power or not. The IMDs that need power are often termed as active devices while those that do not need power are categorized as passive ones. Artificial joints, vascular grafts and orthopedic devices, which are familiar to human life, are typical passive devices. The active devices, such as cardiac pacemaker, cochlear implants and drug pump, need electrical power for their appropriate operation. In this paper, discussions are focused on the active devices for brevity. Table 1 lists a set of typical IMDs introduced before 2007.

IMDs have been very popular, with a great number of people having received IMDs, and this number is still increasing. For instance, over 600 million people have pacemakers over the world, and 150 thousand pacemakers are consumed in the US each year [2]. Meanwhile, over 60 million people, including 20 million children around the world take cochlear implants for listening assistance [3]. In China, more and more people turn to IMDs to manage various health issues (Fig. 2) [2].

So far, tremendous progresses have been made in IMDs. The IMD family is increasingly adding new innovational members, and the working boundary of IMD is significantly expanded. For example, the journal *Nature* reported a story in 2006 [4] that, thanks to the implantation of a bionic device in his brain, a young man named Matt Nagle, who was stabbed and paralyzed in all four limbs, is now able to use a modified computer to receive e-mails, adjust the volume of his television, move

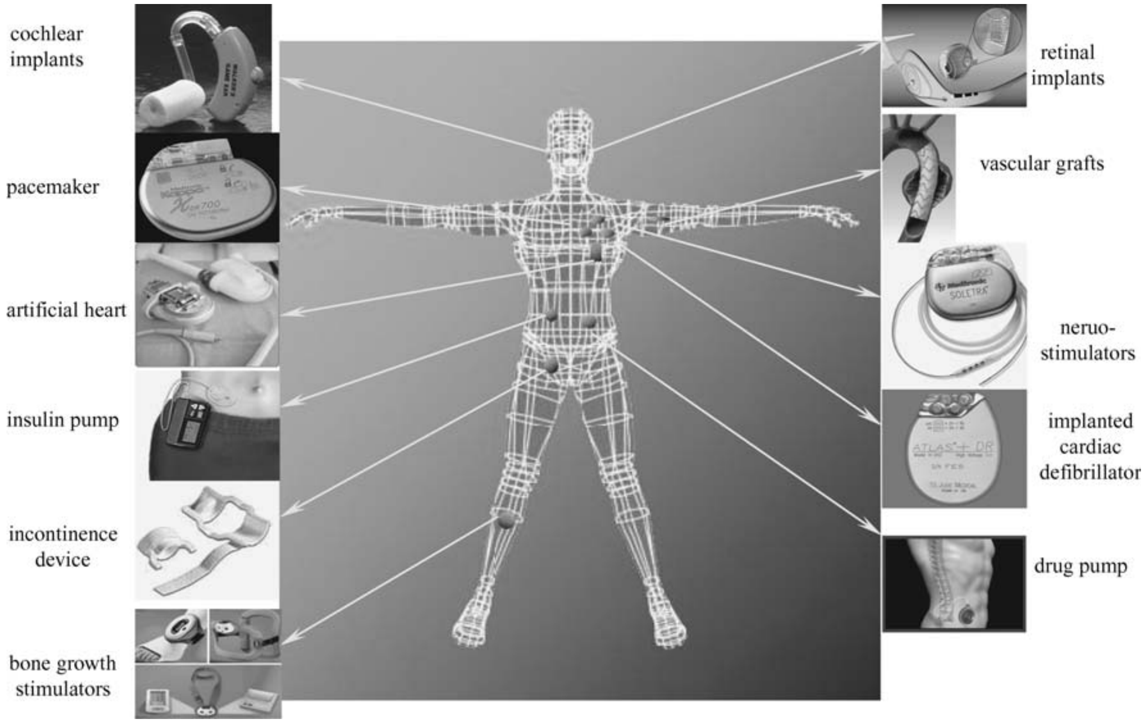


Fig. 1 Schematic for applications of various implanted medical devices

Table 1 Some typical implantable medical devices emerged before 2007

	passive devices		active devices						
IMD type	artificial joints	vascular grafts	cardiac pacemaker	cardiac defibrillator	neuro-stimulators	left ventricular assist devices	drug pump	cochlear implants	retinal implants
function	support human body	blood liquidity	bradycardia (too slow heartbeat)	ventricular tachycardia (too slow heartbeat) or fibrillation (disorganized beat)	treatment of urinary incontinence, intractable spasticity and tremor control [1]	heart failure	management of chronic pain, diabetes, and cerebral palsy etc.	deaf	blind

a robotic arm and even play computer games (Fig. 3). Such achievement is very encouraging in the investigation of "brain-computer interfaces". A prosperous development can be expected along this direction in the near future.

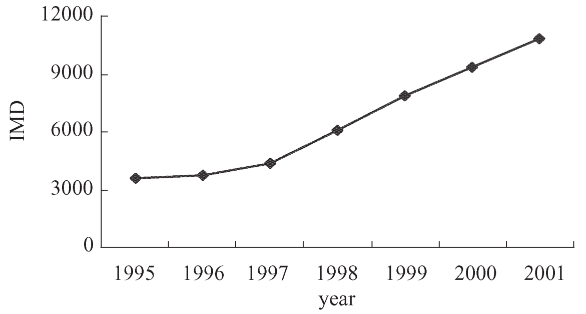


Fig. 2 Increasing number of people using IMD in China

With more and more people using IMDs, the mismatches between longevity of the patients and service life of IMDs come into focus, especially in the devices which need batteries to provide power. For example, the average life of an implanted cardiac defibrillator (ICD) patient can now reach nearly 10 years after the surgical implantation. However, the service life of an ICD is only 4.7 years. When the service life of an ICD ends, its host will have to suffer for the ICD to be changed, which will be a significant clinical and economic burden for the patient.

The key to settling this problem is the continuous supply of a stable power source for IMDs. In most cases, an IMD has to be replaced just because of the battery running out inside the device. Therefore, it is the battery that determines the longevity of an IMD. Although the requirement of each IMD is different, the power they need generally falls in the level of μW–mW (Table 2).

