REVIEW ARTICLE
https://doi.org/10.1038/s41928-021-00589-7

nature electronics

# Metasurfaces for bioelectronics and healthcare

Zhipeng Li[1], Xi Tian[1], Cheng-Wei Qiu[1]✉ and John S. Ho[1,2,3]✉

**Bioelectronic systems typically rely on radiofrequency wireless components to interface with the human body, but such components are bulky and energy-demanding, which limits the performance of the systems. Metasurfaces—artificial two-dimensional materials with subwavelength structure—can be engineered to control electromagnetic fields around the human body and could be used to overcome the current limitations of bioelectronic interfaces. Here we review the development of metasurfaces for bioelectronics, and explore their potential for application in current and emerging healthcare technologies. We examine the use of metasurfaces to control electromagnetic fields in the vicinity of the human body, and discuss their application in microwave imaging, magnetic resonance imaging, biosensors, body networks and wireless power transfer. We also consider developments in materials science and artificial intelligence that can enhance the properties of metasurfaces for bioelectronics.**

Wireless technologies are widely used in bioelectronic devices for diagnostics and therapy[1–3]. An early example is the first implantable pacemaker, built in 1958, which incorporated a radiofrequency coil for inductive wireless charging[4]. Today, wireless power transfer is used in implantable biomedical devices, including cochlear implants that assist hearing[5] and retinal implants that can restore sight[6]. Devices that are worn on or implanted in the body also rely on wireless technologies to communicate with the external world. Examples of such devices include wearable health monitors that notify family when abnormalities are detected[7], ingestible cameras that can transmit diagnostic images of the gastrointestinal tract[8] and implanted spinal cord stimulators that are remotely adjusted by patients for optimal pain relief[9]. Recent developments in sensors and mobile computing have enabled additional functionalities and wearable devices that sense, track and transmit physiological signals in real time to provide rich data sets about human health. The widespread acceptance of these devices by clinicians and patients has empowered patients to remotely monitor their health and receive care electronically, outside traditional healthcare settings.

Radiofrequency techniques are the dominant wireless technology used for bioelectronic applications due to their relative safety and maturity, but other modalities are also being actively explored[10]. These systems use components such as antennas, waveguides and phased arrays to control the propagation of electromagnetic fields[10], which are usually the largest and most energy-demanding part of a bioelectronic device and thus determine the safety and efficacy of the system. However, the human body is a lossy, heterogeneous and dispersive medium, presenting major challenges for wireless technologies. Biological tissues, in particular, absorb electromagnetic radiation, which must be within safety limits to prevent adverse thermal or stimulatory effects[11]. Because tissue absorption increases with higher electromagnetic field frequencies, an operating frequency of less than 5 GHz is required to access regions deep in the body[12]. However, this requirement also limits the miniaturization of the components and the ability to focus the electromagnetic field because the wavelength in biological tissues exceeds a centimetre at such frequencies. Furthermore, the human body is in constant motion and its size and composition greatly vary between individuals. These features present formidable challenges for the design of miniaturized, robust and high-performance wireless bioelectronic components for sensing and therapy.

Metasurfaces are flat electromagnetic devices that are structured at subwavelength scale with metallic or dielectric inclusions[13,14] and offer unique properties that can complement, and in some cases replace, conventional components for bioelectronics (Table 1). First, metasurfaces can amplify or suppress interactions between biological matter and electromagnetic fields at the deep subwavelength scale[15]. Second, metasurfaces can engineer the electromagnetic properties of radiofrequency devices and freely manipulate the amplitude, phase and polarization of electromagnetic wavefronts[16]. Third, they can be fabricated in flat, compact and flexible formats[17] that could potentially be placed near otherwise inaccessible physiological regions, and be integrated into wearable or implantable devices.

In this Review, we examine recent advances in metasurfaces that can manipulate electromagnetic fields around, on and in the human body (Fig. 1). We discuss the design and features of these metasurfaces, and their applications in medical imaging, sensor networks, wireless sensing and wireless power transfer (Fig. 1b–f). We also identify emerging functionalities of metasurfaces for bioelectronics based on recent advances in materials science and artificial intelligence (Table 2).

## Controlling fields around the body

Metasurfaces could potentially be integrated into our everyday environments[18] to monitor physiological signals and help understand and manage chronic conditions wherever and whenever they occur. For example, metasurfaces installed in homes may be able to continuously measure physiological motions to detect elderly falls and notify family, or identify asthma attacks and reveal underlying environmental factors[19]. Challenges remain in optimizing the size, power consumption and computational demands of metasurfaces[20], although innovations in algorithms and low-power electronics can help lower their cost. Rigorous evaluation will also be needed to show that they can provide sufficient accuracy and precision to benefit patients.

**Microwave imagers.** Microwave imaging can provide information about objects through walls and clothing without ionizing radiation. It is widely used for security screening applications, and

[1]Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore. [2]The N.1 Institute for Health, National University of Singapore, Singapore, Singapore. [3]Institute for Health Innovation and Technology, National University of Singapore, Singapore, Singapore.
✉e-mail: chengwei.qiu@nus.edu.sg; johnho@nus.edu.sg

**Table 1 | Applications of metasurfaces for bioelectronics**

| Electromagnetic control | Application | Enhancement |
|---|---|---|
| Around the body | Microwave imaging | Resolution and speed<br>Power consumption<br>Compactness |
| | MRI | SNR and speed |
| On the body | Biosensors | Sensitivity<br>Operating range |
| | Body sensor networks | Power consumption<br>Data rate<br>Security and privacy |
| In the body | Wireless power transfer | Transfer efficiency<br>Operating range<br>Robustness |

is also the basis for clinical sleep monitoring[21] and fall detection[22] technologies owing to its ability to detect physiological activity, including small motions arising from respiration and heartbeat. Conventional designs for microwave imagers are based on phased arrays, which require a large number of antennas and complicated feeding networks. As a result, their cost, power consumption and data processing demands are currently prohibitive for many practical applications[23,24].

Metasurfaces can be used to build microwave imagers that meet the speed, resolution and cost requirements for health monitoring[25]. In one approach, the metasurfaces act as passive apertures that generate spatially diverse illumination patterns that vary with frequency, which are used for image reconstruction after computational analysis[25]. This frequency scanning operation can remove the need for the mechanical aperture scanning in conventional approaches and requires only a single active antenna. An early demonstration of the concept used a metasurface aperture consisting of passive microstrip lines (acting as waveguides) loaded with complementary electric inductor–capacitor metamaterial elements[26], where each element functions as a resonator coupling microwaves from the guided mode to free space, allowing different radiation patterns to be generated. The concept was also implemented for imaging at the human scale[27], on the basis of a metasurface design comprising 24 transmit and 72 receive panels that generate distinct illumination patterns as the operating frequency was varied from 17.5 to 26.5 GHz. Computational reconstruction of the scene revealed hidden threat objects on a mannequin relevant to security applications (Fig. 2a).

Reconfigurable metasurfaces, based on programmable unit cells that dynamically shape electromagnetic fields, can achieve faster and higher-resolution imaging compared with approaches based on frequency scanning, but require active control[28]. An imager based on reconfigurable metasurfaces was developed for real-time imaging and recognition of human body poses (Fig. 2b)[29]. This metasurface consisted of digitally programmable meta-atoms—based on subwavelength-scale square metallic patches that are connected via a PIN diode—and used machine learning to extract information from a scene. The metasurface could also be used to manipulate ambient Wi-Fi signals to produce images of the entire human body. These imaging capabilities were used to perform body pose recognition and respiration monitoring, which could have broad applications in home-based health monitoring[19].

**Magnetic resonance imaging (MRI).** MRI is a versatile and ionizing radiation-free medical imaging technique prominently used in diagnostic medicine[30]. To acquire high-resolution images within reasonable scan times, methods to increase the signal-to-noise ratio (SNR) of the measured radiofrequency nuclear magnetic resonance signal are needed. Metasurfaces could potentially improve the signal by directly manipulating the radiofrequency field around the body to increase the SNR in a particular region of interest. In particular, they can resonantly enhance the field strength, as well as spatially redistributing the magnetic field to increase the coupling between the region of interest and the radiofrequency coils. Because of their flat profiles, metasurfaces can be placed near the surface of the body for maximum sensitivity without causing obvious discomfort and can be used with existing MRI scanners and pulse sequences with compatible operating frequency. Metasurfaces are also complementary to other approaches for increasing the sensitivity of MRI, such as using a larger static magnetic field[31], multiple receiver coils[32,33] and dielectric pads[34], and have been recently demonstrated in human trials[35], which highlighted their potential for clinical use in demanding imaging applications.

