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Citation for published version:
Khan, SR, Bernassau, AL & Desmulliez, MPY 2024, 'Passive and Battery-Free RFID-Based Wireless Healthcare and Medical Devices: A Review', *IEEE Journal of Radio Frequency Identification*, vol. 8, pp. 724-742. https://doi.org/10.1109/JRFID.2024.3451230

Digital Object Identifier (DOI):
10.1109/JRFID.2024.3451230

Published In:
IEEE Journal of Radio Frequency Identification

Passive and Battery-free RFID-based Wireless Healthcare and Medical Devices: A Review

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***Abstract*— Passive radio-frequency identification (RFID) technology has recently been applied to many battery-free wireless medical and healthcare (WMH) applications including wearable and implantable medical devices. The presence of the human body near RFID devices creates, however, several challenges in terms of design, fabrication, and testing of such WMH devices. The use of comparatively unsecured wireless links enabled by RFID communication may also jeopardize patient's privacy as well as raise ethical concerns. With these factors in mind, this article provides a systematic review spanning two decades of the wide range of passive RFID applications in medical and healthcare devices based on the classification of RFID frequency bands. The strengths and limitations of these techniques are benchmarked against each other using performance metrics such as communication distance, tissue safety, size of the devices, as well as patient's privacy and ethical implications. The article concludes by discussing the future opportunities and challenges raised by passive RFID for battery-free WMH devices. This comprehensive literature review aims to become a point of reference for experts and non-experts in the field.**

***Index Terms*— Active RFID, medical devices, passive RFID, RFID reader, tag.**

I. Introduction

RADIO-frequency identification (RFID) is a growing technology that allows access, storage and transfer of data in the range of kilobytes to few megabytes through electromagnetic transmission using strategically installed radio-frequency (RF) devices [1]. Advantages of RFID include the use of standards respected worldwide, a unique identification of the tag holder, wireless communication, and low cost of the tag [2]. The medical and healthcare sectors have recently taken advantage of such an advanced information technology to reduce costs and improve health delivery and patient safety [3]. Although the use of bar codes has been widespread in hospitals, such systems can cause significant workflow disruption, increased workload due to manual scanning processes for individual patients and medication errors in situations such as pandemics where the number of patients can overwhelm hospitals [4]. Therefore, bar codes and associated technologies are being gradually replaced with RFID tags and readers in hospitals, care homes and private residents to help manage healthcare products, improve patient monitoring and treatment, reduce inventory level, and achieve cost savings [5]. This technology also helps with the localization of medical assets, detection of counterfeit drugs, identification of under- or overutilization of medical equipment, management of blood distribution, and scanning of information from implanted devices [6], [7]. Through this technology, patient monitoring is simplified, and the accuracy of the data is increased, saving clinician's time, and reducing workload, improving the security of hospitals and healthcare centers. Furthermore, it increases the confidence of the patients to use healthcare and medical devices in a private home setup and reduces the number of hospital visits, thus reducing the pressure on hospitals during emergencies and pandemics [8], [9].

Fig. 1 shows a brief pictorial history of RFID. In 1945, the Soviet Union offered a gift containing a wireless interrogated spy bug to the U.S. ambassador, known as "The Thing", and developed by L. Theremin [10]. In 1948, the concept of radio communication by reflected waves was explained by H. Stockman for the first time, and he was officially credited for inventing RFID [11]. This was used later to identify "Friends or Foe" (IFF) aircraft, that used radar technology during the Second World War. In the 1960's, the first commercial RFID systems were launched as anti-theft devices attached to high-value items and clothing, and used for detecting the presence or absence of a tag in retail stores [3]. Gradually, RFID technology became popular and adopted for car license plates, tracking devices and toll road payment systems in 1977, 1980 and 1987, respectively [3], [12]. In 2000, more than 1,000 patents were submitted for RFID technology-based applications [12]. Today, RFID technology has bloomed, and its use has increased significantly for contactless smart payments in retail shops, in supply chains, construction works, and for animal and pet tracking applications [13]. Considerable attention within the healthcare sector started in the early 2000's [14]. 2005 saw the first RFID installations in hospitals in New York (U.S.A.) for inventory optimization and waste removal [15]. Since then, this technology has efficiently been used to track hospital supplies, security, medical equipment, medications, and patient monitoring in the healthcare industry. More recently, it has attracted significant

Manuscript received *Month Day, Year*; revised *Month Day, Year*; accepted *Month Day, Year*. (*Corresponding author: Sadeque Reza Khan.*)

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This article has been accepted for publication in IEEE Journal of Radio Frequency Identification. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JRFID.2024.3451230

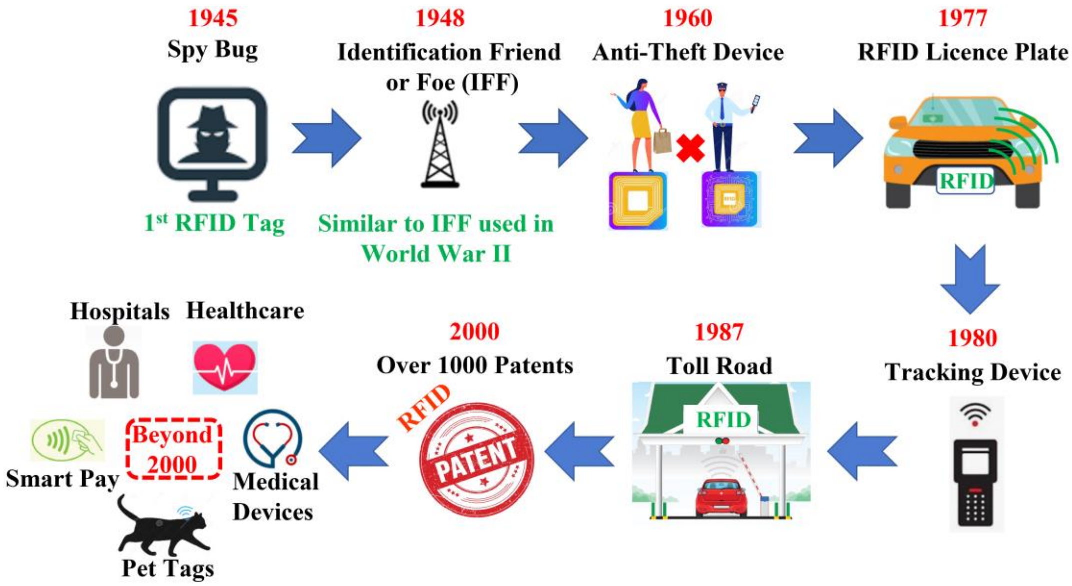


Fig. 1. Pictorial schematic highlighting the brief history of RFID technology and its applications.

interest in the realm of wireless sensing applications, including wearables and implants [16]. In healthcare and medical applications, passive RFID is becoming popular due to their battery-free nature compared to an active RFID which has fixed life span and requires extra space to accommodate the battery [17].

An overview of the use of passive RFID technology in different wireless medical and healthcare devices is presented in this article. First, a brief discussion of the necessary components of RFID, including its working principle, is described in Section II. Section III classifies the RFID technology in two different ways namely (1) the choice of the frequency bands and (2) the type of tag that is being employed. Section IV describes concerns associated with implementing RFID in medical and healthcare devices. Applications of passive RFID are described in Section V for a wide range of medical and healthcare devices over the last two decades classified according to RFID frequency bands. These applications are summarised in Table I which outlines the merits and issues imposed by RFID technology. Section VI describes the issues that need to be addressed in the future to implement RFID as a mature technology in the medical and healthcare sectors. Finally, conclusions are provided in Section VII.

II. Components in RFID Technology

Fig. 2 shows the standard components in RFID technology.

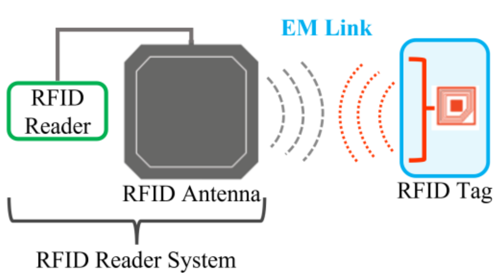


Fig. 2. Basic components needed for RFID.

These include a reader system, a tag and the electromagnetic (EM) link [18], [19]. These are described in the following subsections.

A. RFID Reader System

This component is used to power wirelessly an RFID tag and collect all the information stored in the tag. This system includes an RFID reader to decode information from a tag and an antenna for wireless power, data transmission, and reception. The RFID reader system establishes communication with nearby RFID tags by reading their IDs and reads/writes data from/to tags as necessary[20]. In traditional RFID applications the mapping of the tag ID to an object via an external database or service can be used to sense and monitor the existence of the corresponding object. The readers typically have two interfaces: an RF interface that communicates with the tags in their read range to retrieve tags' identities and a communication interface, such as IEEE 802.11 or 802.3, for communicating with the server [21].

B. RFID Tag

This component stores the necessary information pertaining to the object it is supposed to monitor or identify. In some applications, it also reads sensor data if external sensors are linked to the tag [22]. An electronic integrated circuit (IC) and an antenna are encapsulated together in the tag using a suitable packaging. As mentioned before, a tag is generally attached to an object. The tag has a memory that stores a unique identification number and additional data about its manufacturer, product type, and other related environmental information [20]. Advanced RFID tag ICs include analog to digital converter (ADC) and inbuilt sensors and external sensor interfaces, which can be used to monitor different biomarkers of patients in healthcare applications [22].

C. Electromagnetic (EM) Link

The EM link is the primary element to establish communication between the RFID reader system and the tag when they are in close proximity. Load modulation [23] and backscattering [10] are the two most common techniques for link communication in RFID. In the load modulation technique, the tag is powered by the electromagnetic field of the reader to transmit data back to the reader in the near field [23]. Load modulation involves connecting a passive load to the tag antenna and switching it on and off to modulate the power transfer from the reader to the tag. The data transmitted by the tag is synchronous with the RF field generated by the reader, thereby facilitating the transponder response decoding. Load modulation operates according to ISO/IEC 14443-A/B, which defines how a reader can interact with a tag using the inductive coupling effect where a variation in the impedance of the tag causes amplitude or phase changes to the antenna voltage of the reader, thus, detected by the reader device [24], [25].

