PUBLISHED: 9 MARCH 2017 | VOLUME: 1 | ARTICLE NUMBER: 0051

news & views

BIOELECTRONIC DEVICES

Wirelessly powered implants

Phased-array antennas that conform to body surfaces efficiently transfer electromagnetic energy to miniaturized semiconductor devices implanted in pigs.

Jordan Thimot and Kenneth L. Shepard

The long-term powering of devices implanted in the body — such as cochlear implants, spinal-cord stimulators and pacemakers — remains a technological challenge, particularly as demands to reduce device size increase. In the future, such devices are also expected to include implants that interface with both the peripheral and central nervous systems for regulating organ function, augmenting sensory perception and controlling prosthetics. The larger the implanted device, and consequently the greater the displaced tissue volume, the higher the chances that natural body responses, such as the foreign-body response and fibrotic encapsulation, will lead to device rejection.

Batteries have poor energy densities and limited lifetimes. Energy from biological sources, such as thermal gradients and vibration inside the body, can be harvested, but these sources provide available power levels that are far too low for most implanted devices[1]. Hence, research efforts have focused on the wireless delivery of continuous power from an external source to the implanted device through either electromagnetic energy (generally at radio frequencies) or acoustic energy (generally at ultrasonic frequencies). Ultrasound as an energy transfer mechanism has the advantage of deeper penetration depths and shorter wavelengths. Electromagnetic energy has the advantage of much higher carrier frequencies, supporting higher data rates with modulation when telemetry is combined with powering. Ultrasound energy can also travel through highly electrically conductive materials, which would be opaque to electromagnetic energy[2].

Reporting in *Nature Biomedical Engineering*, John Ho and co-authors demonstrate a marked improvement in the efficiency of energy transfer of electromagnetic power through tissue[3]. Using a 6 cm by 6 cm conformal phased surface, Ho and co-authors focused electromagnetic energy through 4 cm of muscle tissue, delivering 830 μW of power to an implant (Fig. 1). *In vivo* experimental results were recorded for a cardiac pacing device implanted in an adult pig. Electrocardiographic (EKG) waveforms showed an increase in cardiac rate after 2–4 s of stimulation, with normal cardiac activity returning when stimulation was ceased.

The wavelength and attenuation factor of the electromagnetic energy transmitted through tissue (Fig. 2) determine engineering trade-offs in wireless-power delivery. The wavelength defines length scales that determine implant size, and the attenuation factor governs energy-transfer efficiency. In addition, power absorbed by tissue creates heat. Because of this, safety considerations ultimately limit the amount of power that can be delivered. Attenuation coefficients reflect a minimum in dielectric loss that generally occurs in the few-GHz regime in tissue, favouring these frequencies for energy transfer. Even so, the attenuation is severe at more than 14.6 dB cm^{-1} at 3 GHz, and rapidly rises at higher frequencies as dielectric losses begin to dominate, greatly increasing the dissipation of electromagnetic energy by bone and tissue.

The antenna sizes required for efficient energy transfer depend on the distance between transmitter and receiver relative to the transmission wavelength, λ. When the transmitter–receiver distance is less than λ, then electromagnetic coupling occurs in the near-field, quasi-static modelling of the fields (which does not require consideration of retardation and radiated energy) is possible, and for efficient energy transfer the transmitter and receiver antennae need to both be of a size comparable to the spacing between them. For spacings greater than λ, as is the case in Ho and co-authors' work, propagating electromagnetic radiation is produced, and it is preferred that both antennae be of a scale comparable to λ to achieve efficient coupling. Smaller antennae can be used (usually for the receivers) at a significant efficiency cost. This wavelength-determined size requirement is most significant for implanted devices, and places constraints on device scaling if energy-transfer efficiency is to be maintained. Higher carrier frequencies mean shorter wavelengths, but higher attenuation of the

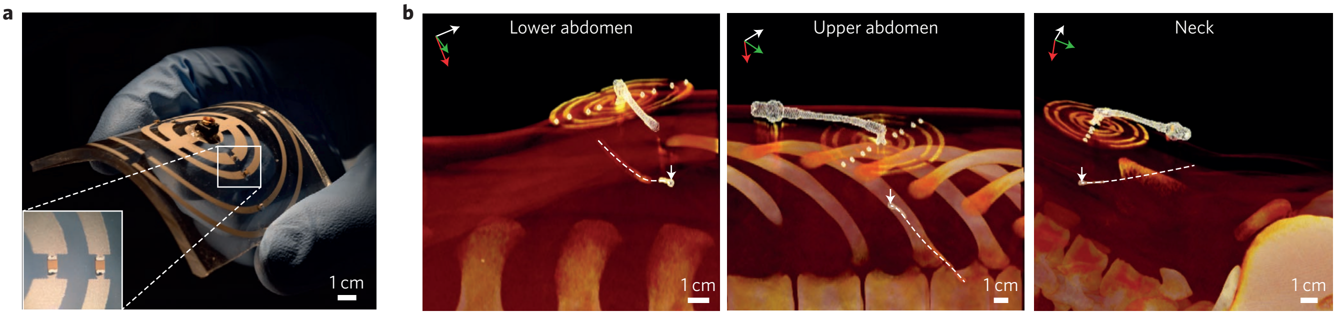

Figure 1 | Conformal phased-array surfaces for wireless power transfer. **a**, Example of the flexibility of the surface, which can tolerate a radius of curvature of up to 8 cm without affecting the focal point. **b**, 3D computed tomography of the cardiac-pacing experiment. The arrows point to the implanted microdevice; the dotted lines indicate the trajectory of the microdevice at implantation. Figure reproduced from ref. [3], Macmillan Publishers Ltd.