Most reported metasurfaces for enhancing MRI are passive devices that alter the radiofrequency field over the physiological area of interest. An early example is a metasurface comprised of a $14\times2$ wire array of metallic wires exhibiting a fundamental Fabry–Perot resonance at 63.8 MHz (Fig. 2c)[36]. MRI scans of a biological specimen showed that the SNR was enhanced by more than twofold compared with the case without the metasurface. Similar signal enhancement has also been achieved using negative-permeability metasurfaces composed of split-ring resonators[37]. To accommodate the curved surface of the human body, flexible metasurfaces for MRI have been developed. For example, a head-conforming metasurface consisting of thin conductor strips on a high-permittivity substrate ($CaTiO_3$) was used to enhance brain imaging in an ultrahigh-field MRI system (Fig. 1c)[38]. When placing the metasurface near the occipital cortex, the SNR of the image was enhanced by 50%, corresponding to a twofold decrease in the total scan time. In vivo imaging with a metasurface resonator at 1.5 T improved the local radiofrequency transmission efficiency by a factor of 3.3 (ref. [39]). Similarly to other approaches that rely on non-volumetric receivers, an inherent limitation is that the SNR degrades with depth.

To optimize image quality, reconfigurable metasurfaces can be used to tailor the local field to the curvature and composition of the region of interest. For example, a hybrid dielectric and metallic metasurface with dynamically tunable effective permittivity was implemented by controlling the water level at the edges of a wire array[40]. The metasurface could enhance the SNR of an MR image of a grapefruit by 7.6-fold through the optimization of the coupling between the metasurface's eigenmodes and the MRI system's radiofrequency coils. Nonlinear reconfigurable metasurfaces have also been used to tune the response during the imaging process[41]. In this design, a helical array was loaded with a varactor (Fig. 2d) that suppresses the resonance of the metamaterial during the pulse transmission phase; it recovers during the reception phase to provide selective enhancement of the magnetic field. These demonstrations suggest the potential of adaptive and reconfigurable metasurfaces that can optimize signal reception in real time to improve imaging resolution and scan times.

## Controlling electromagnetic fields on the body

Metasurfaces can address limitations in wireless communication and the interconnection of sensor networks by manipulating electromagnetic fields on the surface of the body. Furthermore, the structures can be made to conform on the body surface or be integrated into clothing for unobtrusive use during daily life.

**Wireless biosensors.** Wireless biosensors can measure a wide range of physiological parameters, including respiration, heart rate, body temperature, pulse oxygenation, blood pressure and blood glucose[42], and transmit the data to patients and doctors. To remove

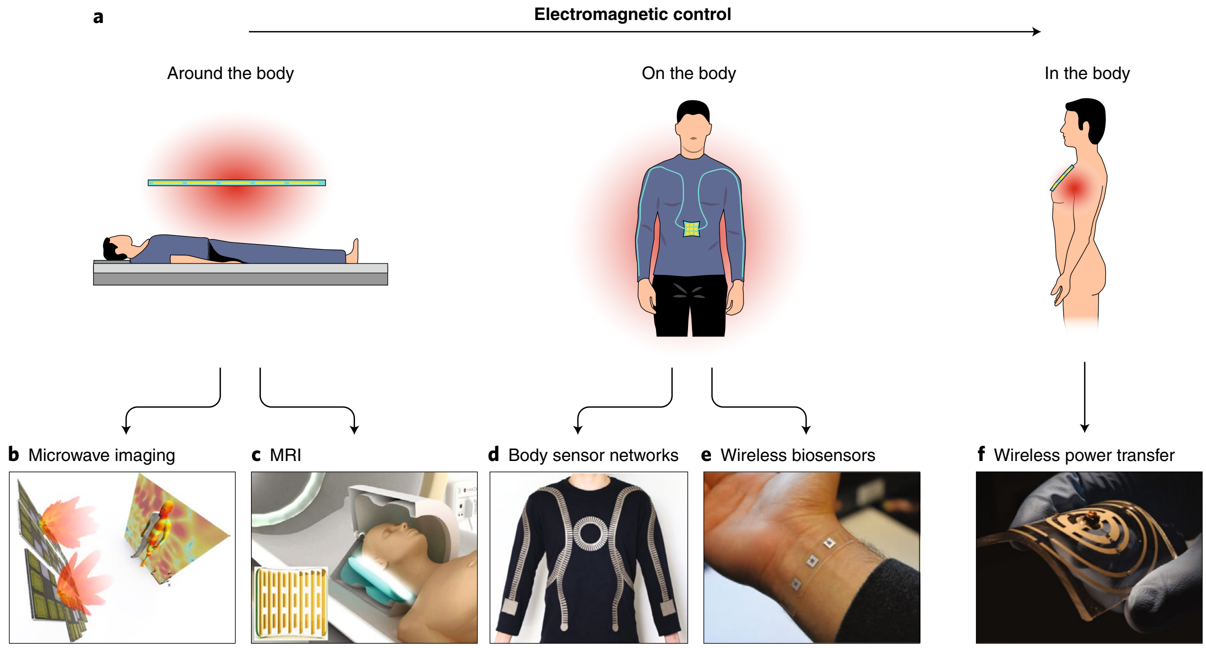


**Fig. 1 | Metasurfaces in bioelectronic applications.** **a**, Metasurfaces can manipulate electromagnetic fields around, on and within the human body to enhance the diagnostic or therapeutic function of bioelectronic systems. **b**–**f**, Examples of healthcare technologies that exploit the capabilities of metasurfaces include microwave imaging (**b**), MRI (**c**), body sensor networks (**d**), wireless biosensors (**e**) and wireless power transfer (**f**). Figure adapted with permission from: **b**, ref. [27], under a Creative Commons license CC BY 4.0; **c**, ref. [38], under a Creative Commons license CC BY 4.0; **d**, ref. [56], Springer Nature Ltd; **e**, ref. [46], Wiley; **f**, ref. [74], Springer Nature Ltd.

**Table 2 | Emerging research directions in metasurfaces for bioelectronics**

| | Area | Emerging applications |
|---|---|---|
| Electromagnetic control | Polarization control | Orientation invariance |
| | Temporal control | Non-reciprocity |
| | Nonlinearity | Frequency conversion |
| | Reconfigurability | Motion adaption |
| Materials | Flexible and stretchable materials | Wearability Conformability |
| | Bioresponsive materials | Biochemical sensing |
| Artificial intelligence | Inverse design | Personalization |
| | Data interpretation | Classification Medical diagnosis |
| | Adaptive control | Closed-loop therapy |

the need for batteries, passive wireless telemetry techniques can be employed for the remote readout of data from a battery-free sensor. Most telemetry approaches are based on the resonant sensor architecture, where the physiological parameter of interest produces shifts in the resonant frequency of the sensor's capacitive or inductive circuit[43]. Several wireless pressure sensors are based on this architecture, including medical devices that can be inserted into the heart for heart failure detection[44] and contact lenses for monitoring glaucoma[45].

Resonant sensors can be arranged in arrays reminiscent of metasurfaces to provide wireless sensing at multiple locations (Fig. 3a,b). Skin-mounted sensors comprising an array of bilayered split-ring resonators have been used to wirelessly monitor pressure, sweat and temperature from the wrist[46]. Passive arrays of resonators fabricated on soft substrates have also been used for mapping pressure inside the body[47] and for monitoring intracranial pressure in mice when wirelessly coupled to an external readout coil (Fig. 3b). These sensors, however, rely on near-field coupling to an external device and have a maximum readout range of only a few centimetres.

Metasurfaces that operate in the far-field may provide a platform for battery-free biosensors that communicate with distant wireless devices. Far-field metasurfaces have been previously explored in the context of 'chipless' radiofrequency identification (RFID) tags. Whereas conventional RFID tags rely on an integrated circuit to generate a temporal backscattering identifier, chipless RFID tags are based on electromagnetic structures with unique scattering signatures[48]. For example, metasurfaces with sharp frequency-selective reflections can be used to encode identification bit sequences through the presence and absence of resonant peaks in the reflection spectrum[49]. They can also provide distinct polarization responses, such as cross-polarized reflection, to enable the signal from the RFID to be distinguished from the background[50]. These scattering signatures may be engineered to respond to physiological signals for low-cost and potentially disposable wireless sensors. Because no batteries or fragile silicon components are used, such sensors could be fabricated on flexible substrates suitable for mounting on the skin or incorporated into clothing[51]. Challenges include distinguishing the reflection of the metasurface from that of the background, and designing sensors that can transduce small physiological signals into large changes in conductivity or dielectric permittivity.