RFID backscatter coupling operates outside of the near-field region. In this technique, the reader propagates radio signals. Then, the tag receives the signal and applies it by using part of it as its own power source and reflects some energy as the tag's data toward the reader [10], [16].

III. RFID Classification

Fig. 3 shows a high-level taxonomy of RFID technology. Near/far fields here are defined when the distance between the reader and tag is less/greater than one full wavelength [26]. Near-field RFID allows a communication distance of around tens of centimeters, and far-field RFID allows a typical communication distance of a few meters [10]. The main difference between the two categories is the operating frequency and, therefore, the type of tag and reader antennas. Near-field RFID commonly uses loop antennas at both the reader and tag, and the communication is achieved by magnetic coupling between the two loop antennas, which limits the communication distance. In far-field RFID, high-frequency microwave antennas, such as circular-polarised flat panel and patch antennas are used in reader and tag, respectively, which allows communication distances up to 25 meters.

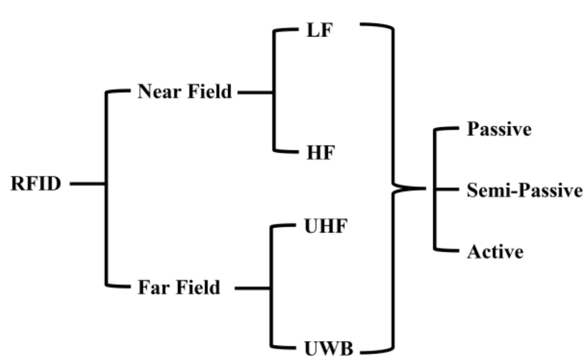


Fig. 3. Classification of RFID.

A. Classification According to Frequency Bands

RFID systems use different frequency bands for different applications [19]. Common frequency bands for near-field RFID include low-frequency (LF) bands and high-frequency (HF) bands. RFID far field frequency bands include ultra-high frequency (UHF) and ultra-wideband (UWB) [18].

1) Near field frequency bands

LF tags operate at frequencies ranging between 100 to 500 kHz. The limited reading distance, 30 cm, and slow data reading speed, 10 kbps, limit the number of LF applications, which, in the medical, sector are commonly patient access control, animal identification, and equipment inventory. In HF, the popular frequency is 13.56 MHz [27]. The most important characteristics are the long reading range of around 1 m, the high reading speed, the requirement for line-of-sight communication and high costs.

2) Far-field frequency bands

Typical applications are focused on patient identification and sensing. UHF band (850–960 MHz) is most popular for implants because of its better-read range of 3 to 5 m, faster data identification/ transfer rate of 40 kbps to 640 kbps depending on its modulation type, and good anticollision capability [19]. A newer technology using an ultra-wideband (UWB) is also gaining recognition for future RFID applications. UWB spectrum covers lower GHz to 10.6 GHz region, and advantages include high data rate up to 1 Gbps, long read range, low average radiated power, easy RF circuitry, and less interference than other available bands [19], [28].

B. Classification According to Types of Tags

Another classification of RFID technologies is related to their tags, which can be defined as passive, semi-passive and active.

1) Passive tag

Passive tags have no internal power supply and are activated when within the RFID reader range. These tags commonly communicate with the reader by backscattering the carrier signal received from a reader using an electromagnetic resonance structure [21]. Passive tags have a smaller size of area of around 4-by-4 mm^2 of less, are lighter, and are low-cost with a longer lifetime. The size of the antenna in the tag will depend on the application, with increased reading distance trade-off against cost and weight. Passive tags have minimal functionalities as they cannot transmit their own radio waves. They have typical information storage capacity of 32 or 64 bits only and limited computing capability [29].

2) Semi-passive tag

Semi-passive tags have a battery used only to power the internal circuitry. Unlike active tags, they use the electromagnetic field generated by the reader for communication, with the battery remaining inactive until activated by a signal from a reader. This mechanism saves battery power and significantly increases the lifetime of the tag [19]. The inclusion of a battery allows for a longer reading range and the application of additional features such as environmental sensors, real-time tracking and quick

This article has been accepted for publication in IEEE Journal of Radio Frequency Identification. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JRFID.2024.3451230

notifications.

3) Active tag

Active tags are constantly powered by an embedded battery. These tags are capable of communicating with the reader at any time. These tags have higher read/ write speeds with longer reading distances of approximately 90 m [19]. Such tags are bulky and more expensive than passive tags due to the embedded battery, which limits the lifetime of the device [3]. An active tag can also facilitate additional functionalities such as memory, power-hungry sensing modalities, and cryptography capabilities [21].

IV. Concerns of RFID used in Medical and Healthcare Devices

The presence of a human body in close proximity to the RFID device creates several challenges regarding tissue safety, security and privacy-related issues, and ethical implications.

A. Safety Against EM

Biological tissues exhibit frequency-dependent permittivity and loss-tangent values that far exceed those of free space [30], [31], [32]. Therefore, RFID antennas for body-area applications should be designed with the presence of surrounding biological tissues in mind. Canonically and/or anatomically shaped tissue models can be utilised during the design process of the RFID antennas and systems [33]. In [34], the performance of RFID antennas (impedance and gain) is demonstrated not to be particularly sensitive to minor changes in the surrounding tissues. However, larger body parts can cause variations in input impedance and frequency shifts and reduce the efficiency of the antenna. Like cell phones, wearable and implantable RFID technologies need to conform to international and national safety guidelines for the specific absorption rate (SAR) [35], [36]. The evaluation of the SAR levels associated with body-area RFID devices is a key design parameter. Most important is the maximum wireless exposure for the head and trunk in the case of RFID systems held close to these regions of the body. According to IEEE standard C95.1-2019 [37], the SAR for average exposure time of 6 minutes is required to be less than 2 W/Kg for 10 g of tissue that is absorbing the most signal [38], [39], [40], [41]. This standard defines exposure criteria and associated limits for the protection of persons and patients against adverse health effects from exposures to EM fields generated from RFID systems in the frequency range 0 Hz to 300 GHz.

B. EMI Caused by RFID

RFID can cause electromagnetic interference (EMI) with other medical and healthcare devices or equipment within a hospital environment [42]. There are multiple studies demonstrating EMI issues caused by RFID tags. In [42], a study was conducted to replicate EMI due to RFID with a drug infusion device. Infusion pumps known to have failed due to EMI were placed in RF fields with varying strengths due to varying numbers of RFID readers; high-gain antennas, varying distance between readers to the infusion pump and the presence of an RFID tag on the infusion pump. The results concluded the infusion pump was not affected by low-power RFID readers even when they were in direct contact. However, the pump attached to a tag was disrupted when a high-power reader of maximum output power of 2.2W was used at a distance of 10 cm [43]. In [44], an EMI study of an RFID-based mother-infant identification system was conducted where one tag is inserted in the mother's wrist bracelet and the other tag is inserted into the infant's wrist or ankle bracelet. Experiments showed higher levels of electromagnetic exposure for both the mother and infant in the regions of the body that were closer to the reader, with a trend for higher values in the infant compared to the mother for all reader positions. Furthermore, the highest exposure value for the infant was not only restricted to the proximal limb but also extended to the trunk, genital organs and head/neck regions. Therefore, it is recommended that the tag be positioned on the ankle instead of the wrist so the reader is at a greater distance from sensitive organs. In [45] a study assessed the EMI interference from RFID in a controlled environment without patients using active 125 kHz and passive 868 MHz tags. In this work, 41 medical devices under 17 different categories from 22 different manufacturers were tested. The results showed that out of 123 EMI tests, 34 EMI incidents were induced by RFID, of which 22 were classified as hazardous, 2 as significant and 10 as light. The authors concluded that RFID can potentially induce hazardous incidents in medical devices, and implementing RFID in healthcare and medical setups should require onsite EMI testing and follow international standards.

C. Security and Privacy Issues

In [46], [47], [48], several security risks associated with using RFID in healthcare were addressed. These include threats to patient privacy and safety based on interception of messages, interruption of communication, modification of data, and fabrication of hacking messages and devices. Interception can be carried out by wireless sniffing and man-in-the-middle (MITM) attacks. An attacker listens to the communications between tags, and the reader attempts to retrieve the information. Interruption attacks are accomplished by jamming the network and blocking reader-tag communication. Currently, only physical security offers the best defence against these attacks. However, monitoring for abnormal conditions adds some value but does not entirely solve the problem. Modification message attacks focus on maliciously modifying the information in the RFID system by performing injection attacks whereby untrusted inputs are injected in the system. Countermeasures such as mutual authentication, encryption, and challenge-response methods are suggested for this type of attack. Encryption schemes include symmetric and asymmetric cryptography algorithms, such as advanced encryption standard (AES), data encryption standard (DES) and public-key encryption, digital signatures, respectively for RFID systems. Attacks based on fabrication of information use a separate device to inject false information into the system. As a countermeasure, strong authentication schemes and two-factor authentication schemes are suggested. The authors mentioned that, while countermeasures do exist, some are too expensive to be implemented in low-cost medical devices.

D. Ethical Implications

Ethical implications of the effects of RFID have not been significantly addressed. In [49], a study was reported regarding using an RF identification system for patients in 23 US hospitals. Semi-structured interviews were used to find the social and ethical implications of such a system. Important findings included unfair prioritization of patients, diminished trust of patients and endangerment of patients. More detailed and commendable work in this area was reported in [50]. Key concerns about privacy and forced implantations of RFID were discussed, emphasizing the need for a national and international discussion to identify the limits regarding implantable RFID tags in humans. In [51], a study was presented highlighting the significant social, cultural, philosophical, and religious issues associated with the implantation of RFID chips.

