The future of near-field communication-based wireless sensing

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Near-field communication emerged as a high-security, wireless, short-range, data exchange technology nearly two decades ago; its ability to simultaneously transfer power and data between devices offers exciting opportunities for the design of miniature, battery-free and disposable sensing systems in health care and food quality monitoring.

Near-field communication (NFC) is based on a simple idea. Two coils of conductors in close proximity can exchange electrical power over short distances (<5 cm) through wireless inductive coupling. The amplitude of the radio frequency signal (13.56 MHz based on ISO/IEC 14443 standards) can be modulated through amplitude (similar to Morse code) or phase shift keying to read and write digital data onto a silicon chip, allowing the simultaneous transfer of data (with speeds up to 424 kbit s^{-1}) and power.

Most smart devices, contactless (bank) cards and electronic passports are equipped with NFC technology. NFC can transfer electrical power large enough (10 mW) to power most low-power and low-cost electronics (including microcontrollers) and sensors. NFC does not require batteries, and NFC tags can be produced by established high-volume (for example, roll-to-roll) manufacturing methods on substrates of polyethylene terephthalate (PET) or paper at low cost (as low as US $0.03).

The combination of NFC-based wireless power and data exchange with low-cost electronics and sensors enables a myriad of new sensing applications (FIG. 1), previously considered to be technologically and economically unfeasible. Cost, size, and ease-of-use are critical in defining new use-cases for connected sensors; NFC can fill an important technological gap that cannot be sufficiently addressed with other wireless technologies (such as Bluetooth and WiFi), in particular, for developing Internet of Things or 5G applications.

Current NFC-based sensing technologies

Only few NFC-based sensors are commercially available today, with a technology readiness level (TRL) of 7 or above (TRL is a method for estimating the maturity of a technology, with 9 being highest). Most of these NFC-based sensors focus on health, with only few devices truly exploiting both wireless power and communication capabilities. Examples include the intraocular pressure sensor, Eyemate by IOP GmbH, and the wearable glucose monitoring system, FreeStyle Libre by Abbott (powered using a battery rather than NFC). In the food industry, NFC-based sensors have been commercially piloted by Kraft Heinz Company for tamper-proofing and marketing; HZPC, a seed potato supplier, is trialing an NFC-based temperature sensor.

NFC-based sensing technologies are increasingly explored by the academic community (TRL ≤6), with a major focus on applications in health care and food quality monitoring. In health care, NFC-based 'tattoo-like' wearable disposable sensors are perhaps the most developed technology. These sensors use a thin and flexible polymer substrate (polydimethylsiloxane (PDMS) is standard) that is adhered to the skin in order to provide non-invasive and mostly biophysical measurements (for example, electrocardiogram (ECG), skin temperature and haemodynamic parameters), typically using a smartphone as the reader[1,2]. Non-invasive biochemical sensing of biofluids, such as analytes in sweat, is also explored[3], and working prototypes have been tested on humans[1,2]. Commercial translation is currently limited, however, by poor durability, noise (for example, electrical noise) and high manufacturing costs (PDMS, or more broadly, silicones, are not a standard material for high-volume manufacturing of flexible devices).

A completely disposable NFC-based electrochemical point-of-care immunosensor has also been developed for detecting viruses such as the hepatitis B virus, providing a viable alternative to current disposable electrochemical point-of-care diagnostics, which require a dedicated reader (for example, glucose test strips)[4].

In addition, implantable NFC-based sensors have been developed to address longstanding issues associated with batteries (that is, toxicity, bulkiness and battery recharging or removal)[5,6]. Clinical translation is currently hindered by low biocompatibility, low robustness (operational lifetime and mechanical integrity), invasiveness and lengthy regulatory processes.