**Body sensor networks.** Multiple wearable sensors can form a network of connected devices—called a body sensor network—that can continuously track physiological signals and transmit data to a central hub to support health monitoring and clinical decision-making. Wireless communication is essential to interconnect sensor nodes without cumbersome wires, but the reflection and absorption of

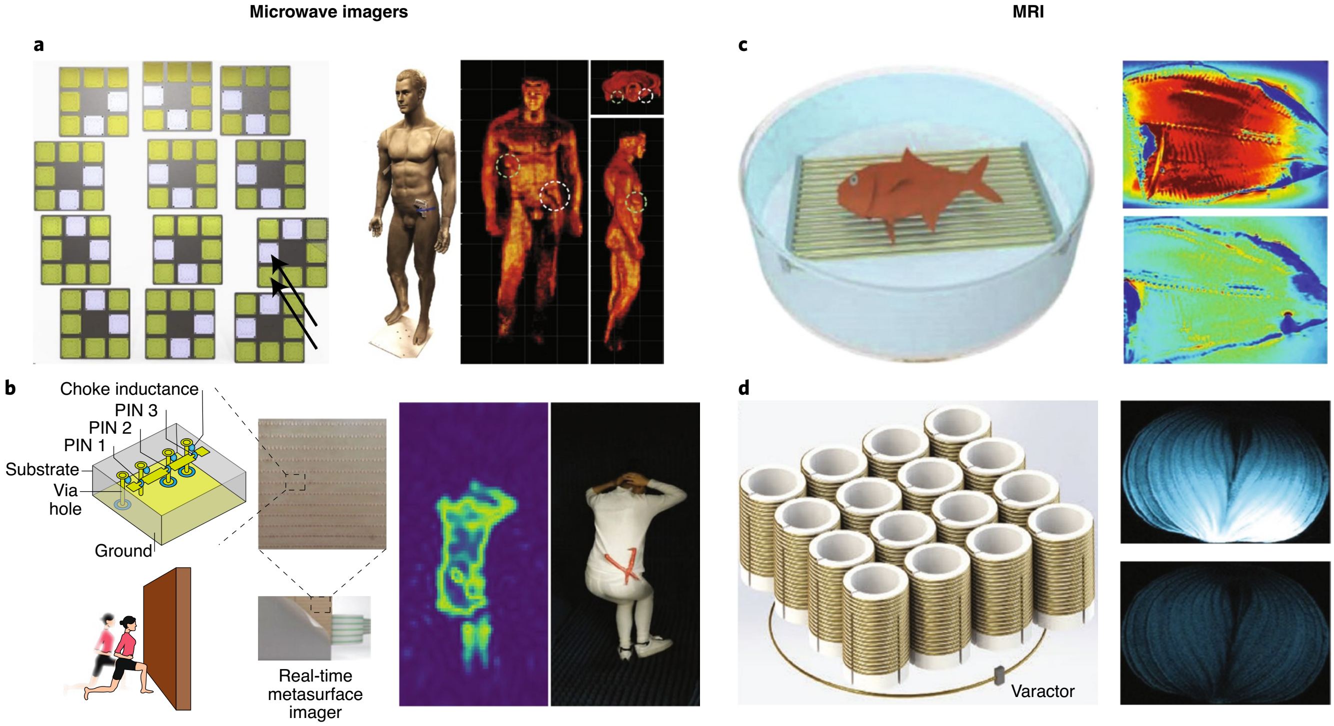


**Fig. 2 | Metasurfaces for electromagnetic control around the body. a**, A human-scale microwave imager. The metasurface consists of 24 transmit and 72 receive frequency-diverse panels, which can acquire images for security screening. **b**, A real-time, reconfigurable metasurface imager operating at around 3 GHz. Following an initial training step, a machine learning algorithm was used to identify configurations of the meta-atoms that generate radiation patterns that are superior to random projection for extracting information from the scene. **c**, A metasurface for enhancing MRI. Images show the SNR when imaging a fish with and without the metasurface. **d**, A reconfigurable metasurface for adaptive MRI. Images show the SNR when imaging an onion with and without the metasurface. A 15-fold enhancement of SNR was achieved using a metasurface. Figure adapted with permission from: **a**, ref. [27], under a Creative Commons license CC BY 4.0; **b**, ref. [29], under a Creative Commons license CC BY 4.0; **c**, ref. [36], Wiley; **d**, ref. [41], Wiley.

electromagnetic waves by the human body present major obstacles for radiofrequency signal transmission[52]. Metasurfaces that can control the propagation of electromagnetic fields on the surface of the body can be used to overcome these challenges and enable new sensor network functionalities.

Metasurfaces can enable more compact and efficient wearable antennas. An important use of metasurfaces is to provide a functional plane between the antenna and human skin that both reduces tissue absorption and acts as a reflector to increase high antenna gain. Metasurface concepts relevant for this purpose include electromagnetic band-gap structures, high-impedance surfaces and artificial magnetic conductors. For example, using arrays of alternating high- and low-dielectric-permittivity regions, band-gap structures have been used to prevent radiation from wearable devices in the direction of the human body[53]. The flat profile of such ground-plane structures has been used to realize a flexible antenna that can conform to non-planar body surfaces while maintaining stable gain and impedance[54] (Fig. 3c). Reconfigurable wearable antennas based on metasurfaces with reconfigurable elements, such as loaded vias and switchable stubs, have also been developed[55]. Such antennas can, for example, switch between an omnidirectional radiation pattern desirable for the communication between sensor nodes and a broadside radiation pattern that favours communication with an external device.

Metasurfaces fabricated from conductive textiles can also be used to enable wireless signals to propagate along the surface of the body instead of radiating into surrounding space. This strategy can enhance the energy efficiency of radiative wireless communication and limit its vulnerability to eavesdropping. Metamaterial textiles comprising comb-shaped patterns that support surface plasmon-like modes have been incorporated into clothing covering the upper body (Fig. 3d). These textiles allow 2.4–2.5 GHz wireless signals emitted by devices near the clothing to propagate as surface waves confined within 10 cm of the body[56]. The use of this metamaterial textile can increase the signal transmission efficiency between two sensors on the body by up to three orders of magnitude compared with radiative transmission. In addition, networks that are wirelessly interconnected by the metamaterial textiles can provide functionalities in wireless power transfer and touch sensing (Fig. 3d). Such textiles can also be designed to redirect the propagation of signals around the torso to provide a near-omnidirectional radiation pattern for a wearable wireless device, overcoming the obstruction of the human body[52]. Clothing integrated with metamaterial textiles is potentially robust to washing, sweat and daily use because they do not involve fragile silicon components or wired connectors. However, losses associated with sharp corners and proximity to biological tissues remain challenges, and further evaluation is needed to establish their long-term reliability.

Wearable metasurfaces that provide enhanced wireless connectivity may open opportunities for mapping physiological parameters across the body. Such physiological maps can provide more detailed health information than conventional wearables, which measure parameters from a single anatomical location. For example, wireless and battery-free sensors based on near-field communication have been used to create full-body spatiotemporal maps of the temperature and pressure distribution for monitoring circadian rhythms and mitigating risk of pressure-induced ulcers during sleep[57]. Another example is non-invasive monitoring of systolic blood pressure, which can be achieved by synchronously measuring the pulse arrival time and pulse transit time from multiple

