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Chapter 7: From Identification to Intelligence: RFID Sensors in the Healthcare Internet of Things

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Abstract: Radio Frequency Identification implemented into Internet of Things (IoTs) frames transforms healthcare into a connected, data-driven, and patient-centered prototype. This technology evolved into a sensing one, enabling the monitoring of safety of pharmaceuticals, the tracking of medical assets, the vital signs and personalized care. The current chapter describes the basic principles of RFID systems, including tag types, frequency reserved bands, and sensor topologies. Then, we present their applications for cardiovascular monitoring, asset management, medication tracking, environmental monitoring, and senior healthcare. A particular focus is given to highlight recent innovative technologies: starting from chipless RFIDs to implantable smart prostheses. Finally, regulatory and standards considerations are rapidly discussed, underscoring data privacy and safety concerns.

Keywords: RFID, Wearable Sensors, Healthcare, Cardiovascular, Internet of Things (IoT).

1 Introduction

New digital technologies integrated into healthcare systems are shifting traditional models of care toward connected, patient-centered, and data-driven approaches. Among them, IoT features at the forefront, which enables continuous monitoring, automated data collection, and real-time communication of a patient with his/her health provider or medical infrastructure. Wearables, implantable sensors, smart hospital infrastructure, and cloud-based platforms constitute H-IoT intended for application in improving patient outcomes and efficiency in healthcare (Surantha et al., 2021; Ledet et al., 2012; Kwon et al., 2022; Hassanalieragh et al. 2015; Cantor et al., 2018; Hussey et al. 2009).

In this setting, RFID has come to the lead as one of the enabling technologies. Innovated for supply chain management, RFID has rapidly reached healthcare domain, owing to its characteristic advantages: it provides wireless communication without line-of-sight, miniaturization, and low cost, and it is battery-free for many applications (Yao et al.,

2010; Yao et al., 2012; Amendola et al.; 2014). When sensor functionalities are joined to RFID systems, these latter go beyond simple identification and allow physiological monitoring, tracking of medication adherence, or implantable diagnostics (Mulloni et al., 2020; Costa et al., 2021).

The relevance of RFID is even more important within the scope of chronic diseases, which continue to be the major cause of mortality in the world. For instance, cardiovascular diseases burden millions and cause over 17 million deaths annually (Pagidipati et al., 2013; Tsao et al., 2022). These issues need continuous monitoring and can only be treated if detected early. Nonetheless, this is hardly possible with traditional hospital-based systems. As showed by the COVID-19 pandemic, such conditions exposed the weaknesses of traditional systems because patients suffering from cardiovascular conditions faced late consultations and reduced routine monitoring (Adam et al., 2021). These are challenges that reinforce the urgent requirement for wireless, reliable, and contactless monitoring technologies.

This chapter give a general overview of RFID technology as a sensing policy for healthcare IoT applications. Section 2 presents the basics of RFID technology and healthcare IoT following by describing the operating principles, frequency bands, and sensor topologies. Section 3 outlines possible applications of RFID sensors in various healthcare domains. Section 4 surveys the relevant regulatory and standards frameworks that govern RFID deployment in healthcare environments. Finally, Section 5 concludes the chapter by pointing out the major challenges and the emerging research directions.

2. Background and Fundamentals

2.1 IoT in Healthcare

Healthcare IoT is an environment of components and platforms that collect, transmit, and process health-related information in real time. As illustrated in Fig. 7.1, an H-IoT includes 3 main layers:

- **Perception layer:** It contains wearable and implantable sensors, tags, and other devices that collect data.
- **Network layer:** It works on wireless communication protocols to transmit information. (e.g. Bluetooth Low Energy (BLE), ZigBee, IEEE 802.15.6, Wi-Fi, or cellular networks) (Wei et al., 2024; Alharbe et al., 2013; Akbar et al., 2022; Subrahmannian et al., 2022).
- **Application layer:** where healthcare services are implemented, including remote monitoring, telemedicine, and predictive analytics (Subrahmannian et al., 2022).