V. Passive RFID in Wireless Medical and Healthcare Devices

There are a wide range of wireless medical and healthcare devices available including portable, wearable, cutaneous, subcutaneous, prosthesis and implant. These devices are used for diagnosis, monitoring, curing and sensing of different diseases and body parts where RFID technology commonly offers identification and sensing. This section discusses the application of passive RFID classified according to RFID frequency bands in different medical and healthcare devices.

A. Low Frequency (LF) RFID

1) Gastroesophageal reflux diagnosis

Gastroesophageal reflux disease (GERD) is a medical condition that affects approximately 20% of the adult population worldwide and is one of the most prevalent clinical conditions afflicting the gastrointestinal tract [52]. GERD refers to symptoms or tissue damage caused by stomach acid reflux into the oesophagus and pharynx. The most common symptom of GERD is heartburn [53], although complications include oesophageal cancer and lung damage. GERD can be diagnosed by monitoring the electrical impedance of the oesophagus. In [54], a passive 850 kHz RFID-based wireless impedance sensing device was proposed where the tag was designed to be implanted on the oesophagus wall, as shown in Fig. 4. The tag was fabricated on a flexible polyimide (Kapton™) substrate. The tag includes both the wireless coils and impedance-sensing electrodes. The size of the implant was approximately 2 × 2 cm^2. The size of the reader antenna was 6 × 6 cm^2, and the measurement distance was 3 cm. The authors suggested an operating frequency of 125 kHz to reduce tissue absorption.

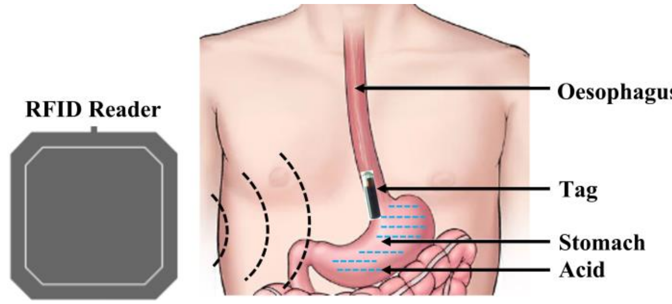


Fig. 4. Implantable passive LF RFID for GERD monitoring.

2) Patient identification

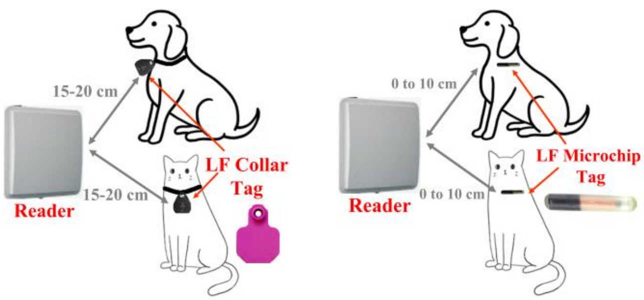
Data capacity in an RFID chip is usually insufficient for storing significant medical information. A patient identifier is written on the tag, which links to a complete electronic record stored elsewhere [55]. Commonly, LF RFID of frequency 134.2 kHz frequency is used for patient identification applications [16].

In [56], an off-the-shelf, parylene-coated, 134.2 kHz operating frequency RFID tag was disassembled and embedded into a dental cavity using existing dental filling materials (EasyTrac-ID, Antwerpen, Belgium). Two 2.21 mm diameter capsules of length of 8 and 12 mm were created, weighing 60 and 95 mg, respectively. Tag components included a 1,300 loops antenna coil, a matching capacitor, a 0.5 mm^2 microchip, the connections, a protecting gel and the bioglass cylinder. The antennas had a ferrite core surrounded by a cylindrical wire-wound copper coil. The coil of the 8 mm tag was 3.4 mm in length and 1.1 mm in diameter. The diameter of the loop wire was between 25 and 30 microns. The chip had a fixed memory with a 64-bit code according to the ISO 11784 norm. To fit this tag into a dental cavity, the tag had to be manually disassembled and the parylene coating mechanically removed. The bio-glass cover was dissolved chemically. The final size obtained for the tag was 6 mm long for a 1.5 mm and 1.0 mm diameter, respectively.

In [57], a 125 kHz, 12 mm long RFID system from AVID Microchip (Norco, USA) and supplied by PETtrac (Bangkok, Thailand) was injected using a 12-gauge (2.6 mm inner diameter) hypodermic needle equipped with an internal plastic ejector rod. A battery-powered mobile reader, AVID Power Tracker II, with a reading distance of up to 15 cm, was used. This work was proposed for disaster victim identification, although the tag can easily be modified for patient identification in hospitals and healthcare centres.

3) RFID in animals

In LF RFID, the frequency of 134.2 kHz has been adopted worldwide as a standard by the International Organization for Standardization (ISO) for devices for companion or pet animals [58]. These devices are included in this review as they are popularly used worldwide for health sensing, monitoring, identification, and tracking of animals in their different environments [59]. The RFID system for animal identification consists of three core components: the microchip including loop antenna, a reader and a database that links the chip number to the pet owner. Figs. 5(a) and (b) show two implementation techniques for this application: collar tag and implanted microchips [60]. In the case of farm animals, a collar tag is generally clammed on their ear [59]. The tag is used mainly for identification and tracking. It is relatively large in size and can have a longer communication distance of 15 to 20 cm. Microchip RFID tag is generally implanted under the skin of pets and farm animals using a syringe injector system. This tag is 8 to 12 mm in size with a communication distance of less than 10 cm [60]. Along with its identification application, some modern tags have sensors such as temperature sensors to monitor the health of the animal [61], [62]. RFID Inc [63] and Dipole RFID [64] are examples of commercial suppliers of tags for farm animal and pet RFIDs, respectively.



(a) (b)

Fig. 5. (a) LF RFID-based (a) Collar tag. (b) Microchip tag.

B. High Frequency (HF) RFID

1) Management of blood donation

blood donation between sites managed by HF RFID is presented in [65]. Sets of blood collection bags containing a particular blood group are RFID tagged using a 14 × 31 mm^2 RFID tag with an international standard for blood transfusion (ISBT) 128-digit donation identification number (DIN) label. All blood collection bags are tagged at the donation site to detect missing or unused bags from that set. Wi-Fi connected Unitech PA600 mobile clinical assistant personal data terminals, including barcodes and HF RFID readers, are used at the donation sites to read the DIN barcode and perform the tag initialization. All tag data are uploaded to a mobile RFID application database for transfer to the blood centre to check in the RFID-enabled donation. Donation shipping containers are also tagged. The blood centre also follows a similar RFID-based check-in method where the bags with the tags are recorded using 50 × 50 cm^2 aperture local area network (LAN)-connected TAGSYS Medio L-400 4 channel tunnel readers [66] using the RFID tags on the container and the collection sets. Wi-Fi-connected Unitech PA600 Mobile clinical assistant personal data terminals are used for the inventory. Since the blood products are RFID tagged, the hospital blood bank can utilize all the same check-in, inventory management, and returns capabilities available in the blood centre. It can also use RFID to release or return blood from satellite storage locations such as the operating or emergency rooms. RFID-augmented three-way matching of the patient ID, transfusion order, and the unit to be transfused can be performed at the point of patient care. This increases transfusion safety by reducing or eliminating clerical or transfusion errors, as well as automating issue and release of blood and the recording of chain of custody.

2) Smart nappy

In [67], a smart nappy equipped with a battery-less NFC tag with a frequency of 13.56 MHz is presented. Moisture in the nappy is detected by changes in capacitance between two electrodes located on the back sheet of the nappy. The value of the capacitance is determined using a microcontroller from the charge time through a high-value resistor as shown in Figure 6.

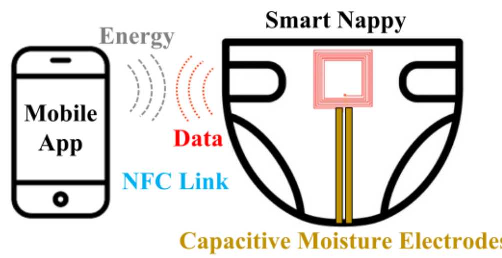


Fig. 6. HF RFID-based smart nappy.

The change in capacitance as a function of the wetness of the diaper is monitored through a mobile App. The power required to feed the electronics and microcontroller is obtained from the magnetic field generated by a smartphone with the NFC used as a reader. This study uses the M24LR04E NFC IC from ST Microelectronics [68] in the nappy. The flexible tag was designed on a flexible Rogers Ultralam 3000 substrate. The antenna is a 6-turn, 0.5 mm width and space loop with an area of 25 × 25 mm^2. The maximum reading range between the nappy and mobile phone is 14 mm. Fig. 7 shows the manufactured tag and capacitive sensor adhered to a smart nappy and the status of the nappy read through a mobile app.

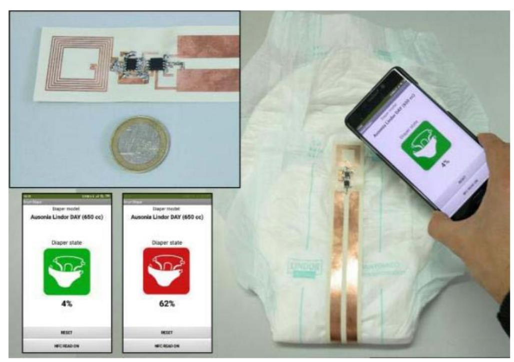


Fig. 7. HF RFID-tag adhered to a nappy and data read through mobile app. Copyright © 2019, IEEE.