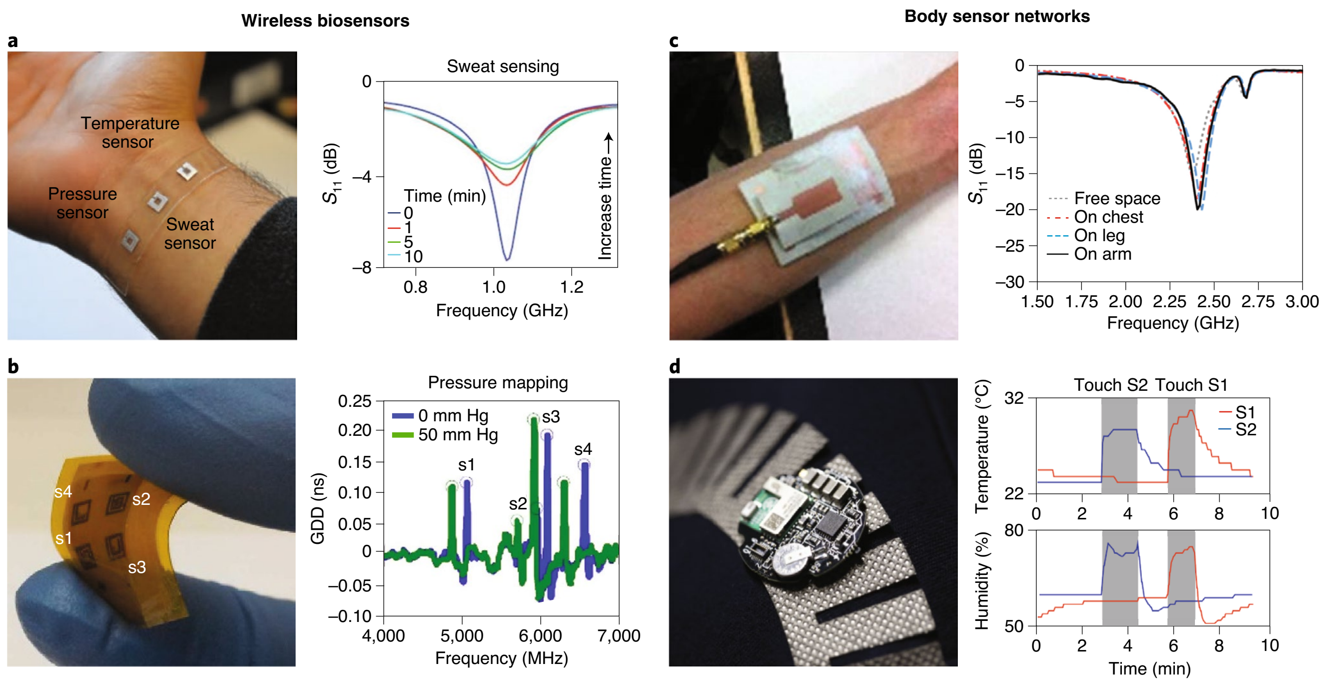


**Fig. 3 | Metasurfaces for electromagnetic control on the body. a**, A wearable wireless biosensor. The sensor consists of split-ring resonators that convert changes in sweat, pressure and temperature into resonant frequency shifts. These resonators feature a hydrogel interlayer, whose dielectric permittivity varies with the physiological parameters, and each sensor can be individually addressed through its unique resonant frequency. **b**, A soft wireless pressure sensor array. The array maps pressure through shifts in multiple resonances. **c**, A metasurface-based antenna for wearable wireless communications. The metasurface ground plane enables robust operation when worn on different parts of the body. **d**, A metasurface textile for body sensor networks. The conductive textile design supports surface plasmon-like modes that enable wireless signals to efficiently propagate between sensor nodes. Figure adapted with permission from: **a**, ref. [46], Wiley; **b**, ref. [47], Springer Nature Ltd; **c**, ref. [54], IEEE; **d**, ref. [56], Springer Nature Ltd.

biosensors placed on the chest and limb. A wireless and battery-free system for monitoring core vital signs in a neonatal and paediatric intensive care unit has been demonstrated using this approach[58]. The operation of such multinode networks, however, has so far been limited to patients in close proximity to a readout coil integrated in a hospital bed. Clothing integrated with metasurfaces and advanced electromagnetic structures could facilitate the exchange of data and power across the body, and open new opportunities for mapping physiological signals relevant to health during daily activity.

## Controlling electromagnetic fields in the body

Metasurfaces can systematically control electromagnetic fields within the body to wirelessly interface with implanted or ingested bioelectronic devices. Furthermore, they can manipulate interactions between radiofrequency waves and biological tissues for non-invasive sensing and therapy.

**Wireless power transfer.** Power is a fundamental bottleneck for implantable devices that limits the operating lifetime and available range of function. Today, most clinically used devices are powered by an on-board battery, which occupies a large portion of the device's volume and needs to be surgically replaced when depleted[59]. Wireless power transfer can overcome these challenges by enabling the battery to be remotely recharged, or in some cases removed altogether[60]. Near-field inductive coupling has been used for wireless power transfer since the first implantable pacemaker and remains the dominant approach for powering devices more than a centimetre in size, such as cochlear implants. However, because this approach is based on the near-field, it suffers from inherently low efficiencies when the device dimensions are much smaller than the operating depth[61]. Mid-field wireless power transfer has been explored as an alternative approach, operating with electromagnetic waves at gigahertz frequencies, which propagate deeper and are compatible with miniaturized antennas[60]. Tissue absorption and the efficiency limits of subwavelength antennas, however, pose fundamental challenges for this approach. Leveraging the wide use of ultrasound in clinical imaging[62], ultrasonic techniques have emerged as an attractive modality for a wireless power transfer[63]. This approach benefits from the lower attenuation of ultrasound in biological tissues compared with electromagnetic waves[64] and shorter wavelengths, which provides smaller resonant dimensions and improved capacity for focusing. However, reflections at soft–hard tissue interfaces and losses related to electroacoustic conversion, including sensitivity to orientation, are major challenges[65]. Photonic techniques have also been explored for wireless power transfer[66], although optical scattering has so far limited the operating depth to less than a centimetre even at near-infrared wavelengths[67]. Although all of these approaches are active areas of research, we focus here on the use of metasurfaces for radiofrequency wireless power transfer.

Near-field metasurfaces can be used to extend the range of wireless power transfer. These designs generally exploit the collective resonances of multiple unit cells to enhance wireless power transfer from the transmitter to the receiver with efficiency greater than that of conventional coil-based relays[68]. For example, a wearable metasurface composed of a dual-layer structure of square spirals was used to increase magnetic coupling between an external transmitter coil and an implant at 3 mm depth under the skin[69]. Beyond power transfer efficiency, clinical applications also require techniques to ensure a reliable supply of power under a wide range of conditions. Nonlinear parity–time symmetry has recently been shown to provide robust wireless power transfer without the need for manual tuning of system parameters[70], and might be applied to near-field

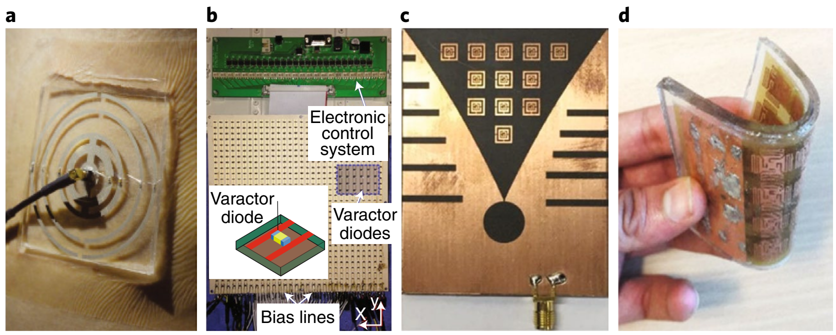


**Fig. 4 | Metasurfaces for electromagnetic control in the body. a**, A conformal metasurface for wireless power transfer. When excited from a single port, mutual coupling between the rings resonates with the reactive loads, resulting in a phase response that was optimized for wireless power transfer at about 5 cm depth in tissue. **b**, A reconfigurable metasurface for manipulating electromagnetic focusing. The metasurface consists of an array of copper strips printed on a copper-backed dielectric substrate. **c**, A metasurface-integrated microwave imager for breast tumour detection. **d**, A flexible metasurface for wearable microwave imaging. Figure adapted with permission from: **a**, ref. [74], Springer Nature Ltd; **b**, ref. [75], APS; **c**, ref. [79], under a Creative Commons license CC BY 4.0; **d**, ref. [80], IEEE.

metasurfaces. These designs are, in principle, compatible with many clinically used wireless power transfer systems, but testing is needed to establish potential clinical advantages over the current standard.

Metasurfaces that operate at low-gigahertz frequencies have been employed to focus electromagnetic energy in the vicinity of the microdevice for wireless power transfer. In contrast to inductive wireless power transfer, this approach operates in the mid-field (distance comparable to the wavelength in tissue), where both the evanescent and propagating components of the field are dominant[71]. In this regime, the distribution of electromagnetic energy within the body can be controlled by interfering components of the field radiated by different elements to improve the efficiency of power transfer to the implanted device[72]. While this can be accomplished using multiple antennas placed on the surface of the body, such phased arrays are generally very complex and bulky because they rely on phase-control circuitry. In addition, the mutual coupling between adjacent antennas limits the spatial phase resolution of such arrays and thus the optimal shaping of the field within the body, which has a much higher dielectric permittivity than free space[73]. To overcome this challenge, a conformal metasurface (Fig. 4a) based on reactive loading elements to control the spatial phase distribution of the electromagnetic field in the body was designed[74]. The metasurface was fabricated on a soft substrate and could be placed on curved body surfaces with minimal distortion of the generated field pattern for moderate curvatures comparable to those of the adult human torso. Experiments in a porcine animal model demonstrated the wireless transfer of 0.45 mW to a light-emitting microdevice (1.5 mm diameter, 3 mm length) at a depth of 4.3 cm under safety limits corresponding to less than 1 °C heating of the skin. This level of power transfer was sufficient to activate a wireless stimulator of the same dimensions inserted into the heart using a catheter, and regulate cardiac rhythm in an adult pig[74]. However, a limitation of the design is that the phases imposed by the metasurface are fixed and cannot be reprogrammed in real time to adapt to variations in the tissue environment.

Reconfigurable metasurfaces have been explored for wireless power transfer in free space. Using programmable electronic elements, such metasurfaces can adaptively optimize the field distribution to maintain high powering efficiency in dynamic environments. For example, a metasurface capable of creating microwave focal spots with desired number and positions has been developed (Fig. 4b)[75]. Programmable voltage-controlled varactor diodes were used to reconfigure the phase profile and control the position of the focal point. Reconfigurable metasurfaces that can be conformally placed over the surface of the body could provide near-complete control over the electromagnetic field for efficient and robust powering.