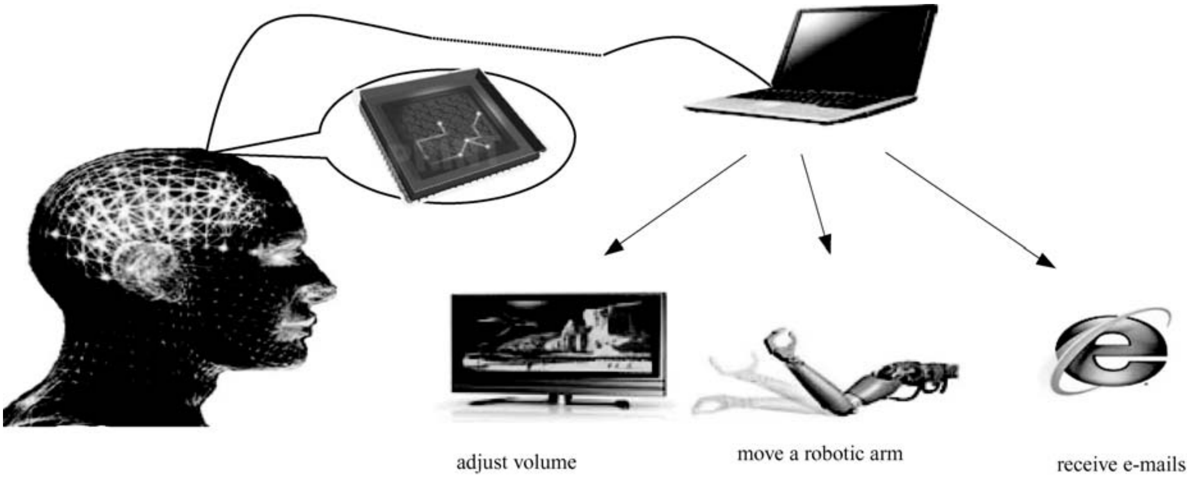


Fig. 3 Schematic for brain-computer interfaces

Table 2 Requirement of different IMDs for electricity [5]

implanted device	typical power requirement
pacemaker	30–100 μW
cardiac defibrillator	30–100 μW
neurological stimulator	30 μW to several mW
drug pump	100 μW to 2 mW
cochlear implants	10 mW

In addition, it is important to mention some demanding requirements for an adequate IMD, because the manufacture of IMDs is a complicated process. For example, a good IMD should have such properties as miniaturized size, light weight, long running life, low self-discharging rate, hermeticity, high reliability over a long period of time, and compatibility with the internal body chemistry of the patient. More details can be found in Table 3.

Table 3 General requirements for fully implantable medical devices [6]

properties	value
temperature limitation	$< 50^\circ\text{C}$
long and stable operational lifetime	> 3 a
excellent reliability and/or failsafe	failure $< 5\%$/a
compact/implantable size	10^{-6} m^3
daily energy consumption	< 1 Wh
compatible with other medical equipment (e.g. MRI)	good
bio- and hemocompatible	good

With the development of IMDs, their function is becoming more complicated and integrated. These IMDs will consume more electricity or other kinds of energies. How to charge IMDs in a continuous and stable way has become an issue of great importance. This paper is dedicated to presenting a relatively complete review on the latest advancements made in the IMD power system.

3 Typical batteries for IMDs

3.1 Lithium cell

The first implanted lithium cell used to power a pacemaker was designed by an Italian scientist in 1972 [7]. It soon replaced zinc/mercuric oxide batteries that appeared in the 1960s, and became dominant in the area of powering implantable cardiac pacemakers. By the late 1980s, almost all cardiac pacemakers had been driven by lithium system, which is still the case even today [8]. With the advent of lithium batteries, the longevity of an implanted cardiac pacemaker had been extended to 10 years, and more than five million people have benefited from such advancement so far [1].

By now, the lithium primary battery has been widely adopted in IMDs. Besides the implanted cardiac pacemaker, lithium battery has been chosen as the power source for many other IMDs. More details for three typical IMDs utilizing lithium battery can be found in Table 4.

Up to now, lithium batteries have been developed to include Li/I_2, $LiMnO_2$, $LiSO_2$ and so on. Li/I_2 batteries appear safer and more reliable than other batteries when used to power implantable cardiac pacemakers. Therefore, they are widely accepted by almost all manufacturers and users for over 35 years. The configuration of a Li/I_2 battery is shown in Fig. 4.

The anode of Li/I_2 batteries is made of $PZVP{\cdot}nI_2$, while its cathode is made of lithium. LiI generates as an electrolyte when its cathode and anode contacts each other via an external circuit. This activity is performed by the following relations [11]:

$$\begin{gathered}\text{Cathode}\\ \text{Li}\rightarrow\text{Li}^{+}+\text{e}.\end{gathered} \tag{1}$$

Table 4 Three typical IMDs utilizing lithium battery

IMD type	battery type	description
neuro- stimulators	lithium/thionyl chloride or lithium/carbon monofluoride batteries [9]	neuro-stimulators are essentially pacemakers that operate at higher currents, typically 1–5 mA pulses
drug delivery system	lithium/thionyl chloride or lithium/carbon monofluoride batteries[9]	high intermittent power pulses are needed
defibrillators	lithium-SVO or lithium-MDX batteries [9]	energy densities of 650 mWh/cm^3 for the MDX battery with a load of 30 kΩ to an end voltage of 2.5 V have been confirmed [10]

Notes: SVO—silver-oxovanadium; MDX—manganese-dioxide.

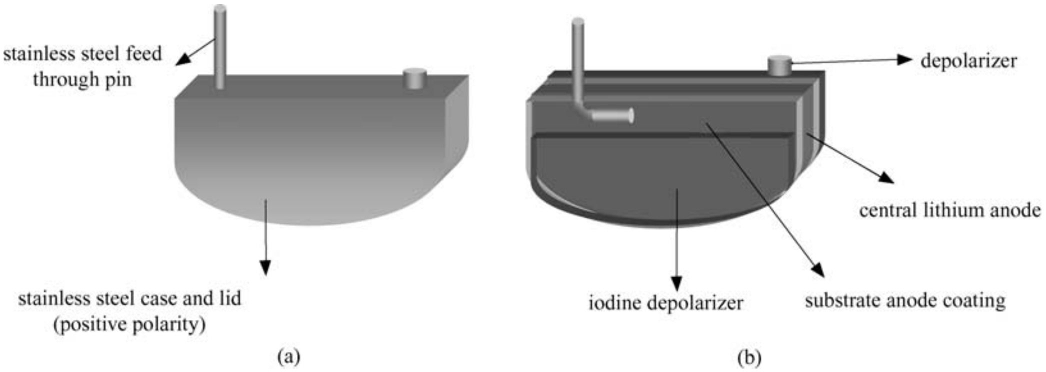


Fig. 4 Configuration of a lithium iodine battery
(a) External configuration; (b) internal configuration