3) Wound wetness detection

A passive smart bandage with HF RFID is illustrated in Fig. 8(a) [69]. The sensor impedance is monitored while the bandage switches from the dry to the wet state several times, as shown in Fig. 8(b). In this figure, the impedance variation lies in the same range for each cycle, confirming the reliability, result reproducibility and reversibility of the smart moisture sensor. A proper combination of gauze and absorption layer is used to obtain an entirely passive smart bandage that gives an RFID tamper alarm when the wound switches from wet to dry and vice-versa. The large impedance variation recorded when the sensor passes from the dry to wet states allows for direct integration with a passive RFID chip, achieving a low-cost, passive, humidity sensor tag. The integrated "smart" humidity sensor exploits the tamper function of the RFID, in which the "tamper bit" changes state (0–1) when impedance varies above and below a set threshold.

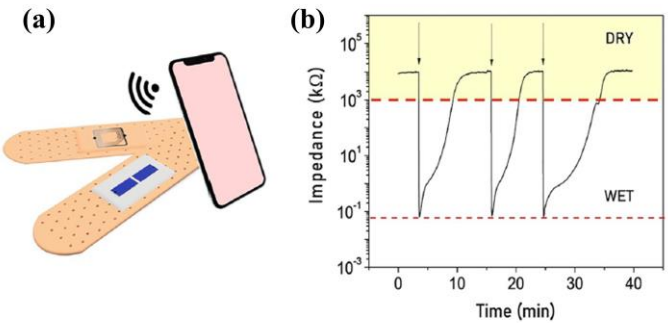


Fig. 8. (a) Illustration of the smart moisture bandage with the electrodes in the internal parts of the bandage and the passive HF RFID system on the external side. (b) Real-time monitoring of the impedance of the sensor when the status switches between wet and dry showing a reversible behaviour. Reproduced by permission from open access article from Frontiers in Physics (CC-BY).

In [70], a wireless detection of infection on wounds (WINDOW) system is proposed, using a HF RFID-based battery-free sensor. This sensor includes a custom DNA hydrogel (DNAgel) that provides a radio frequency detectable response to deoxyribonuclease (DNase). DNase is an enzyme secreted by opportunistic pathogens, including *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Streptococcus pyogenes* commonly implicated in clinical wound infections. DNase can act as a virulence factor that facilitates bacteria dissemination from biofilms and bacteria evasion of neutrophil extracellular traps deployed by the host immune defence. When exposed to extracellular DNase, the DNAgel is degraded via nonspecific cleavage of DNA strands, resulting in the dissolution of the hydrogel, which changes the dielectric permittivity of the region above an interdigitated electrode and, therefore, varies its capacitance. This electrode is connected to the analogue-to-digital converter (ADC) pin of an HF RFID chip RF430FRL152H through a resonating coil (*LC* circuit). There is another coil connected to the antenna pins of the RFID chip. A smartphone is used to resonate the sensor coil and power up the RFID chip simultaneously, as shown in Fig. 9. This technology may facilitate the timely detection of wound infections for improved management of surgical or chronic wounds. Fig. 10 shows the manufactured WINDOW system mounted on the index finger, where the readout signal changes with the bending of the finger.

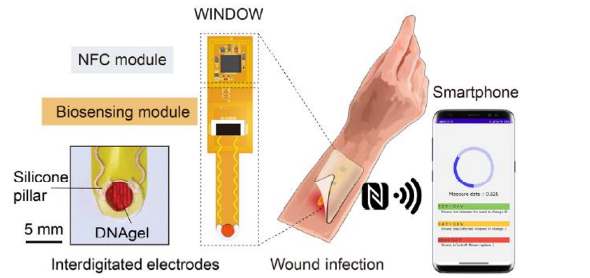


Fig. 9. Schematic of the wireless wound infection sensor. WINDOW integrates the bio-responsive DNAgel, a half-wave–rectified *LC* biosensing module, and an NFC module to enable smartphone readout of the wound status. Reproduced by permission from open access article from Science Advances (CC-BY-NC).

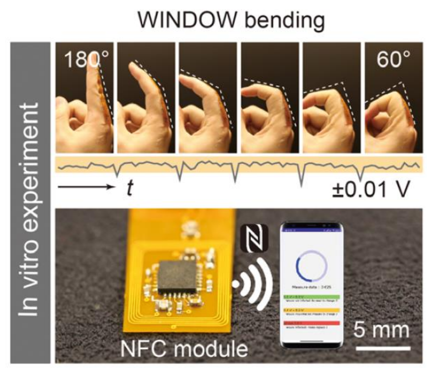


Fig. 10. WINDOW mounted on the index finger. The yellow region shows the readout signal corresponding to the bending angles indicated by the dotted white lines. Inset shows the image of the manufactured HF RFID module (NFC). Reproduced by permission from open access article from Science Advances (CC-BY-NC).

Fig. 11 shows a fully functional smart bandage circuit, based on NFC RFID, and manufactured on a flexible Kapton™ substrate suitable for integration in a textile bandage [71] inspired by [72]. Copper-coated Kapton substrate is a flexible substrate for the battery-free smart bandage system. NFC RFID chip MLX90129 was chosen for this device with a Sensirion SHT30-ARP low power combined humidity and temperature sensors to record information regarding the wound's humidity.

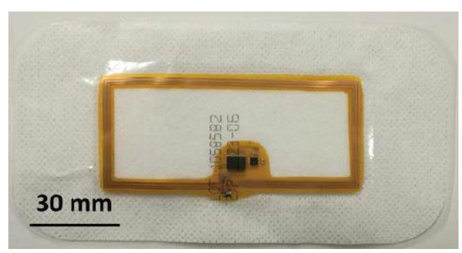


Fig. 11. Proposed smart bandage with embedded battery free wireless temperature and humidity sensor. Copyright © 2020, IEEE.

In Fig. 12, a smart bandage with wireless strain and temperature sensors and a passive NFC tag is presented [73]. The main electronic component in the smart bandage comprises of an NFC ISO15693 sensor transponder RF430FRL152H from Texas Instruments (TI, Dallas, Texas, USA). The temperature sensor is built with polystyrene sulfonate (PEDOT:PSS) polymer, which is sensitive to temperature variation and can measure a temperature range of 25°C–85°C. Transparent polymer polydimethylsiloxane

(PDMS) is used to fabricate the strain sensor.

Fig. 12. NFC-based smart bandage attached on the arm for wireless strain and temperature monitoring using a custom smartphone app. (CC-BY).

A similar smart NFC-based bandage with continuous wound impedance and temperature monitoring is presented in [74] and [75].

4) Patient identification

The design, implementation, and evaluation of a hand-held patient identification system using an HF 13.56 MHz RFID is presented in Fig. 13 [76]. Each patient is given a wristband with a Tag-it HF passive RFID chip, which contains demographic information (patient ID number, ward number, hospital code, etc.). A hand-held device (Hewlett-Packard1 iPAQ h5555) equipped with IEEE 802.11b wireless local area network connectivity and an RFID reader (Skyetek M1 RFID) is then used by the medical staff to read the patient's wristband, enabling thereby their identification, and access to their relevant records.

Fig. 13. HF RFID-based patient identification.

A 13.56 MHz RFID transponder, fabricated from an ISO/IEC15693 integrated circuit chip SRF55V10S (Infineon Technologies, Germany), was customized into a rectangular bar to be embedded in the cylindrical endodontic space of a tooth [77]. The maximum communication distance between the transponder and the reader is 25 mm. Initially tested in the tooth of a dog, the authors suggest that the system could be applicable in some cases to identify hospitalized patients instead of an identification wristband. A similar identification RFID tag is presented in [78] to identify dental prosthesis where the tag is suggested to be implanted on the buccal area of bilateral molars for easy detection. The tag retrieves the design date, materials used for the prosthesis and the certificate number of the dentists who implanted it.

An HF RFID-based smart patient management, monitoring and tracking process useable in hospitals to automate and organize their information management is proposed in [79]. This system can create unique identification numbers for each patient, which are then linked to all patient vital signs recordings and saved in a database for further analysis and historical consultation. The system can also provide real-time patient monitoring of vital signs during their stay in an emergency and critical care unit in a hospital. It also alerts hospital staff if any abnormality is detected. An HF RFID-RC522 reader of 13.56 MHz frequency with a passive tag is used in this research.

5) Wearable patch

An NFC-based glucose monitoring patch is shown in Fig.14 [80]. A flexible abiotic glucose hybrid fuel cell can generate an open circuit voltage of 0.45 V in the presence of 7 mM physiologic glucose in the skin. This fuel cell is correlated with glucose level and acts as a sensor to provide a corresponding analogue voltage signal. TI RF430FRL152H (Texas Instrument, Texas, USA) is used as an NFC transponder in the patch. An NFC-enabled smartphone powers the patch and accesses glucose data wirelessly.

Fig. 14. HF RFID-based glucose monitoring patch. Reproduced by permission from open access article from Scientific Reports (CC-BY).

A vanadium dioxide (VO_2)-based chemoresistive sensor that detects the level of nicotine exposure is presented in [81]. In this work, nicotine vapor from e-cigarettes in the air is monitored using the proposed sensor built into an epidermal NFC patch with a TI RF430FRL152H used as a transponder and a TI TRF7970A chip as an NFC reader.

A TI RF430FRL152H-based wearable e-nose sensor patch readable through any NFC-enabled mobile phone is presented in [82]. The sensor can be worn anywhere on the body to measure volatile organic compounds (VOCs) excreted through the skin or exhaled breath. VOCs are the end products of human metabolism, which can be a useful marker for disease diagnosis. A similar healthcare patch with TI RF430FRL152H is presented in [83] and can monitor heart rate and skin temperature. The data can also be read through any NFC-enabled smartphone.

6) Implantable device

An HF RFID-based implantable real-time glucose monitoring microsystem is shown in Fig. 15 [84]. The microsystem includes an electrochemical glucose sensor, a ferrite antenna, a high-frequency (HF) front end, a digital baseband, and a sensor interface circuit. The sensor tag, regarded here as a low-cost, long-term glucose monitoring device, can detect the glucose level and wirelessly transmit the sensor data to an external reader. The authors also developed a custom-built application-specific integrated circuit (ASIC), including the RFID and glucose sensor.