**Communication.** Metasurfaces have been used to enhance wireless communication between devices in the body and the external world. In one approach, metasurfaces were used to eliminate the impedance mismatch between free space and the body, which accounts for more than 80% of total transmission loss from an implanted device emitting in the 100 MHz to 10 GHz frequency range[76,77]. In contrast to dielectric matching layers, the thickness of these metasurfaces can be deeply subwavelength (less than 1 cm), enabling the metasurfaces to be placed on the body as a flexible adhesive patch or even integrated into clothing[78]. However, practical use of such metasurfaces will require design techniques to address the variability of the tissue composition between different body regions and individuals as well as uncertainty in the angle and polarization of the electromagnetic wave.

**Imaging, localization and hyperthermia therapy.** Microwave imaging inside the body is of clinical interest for cancer detection, stroke monitoring and other diagnostic applications because of the large difference in dielectric permittivity between normal and pathological tissues[27,29]. Metasurfaces can be used to realize high-gain and low-profile imaging antennas that provide highly directive transmission into the body. For example, an array of 16 microstrip antennas loaded by index-zero metasurfaces (Fig. 4c) was used to improve imaging resolution in a breast phantom[79]. To circumvent the reflection of radiofrequency waves from the air–tissue interface, conformal metasurfaces have been applied for brain stroke diagnosis[80]. This design consisted of a head-mounted antenna array in which the antenna elements are $4\times4$ radiating patches with an electromagnetic band-gap metamaterial reflector fabricated on a soft polydimethylsiloxane substrate (Fig. 4d). Using an array of eight such antenna elements, confocal microscopy imaging experiments demonstrate the ability to detect abnormalities within a head phantom[80]. Several clinical trials have demonstrated increasing evidence of the contrast in dielectric properties of healthy and cancerous tissue, although variations in the design of microwave imaging systems still impede adoption into clinical practice[81].

In applications ranging from endoscopy[8] and inductor–capacitor biosensors[82] to drug delivery systems[83], accurate localization is important to diagnose diseases and deliver therapeutics at the correct anatomical location. Metasurfaces can be used to improve the localization of implantable and ingestible devices within the body. Compared with imaging methods based on ultrasound, magnets and X-rays[84], which require relatively complex equipment, radiofrequency localization is based on low-cost receivers and can be combined with wireless data transmission. Most radiofrequency

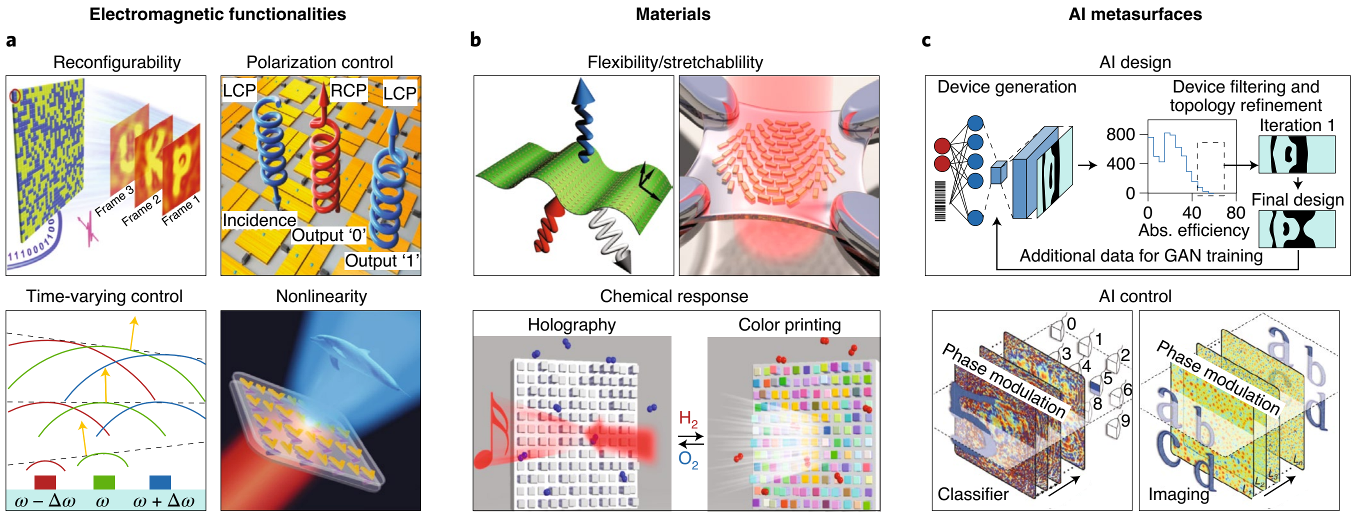


**Fig. 5 | Emerging research directions. a**, Electromagnetic functionalities such as reconfigurability, polarization control, time-varying control and nonlinearity can create more robust wireless interfaces with bioelectronics. LCP, left-handed circular polarization; RCP, right-handed circular polarization. $\omega$, operating frequency; $\Delta\omega$, modulation frequency. **b**, Flexible, stretchable and chemically responsive materials can address challenges in integration and sensing. **c**, Artificial intelligence (AI) can be used to design metasurfaces and control their reconfigurable elements to adapt to changing physiological environments. GAN, generative adversarial network. Figure adapted with permission from: **a** (top left), ref. [115]; **a** (bottom right), ref. [97]; **b** (top left), ref. [17]; **b** (bottom), ref. [106], under a Creative Commons license CC BY 4.0; **a** (top right), ref. [96], Wiley; **a** (bottom left), ref. [98]; **c** (bottom), ref. [113], AAAS; **b** (top right), ref. [116]; **c** (top), ref. [111], American Chemical Society.

localization techniques are based on triangulation of the device position using multiple receiver antennas placed around the body, with various propagation models to account for variations in the tissue properties[85–87]. Reconfigurable metasurfaces with dense arrays of unit cells could increase the effective number of receiving antennas to improve the localization in real time. Negative-index metasurfaces have also been developed to focus electromagnetic fields beyond the diffraction limit[88], including in disordered media. Such concepts may be applied in the medium of the human body to enable localization with subwavelength resolution. An alternative localization concept is based on microdevices that can vary their transmission frequency in proportion to applied magnetic field gradients, in analogy to magnetic spins in MRI[89]. The advantages that metasurfaces offer for MRI may be translated here for enhancing local reception of the radiofrequency field[36,38,41].

Microwaves are clinically used in cancer hyperthermia therapy to thermally increase perfusion for drug uptake, stimulate the immune response and/or directly destroy cancer cells, often in combination with radiotherapy[90,91]. Metasurfaces have been explored for improving the therapeutic application of microwaves by focusing them to selectively heat the tumours while minimizing damage to healthy tissues. Left-handed and zero-index metamaterials have been theoretically analysed for microwave hyperthermia[92,93]. In particular, a left-hand metamaterial lens[92] has been used to focus microwave fields (2.45 GHz) into a tissue region 1 cm in width and 1.2 cm in depth and elevate the temperature above 42 °C. The use of metasurfaces in microwave therapy is currently in the exploratory stage and has so far been limited to theoretical and numerical studies[92]. However, they are of increasing interest in view of recent advances in precision nanomedicine, particularly metallic nanoparticles that have strong radiofrequency absorption[94].

## Outlook

To address the challenges involved in the development of metasurface-based bioelectronics, innovations on terms of circuit design and materials will be required. Advances in artificial intelligence can also optimize the design of metasurfaces and enhance their functionality.

**Full electromagnetic control.** Despite impressive progress in reconfigurable metasurfaces, achieving full control of the electromagnetic field in the vicinity of the human body remains a challenge. In particular, current designs have a limited number of unit cells and degree of tunability due to the complexity of the control circuitry. New circuits and control architectures, such as mechanical actuation, phase-change materials and optical control, may provide higher resolution and tunability[95]. Dynamic control of the polarization response could potentially address important challenges related to the uncertain orientation of bioelectronic devices worn on or implanted in the body. These concepts have been explored in optical[16] and radiofrequency metasurfaces[96], but have not been widely implemented in bioelectronic wireless systems. In addition, emerging concepts in nonlinear[97] and time-varying[98] metasurfaces can introduce novel features based on Doppler shifts, broken Lorentz reciprocity and time-reversed fields. Such phenomena could potentially increase the sensitivity of biosensors, allow the control of multiple bioelectronic devices and achieve power transfer to moving devices.