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.

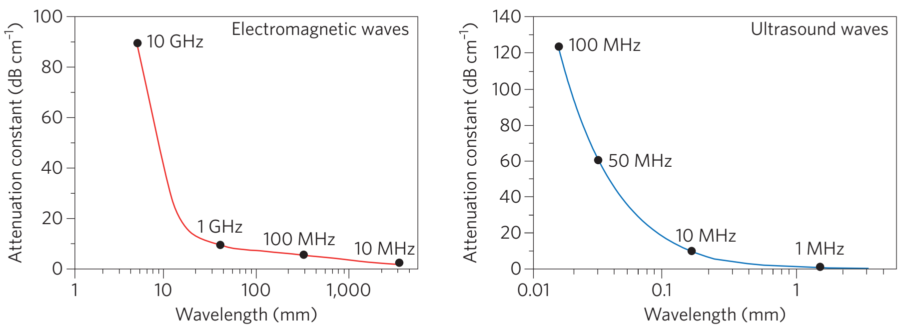

Figure 2 | Comparison of electromagnetic and ultrasound attenuation coefficients and wavelengths for power delivery in white brain matter. Data for electromagnetic attenuation and wavelength are derived from tabulated data of the real and imaginary components of the dielectric constant and conductivity. Ultrasound data assumes that the speed of sound in brain matter is similar to that in water[7–9].

electromagnetic energy at higher frequencies limits this scaling[4].

Given all these factors working against radio-frequency power transfer, how can it be optimally delivered. Ho and co-authors put forward two optimizations. The first is to use a phased array to focus the electromagnetic energy to a specific location. This focusing is only possible in the propagating regime, where interference can be used to structure the waveforms and does not apply to near-field coupling. This technique was previously studied by the same authors using external circuitry to control the phases in the antenna structure[5]. In the current work[3], they use reactive elements to do this within the antenna structure itself at a given designed operating frequency. The second optimization that they perform is to make the transmitting antenna conformal and in direct contact with the tissue. This improves the electromagnetic coupling of the antenna to the tissue, taking full advantage of the higher dielectric constant of the tissue to 'suck in' the electromagnetic energy. Other groups have explored such conformal antennae, but Ho and co-authors combined these conformal antennae with phased arrays for energy focusing. Clearly, the effectiveness of the focusing and phasing is dependent on the exact conformation of the antenna array. The net result of these two optimizations is the demonstration of 0.1% efficient power transfer at 1.6 GHz for an implant of size 3 mm in length and 1.5 mm in diameter, and for a separation of 4 cm.

It is useful to contrast radio-frequency power delivery with what is possible with ultrasound[6]. Because acoustic velocities are significantly slower than the speed of light, wavelengths for a given frequency are significantly shorter for ultrasound (Fig. 2). In addition, attenuation constants are also significantly lower for ultrasound, and a majority of tissues have a similar acoustic phase velocity, leading to smaller variation in wavelength. Furthermore, phased arrays can also be used with ultrasound to focus energy, and proximity between the transmitter and the body is also essential for efficient energy coupling. As a result, many of the conclusions of Ho and co-authors would also apply to ultrasound energy transmission. If ultrasound is so great, then why bother with electromagnetic energy transfer? There are several reasons why electromagnetic energy remains attractive in many cases. Relative to tissue, electromagnetic energy is still better at getting through bone than ultrasound. In tissue, attenuation coefficients at 1 GHz for electromagnetic energy are 9.2 dB cm^{-1}, whereas for 1-MHz ultrasound it is 0.6 dB cm^{-1} (Fig. 2). In bone, the electromagnetic attenuation coefficient increases by at most a factor of two, yet for ultrasound this attenuation degrades by more than an order of magnitude. When simultaneous data telemetry is required, the available bandwidth is significantly higher for radio-frequency transmission given the higher carrier frequencies. Furthermore, ultrasound transmission cannot be implemented using standard complementary metal-oxide–semiconductor (CMOS) processes alone; technology augmentation, in the form of microelectromechanical systems or piezoelectric transducers, is necessary.

For these reasons, electromagnetic energy delivery is arguably here to stay and the work by Ho and co-authors provides clever new ways to push the limits of wireless-power-transfer technology as implant size is driven ever lower. ❐

Jordan Thimot and Kenneth L. Shepard are in the Department of Electrical Engineering, Columbia University, New York, New York 10027, USA.
e-mail: shepard@ee.columbia.edu

References

1. Iniewski, K. *VLSI Circuits for Biomedical Applications* (Artech House, 2008).
2. Ashdown, J. D. *et al. IEEE Trans. Ultrasonics Ferroelectrics Frequency Control* **60,** 587–595 (2013).
3. Agrawal, D. R. *et al. Nat. Biomed. Eng.* **1,** 0043 (2017).
4. Choi, J. *et al. IEEE Trans. Circuits Sys. I: Reg. Papers* **62,** 1950–1958 (2015).
5. Ho, J. S. *et al. Proc. Natl Acad. Sci. USA* **111,** 7974–7979 (2014).
6. Seo, D., Carmena, J. M., Rabaey, J. M., Maharbiz, M. M. & Alon, E. *J. Neurosci. Methods* **244,** 114–122 (2015).
7. Goss, S., Frizzell, L. & Dunn, F. *Ultrasound Med. Biol.* **5,** 181–186 (1979).
8. Gabriel, C. *Compilation of the Dielectric Properties of Body Tissues at RF and Microwave Frequencies* (DTIC Document, 1996).
9. Chivers, R. & Hill, C. *Ultrasound Med. Biol.* **2,** 25–29 (1975).

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.