Anode

$$\frac{1}{2}\mathrm{I}_2+\mathrm{e}\rightarrow\mathrm{I}^-. \tag{2}$$

General

$$\mathrm{Li}+\frac{1}{2}\mathrm{I}_2\rightarrow\mathrm{LiI}. \tag{3}$$

The main reason why Li/I_2 batteries take a dominant place in powering implantable cardiac pacemakers is their high discharge voltage and energy density. The discharge voltage of Li/I_2 batteries can reach 3.6 V, which allows for its use in place of three nickel-cadmium cells or three nickel-metal hydride cells [12]. Its energy density can reach 210 W h/kg and 810 W h/L [12], which is good enough to power a cardiac pacemaker for several years.

Another reason for Li/I_2 batteries to advance as the power source for implanted cardiac pacemakers lies in their discharging character. Other lithium systems generally have a steady discharge voltage [13]. Only when the capacity is going to run up, its discharge voltage changes significantly, which would endanger the patient since there may not be enough time to replace the battery. However, the discharge voltage of Li/I_2 batteries differs from that. They change obviously with the reduction of the remaining energy, which makes it easy to observe the working status inside the batteries. Besides, they are safer and more reliable when implanted in the human body. Li/I_2 batteries used in IMDs belong to the type with a solid electrolyte. In solid status, Li/I_2 batteries leak less than other liquid batteries.

3.2 Bio-fuel cell

In the 1780s, Galvani, an Italian physiologist, noticed that the leg of a frog would twitch when it was stimulated by an electrical current. Since then, the connection between biology and electricity has been gradually studied. It is now common sense that, in a contrary way, a biological action can also cause an electrical response [14].

One of the earliest advancements in this area was made by Potter in 1911. When a platinum electrode was placed into cultures of yeast or E. Coli, an electrical potential difference up to 0.3–0.5 V was generated with a current of 0.2 mA [15]. This famous experiment proved soundly that microorganisms can produce electrical energy. In 1931, Cohen developed microbial fuel cells capable of generating potentials in excess of 35 V [16].

In the 1960s, owing to the technological progress of using microbial biofuel cells in the US space program for waste disposal, the cell-free enzyme systems based biofuel cells began to incubate in its early goal as a power supply for a permanently implantable artificial heart [17].

In the 1970s, studies on the biofuel cells used in IMDs were mainly focused on the enzyme-based biofuel cells using glucose as fuel and oxygen as oxidizer. The energy density of biofuel cells had been improved significantly [18]. In 1984, Turner applied transition metalcomplex redox mediators in biofuel cells. In 1986 Persson and Gorton reported an adsorbed redox mediator-based anode. In 1999, Palmore and Kim described a significantly improved membrane-type cell, with diffusing components in both compartment, operating at over 1 V. Since 1994, many improvements on biofuel cells have been made, which can be found in a review on the journal of Biosensors and Bioelectronics [19].

According to the types of catalyzer used, biofuel cells can be classified as microbial-based or enzyme-based ones. When considering the way in which electron moves from anode to cathode, biofuel cells can be catalogued into direct or non-direct ones [19]. Nevertheless, the basic fact for biofuel cells is more or less the same. Their fundamental components can be shown in Fig. 5. The fuel (such as glucose) is oxidized in the anode by the action of a catalyst (such as enzyme, microorganism, and so on). The producing electrons travel to the cathode by the external circuit. At the same time, the protons move to the cathode through an ion exchange membrane that only protons are permitted. In the cathode, the oxidant (such as oxygen) accepts the coming electrons and turn to be reduced oxidant.

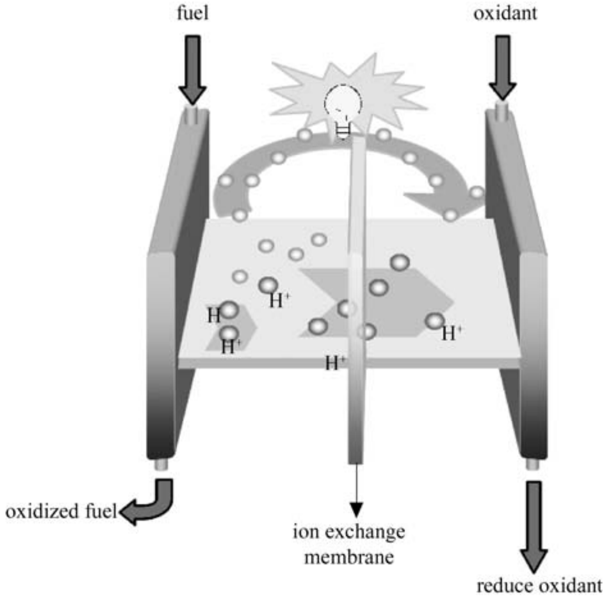


Fig. 5 Schematic diagram of a biofuel cell

The advantages of biofuel cells can be summarized as follows: First, there are various recycle materials in nature that can serve as the fuel in biofuel cells, such as glucose, amylum and so on. They can replace those non-recycle sources in reproducing energy. Second, the condition for reaction of a biofuel is very mild [20]. Normal temperature, normal pressure, and pH7 would be sufficient for a highly efficient electricity generation, which will make it easier for the operation, control and maintenance of the battery. Finally, the biocompatibility between biofuel cells and the human body is good enough for the biofuel cells to be implanted in the human body to power IMDs or biosensors.

Currently, attention is mainly focused on enzyme-based biofuel cells, which utilize the enzyme extracted from the human body as the catalyst. For example, the self-powering glucose sensing to use in diabetics or the long-standing goal of the implantable power supply for a cardiac pacemaker is a typical enzyme-based biofuel cell. The fuel comes from the glucose and oxygen in the blood. The chemical reaction can be shown as follows:

Anode

$$C_6H_{12}O_6 \rightarrow C_6H_{10}O_6 + 2H^+ + 2e^+. \tag{4}$$

Cathode

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O. \tag{5}$$

General

$$C_6H_{12}O_6 + \frac{1}{2}O_2 \rightarrow C_6H_{10}O_6 + H_2O. \tag{6}$$

An important subject that can affect the efficiency of energy generation is the fixing of the catalyst and the maintaining of the activation of such reaction. Halliwell and Simon [21–23] proposed to achieve this by fixing the catalyst on the polyaniline. Their experimental result showed that a greater current can be obtained by this means.