Due to the scale invariance of Maxwell's equations, many of the powerful capabilities developed for optical metasurfaces can be translated to radiofrequencies for application to bioelectronics[13,14]. However, fundamental differences beyond the scaling of the wavelength exist between metasurfaces in the optical and radiofrequency regimes. For example, metals with excellent conductivity are readily available at radiofrequencies, but dielectric materials are preferred at optical frequencies because of the high loss exhibited by metals[13]. In addition, optical metasurfaces can exploit the molecular selectivity of light in interacting with biological matter[99], while the ability of radiofrequency metasurfaces to analyse the molecular composition of tissues and organs is limited. Conversely, the penetration depth of light is limited to about a centimetre in biological tissue, even at near-infrared wavelengths[67], whereas radio waves can penetrate many centimetres into the body.

**Functional materials.** In contrast to conventional radiofrequency components, metasurfaces designed for bioelectronics need to be flexible and even stretchable to comfortably interface with the human body[100]. Materials and layouts developed for flexible electronics provide important fabrication strategies for realizing flexible metasurfaces. Metasurfaces can be fabricated on plastic (polyimide, polyethylene terephthalate), elastomeric (ecoflex, polydimethylsiloxane) and textile substrates[100] using a wide variety of processes, including direct printing and transfer printing[101]. Due to the relatively long wavelength, the resolution requirements are substantially less stringent than for most electronic and optical applications. Conductors that are intrinsically rigid, such as copper, gold and aluminium, can be made flexible through the structural mechanics of motifs such as serpentine lines, helical coils and open meshes[102]. However, the associated inductances and capacitances need to be incorporated into the electromagnetic design. Intrinsically flexible conductive materials, such as conductive polymers, hydrogels and ionogels, are promising material candidates for metasurfaces, although their relatively low conductivity remains a major limitation[100]. Poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT:PSS), in particular, has one of the highest conductivities among conductive polymers and has been explored for use in flexible antennas[103]. Liquid metals are also noteworthy in that they are both intrinsically flexible and have excellent conductivity. They have been used to realize microfluidic reconfigurable antennas, pressure sensing fibres and fabric-integrated transmission lines[104]. In addition, composites of inorganic conductive materials in soft polymeric matrices are widely being studied for flexible electronics, and can achieve both flexible mechanics and high conductivity at radiofrequencies[105].

Functional materials can also enable sensing by transducing biochemical quantities into changes in the electromagnetic response of a metasurface. For example, hydrogels whose dielectric permittivity changes with the pressure or the presence of sweat produce wirelessly detectable shifts in the resonance frequency of the unit cells[46]. Using magnesium pixelated cavities, a chemically tunable optical metasurface has been demonstrated for hydrogenation-induced switching between different display modes[106]. Functionalized two-dimensional materials, including graphene and transition-metal dichalcogenides, may be used to build capacitive or resistive sensors that are sensitive to the biological environment, such as the presence of pathogenic bacteria[107]. Biodegradable metasurfaces that disappear after their functional lifetime can also be made from materials that are transient in biological media, such as magnesium, silk and cellulose. Such materials may be used to avoid the need for retrieval of devices that are implanted in the body[108]. Conversely, self-healing electronic materials that can repair damage could be used to fabricate metasurfaces that are robust and last longer when worn on the body[109,110].

**Artificial intelligence.** Generative adversarial neural networks have been explored for inverse design of metasurfaces, in which designs are automatically generated from a desired input–output relationship[111,112] (Fig. 5c). Such algorithms may facilitate rapid prototyping or even personalized designs that address the variability in tissue structure between individuals. Recent developments in deep neural networks have yielded remarkable success in medical image analysis. Similar techniques may be leveraged to perform classification and diagnosis with data obtained from metasurface-based monitoring devices, which are generally multidimensional in time, frequency and range[113]. Finally, reinforcement learning techniques may be used for optimal control reconfigurable metasurfaces in tasks such as power transfer, tracking and sensing in the presence of uncertainty[29]. Intelligent metasurfaces may be essential components in envisioned 'closed-loop' therapies in which bioelectronic devices are used to sense abnormalities and deliver the appropriate treatment without human intervention[114].

## Conclusions

Because of their versatility and compactness, metasurfaces can provide functionalities that are not possible with conventional bulky radio-wave components in biomedical applications, including medical imaging and wireless power transfer. In particular, metasurfaces offer optimized control of electromagnetic waves in and around the body for connected personal healthcare systems. Recent developments have illustrated the potential of these structures for the integration of bioelectronics with the body, and the design of devices for wireless health monitoring and therapy. However, further testing will be needed to verify their use for medical purposes.

Received: 30 August 2020; Accepted: 22 April 2021;
Published online: 14 June 2021

## References

1. Goodman, R. & Blank, M. Insights into electromagnetic interaction mechanisms. *J. Cell. Physiol.* **192**, 16–22 (2002).
2. Pasek, J., Pasek, T., Sieroń-Stołtny, K., Cieślar, G. & Sieroń, A. Electromagnetic fields in medicine—the state of art. *Electromagn. Biol. Med.* **35**, 170–175 (2016).
3. Polk, C. & Postow, E. *Handbook of Biological Effects of Electromagnetic Fields* (CRC Press, 1995).
4. Elmqvist, R. & Senning, A. An implantable pacemaker for the heart. In *Proceedings of the Second International Conference on Medical Electronics, Paris* (ed. Smyth, C. N.) 27 (Iliffe, 1959).
5. Zeng, F.-G., Rebscher, S., Harrison, W., Sun, X. & Feng, H. Cochlear implants: system design, integration, and evaluation. *IEEE Rev. Biomed. Eng.* **1**, 115–142 (2008).
6. Weiland, J. D. & Humayun, M. S. Visual prosthesis. *Proc. IEEE* **96**, 1076–1084 (2008).
7. Wu, G. & Xue, S. Portable preimpact fall detector with inertial sensors. *IEEE Trans. Neural Syst. Rehabil. Eng.* **16**, 178–183 (2008).
8. Iddan, G., Meron, G., Glukhovsky, A. & Swain, P. Wireless capsule endoscopy. *Nature* **405**, 417–417 (2000).
9. Samineni, V. K. et al. Fully implantable, battery-free wireless optoelectronic devices for spinal optogenetics. *Pain* **158**, 2108 (2017).
10. Pozar, D. M. *Microwave Engineering* (Wiley, 2011).
11. Lin, J. C. A new IEEE standard for safety levels with respect to human exposure to radio-frequency radiation. *IEEE Antennas Propag. Mag.* **48**, 157–159 (2006).
12. Poon, A. S., O'Driscoll, S. & Meng, T. H. Optimal frequency for wireless power transmission into dispersive tissue. *IEEE Trans. Antennas Propag.* **58**, 1739–1750 (2010).
13. Glybovski, S. B., Tretyakov, S. A., Belov, P. A., Kivshar, Y. S. & Simovski, C. R. Metasurfaces: from microwaves to visible. *Phys. Rep.* **634**, 1–72 (2016).
14. Zhang, L., Mei, S., Huang, K. & Qiu, C. W. Advances in full control of electromagnetic waves with metasurfaces. *Adv. Opt. Mater.* **4**, 818–833 (2016).
15. Willets, K. A. & Van Duyne, R. P. Localized surface plasmon resonance spectroscopy and sensing. *Annu. Rev. Phys. Chem.* **58**, 267–297 (2007).
16. Arbabi, A., Horie, Y., Bagheri, M. & Faraon, A. Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission. *Nat. Nanotechnol.* **10**, 937–943 (2015).
17. Wu, K., Coquet, P., Wang, Q. J. & Genevet, P. Modelling of free-form conformal metasurfaces. *Nat. Commun.* **9**, 3494 (2018).
18. Liaskos, C. et al. A new wireless communication paradigm through software-controlled metasurfaces. *IEEE Commun. Mag.* **56**, 162–169 (2018).
19. Li, L. et al. Intelligent metasurface imager and recognizer. *Light Sci. Appl.* **8**, 97 (2019).
20. Yoo, I., Imani, M. F., Pulido-Mancera, L., Sleasman, T. & Smith, D. R. Analytic model of a coax-fed planar cavity-backed metasurface antenna for pattern synthesis. *IEEE Trans. Antennas Propag.* **67**, 5853–5866 (2019).
21. Liu, X., Cao, J., Tang, S. & Wen, J. Wi-Sleep: Contactless sleep monitoring via WiFi signals. In *2014 IEEE Real-Time Systems Symposium* 346–355 (IEEE, 2014).
22. Wang, Y., Wu, K. & Ni, L. M. Wifall: device-free fall detection by wireless networks. *IEEE Trans. Mob. Comput.* **16**, 581–594 (2016).
23. Fear, E. C., Hagness, S. C., Meaney, P. M., Okoniewski, M. & Stuchly, M. A. Enhancing breast tumor detection with near-field imaging. *IEEE Microw. Mag.* **3**, 48–56 (2002).
24. Meaney, P. M., Fanning, M. W., Li, D., Poplack, S. P. & Paulsen, K. D. A clinical prototype for active microwave imaging of the breast. *IEEE Trans. Microw. Theory Tech.* **48**, 1841–1853 (2000).
25. Imani, M. F. et al. Review of metasurface antennas for computational microwave imaging. *IEEE Trans. Antennas Propag.* **68**, 1860–1875 (2020).
26. Hunt, J. et al. Metamaterial apertures for computational imaging. *Science* **339**, 310–313 (2013).
27. Gollub, J. et al. Large metasurface aperture for millimeter wave computational imaging at the human-scale. *Sci. Rep.* **7**, 42650 (2017).