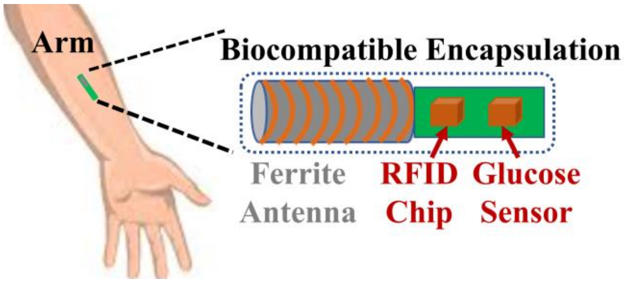


Fig. 15. Implantable HF RFID-based glucose monitoring system.

In [85], an HF RFID-based implantable thoracoscopic surgery support system is presented, which can identify or locate a tumour inside organ tissue. Star Engineering Co. Ltd. RFID transponder TR3-LD003C marks the small lung tumour position by measuring the signal strength emitted from the target tag.

An RFID-based orthopedic implant is presented in [86], [87] and used to observe and obtain detailed information about the implant once the surgery is completed. However, a major drawback of using an RFID tag embedded in an orthopedic implant is its low data transfer efficiency due to the metallic interface. Therefore, an alternative method is proposed here where the electric field interaction between two pairs of electrodes is utilized, as shown in Fig. 16. One electrode is the touch probe placed on the surface of the tissue, and the other is a part of the tag installed under the tissue for orthopaedical implant identification. This proposed method uses the property that ionic fluids within biological tissues can conduct electrical current, which, when intentionally manipulated, can be used to transmit information and energy. If two pairs of electrodes, one internally and the other externally, are both attached to the tissue, energy transfer will occur by capacitive coupling between the two pairs. Authors claimed to achieve better efficiency than with a conventional RFID antenna, such as a loop antenna, by reducing the interference with the orthopaedic implant. The authors achieved close to 100% read efficiency when they used matched antenna for the RFID tag for 3 layers of pig skin. It reduces to 10% for 6 layers of pig skin.

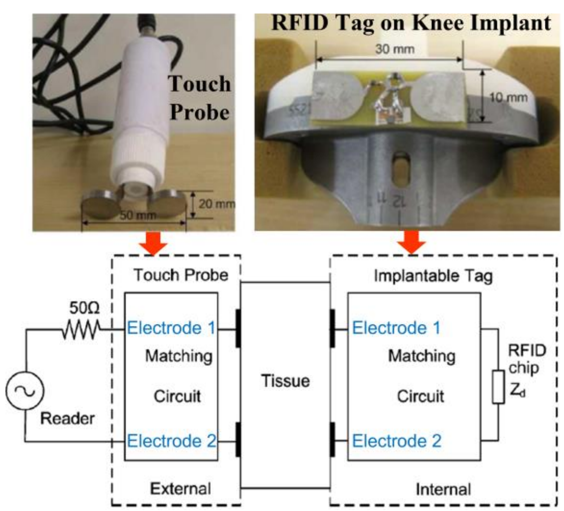


Fig. 16. Touch probe method for RFID-based orthopedic implant. Copyright © 2013, IEEE.

7) Honeybee tracking

In [88], the Track-a-Forager system is proposed to observe honeybees. The host colony includes two frames of brood, one frame with stored pollen and honey, a queen and around 3000 host colony workers. It is placed indoors at room temperature and are connected to the outside via a single entrance tunnel to allow free foraging. At the end of the tunnel two iID® MAJA 4.1 RFID scanner modules (Microsensys, Germany) are placed in series, which are connected to a MAJA 4.1 host computer (Microsensys, Germany) to record and log the timing of all RFID tagged honeybees leaving or entering the hive. A total of 400 bees are tagged with a mic3® 64-bit read-only RFID transponder (Microsensys, Germany) by gluing the tag to the bee's thorax using Kombi Turbo two-component glue (Bison, Netherlands). The tags are weighed less than 5 mg 2 × 1.7 × 0.5 mm in size and transmitted at 13.56 MHz.

C. Ultra High Frequency (UHF) RFID

1) Implantable device

UHF is the most common choice of frequencies for RFID used in implantable devices. Commercially available UHF RFID chips are low cost, smaller in size and provide larger communication distance [22]. However, higher absorption of wireless energy in human tissues at this range of frequencies can cause tissue safety.

In [89], a complete procedure for designing self-sensing implanted UHF RFID tags is presented for the monitoring of biological ducts hosting a stent implant. A vascular stent is typically fabricated with biocompatible metallic alloys such as Nickel-Titanium (Nitinol), which has promising electrically conducting properties. The stents used as a self-sensing implanted RFID tag combines mechanical and sensing capabilities. Fig. 17 shows the named "STENTag", obtained from an existing stent after minimal geometrical modification and by including a UHF RFID IC NXP-G2X. UHF band (840–960 MHz) ready by a UHF Thing-Magic M5e system.

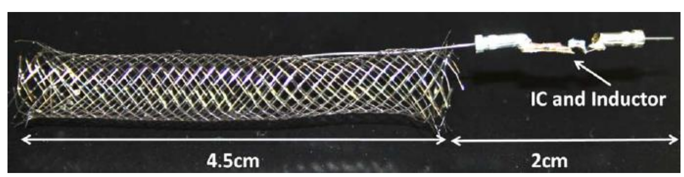


Fig. 17. STENTag prototype. Copyright © 2012, IEEE.

A battery-less and metal-free aortic valve prosthesis with sensing and communication modalities is presented in [90], [91]. The RFID IC Magnus S3 is integrated with a stent with the wireframe of the valve acting as a 900 MHz frequency dipole antenna (a thin copper wire with 35 μm diameter is wound around the perimeter of the valve and incorporated into the external dielectric coating), as shown in Fig. 18. This non-invasive monitoring facility can provide early diagnosis of any potential structural and functional deterioration of the implant. In [92], a similar device is presented to monitor core-body temperature of patients.

A prototype of a cyber-tooth is demonstrated in [93] whereby a dental implant acts as an antenna to identify any

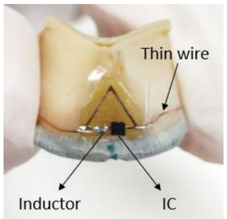


Fig. 18. RFID-based valve prototype. Copyright © 2022, IEEE.

infection in the prosthesis of the mouth cavity. In this work, a molar tooth is replaced with a dental prosthesis consisting of a screw replacing the root of the tooth, an abutment placed on the top of the dental implant to connect it to the replacement tooth, and a crown, a custom replacement tooth. The screw and abutment are engineered to work as a harvesting antenna operating at 868 MHz frequency. Temperature sensor RFID tag IC Axzon's Magnus-S3 is used with Voyantic Tagformance RFID measurement system to validate the proposed technique.

An implantable partially folded dipole antenna with Monza 4 RFID chip is presented in [94] for dental prosthesis. A hand-held reader/writer JIS U524R 4 CH UHF is used to evaluate the proposed denture implanted RFID tag where the operating frequency is 920 MHz.

The feasibility of direct forward links using a non-contact reader's antenna for UHF-RFID (860–960 MHz) tags implanted into human limbs is demonstrated in [95]. This work aims to label a patient with an identification number and collect data about the health status of an implanted orthopedic prosthesis. A stable communication link is demonstrated with tags implanted inside limbs within 10–35 cm depth in the body in full compliance with electromagnetic exposure guidelines [38], [39], [40]. A commercial Impinj (USA) Monza-4 die, and Thing-Magic M5e are used as the tag and reader, respectively. The worst-case simulated SAR is 0.36 W/kg in the elbow and hip part of the body. A more implementation and measurement-based approach to a family of real orthopaedic prosthesis with the same UHF RFID tag and reader is recorded in [96].

Another major problem with implanted prostheses is the generation of micro-cracks due to fatigue. Such cracks are mostly identified by periodic X-rays or nuclear magnetic resonance-based screening. Detection is sometimes directly based on the onset pain of in the patient. A surgery then confirms and mitigates the early generation of micro cracks. In [97], [98], a UHF RFID-based sensing tattoo is presented to detect early onset of cracks in implanted metal orthopaedic prostheses. The detection stems from changes in resistance incurred by cracks in the space-filling curves (SFC) sensor. The status of the bone is then sent as a backscattered signal by the RFID tag NXP UCODE G2iM+ operated at 900 MHz.

2) Infection monitoring

Infection is a common threat to any orthopaedic implant that can also force its removal as a last resort. The diagnosis of infections is currently achieved by time-consuming and costly imaging techniques, such as X-rays, MRI and CT or just by the onset of the patient's pain when the problem is already at an advanced state. In [99], [100], an alternative early-time infection diagnosis and monitoring system is developed by equipping the prosthesis with a local temperature sensor and UHF RFID communication. In this work, an orthopaedic device is provided with holes, like for a bone fixation plate, to install a harvesting antenna integrating an RFID sensor, as shown in Fig. 19. A single Axzon Magnus S3 passive RFID chip is used with an antenna to monitor wirelessly local deep infections in orthopedic bone-plate at 860-960 MHz frequency. Simulations and experimentations with several prototypes demonstrated that the augmented implanted device could establish a stable RFID link up to 0.5 m and monitor local temperature variations of 37°C - 40°C of the bone as in the case of typical deep infections.

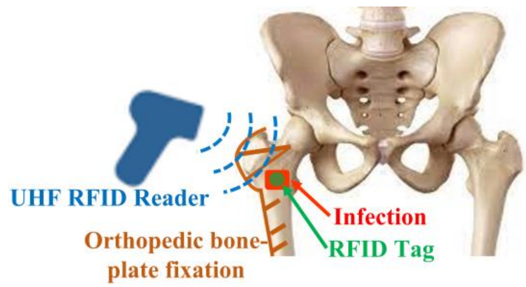


Fig. 19. UHF RFID-based smart prosthesis to identify inflammation due to bacterial proliferation that overall produces a local temperature increase.