If employing some conductive polymer, the exchange membrane would not be needed in enzymatic biofuel cells (EBCs), which can greatly reduce the volume of EBCs. Several groups [24–27] had made the EBCs more compact and efficient. As it was realized [18], miniaturized enzymatic biofuel cells (mEBCs) convert blood sugars into electrical energy by employing, for example, glucose oxidase (GO_x) on the anode and bilirubin oxidase on the cathode. When the volume of the fibers is 0.0026 mm^3, the current of the cell operating at 0.52 V in a physiological buffer solution at 37°C is 8.3 μA. The 4.3 μW power output of the cell is expected to suffice for the operation of implanted sensors and intermittent transmission of collected data to an external receiver. Other potential applications for miniature fuel cells include power sources for drug delivery systems [28]. To match practical demands, it is crucial to increase the lifetime and the power output of mEBCs. The power output has been limited by the performance of GO_x (gaseous oxygen) on the anode. In this direction, GO_x properties can be improved by a directed protein evolution [29].

EBCs are promising power sources to drive miniaturized electronic devices and biosensors within the human body. The advantages of EBCs are as follows. First, an implanted biofuel cell could use a biological metabolite fuel source such as glucose or lactate, both of which are readily available in physiological fluids such as blood. Both glucose and oxygen are present abundantly within the cells of most biological organisms. Second, the high turnover of a "wired" enzyme electrode in such applications could generate power levels capable of meeting the needs of many devices without using a mediator [30]. However, such EBC also has the following disadvantages. First, most of the biofuel cells described today would be capable of only meeting the demands of biomedical devices implanted for short-term application. Another issue that must be addressed is biocompatibility. A biofuel cell should be able to exist in the physiological environment without an unacceptable degree of biofouling occurring over extended periods of time. Otherwise, it would lead to the damage of the device or physiological harm to the patients.

3.3 Nuclear cell

Nuclear batteries were introduced in the IMD industry around 1972 to prolong the longevity of an implanted device. A small isotope-fueled beta-voltaic battery, "Betacel", was developed by McDonnell Douglas Astronautics Company in the US [31]. Several pacemaker manufacturers introduced nuclear models to their product lines at that time. These devices offered young patients the possibility of having a single pacemaker implanted to last their whole life. By the mid-1970s, nuclear cells were replaced by lithium cells in the IMD industry. The lithium-powered units had a calculated longevity of approximately 10 years, and it is good enough for some elder patients. The implantation of nuclear-powered pacemakers ceased in the mid-1980s, since some physicians proposed that it was much better for patients to be updated once a decade by incorporating new technologies rather than carrying a large old-technology pacemaker through out their life [32].

Nuclear batteries utilize energy carried by particles emitted from radioisotopes. Different nuclear batteries convert such energy into electrical via different ways. For example, some nuclear batteries utilize the electric potential difference produced by the particle emitted from the radioisotope; a few utilize the electric potential coming from the ionization of emitted particle bundle; others utilize the electric energy produced by photoelectrical conversion prompted by a fluorescent material or utilize the heat energy of the radiation to produce electrical energy.

Currently, some pacemakers are powered by a radioisotope thermoelectric generator. Such technology has already been fully developed. The nuclear battery (Fig. 6) in the Medtronic device use a tiny 2.5 Ci slug of metallic

(a) (b)

Fig. 6 Nuclear pacemaker developed for Medtronic used a tiny slug of Plutonium 238 [33]
(a) A nuclear pacemaker; (b) the same one with plutonium removed

plutonium 238 (Pu-238). The radiation produced by the Pu-238 bombard the walls of its container, producing heat that a thermopile then convert to an electrical current based on Seebeck effect.

The nuclear battery has been proved safe and reliable for IMDs. The materials used to keep nuclear hermetic mainly include a metal alloy, carbon, and ceramic. For the application in powering IMDs, some inert metal alloys, such as platinum, tantalum, and gold or gold alloy, are competent to be adopted as good shield materials.

The Betacel battery as referred in Fig. 6 has a volume of 1.8 mL with a height of 1.02 cm and a diameter of 1.52 cm. Though small, it is rated at 50 μW and 1.6 V at the maximum power output point [26]. If Pu 238 is chosen as radiation, only 150-mg is needed to power an implantable pacemaker for over 10 years [33]. Nuclear batteries can offer a much longer service-life than lithium batteries. Its high energy density is clearly the most outstanding merit that attract people's attention. Another advantage of the nuclear cell is that its output energy is stable, which is almost not affected by external factors, such as surrounding temperature, chemicals, pressure or electromagnetic field, etc. This is rather significant for IMDs when considering that there are many events that occur in the human body. A steady output of electrical energy can be guaranteed even under an adverse situation.

So far, the cost of a nuclear cell is still very high. The reason for this is that the materials used inside the cell, especially the radioisotope, are very hard to be extracted and operated. A similar isotopic thermoelectric generator as developed by Numec Corporation in the US was sold for $3200 (back in 1974) [33].

3.4 Recharging strategies to power an IMD

To settle the problem of the mismatch between the service life of an IMD and the longevity of patients, many innovational recharging systems were also proposed, such as based on electromagnetic energy transmission, piezoelectric power generation, thermoelectric devices, ultrasonic motors, radio frequency recharging battery, and optical recharging battery, etc. Such technologies usually synthesize the knowledge of several different fields. In some cases, they may possibly serve as reasonable candidates to replace conventional IMD batteries. With more and more new IMD applications developed for the human body, special functional requirements have been raised. To fulfill these requirements, different ways to generate electrical power emerged. The review of some innovational recharging systems emerged recently is as follows.