28. Tsilipakos, O. et al. Toward intelligent metasurfaces: the progress from globally tunable metasurfaces to software-defined metasurfaces with an embedded network of controllers. *Adv. Opt. Mater.* **8**, 2000783 (2020).
29. Li, L. et al. Machine-learning reprogrammable metasurface imager. *Nat. Commun.* **10**, 1082 (2019).
30. Lauterbur, P. C. Image formation by induced local interactions: examples employing nuclear magnetic resonance. *Nature* **242**, 190–191 (1973).
31. Hartwig, V. et al. Biological effects and safety in magnetic resonance imaging: a review. *Int. J. Environ. Res. Public Health* **6**, 1778–1798 (2009).
32. Mueller, M. F. et al. Double spiral array coil design for enhanced 3D parallel MRI at 1.5 Tesla. *Concepts Magn. Reson. B* **35**, 67–79 (2009).
33. Roemer, P. B., Edelstein, W. A., Hayes, C. E., Souza, S. P. & Mueller, O. M. The NMR phased array. *Magn. Reson. Med.* **16**, 192–225 (1990).
34. Teeuwisse, W. M., Brink, W. M. & Webb, A. G. Quantitative assessment of the effects of high-permittivity pads in 7 Tesla MRI of the brain. *Magn. Reson. Med.* **67**, 1285–1293 (2012).
35. Shchelokova, A. et al. Enhancement of magnetic resonance imaging with metasurfaces: From concept to human trials. In *2017 11th International Congress on Engineered Materials Platforms for Novel Wave Phenomena (Metamaterials)* 31–33 (IEEE, 2017).
36. Slobozhanyuk, A. P. et al. Enhancement of magnetic resonance imaging with metasurfaces. *Adv. Mater.* **28**, 1832–1838 (2016).
37. Freire, M. J., Marques, R. & Jelinek, L. Experimental demonstration of a $\mu=-1$ metamaterial lens for magnetic resonance imaging. *Appl. Phys. Lett.* **93**, 231108 (2008).
38. Schmidt, R., Slobozhanyuk, A., Belov, P. & Webb, A. Flexible and compact hybrid metasurfaces for enhanced ultra high field in vivo magnetic resonance imaging. *Sci. Rep.* **7**, 1678 (2017).
39. Shchelokova, A. V. et al. Experimental investigation of a metasurface resonator for in vivo imaging at 1.5 T. *J. Magn. Reson.* **286**, 78–81 (2018).
40. Shchelokova, A. V. et al. Locally enhanced image quality with tunable hybrid metasurfaces. *Phys. Rev. Appl.* **9**, 014020 (2018).
41. Zhao, X., Duan, G., Wu, K., Anderson, S. W. & Zhang, X. Intelligent metamaterials based on nonlinearity for magnetic resonance imaging. *Adv. Mater.* **31**, 1905461 (2019).
42. Pantelopoulos, A. & Bourbakis, N. G. A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Trans. Syst. Man Cybern. C* **40**, 1–12 (2009).
43. Huang, Q.-A., Dong, L. & Wang, L.-F. LC passive wireless sensors toward a wireless sensing platform: status, prospects, and challenges. *J. Microelectromech. Syst.* **25**, 822–841 (2016).
44. Heywood, J. T. et al. Impact of practice-based management of pulmonary artery pressures in 2000 patients implanted with the CardioMEMS sensor. *Circulation* **135**, 1509–1517 (2017).
45. Dunbar, G. E., Shen, B. Y. & Aref, A. A. The Sensimed Triggerfish contact lens sensor: efficacy, safety, and patient perspectives. *Clin. Ophthalmol.* **11**, 875 (2017).
46. Dautta, M. et al. Multi-functional hydrogel-interlayer RF/NFC resonators as a versatile platform for passive and wireless biosensing. *Adv. Electron. Mater.* **6**, 1901311 (2020).
47. Chen, L. Y. et al. Continuous wireless pressure monitoring and mapping with ultra-small passive sensors for health monitoring and critical care. *Nat. Commun.* **5**, 5028 (2014).
48. Finkenzeller, K. *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication* (Wiley, 2010).
49. Preradovic, S. & Karmakar, N. C. Chipless RFID: bar code of the future. *IEEE Microw. Mag.* **11**, 87–97 (2010).
50. Andriamiharivolamena, T., Vena, A., Perret, E., Lemaitre-Auger, P. & Tedjini, S. Chipless identification applied to human body. In *2014 IEEE RFID Technology and Applications Conference (RFID-TA)* 241–245 (IEEE, 2014).
51. Vena, A. et al. Design and realization of stretchable sewn chipless RFID tags and sensors for wearable applications. In *2013 IEEE International Conference on RFID (RFID)* 176–183 (IEEE, 2013).
52. Tian, X., Zeng, Q., Nikolayev, D. & Ho, J. S. Conformal propagation and near-omnidirectional radiation with surface plasmonic clothing. *IEEE Trans. Antennas Propag.* **68**, 7309 (2020).
53. Salonen, P., Yang, F., Rahmat-Samii, Y. & Kivikoski, M. WEBGA-wearable electromagnetic band-gap antenna. In *IEEE Antennas and Propagation Society Symposium* 451–454 (IEEE, 2004).
54. Jiang, Z. H., Brocker, D. E., Sieber, P. E. & Werner, D. H. A compact, low-profile metasurface-enabled antenna for wearable medical body-area network devices. *IEEE Trans. Antennas Propag.* **62**, 4021–4030 (2014).
55. Yan, S. & Vandenbosch, G. A. Radiation pattern-reconfigurable wearable antenna based on metamaterial structure. *IEEE Antennas Wirel. Propag. Lett.* **15**, 1715–1718 (2016).
56. Tian, X. et al. Wireless body sensor networks based on metamaterial textiles. *Nat. Electron.* **2**, 243 (2019).
57. Han, S. et al. Battery-free, wireless sensors for full-body pressure and temperature mapping. *Sci. Transl. Med.* **10**, eaan4950 (2018).
58. Chung, H. U. et al. Skin-interfaced biosensors for advanced wireless physiological monitoring in neonatal and pediatric intensive-care units. *Nat. Med.* **26**, 418–429 (2020).
59. Mond, H. G. & Proclemer, A. The 11th World Survey of Cardiac Pacing and Implantable Cardioverter-Defibrillators: calendar year 2009—a World Society of Arrhythmia's project. *Pacing Clin. Electrophysiol.* **34**, 1013–1027 (2011).
60. Lee, P. M., Xiong, Z. & Ho, J. Methods for powering bioelectronic microdevices. *Bioelectron. Med.* **1**, 201–217 (2018).
61. Hannan, M. A., Mutashar, S., Samad, S. A. & Hussain, A. Energy harvesting for the implantable biomedical devices: issues and challenges. *Biomed. Eng. Online* **13**, 79 (2014).
62. Sinisterra, J. Application of ultrasound to biotechnology: an overview. *Ultrasonics* **30**, 180–185 (1992).
63. Hinchet, R. et al. Transcutaneous ultrasound energy harvesting using capacitive triboelectric technology. *Science* **365**, 491–494 (2019).
64. Charthad, J. et al. A mm-sized wireless implantable device for electrical stimulation of peripheral nerves. *IEEE Trans. Biomed. Circuits Syst.* **12**, 257–270 (2018).
65. Nelson, B. D., Karipott, S. S., Wang, Y. & Ong, K. G. Wireless technologies for implantable devices. *Sensors* **20**, 4604 (2020).
66. Goto, K., Nakagawa, T., Nakamura, O. & Kawata, S. An implantable power supply with an optically rechargeable lithium battery. *IEEE Trans. Biomed. Eng.* **48**, 830–833 (2001).
67. Jelínková, H. *Lasers for Medical Applications: Diagnostics, Therapy and Surgery* (Elsevier, 2013).
68. Wang, B. et al. Experiments on wireless power transfer with metamaterials. *Appl. Phys. Lett.* **98**, 254101 (2011).
69. Li, L., Liu, H., Zhang, H. & Xue, W. Efficient wireless power transfer system integrating with metasurface for biological applications. *IEEE Trans. Ind. Electron.* **65**, 3230–3239 (2017).
70. Assawaworrarit, S., Yu, X. & Fan, S. Robust wireless power transfer using a nonlinear parity–time-symmetric circuit. *Nature* **546**, 387–390 (2017).
71. Kim, S., Ho, J. S. & Poon, A. S. Midfield wireless powering of subwavelength autonomous devices. *Phys. Rev. Lett.* **110**, 203905 (2013).
72. Hui, S. Y. R., Zhong, W. & Lee, C. K. A critical review of recent progress in mid-range wireless power transfer. *IEEE Trans. Power Electron.* **29**, 4500–4511 (2013).
73. Wu, L., McGough, R. J., Arabe, O. A. & Samulski, T. V. An RF phased array applicator designed for hyperthermia breast cancer treatments. *Phys. Med. Biol.* **51**, 1 (2005).
74. Agrawal, D. R. et al. Conformal phased surfaces for wireless powering of bioelectronic microdevices. *Nat. Biomed. Eng.* **1**, 0043 (2017).
75. Ratni, B. et al. Dynamically controlling spatial energy distribution with a holographic metamirror for adaptive focusing. *Phys. Rev. Appl.* **13**, 034006 (2020).
76. Nikolayev, D., Zhadobov, M., Karban, P. & Sauleau, R. Electromagnetic radiation efficiency of body-implanted devices. *Phys. Rev. Appl.* **9**, 024033 (2018).
77. Yang, F., Lee, P. M., Dong, Z., Tian, X. & Ho, J. S. Enhancing wireless transmission from the body with wearable diffractive patterns. *Phys. Rev. Appl.* **12**, 054020 (2019).
78. Genovesi, S., Butterworth, I. R., Serrallés, J. E. C. & Daniel, L. Metasurface matching layers for enhanced electric field penetration into the human body. *IEEE Access* **8**, 197745–197756 (2020).
79. Islam, M. T., Samsuzzaman, M., Kibria, S., Misran, N. & Islam, M. T. Metasurface loaded high gain antenna based microwave imaging using iteratively corrected delay multiply and sum algorithm. *Sci. Rep.* **9**, 17317 (2019).
80. Alqadami, A. S., Bialkowski, K. S., Mobashsher, A. T. & Abbosh, A. M. Wearable electromagnetic head imaging system using flexible wideband antenna array based on polymer technology for brain stroke diagnosis. *IEEE Trans. Biomed. Circuits Syst.* **13**, 124–134 (2018).
81. O'Loughlin, D. et al. Microwave breast imaging: clinical advances and remaining challenges. *IEEE Trans. Biomed. Eng.* **65**, 2580–2590 (2018).
82. Collins, C. C. Miniature passive pressure transensor for implanting in the eye. *IEEE Trans. Biomed. Eng.* **2**, 74–83 (1967).
83. Nelson, B. J., Kaliakatsos, I. K. & Abbott, J. J. Microrobots for minimally invasive medicine. *Annu. Rev. Biomed. Eng.* **12**, 55–85 (2010).
84. Than, T. D., Alici, G., Zhou, H. & Li, W. A review of localization systems for robotic endoscopic capsules. *IEEE Trans. Biomed. Eng.* **59**, 2387–2399 (2012).
85. Pourhomayoun, M., Jin, Z. & Fowler, M. L. Accurate localization of in-body medical implants based on spatial sparsity. *IEEE Trans. Biomed. Eng.* **61**, 590–597 (2013).