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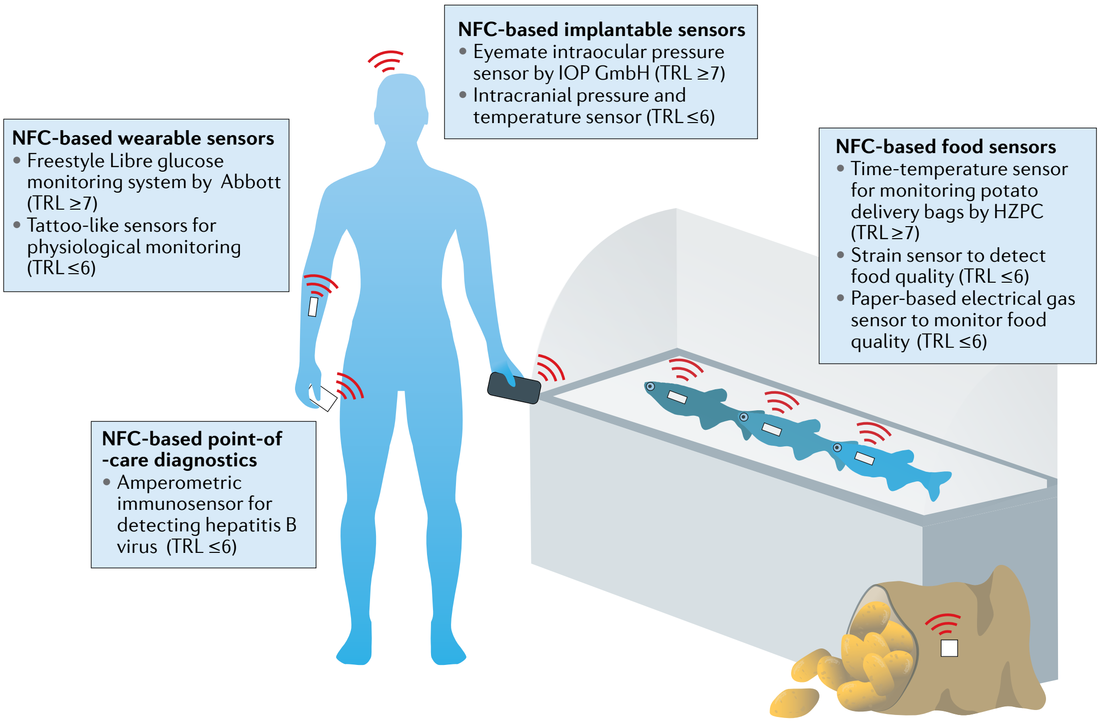

Fig. 1 | **Near-field communication-based sensors in health care and food quality monitoring.** Current near-field communication (NFC)-based commercial sensors (technology readiness level (TRL) ≥7) and research sensor prototypes (TRL <6). Sensors are categorized into four classes according to the type of application. Health-care sensors: wearable (adhered onto skin), implantable (inserted in the body) and point-of care (near-patient monitoring) sensors; and food quality (attached to packaging) sensors.

Disposable NFC-based electrical gas sensors show potential for monitoring food quality. These sensors can be included in food packaging to monitor food freshness and safety by measuring gases released by microbial spoilage[7,8]. This technology could replace the static (and often confusing) 'best-before' dates, providing dynamic information about the chemical or microbial state of a product, which will help reduce food waste and foodborne illnesses. The price constraints of a few cents remain a major challenge, however.

Future requirements for materials

Robustness. Whether used inside or on the surface of the body, medical sensors are subject to deformation (that is, bending, twisting and stretching), which can compromise the integrity of NFC-based sensors. Creases in the traces of the coil antenna can affect performance and impact energy and data transmission; a tear in the trace would halt operation altogether. Metals, such as GaInSn and EGaIn alloys, are liquid at room temperature and offer high thermal and electrical conductivity as well as low toxicity. Such liquid metals can be inserted into soft polymer microchannels (<100 μm in height) to create traces for NFC-tags, which can be stretched, squeezed and folded with a minimum bending radius of 0.15 mm[9]. Off-the-shelf rigid electronic and sensing elements remain susceptible to fracture, however, leading to device failure. Flexible and stretchable electronic (computational) components are, therefore, required to realize truly robust NFC-based sensors.

Cost. The cost of disposable NFC-based sensors needs to asymptotically approach zero for low-margin, high-volume applications, for example, food quality sensors. Flexible synthetic (PET) or natural (cellulose) substrates with metal traces can be inexpensively manufactured as part of packaging. However, sensing elements and electronics remain the costliest factor. This can be resolved by exploiting the intrinsic properties of the substrate or conductive traces for sensing[8]. Additionally, films that form part of the packaging can be used as protective layers for sensors. Some films are hydrophobic and gas permeable — essential characteristics for the barrier layers of gas sensors used for monitoring food quality. Most NFC-based sensors depend on microcontroller-based multicomponent designs; the versatility (and underused capabilities) of these designs, however, comes at a premium. First examples of application-specific integrated circuits (ASICs) have already been developed for low-cost NFC-based sensors (for example, potentiostat), but a large gap remains between available and required technologies, owing to high initial investments needed for the development of ASICs[4].

Size. NFC-based sensors are normally designed as 2D devices with a planar coil. The coil must generate a certain inductance to optimally function at 13.56 MHz, which restricts the minimum size of the coil (to a few centimeters in diameter). For further miniaturization, multilayer coils can be implemented to boost the efficiency of exchanged power. Coil antennas as small as 10 mm (double layer) have been reported[1], providing a suitable length-scale for most applications. Implantable sensors at this size, however, require invasive surgery for insertion and removal, increasing the risk of infection and incurring high costs. Thus, additional miniaturization techniques must be developed for implantable NFC-based sensors.