3.4.1 Electromagnetic energy

Suzuki et al. designed an electric power generating system for IMDs [34], in which a micro-generator, a high-ratio gear, and a metal magnet were implanted inside a human body, while two-phase exciting coils were placed outside. By the exciting coils, the rotating magnetic field is applied to the metal magnet implanted and thus drives the micro-generator to rotate. Via the high-ratio gear, the rotating speed of the micro-generator is much higher than that of the metal magnet, and a large voltage can be produced. A schematic design of such modeling can be illustrated in Fig. 7. The experimental result of the proposal is rather useful for powering IMDs. It has been found that when the outside exciting frequency reaches 16.7 Hz, a current

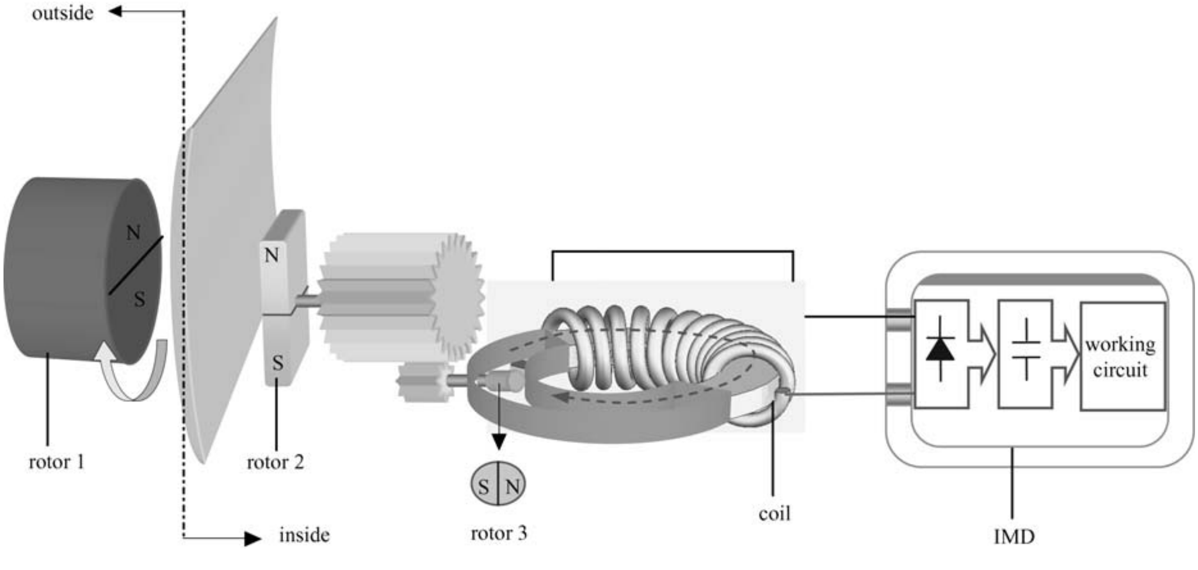


Fig. 7 Schematic view of the proposed generating system to be implanted

of 0.48 A is induced and an output power of 11 mW is available [34].

Later, Suzuki et al. presented another proposal to power IMDs [35]. The electric power-generating system used a magnetic couple to transmit energy into deeply implanted medical electronic devices. From Fig. 8, it can be found that, when rotor 1 rotates outside the human body, rotor 2 driven by the external torque rotates synchronizing to rotor 1, since both rotors are coupled to each other. Several magnetic poles (12 poles in Fig. 8) were fixed in the internal wall of rotor 2, which can significantly accelerate the rotating speed of the magnetic field applied in the coils and therefore can obtain a high voltage. The output of the generator is inputted to the rechargeable battery via the rectifier and the charger. By this means, an output power of 1.9 W can be obtained (4.9 V, 390 mA). Also, the rechargeable battery takes 10 hours to charge [35].

The two electromagnetic power supply systems are both simple in instrument and manufacture. They work as a micro-motor and the technique of producing the motor is mature now. Since no expensive materials are needed, the price of such system is not as high as that of nuclear cells. However, they never lose their advantages in recharging the implantable battery.

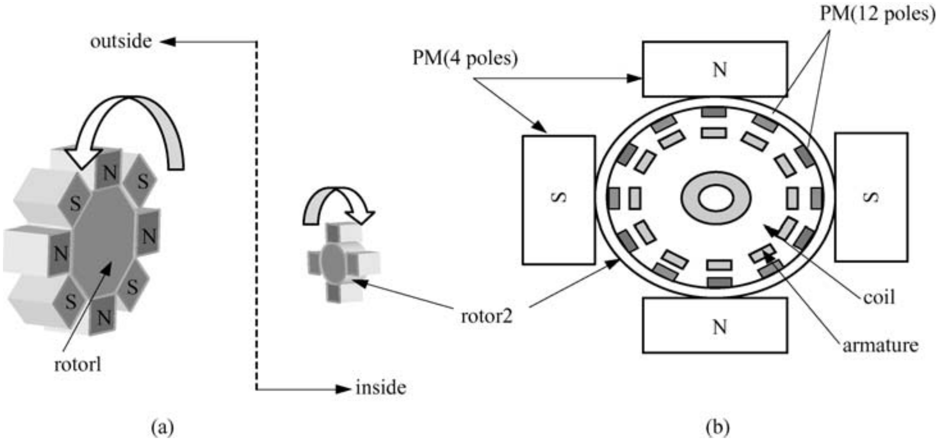
The disadvantages of such power are as follows. First, the electromagnetic waves coming from the electromagnetic power supply systems may have certain negative influences on the human body and its surroundings. Second, the magnetic field may have some leakages during its long service time, which will reduce the working efficiency. Finally, documentation focusing on the biocompatibility between these implantable electromagnetic power generators and the human body is still not available.

3.4.2 Piezoelectric power

Many drug pumps use piezoelectric materials as drivers to convert electric signal into mechanical action. These pumps are usually used in drug delivery systems, especially for diabetes care. For instance, an electronically controlled miniature piezoelectric pump and valves was first designed by Spencer et al. in 1978 [36]. A piezoelectric actuator was developed that allowed accurate dosing release in a pressure-independent micro pump for low flow drug delivery systems [37]. Figure 9 illustrates the concept of a micro-needle integrated piezoelectric micro-pump for diabetes care [38]. In this application, the piezoelectric pump converts electricity into mechanical pressure, driving the insulin reservoir to release accurately into the skin supplying insulin for diabetes.