RFID technology is a critical part of the perception layer, providing identification and sensing functions. RFID sensors support in the integration of physiological data into healthcare IoT systems for patient monitoring, ability tracking, and personalized healthcare services.
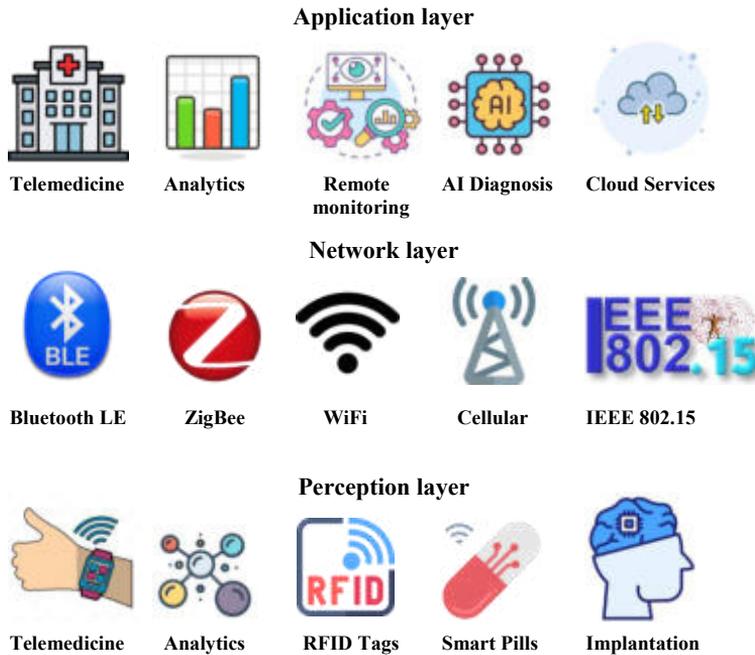
Application layer

Telemedicine	Analytics	Remote monitoring	AI Diagnosis	Cloud Services

Network layer

Bluetooth LE	ZigBee	WiFi	Cellular	IEEE 802.15

Perception layer

Telemedicine	Analytics	RFID Tags	Smart Pills	Implantation

Fig. 7.1 Healthcare IoT framework: from perception to application through network layer.

2.2 Fundamentals of RFID Technology

An RFID system fundamentally consists of three main components: the reader (or interrogator), the tag (or transponder), and the back-end system. The reader sends out radio signals that turn passive nearby tags into active ones that return sensed or stored data to the reader. Mainly, RFID tags are categorized based on the source of power (Costa et al., 2021):

- Active RFID tags: It include an internal power source and allow independent data transmission over longer distances.
- Semi-passive (or battery-assisted RFID tags): It use an internal battery to supply the circuit. However, it depends on the reader's electromagnetic field (EMF) for communication.
- Passive RFID tags/ It lack an internal power source and harvest energy directly from the reader's signal. Since of their compactness, low cost, and maintenance-

free operation, passive tags are one of the widely used kind, specifically in healthcare applications.

RFID systems function in many frequency bands, each one suited to particular applications:

- Low Frequency (LF) 125–134 kHz: short range with high penetration, usually employed in implantable medical devices.
- High Frequency (HF) 13.56 MHz: range up to 1 meter, appropriate for patient identification cards and smart wristbands.
- Ultra-High Frequency (UHF) 860–960 MHz: range of several meters, commonly used in asset tracking and physiological monitoring.
- 2.4 GHz ISM band: often shared with BLE, ZigBee, and IEEE 802.15.6 systems. Although less common for passive RFID, it is gaining interest in active and semi-passive RFID research due to its higher bandwidth and better compatibility with IoT systems.

Table 7.1 outlines the primary trade-offs among LF, HF, UHF, and 2.4 GHz ISM bands, the latter often overlapping with BLE, ZigBee, and IEEE 802.15.6 medical WPANs, while a more detailed discussion of RFID fundamentals can be found in Cui et al. (2019). When integrated with sensing capabilities (such as for temperature, pressure, or biochemical detection), RFID tags become RFID sensors and close the gap between object identification and health monitoring. Complementing the more traditional division into active, semi-passive, and passive tags, RFID sensors can also be categorized by their design architecture, depending on how sensing is carried out and integrated. The principal strategies are illustrated in Section 2.3.

2.3 Sensor Architectures (Chip-Based, Antenna-Based, Smart, Chipless)

Beyond the traditional categorization of active, semi-passive, and passive tags (Section 2.2), RFID sensors can also be distinguished based on architectural design and sensing strategy. Every strategy presents different trade-offs in cost, complexity, reliability, and suitability for healthcare IoT applications.

Chip-based RFID sensors: In this configuration, the sensing element is integrated into an RFID IC. Since there is a clear separation of the sensing and communication functionalities, chip-based designs normally offer reliable and accurate measurements. However, due to the additional circuitry required, tag size and cost increase, making chip-based RFID sensors unfeasible for large-scale healthcare applications (Ahmadihaji et al., 2023).

Table 7.1. Frequency bands commonly used with RFID sensors and companion H-IoT links (indicative values).