In [101], a self-sensing UHF RFID tag is demonstrated for the non-invasive sensing of microbial growth within a voice prosthesis, which can result in device failure or infection symptoms in patients. Fungal species C. albicans is a common colonizer of voice prostheses which can form a multi-layer biofilm upon the device. The detection of the growth of such microbial is only possible when the implant stops operating or symptoms of serious infection occurs in the patients. Therefore, a TagformancePro Voyantic RFID antenna measurement system is used with Higg-3 Gen 2 RFID tag IC at 867 MHz frequency to detect the level of microbial growth in the implant and assess the need for replacement. This can also help to avoid any unnecessary cost and hassle of surgery.

3) Movement monitoring

Wearable RFID tags harvest RF power from the impinging field emitted by the reader and reply by modulating the reflected field via digital encoding. When a tag is placed over a limb, trunk or any other body part, its response will embed movement-dependent amplitude modulation.

In [102], a battery-free wearable HF RFID antenna, shown in Fig. 20, is operated in the 866–868 MHz band to classify limb gestures. The processing of the electromagnetic response uses algorithms borrowed from machine-learning techniques generally applied to brain–computer interfaces (BCIs) to recognise electroencephalographic patterns. Human motor gestures can similarly relate to the spatiotemporal changes of the power backscattered by wearable tags. The different movements modulate the signals according to specific patterns that can be classified. The UHF RFID microchip transponder connected to the tag is the Impinj Monza 4 IC with a nominal RF input impedance and power sensitivity. The scanning system used for this work comprises a ThingMagic M5 UHF RFID reader with an interrogation distance of 5–7 m.

A similar system is proposed in [103] to monitor limbs for sleep related diseases, such as restless legs syndrome, using a UHF RFID system.

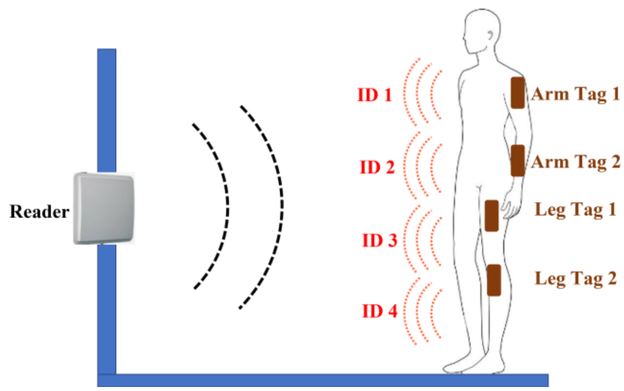


Fig. 20. The setup of the RFID scanning system and the position of wearable tags over the leg and the arm.

4) *Smart nappy*

In [104], a novel disposable sensor for moisture detection is proposed that leverages the material properties of the water absorbing polymer gel common to most diapers. A hybrid sensor design utilizing metal and hydrogel is optimized for a specific diaper geometry and can achieve a 1-meter read range. Fig. 21 shows the RFID tag antenna implemented with super absorbent polymer (SAP), a subclass of hydrogel, as a body-safe, flexible sensing element. SAP is already the primary absorbent material in diapers. Using this material as an antenna element can significantly reduce the cost of RFID sensors by reducing the metal content and simplifying manufacturing and assembly. The dielectric properties of the SAP changes for dry and wet states. The measured reflection coefficient indicates the change in the conductivity in diaper core in the presence of saline liquids which indicates dry or wet state.

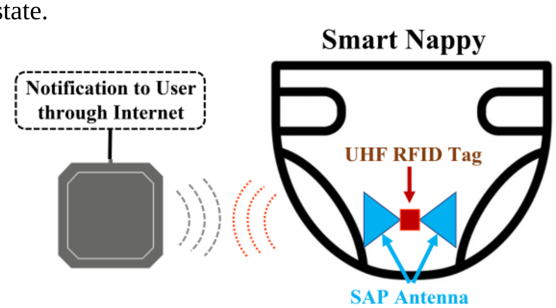


Fig. 21. UHF RFID-based smart nappy.

In another work, a flexible, reusable, and battery-free RFID sensor tag is attached to the front side of a diaper, where an external RFID reader antenna energizes and monitors the tag [105]. In the presence of urine, the tag on the diaper reflects little interrogation energy, resulting in a sharp decline in the received signal strength indicator (RSSI). As a result, an alarm is generated, requesting a change of diaper. In this work, a passive UHF RFID sensor of 902-928 MHz frequency used with an extended on-body allows a read distance of 3.6 meters with a Monza R6 chip integrated as a tag chip.

5) *Smart lens*

A wireless smart contact lens (SCL) system is proposed in [106], composed of a reconfigurable capacitive sensor interface circuitry and wirelessly powered UHF RFID addressable system for sensor control and data communication. A capacitive pressure sensor was embedded on a soft 200 µm thick contact lens using commercially available bio-compatible lens material and a standard manufacturing process to improve compliance and reduce user discomfort. Intraocular pressure (IOP) measurement for glaucoma prevention was used to illustrate the functionality of the proposed SCL system, as shown in Fig. 22. A custom-built ASIC is used as the RFID tag, with the reader integrated into an eye glass. The experimental setup is demonstrated in Fig. 23, where a porcine eye was used to validate the manufactured system.

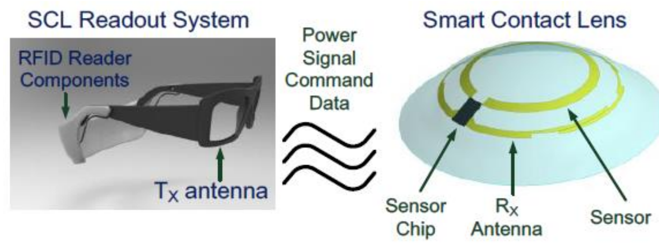


Fig. 22. Smart lens for glaucoma monitoring using UHF RFID. Reproduced by permission from open access article from MDPI Sensors (CC-BY).

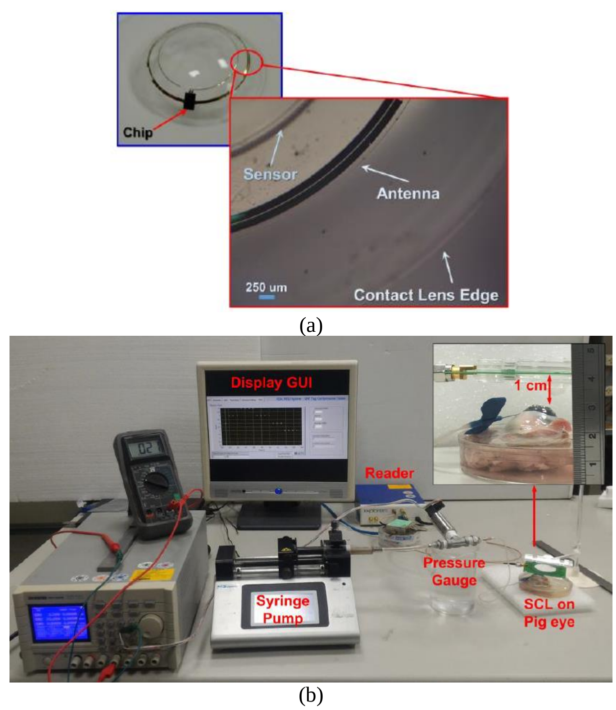


Fig. 23. (a)Manufactured contact lens with custom built UHF RFID chip. (b) Experiment setup. Reproduced by permission from open access article from MDPI Sensors (CC-BY).

6) *In-ear temperature sensor*

A battery-free temperature monitoring device fitted inside the ear is proposed in [107] the accurate body temperature measurement of a patient. The 866 MHz operating frequency

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system can record changes in local temperature with an average accuracy of ± 0.14 °C and a latency of 501 ms. The monitoring device, placed close to the tympanic membrane, can be fitted similarly to a receiver-in-canal hearing aid. The RFID sensor is powered up, and multiple temperature readings are taken when the user walks within a range of less than 1 m from an RFID reader, as shown in Fig. 24(a). A UHF RFID chip SL900A is used with an external medical grade thermistor sensor and an Amphenol Advanced Sensors device (MA100GG103AN), as shown in Fig.24(b). The device, used for constant symptom monitoring of key workers, showed promising results and could be of value in care homes and private home settings for early-stage detection of COVID-19 or similar highly infectious disease symptoms.

(a) (b)

Fig. 24. (a) Body temperature measurement using UHF RFID-based in-ear temperature sensor. (b) Manufactured system. Copyright © 2021, IEEE.

Similar UHF RFID-based systems for pandemic situations, such as Covid-19, are presented in [108]. These devices can detect life-threatening viral infections early by measuring body temperature and respiratory rate and help isolate faster to reduce the spread of such infection. These UHF RFID devices can be used by healthcare workers in hospital setups, care homes and private homes.

7) Nov-invasive glucose monitoring

A complex dual RFID tag-based non-invasive glucose sensing system is proposed in [109]. In this work, the antenna coupling between two RFID tags is regarded as plate capacitor. If the dielectric material between two antennas (or plates) is replaced with glucose, the capacitance value changes with the glucose concentration level. The commercial UHF RFID tags RFMicron 3200-AFR with self-tuning circuit are selected to avoid impedance mismatch. The glucose concentration is then calculated by a particle swarm optimization algorithm from the capacitance values received by the reader at 902 to 928 MHz operation frequency.

8) Animal tracking

In [110], a prototype UHF RFID tag is proposed for detecting the visitations of bumblebee within fragmented landscapes. The prototype tags use a UHF RFID strap chip muRata MAGICSTRAP® LXMS31 with a custom inductively loaded, half dipole whip antenna. To energise the tag and receive its transmission, a 2 W UHF long-range reader (ID ISC.LRU1002 reader, Feig GmBH, Weiburg, Hessen, Germany) of 860–960 MHz frequency is used which is equipped with two antennas. In [111], a very small size UHF RFID tag antenna is presented for racing pigeon ring application to record the arrival time of the pigeon automatically. A tag chip Alien Higgs 4, SOT232 package with the cylindrical ring antenna is used. An RFID transmitter system with EIRP of 4 W is used at the frequency range of 902 to 928 MHz.