Meanwhile, many micro generators use piezoelectric materials to convert mechanical energy into electricity. In 1995, Williams and Yates proposed a micro-electric generator that can produce electrical power from the vibration in the environment [39]. Later, Glynne-Jones et al. advanced this generator using thick-film piezoelectric technologies. As shown in Fig. 10, when the beam structure oscillates, the piezoelectric layer adhered to the surface of the beam will be deformed. The deformation causes charge to the displaced electrodes positioned on the top and the bottom surfaces of the piezoelectric element, producing an output of 3 μW [40]. Such piezoelectric effect is an appropriate solution for powering some MEMS/NEMS devices and IMDs.

The mechanical energy dissipated by human body movements have been noticed long before. Several proposals were thus made to convert such mechanical energy into electrical energy. Kymissis et al. examined three different devices that can be built into a shoe and used for generating electrical power "parasitically" while walking [41]. They showed that the piezoelectric way is easier to be integrated into the design of a conventional footwear (as shown in Fig. 11). It was estimated that a 10 mW in-shoe generating system that lasts for about 2 years of average use is equivalent to 150 cm^3 of lithium-thionyl chloride batteries. The result is of significant



(a) (b)

Fig. 8 Principle of the electricity generation system (a) and construction of the implanted equipment (b) [35]

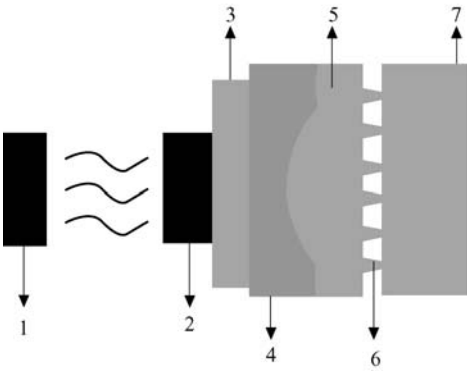


Fig. 9 Concept of a micro-needle integrated piezoelectric micro-pump for diabetes care
1—remote control component; 2—wireless telemetry; 3—piezoelectric pump, which is connected to controller; 4—membrane; 5—insulin reservoir; 6—micro-needle; 7—skin

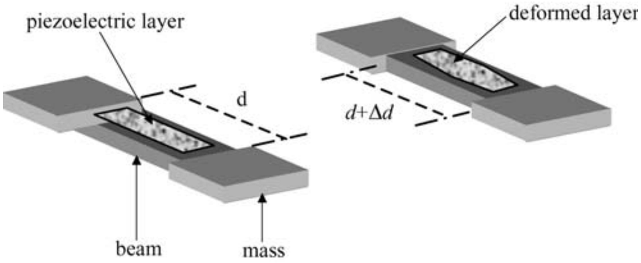


Fig. 10 Piezoelectric generator

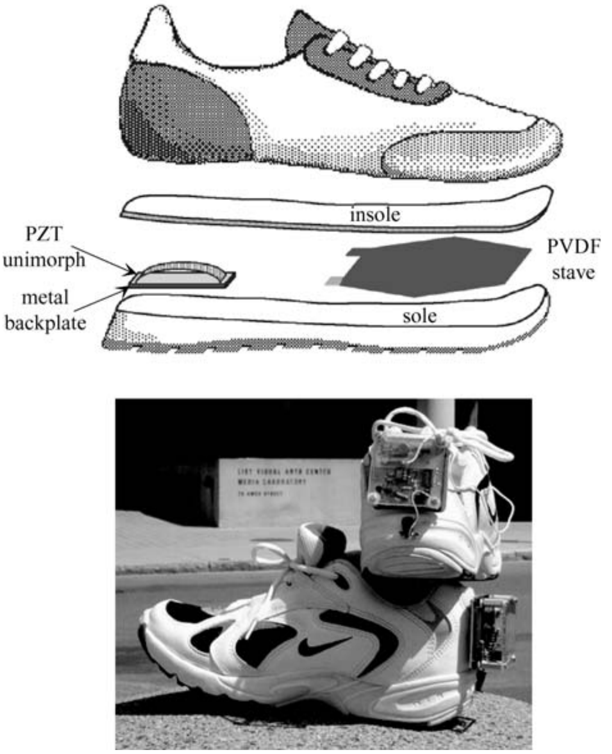


Fig. 11 Exploded view showing integration of piezos [41]

reference for solving the powering problems in IMDs. The piezoelectric shoe suggests that internal human body movement may possibly be used to generator electricity.

Recently, Wang and Song proposed to use piezoelectric zinc oxide nanowire (NW) arrays to convert nanoscale mechanical energy into electrical energy (Fig. 12). When the density of NWs per unit area on the substrate is 20 μm^{-2}, the output power density could reach about 10 pW/μm^2 [42]. By converting mechanical energy from body movement, muscle stretching or water flow, into electricity, these "nanogenerators" could make possible a new class of self-powered implantable medical devices, sensors, and portable electronics.

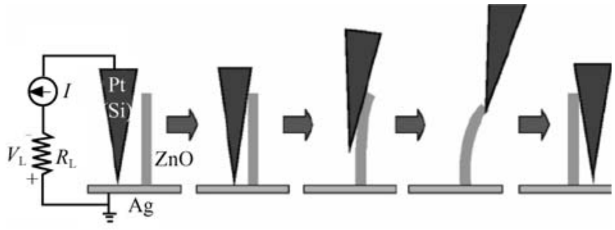


Fig. 12 Procedures of generating electricity by deforming a PZ NW with a conductive AFM tip in contact mode [42]

3.4.3 Thermoelectric devices

The thermoelectric power generator is a highly promising alternative to traditional batteries. This is because heat energy can be obtained directly from the human body, which is continuously dispersed to the environment otherwise. Besides, thermoelectric power generators are environment-friendly.

Temperature differences inherently exist through out the whole human body [43]. In addition, the maximum temperature difference between body core and the skin surface is about 8 K, which is big enough to be utilized to generate electricity.

Although having perfect self-powering capability by directly using the body heat, the thermoelectric generator has been far from being fully developed. There are many thermoelectric generators available in their fabrications [43–46]. One of such proposals by Weber et al. is a coin-sized coiled-up polymer foil thermoelectric power generator for wearable electronics (Fig. 13). Materials like antimony and bismuth are deposited on a polyimide substrate with the thickness of 12.5 μm. The metal thickness is 1 and 3 μm, respectively, and the stripe width is 10 mm. For such size, it can be calculated that the linear dependence between the temperature difference and the voltage of one single screen-printed thermocouple leads to a value of about 97 μV/K.