Band	LF (125–134 kHz)	HF (13.56 MHz)	UHF (860–960 MHz)	ISM (2.4 GHz)
Typ. standards /examples	ISO 18000-2	ISO 14443/ ISO 15693, NFC	ISO 18000-63/ EPC Gen2	BLE, ZigBee, IEEE 802.15.6;
Nominal range*	cm–10 cm	up to ~1 m (with large readers)	1–8 m (envi. dependent)	1–30 m
Tissue penetration	High (good through water/tissue)	Moderate	Lower than LF/HF	Low
Data rate (order)	kb/s	10^2–10^3 kb/s	Mb/s[#]	Mb/s
Power profile	Passive	Passive	Passive/BAP/Active	Active/Semi-passive
Typical healthcare uses	Implants, access control	Patient ID cards, wristbands	Asset tracking, wearable sensing, logistics	WBANs, high-rate sensor streaming
Notes	Short antennas, slow data, robust in-body links	Mature ecosystem, strong anti-collision	Long range, higher sensitivity to detuning near tissue/metal	Shared band; good with active/BAP tags and IoT radios

*Actual ranges depend on antenna design, EIRP limits, human body proximity, and environment.

[#]uplink limited by backscatter.

Antenna-based RFID sensors*:* An antenna itself is used here as a sensing element. Some environmental parameter, temperature, humidity, or pressure, causes variation in the electromagnetic response of the antenna that can be detected by the reader. It allows low-cost and compact designs, but the measurement is more sensitive to placement and environmental noise. Antenna-based sensors already find widespread applications for cold chain monitoring and sterile storage control in hospitals (Zhang et al. 2017).

Smart RFID tags*:* The latest developments include the so-called "smart tags," that integrate RFID tags with MCU and extra sensors. Now, these smart tags are capable of carrying out minor local processing, data filtering, or decision-making before sending information to a reader. Smart RFID sensors basically transfer part of the intelligence to the tag and therefore also fit within the general vision of ubiquitous computing in healthcare IoT, enabling applications such as wearable monitoring devices or interactive drug dispensers (Amendola et al., 2014).

Chipless RFID sensors*:* Chipless RFID sensors represent a growing research direction in designing chipless RFID without the use of an IC. In this context, information is encoded into the unique electromagnetic signature from resonant structures. Chipless radio-frequency identification tags are compatible with both planar and printed electronics; therefore, the possibility of low-cost, large-area manufacturing, for example, using roll-to-roll printing, is feasible. They also tend to boast of longer operational lifetimes and disposability, making them highly attractive for applications concerning single-use biomedical sensors, pharmaceutical packaging, and point-of-care diagnostics (Subrahmannian et al., 2022; Zahid et al., 2024).

3. RFID Sensor in the Healthcare industry.

From a simple identification technology, RFID has evolved into a versatile sensing platform, and its applications have spanned from patient monitoring to pharmaceutical safety and chronic disease management. The unique advantages offered by RFID sensors, such as batteryless operation, low cost, native identification, and compatibility with IoT platforms, make it very attractive for healthcare applications where reliability, scalability, and patient safety are of prime importance. Fig. 7.2 shows a conceptual diagram of the main domains where RFID sensors are being currently deployed.
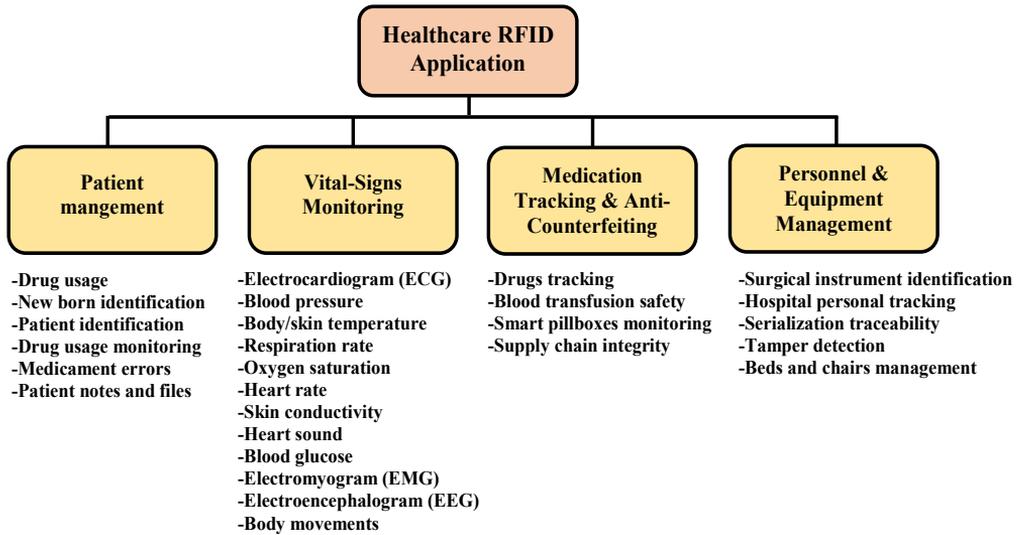
Fig. 7.2 Overview of key healthcare applications enabled by RFID technology.