86. Bao, G., Pahlavan, K. & Mi, L. Hybrid localization of microrobotic endoscopic capsule inside small intestine by data fusion of vision and RF sensors. *IEEE Sens. J.* **15**, 2669–2678 (2014).
87. Chandra, R., Johansson, A. J., Gustafsson, M. & Tufvesson, F. A microwave imaging-based technique to localize an in-body RF source for biomedical applications. *IEEE Trans. Biomed. Eng.* **62**, 1231–1241 (2014).
88. Pendry, J. B. Negative refraction makes a perfect lens. *Phys. Rev. Lett.* **85**, 3966 (2000).
89. Monge, M., Lee-Gosselin, A., Shapiro, M. G. & Emami, A. Localization of microscale devices in vivo using addressable transmitters operated as magnetic spins. *Nat. Biomed. Eng.* **1**, 736–744 (2017).
90. Falk, M. & Issels, R. Hyperthermia in oncology. *Int. J. Hyperth.* **17**, 1–18 (2001).
91. Simon, C. J., Dupuy, D. E. & Mayo-Smith, W. W. Microwave ablation: principles and applications. *Radiographics* **25**, S69–S83 (2005).
92. Gong, Y. & Wang, G. Superficial tumor hyperthermia with flat left-handed metamaterial lens. *Prog. Electromagn. Res.* **98**, 389–405 (2009).
93. Vrba, D. & Vrba, J. Novel applicators for local microwave hyperthermia based on zeroth-order mode resonator metamaterial. *Int. J. Antennas Propag.* **2014**, 631398 (2014).
94. Paulides, M., Trefna, H. D., Curto, S. & Rodrigues, D. Recent technological advancements in radiofrequency- and microwave-mediated hyperthermia for enhancing drug delivery. *Adv. Drug Deliv. Rev.* **163**, 3–18 (2020).
95. Bao, L. & Cui, T. J. Tunable, reconfigurable, and programmable metamaterials. *Microw. Opt. Technol. Lett.* **62**, 9–32 (2020).
96. Zhang, X. G. et al. Polarization-controlled dual-programmable metasurfaces. *Adv. Sci.* **7**, 1903382 (2020).
97. Almeida, E., Bitton, O. & Prior, Y. Nonlinear metamaterials for holography. *Nat. Commun.* **7**, 12533 (2016).
98. Shaltout, A. M. et al. Spatiotemporal light control with frequency-gradient metasurfaces. *Science* **365**, 374–377 (2019).
99. Lee, Y., Kim, S.-J., Park, H. & Lee, B. Metamaterials and metasurfaces for sensor applications. *Sensors* **17**, 1726 (2017).
100. Ray, T. R. et al. Bio-integrated wearable systems: a comprehensive review. *Chem. Rev.* **119**, 5461–5533 (2019).
101. Torrisi, F. et al. Inkjet-printed graphene electronics. *ACS Nano* **6**, 2992–3006 (2012).
102. Chung, H. U. et al. Binodal, wireless epidermal electronic systems with in-sensor analytics for neonatal intensive care. *Science* **363**, eaau0780 (2019).
103. Manzari, S. et al. Humidity sensing by polymer-loaded UHF RFID antennas. *IEEE Sens. J.* **12**, 2851–2858 (2012).
104. Leber, A. et al. Soft and stretchable liquid metal transmission lines as distributed probes of multimodal deformations. *Nat. Electron.* **3**, 316–326 (2020).
105. Zhang, Y. et al. High precision epidermal radio frequency antenna via nanofiber network for wireless stretchable multifunction electronics. *Nat. Commun.* **11**, 5629 (2020).
106. Li, J., Chen, Y., Hu, Y., Duan, H. & Liu, N. Magnesium-based metasurfaces for dual-function switching between dynamic holography and dynamic color display. *ACS Nano* **14**, 7892–7898 (2020).
107. Mannoor, M. S. et al. Graphene-based wireless bacteria detection on tooth enamel. *Nat. Commun.* **3**, 763 (2012).
108. Lei, T. et al. Biocompatible and totally disintegrable semiconducting polymer for ultrathin and ultralightweight transient electronics. *Proc. Natl Acad. Sci. USA* **114**, 5107–5112 (2017).
109. Wool, R. P. Self-healing materials: a review. *Soft Matter* **4**, 400–418 (2008).
110. Cao, Y. et al. Self-healing electronic skins for aquatic environments. *Nat. Electron.* **2**, 75–82 (2019).
111. Jiang, J. et al. Free-form diffractive metagrating design based on generative adversarial networks. *ACS Nano* **13**, 8872–8878 (2019).
112. Wen, F., Jiang, J. & Fan, J. A. Robust freeform metasurface design based on progressively growing generative networks. *ACS Photon.* **7**, 2098–2104 (2020).
113. Lin, X. et al. All-optical machine learning using diffractive deep neural networks. *Science* **361**, 1004–1008 (2018).
114. Topol, E. J. High-performance medicine: the convergence of human and artificial intelligence. *Nat. Med.* **25**, 44–56 (2019).
115. Li, L. et al. Electromagnetic reprogrammable coding-metasurface holograms. *Nat. Commun.* **8**, 197 (2017).
116. Ee, H.-S. & Agarwal, R. Tunable metasurface and flat optical zoom lens on a stretchable substrate. *Nano Lett.* **16**, 2818–2823 (2016).

## Acknowledgements

J.S.H. acknowledges support from the National Research Foundation Singapore (NRFF2017-07), Ministry of Education Singapore (MOE2016-T3-1-004) and Institute for Health Innovation and Technology grants.

## Author contributions

All authors wrote and commented on the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

**Correspondence** should be addressed to C.-W.Q. or J.S.H.

**Peer review information** *Nature Electronics* thanks the anonymous reviewers for their contribution to the peer review of this work.