The basic equation for the voltage of a thermoelectric generator (without load) can be written as follows:

$$V_{\text{output}} = n\Delta T(\alpha_1 - \alpha_2). \tag{7}$$

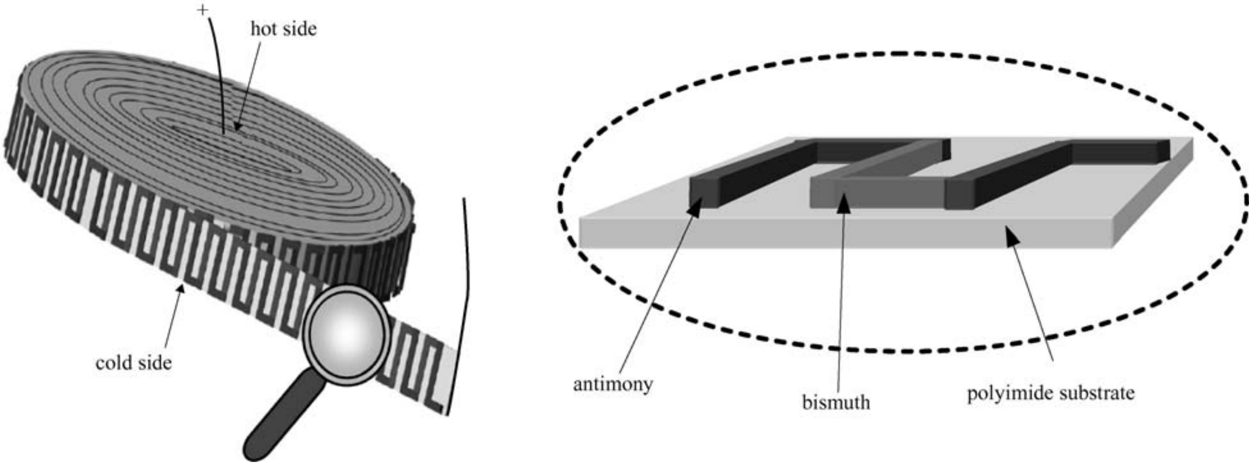


Fig. 13 Schematic of the coiled-up thermoelectric power generator [47]

Since the temperature difference distributed in the human body can reach several centigrades, and $(\alpha_1 - \alpha_2)$ reaches 97 μV/K from foregoing results, the output voltage can be about 1 V when the number of the thermocouples is several thousands. Coiled-up with the thermocouples connected in parallel, several thousands of thermocouples can be fixed on a small space of about 1 cm^2. Meanwhile, by cooling the skin, greater temperature differences can still be attained. Thus, the output voltage can be high enough to meet the electric requirement of the working circuit.

The latest experiments on this subject were done by Yang et al [48]. In their in vitro experiment, the highest temperature difference across the thermoelectric generator (TEG) is found to be about 1.4 K, and an output voltage is at 7 mV-level. In the in vivo experiment, the temperature difference can be 5.7 K, and the output voltage can be about 25 mV at maximum, in the condition where a common TEG was implanted into the body of a rabbit. Clearly, realizing a higher output voltage can still be expected when employing the foregoing coiled-up thermoelectric generator or some other thermoelectric generators with better capacity in converting heat to electricity. In addition, cooling the skin surface would further enhance an ever larger energy output.

These experiments show soundly the possibility of utilizing the heat inside the body to generate the electricity that IMDs need. This technique can be a potential candidate to power IMDs.

3.4.4 Ultrasonic motors

Noninvasive ultrasonic instruments have been very widely used in medical practice for cerebral, ophthalmic, thoracic, abdominal and fetal imaging. In contrast to X-rays, ultrasonic instruments have two principal features: capability for real-time imaging of moving targets such as heart, and complete avoidance of tissue damage by ionizing radiation [49].

Traditional ultrasonic instruments were mainly used as a tool for diagnosis and stimulation. These instruments operate outside the human body. They transmit ultrasound to penetrate the body and receive the echo. By receiving the feedback, they can construct an image of some target structure inside the body or monitor some needed parameters such as the tissue temperature.

Other than serving as a tool for diagnosis and monitoring, an ultrasonically-driven piezoelectric neural stimulator is also under development. In a practical situation, piezoelectric elements are generally implanted in advance in the human body, and the transmitted ultrasound is then used to activate mechanically such implanted piezoelectric elements, which will generate current that can realize neural stimulation. In the experiment of Phillips et al. [50], American bullfrogs were tested as schematically shown in Fig. 14. The frequency of the ultrasound was measured to be approximately 2.25 MHz with spatial peak temporal average intensities of 1.0 to 1.25 mW/cm^2 at maximum excitation [50]. The output voltage of the implant is at the level of 1.0 to 1.8 V in frog skeletal muscle, which is high enough to recharge a secondary battery or run directly the neural stimulation working circuit. Application of external ultrasonic energy to excite a passive neural stimulator offers the possibility of utilizing the external ultrasonic energy to power an IMD.

Recently, Wang et al. developed a direct-current nanogenerator driven by ultrasonic waves [51]. The nanogenerator was fabricated with vertically aligned zinc oxide nanowire arrays that were placed beneath a zigzag metal electrode with a small gap. The ultrasonic wave drives the electrode up and down to bend and/or vibrate the nanowires. A piezoelectric-semiconducting coupling process converts mechanical energy into electricity. This approach presents an adaptable, mobile,

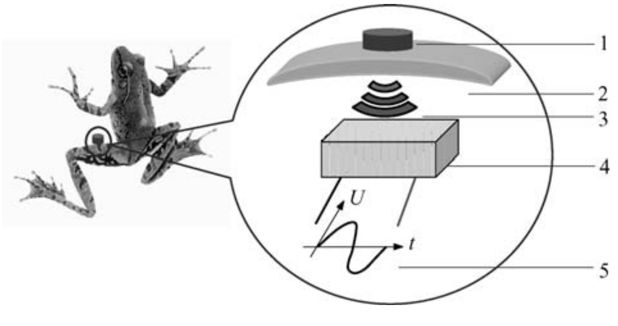


Fig. 14 Experimental arrangement for in vivo implant testing
1—ultrasonic application; 2—secured frog leg skin; 3—ultrasonic waves; 4—piezoelectric chip; 5—generated stimulation potential

and cost-effective technology to harvest energy from the environment, and it offers a potential solution for powering nanodevices.