Implants. To overcome the serious risks (for example, infection) associated with the surgical removal of implants, NFC-based bioresorbable sensors have been developed that resorb into non-toxic byproducts in the body[5]. Molybdenum and magnesium are often used as bioresorbable antennas and conductors; co-polymers, such as poly-lactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA), can be used as substrate and encapsulation materials. For encapsulation, an additional layer of the co-polymer is typically stacked on top of the electronics and adhered to the substrate to seal the device. However, weak interfacial adhesion between layers often results in premature degradation or limited operational lifetime (<6 days). A recently developed long-lived (>30 days) bioresorbable polyurethane achieves greater stability owing to its ability to form covalent bonds with itself, providing stronger adhesion[10].

Most bioresorbable NFC-based sensors are only partially resorbable because not every component or material in the device is able to resorb (including digital NFC chips). NFC and computation require digital logic; silicon, the dominant semiconductor used in digital electronics, is a bioresorbable material, and thus, completely bioresorbable silicon chips may enable fully bioresorbable NFC-based sensors in the future.

Environmental considerations. Disposable NFC-based sensors are made with a combination of materials, which makes them difficult to recycle. For high-volume disposable applications, sensors should ideally be produced from environmentally friendly, non-toxic, biodegradable and sustainable materials, such as cellulose paper, copper and silicon or ceramics. When non-biodegradable materials must be used, designs that maximize overall recyclability should be selected. For example, delamination of sensors should be considered in cases where non-recyclable disposable NFC-based sensors are attached to (single plastic) recyclable packaging. Given that multilayer laminates, which are included in most food packaging, cannot be easily recycled, NFC-based sensors may be attached or embedded in these films for specialized recycling (or incineration).

The road ahead

NFC-based sensing is still in its infancy. The potential of NFC to enable entirely new sensing concepts will likely play an important role in the future of the 'connected' technological revolution. Challenges remain to be addressed, however, particularly in terms of materials and manufacturing, to turn laboratory prototypes into commercial products. Interestingly, the current COVID-19 pandemic stresses the need for contactless interactions beyond payment systems (from zero-touch shopping to wireless diagnostic tests), the effect of which will likely accelerate NFC-based sensing technologies. Moreover, because data security is at the core of NFC, NFC-based sensors may be paired with high-security technologies, such as blockchain, to create trusted, automated and connected sensing systems. This combination would improve integrity, accessibility and speed of operations within food and health-care systems.

1. Kim, J. et al. Miniaturized battery-free wireless systems for wearable pulse oximetry. *Adv. Funct. Mater.* **27**, 1604373 (2017).
2. Lee, S. P. et al. Highly flexible, wearable, and disposable cardiac biosensors for remote and ambulatory monitoring. *npj Digital Med.* **1**, 2 (2018).
3. Xu, G. et al. Smartphone-based battery-free and flexible electrochemical patch for calcium and chloride ions detections in biofluids. *Sens. Actuators B. Chem.* **297**, (2019).
4. Teengam, P. et al. NFC-enabling smartphone-based portable amperometric immunosensor for hepatitis B virus detection. *Sens. Actuators B. Chem.* **326**, 128825 (2021).
5. Kang, S. K. et al. Bioresorbable silicon electronic sensors for the brain. *Nature* **530**, 71–76 (2016).
6. Zhang, H. et al. Wireless, battery-free optoelectronic systems as subdermal implants for local tissue oximetry. *Sci. Adv.* **5**, eaaw0873 (2019).
7. Escobedo, P., Bhattacharjee, M., Nikbakhtnasrabadi, F. & Dahiya, R. Flexible strain sensor with NFC tag for food packaging. *2020 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)* (2020).
8. Barandun, G. et al. Cellulose fibers enable near-zero-cost electrical sensing of water-soluble gases. *ACS Sens.* **4**, 1662–1669 (2019).
9. Teng, L. et al. Liquid metal-based transient circuits for flexible and recyclable electronics. *Adv. Funct. Mater.* **29**, 1808739 (2019).
10. Choi, Y. S. et al. Stretchable, dynamic covalent polymers for soft, long-lived bioresorbable electronic stimulators designed to facilitate neuromuscular regeneration. *Nat. Commun.* **11**, 5990 (2020).

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Author contributions

S.O. and F.G. wrote and edited the manuscript. H.S.L. edited the manuscript and conceptualized the figure.

Competing interests

Güder Research Group receives samples from Silicon Craft Technology PLC for research purposes.