D. Ultra-Wide Band (UWB) RFID

Compared to HF and UHF, UWB is a relatively immature technology for medical and healthcare applications. Therefore, very few examples are found in the literature with UWB RFID.

In [112], a 2.45 GHz UWB RFID-based radar system was used to sense the received second harmonic signal from the human body using harmonic tag. A harmonic tag consists of a tag antenna with a strongly nonlinear element, such as Schottky diode at its port. The incoming signal is then converted to harmonics by the nonlinear element and the tag is designed such that the second harmonics is transmitted back to the received. In this work, the setup is employed to first isolate periodic motion successfully from a tag on a programmable mechanical target in close proximity to other moving objects and to sense the respiratory motion of a human subject. Respiratory data obtained from the tag is compared to a reference.

In [113], a wireless entirely passive neural recording device for unobtrusive neuropotential monitoring is presented with dual-band UWB RFID. The authors proposed a novel realistic recorder that is significantly smaller and more sensitive. The developed prototype is 16 × 15 mm^2 where the sensitivity is improved up to 20 dB. It allows the possibility of entirely passive wireless neural detection for a wide range of applications, such as epilepsy, Alzheimer or mental disorders. The miniaturized UWB RFID dual-band (2.4/4.8 GHz) antenna receives the carrier signal at 2.4 GHz and backscatters the third-order mixing products at 4.8 GHz.

An implantable device for gastroesophageal reflux disease (GERD) monitoring is presented in [114]. This system comprises a battery-less, wireless transponder with integrated impedance and pH sensors. A wearable external reader wirelessly powers the transponder and interprets the backscattered radio-frequency signals. The transponder implant of a total size of 0.4 × 0.8 ×3.8 cm^3 harvests radio frequency energy to operate a dual-sensor and load-modulation circuitry. Powering and communication are done by electromagnetic coupling between two-coil antennas in the reader and transponder. During *in vitro* and *in vivo* animal experiments, the data were transmitted to a base station through a 2.4-GHz wireless link for real-time display and analysis.

A UWB RFID-based wireless drug dosage monitoring system is presented in [115] where the resonant frequency of the helix antenna varies from 2.4 GHz to 2.5 GHz due to the drug concentration in an implanted capsule. The RFID drug dosage sensor can be tracked by a smartphone application.

A chip-less printable sensor-based on split ring microwave resonators working at frequency range of 4 GHz is presented in [116] for glucose monitoring. The proposed sensor detects glucose variation-based on the change in the resonance frequency due to the change in the effective permittivity of the different layers underneath human skin including interstitial fluid and blood depending on senor mounting location.

In [117], a real-time location system (RTLS)-based on UWB RFID is presented for monitoring and tracking dairy cow behaviour in a semi-open free-stall barn. A commercial RTLS-based on UWB technology (Ubisense, UK) is installed in the selected area of the barn to detect the position of eight dairy cows using compact Tags IP65 of 2.45 GHz frequency. A similar RTLS is presented in [118] to track growing-finishing pigs in the farm.

E. Multiple Frequency Band RFID

It was shown in the case of the smart nappy that the application could be implemented by selecting a given frequency band. Conversely in [119], a multiple frequency band RFID system is proposed here for the administration of medication and the tracing of intravenous mixtures using HF and UHF RFID, respectively for hospital settings.

1) Administration of medication

An HF RFID system is proposed in [119], [120] for the traceability and safety of administering medication to the patients in a day hospital. When nursing staff administer an intravenous mixture to a patient, it is essential that they check whether the prescribed medication has been administered in suitable conditions. The 13.56 MHz integrated near-field communication (NFC) reader of an Android phone is used to read the NFC chip from the package of the intravenous mixture and the NFC chip connected to the wrist of the patient, as shown in Fig. 25. NFC is a subclass of RFID, which operates in the short range (maximum 10 cm) [121]. In this system, an NXP NTAG203, ISO14443A NFC tag was designed to record the administration of the medication to the patient with an RD 200-M1-G NFC reader as an alternative to the Android phone if necessary. The mobile application (App) issues alerts relating to the administration of the drug to the patient, including the route, pattern, administration conditions, expiry date of the intravenous mixture, and whether the drug had been prescribed or given to the patient previously. This process is reported to significantly increase patient safety by minimizing the occurrence of adverse events.

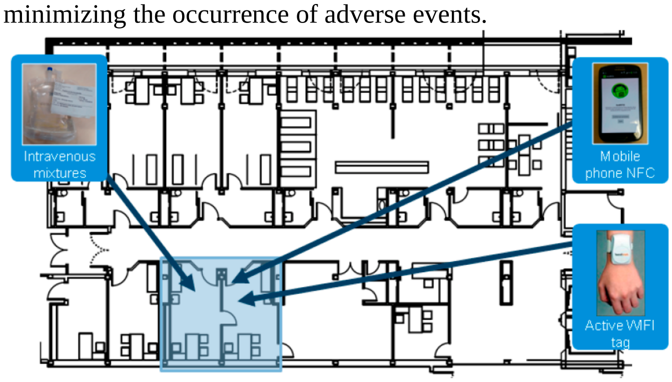

Fig. 25. HF RFID system for medication administration to the patient. Reproduced by permission from open access article from MDPI Sensors (CC-BY).

2) Traceability of intravenous mixtures

In [119], a UHF RFID-based system is implemented to manage the traceability of intravenous mixtures during their transport and elaboration at the pharmacy service until final delivery in the day hospital. Traceability of medications is important for drugs considered high-risk or costly. Currently, a significant portion of the drugs administered to patients in day hospitals are prepared and dosed by the pharmacy service. Hospitals commonly protocolize their processes, and prior to implementation, a record is made of the medication that is prepared for each patient. For each prepared medication, some other important information is registered, which includes the lot number and expiry date of each component, production date, and expiry of the final product. In most hospitals, all these records are paper-based and made manually. It is difficult to ensure the global traceability of the medication, especially if it has been some time since its preparation. The time of the prescription receipt, the departure from the pharmacy service, or its reception at the day hospital are also not registered. In this system, when the intravenous mixtures cart (tagged with UHF RFID) reaches the day hospital, the nursing staff records the delivery of drugs by keeping the deposit mixtures above an RFID tray, which displays data of the mixture and the patient for whom it has been prepared. Fig. 26 shows an example of the proposed system. At the same time, the RFID system reads the UHF chip from that drug, including the time and date of delivery. The system can also provide real-time location of any intravenous mixture with the information provided by the RFID cart and tray since the content and location of the cart are always known. The UHF RFID tag Monza 4, with an 860 to 960 MHz operating frequency, international standards EPC Class 1 Gen 2, ISO 18000-6C, is selected for this work with the reader RD 200-U1-G.

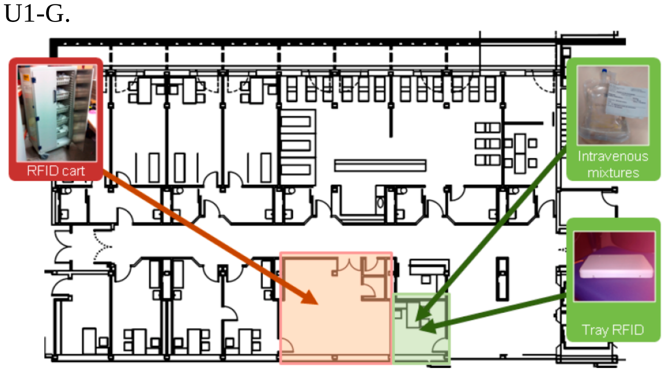

Fig. 26. UHF RFID for the traceability of intravenous mixtures. Reproduced by permission from open access article from MDPI Sensors (CC-BY).

VI. Future Challenges for RFID-Based Wireless Medical and Healthcare Devices

Despite the unique benefits of RFID technology in medical and healthcare applications, challenges remain, a few of which are discussed in this section.

A. Communication Distance

Increased communication range between the RFID tag and the reader is necessary for a number of medical and healthcare

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applications. To address this challenge, technologies reported recently are focusing on the development of active RFID tag-based devices to increase this distance [16]. In the future, the design and optimization steps should focus on achieving larger communication distance similar to existing active devices. Possible avenues of research include optimised design of the antenna, recalibration of the reader, increased tag chip sensitivity and level of transmitted power. The latter is particularly challenging for medical and healthcare devices due to the limitations imposed regarding tissue safety.

B. Cost of RFID Devices

RFID tags are slightly more expensive than printed labels, such as barcodes. However, their capabilities significantly outperform printed label technology, outweighing the concerns associated with their slightly higher cost. The main concern related to cost lies in the significantly higher price of the RFID readers.

C. Reading Data from Multiple Tags

Reading data from multiple tags by a single reader is required in many healthcare applications in hospitals. However, multiple tags can cause severe EMI issues and latency in reading, which can affect the reliability of the received data [122].

D. Data Reliability

Accurate reading of data from an RFID tag is of utmost significance for medical and healthcare applications. Reliability and reproducibility of the RFID readings are key requirements. Therefore, the design of the RFID tags must be robust to changes in their surrounding environment, including environmental conditions, such as temperature and humidity, washing/drying cycles, changes in the properties of the surrounding biological tissues, packaging, and so on. A number of works have already addressed the reliability concerns for RFID devices, including failure analysis and a performance study in different environment conditions [123], [124], [125], [126]. Moreover, any software related to the manipulation and/or processing of the data is considered a medical device and must comply with regulations (Software as A Medical Device – SAMD) in the country where the device is used [127].

E. Biocompatibility

The selection of biocompatible materials is a key requirement for implantable RFID devices [41]. The right materials must be used to prevent serious concerns, such as fibrosis, inflammation, and eventually rejection of implantable medical devices.