However, in practical purpose, the wavelength of the ultrasound is not easy to choose. Though the long-wavelength ultrasounds can penetrate deeper into the human body, they generally spread over an area larger than the target and could affect the neighboring tissues. As a contrast, the short-wavelength waves are easier to focus on the target area. Unfortunately, they cannot penetrate through the body in a desirable depth.

3.4.5 Radio frequency recharging battery

This technique has in fact been widely adopted in IMDs to transfer data and power to the inner circuit. The fundamental setup for the RF technique used in IMDs is shown in Fig. 15. After being introduced to the power amplifier, the output power is connected to the transmitter coil, which is equipped near the skin. When alternating current runs through the transmitter coil, it generates a magnetic field that can convey energy though the skin. A receiver coil is equipped in the human body near the transmitter coil. From the penetrating magnetic field, an electric voltage is produced by induction in the receiver coil. The voltage becomes a DC voltage after being rectified, filtered, and stabilized. This DC voltage can run the IMDs directly, or recharge some implanted secondary batteries.

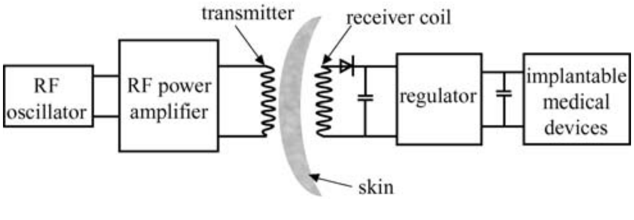


Fig. 15 Schematic for RF technique used in IMD

The efficiency of the electromagnetic energy conveying from the transmitter coil to the receiver coil depends on the mutual electromagnetic coupling between the transmitter coil and the receiver coil. There are always four situations, as schematically shown in Fig. 16, in which (a) shows the ideal position of the coils in common use. The mutual inductances get maximized in this position. However, in practical use, the position between the two coils could not always remain at the ideal situation. It could be in the horizontal misalignment, incline misalignment, or random misalignment, which is shown in Fig. 16(b), (c), (d). All misalignments decline the mutual induction, and therefore reduce the efficiency of energy conveying [52].

3.4.6 Optical recharging

Using external optical energy, a much less invasive power supply for medical implants has been proposed [53]. Employing a near-infrared laser with photovoltaic cell, the power can be transmitted by a laser diode in the near infrared region and received by a photovoltaic cell array which is embedded under the skin. The transmitted power can then be used to run the working circuit of IMDs, and can also be used to recharge a secondary battery. A schematic illustration for such application can be depicted as in Fig. 17.

Recently, some experiments on optical recharging have been conducted. The results show that a photo diode with a surface area of 2.1 cm^2, emitting light in the near infrared region at a wavelength of 810 nm with a power density of 22 mW/cm, can provide sufficient energy within 17 min to allow a regular commercial cardiac pacemaker to work for 24 h [54]. During continuous irradiation for 17 min on the skin, the temperature rise there is only 1.4°C, which is acceptable for safety concerns. The technique can be implemented for the benefit of patients.

4 Conclusions

IMDs have had a history of outstanding successes in medical treatments by saving the lives of millions of people. Following a brief introduction of the function of IMDs, a relatively complete review of the powering sources of IMDs is presented. So far, lithium battery still remains dominant in this area because of its high energy density compared with zinc/mercuric battery. However, the service life of lithium batteries is only about 4.7 years, which is still far from being satisfactory. The biofuel cells have inherent advantages when implanted into the human body, such as abundant fuel, biocompatibility and so on. Further endeavor should be made to overcome its limitation to suffice long service-life. The nuclear cell seems to be perfect in longevity and biocompatibility, but efforts should be made to reduce

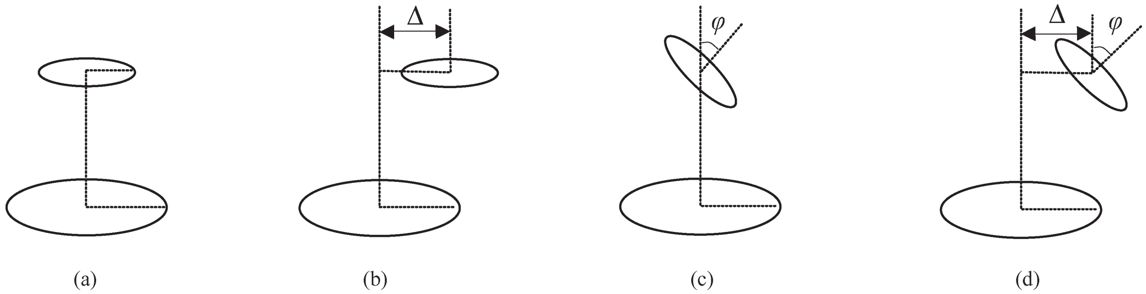


Fig. 16 Schematic for four coupling situations
(a) Ideal position; (b) horizontal misalignment; (c) incline misalignment; (d) random misalignment

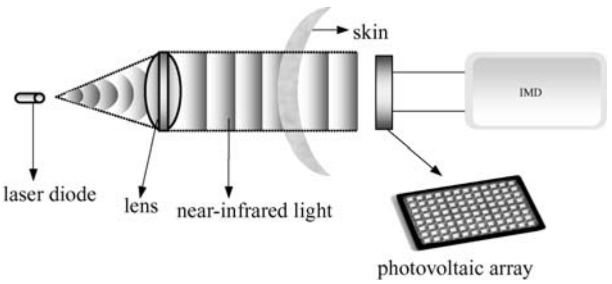


Fig. 17 Schematic for near-infrared laser energy transmission system

its high price. On the other hand, the emergence of many innovative powering systems, such as electromagnetic powering generator, piezoelectric generators, thermoelectric generators, ultrasonic generators, RF technique and optical battery, offers the possibility to regulate the power strength and duration of IMDs through external interference. Having un-replaceable advantages in some aspects, they can possibly become also important power sources in IMDs.

With the development of new technology, the functions of IMDs are being significantly expanded. As outlined in this paper, the powering source for IMDs should be developed to be more effective, longevous, environment-friendly, and synthetic. Further advancements in this area are expected to come in the near future.

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