F. Privacy and Ethical Concerns

Currently, most RFID-based wireless medical and healthcare devices do not follow any standard for data encryption and user privacy. Considering RFID devices may transmit personalized data, serious concerns exist, including unsolicited interference or jamming, misuse of collected data, and unauthorized access to the data. Therefore, RFID-based wireless medical and healthcare devices need urgent research, including signal processing, hardware design, supply chain logistics, privacy rights, ethical approval and cryptography.

TABLE I
SUMMARY OF RFID-BASED WIRELESS MEDICAL AND HEALTHCARE DEVICES

Type	Ref, Applications	Frequency	Distance	Devices	Merits	Issues
LF	[52], GERD	850 kHz/ 125 kHz	3 cm	-	Tissue safety	Larger implant size and lower distance
	[56], Patient identification	134.2 kHz	-	Tag: EasyTrac-ID Reader: PET SCAN II	Tissue safety	Lower distance and privacy
	[57], Patient identification	125 kHz	15 cm	Tag: AVID Microchip Reader: PowerTracker II	Tissue safety	Lower distance and privacy
	[58], Animal and pets	134.2 kHz	0-20 cm	RFID, Inc, Dipole RFID, etc.	Keep track of animals and pets	Lower distance and ethics
HF	[119], Medication administration	13.56 MHz	10 cm	Tag: NXP NTAG203 Reader: RD 200-M1-G	Tissue safety	Lower distance, privacy and ethics
	[65], Blood donation centre	13.56 MHz	-	Reader: TAGSYS Medio L-400	Tissue safety	Lower distance, privacy and ethics
	[67], Smart nappy	13.56 MHz	14 mm	Tag: M24LR04E Reader: Mobile phone	User comfort and tissue safety	Larger device size and lower distance
	[70], Wound detection	13.56 MHz	10-20 mm	Tag: RF430FRL152H Reader: Mobile phone	User comfort and tissue safety	Larger device size and lower distance
	[71], Smart bandage	13.56 MHz	10-20 mm	Tag: MLX90129 Reader: Mobile phone	User comfort and tissue safety	Larger device size and lower distance
	[73], Smart bandage	13.56 MHz	10-20 mm	Tag: RF430FRL152H Reader: Mobile phone	User comfort and tissue safety	Larger device size and lower distance
	[76], Patient identification	13.56 MHz	10-20 mm	Tag: Tag-it Reader: Skyetek M1 RFID	Tissue safety	Lower distance, privacy and ethics
	[77], Prostheses	13.56	25 mm	Tag: SRF55V10S	Tissue safety	Lower distance, privacy and

This article has been accepted for publication in IEEE Journal of Radio Frequency Identification. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JRFID.2024.3451230

	identification	MHz				ethics
	[79], Patient management	13.56 MHz	-	Reader: RFID-RC522	Easy to use and tissue safety	Lower distance, privacy and ethics
	[80], Glucose monitoring patch	13.56 MHz	10-50 mm	Tag: RF430FRL152H Reader: Mobile phone	Noninvasive, wearable and tissue safety	Lower distance and privacy
	[81], nicotine level detection	13.56 MHz	20 mm	Tag: RF430FRL152H Reader: TRF7970A	Noninvasive, wearable and tissue safety	Lower distance and privacy
	[82], E-nose	13.56 MHz	10-50 mm	Tag: RF430FRL152H Reader: Mobile phone	Noninvasive, wearable and tissue safety	Lower distance and privacy
	[84], Implantable Glucose monitoring	13.56 MHz	10-20 mm	Tag: ASIC	Tissue safety	Larger device size and lower distance
	[85], Thoracoscopic surgery support	13.56 MHz	50 mm	Tag: TR3-LD003C	Tissue safety	Complex device setup and lower distance
	[87], Orthopedic implant	13.56 MHz	<10 mm	Reader: Touch probe	Tissue safety	Complex measurement and lower distance
	[88], Honeybee tracking	13.56 MHz	40 mm	Tag: mic3® 64-bit Reader: iID® MAJA 4.1	Smaller size, light weight and easy to implement	Complex measurement and lower distance
UHF	[119], Medication mixture tracing	860-960 MHz	-	Tag: Monza 4 Reader: RD 200-U1-G	Reduced device size and larger distance	Tissue safety, privacy and ethics
	[89], Stent Implant	840–960 MHz	-	Tag: NXP-G2X Reader: Thing-Magic M5e	Reduced device size and larger distance	Tissue safety and privacy
	[90], Aortic valve prosthesis	900 MHz	7–10 cm	Tag: Axzon Magnus S3	Reduced device size and larger distance	Tissue safety and privacy
	[101], Microbial growth detection	867 MHz	65 cm	Tag: Higg-3 Gen 2 Reader: TagformancePro Voyantic	Reduced device size and larger distance	Tissue safety and privacy
	[93], Tooth prosthesis	868 MHz	30 cm	Tag: Axzon Magnus S3 Reader: TagformancePro Voyantic	Reduced device size and larger distance	Tissue safety and privacy
	[94], Dental prosthesis	920 MHz	9 cm	Reader: JIS U524R 4 CH UHF	Reduced device size and larger distance	Tissue safety and privacy
	[95], Limb implant	860-960 MHz, SAR: 0.36 W/kg	10–35 cm	Tag: Monza-4 Reader: Thing-Magic M5e	Reduced device size and larger distance	Tissue safety
	[99], Orthopedic implant	860-960 MHz	35 cm	Tag: Axzon Magnus S3	Reduced device size and larger distance	Tissue safety
	[96], Implant crack detection	900 MHz	50 cm	Tag: NXP UCODE G2iM+	Reduced device size and larger distance	Tissue safety
	[102], Movement detection	866–868 MHz	5–7 m	Tag: Monza-4 Reader: Thing-Magic M5e	Reduced device size and larger distance	Tissue safety, privacy and ethics
	[104], Smart nappy	850-930 MHz	1 m	-	Reduced device size and larger distance	Tissue safety and antenna alignment
	[105], Smart nappy	902–928 MHz	3.6 m	Tag: Monza-4	Reduced device size and larger distance	Tissue safety and antenna alignment
	[106], Smart lens	920 MHz	1 cm	Tag: ASIC	Reduced device size	Tissue safety and lower distance
	[107], Temperature monitoring	866 MHz	1 m	Tag: SL900A Reader: Impinj	Reduced device size and larger distance	Tissue safety, antenna alignment and privacy
	[109], Glucose monitoring	902–928	1 m	Tag: RFMicron 3200-AFR	Non-invasive monitoring and larger distance	Tissue safety, antenna alignment and data sensitivity
	[110], Animal Tracking	860–960	2.25 m	Tag: MAGICSTRAP® LXMS31 Reader: ID ISC.LRU1002	Miniature tag and larger distance	Difficult implementation, antenna alignment and Complex measurement
UWB	[112], Respiratory motion	2.45 GHz	-	-	Reduced device size and larger distance	Tissue safety
	[113], Neuropotential monitoring	2.4/4.8 GHz	-	-	Reduced device size and larger distance	Tissue safety
	[114], GERD	2.4 GHz	-	-	Reduced device size and larger distance	Tissue safety

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[115], Drug dosage monitoring	2.4-2.5 GHz	-	Reader: Mobile phone	Reduced device size and larger distance	Tissue safety
[116],Glucose monitoring	4 GHz	-	Tag: Chip-less resonator	Non-invasive measurement	Data inaccuracy and tissue safety
[117], Farm animal monitoring	2.45 GHz	-	Tag: IP65 Reader: Ubisense	Larger distance and higher accuracy	Accuracy depends on the approximation of the algorithm and tissue safety

VII. Conclusions

The demand for wireless wearable and implantable medical and healthcare devices is growing at a phenomenal speed. RFID technology brings forward unique advantages for this class of applications, including low profile, feasibility for battery-less operation, unobtrusiveness, flexible and conformal realizations, and low cost.

A summary of the characteristics of RFID-based wireless medical and healthcare devices is in Table I listing the operation frequency, communication distance, type of tag and reader devices used, merits and issues with different applications for a given RFID band type. The RFID technologies for medical and healthcare applications presented are passive RFID or battery-free devices popular among researchers and medical device manufacturers which are commonly adopted compared to active and semi-passive RFIDs.

LF RFID devices are more popular for patient identification, animal tracking and pet monitoring. In LF RFID, tissue absorption for this band is significantly lower at the expense of the size of the device, which is larger due to the antenna size. The communication distance is also significantly lower.

HF RFID-based devices offer good tissue safety. However, low communication distance, albeit greater than with LF RFID devices, and device size are still the major issues for this technology. HF RFID is more suitable for medical and healthcare devices that are wearable.

Compared to LF and HF RFID-based wireless medical and healthcare devices, UHF RFID offers smaller device size and larger communication distance, making them good candidates for implantable medical devices. However, the higher operation frequency can cause higher tissue absorption, necessitating SAR and any necessary tissue safety assessments before patient implantation.

UWB RFID is a relatively new topic in medical and healthcare devices, mostly for deep implants due to its smaller size and larger communication distance. However, the tissue safety of the patients is a significant concern at this higher operation frequency.

In summary, this article has presented a comprehensive review of the different applications of passive RFID in battery-free wireless medical and healthcare devices. Its goal is to provide a comprehensive guide for experts and nonexperts in the field to select the correct RFID technology for their application. Several key issues and challenges were discussed, which must be addressed and considered before adopting any RFID technology.

Acknowledgments

Dr. Sadeque Reza Khan acknowledges the financial support from the Heriot-Watt University Kickstart Research fund. Dr Bernassau and Prof. Marc Desmulliez acknowledge the Royal Society of Edinburgh funding through the programme Saltire Research Award, RSE reference 1903. The authors would like to acknowledge the financial support of UK Research and Innovation (UKRI) through the Engineering and Physical Sciences Research Council (EPSRC) under the grant Stream1: Accelerating Impact of Community Helthcare in Tayside-AICCET (EP/Y023978/1).

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