3.1 Patient Identification and Safety

RFID-enhanced wristbands, HF/NFC cards, and passive UHF tags guarantee contactless line-of-sight-free identification in hospitals for medication verification (Peris-Lopez et al., 2011), blood transfusion safety (Hohberger et al., 2012), and surgical workflows (Liu et al., 2011). The integration into hospital information systems allows for closed-loop medication administration and reduces human errors compared to barcode-only systems. An extensive review of RFID applications and adoptions in healthcare, with emphasis on patient safety, can be found in Ref. (Haddara et al., 2018).

3.2 Vital-Signs Monitoring and Cardiovascular Care

In particular, the potential of RFID is evident in cardiac monitoring, where continuous sensing should be non-intrusive.

As can be seen from Fig. 7.3 below, Hui et al. (Hui et al., 2019) presented a microwave stethoscope based on near-field coherent sensing using passive harmonic RFID tags to detect S1/S2 heart sounds through clothing. As can be seen from Fig. 7.4 below, NCS preserved waveform features under shirts, sweaters, and coats, outperformed acoustic stethoscopes in noisy environments and improved comfort and privacy (Hui et al., 2019; Sharma et al., 2020).
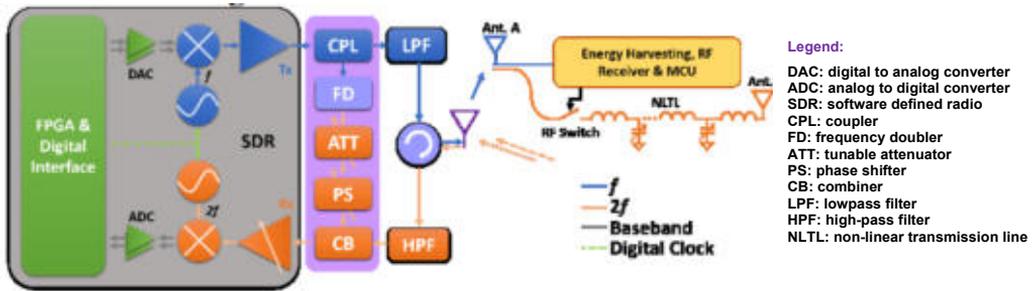
Fig. 7.3 NCS experimental setup with a passive RFID sensor tag on the chest (front pocket placement).
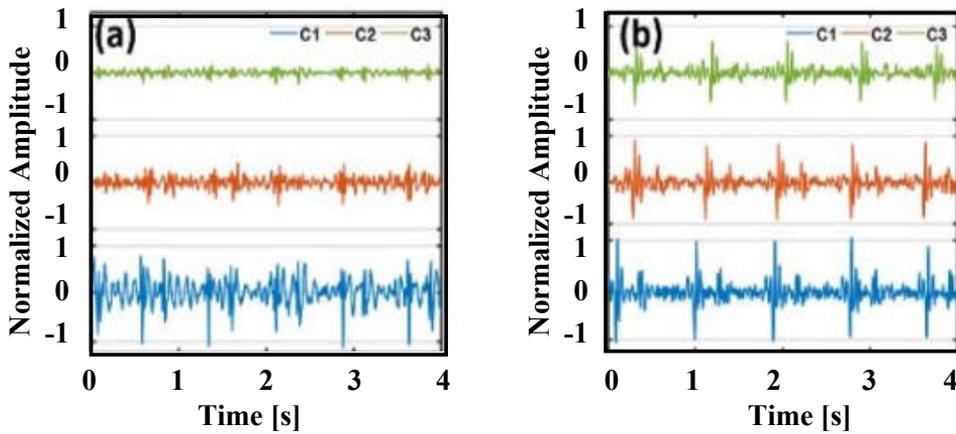

Fig. 7.4 Phonocardiogram (PCG) signals acquired through multiple layers of clothing.

RFID has also empowered wireless implantable diagnostics without batteries. In Fig. 7.5, an aortic valve prosthesis has been designed to be used as a UHF RFID antenna: the metallic stent collects energy without compromising mechanical strength (Gagliardi et al. 2022). A reader worn on the chest sets up a backscatter link through highly lossy thoracic tissue for enabling temperature sensing, a proxy for prosthesis failure, without affecting fluid dynamics (Capodanno et al., 2017; Goldstone et al., 2017).

Fig. 7.5 Concept of an RFID-based smart prosthesis.

For electrical monitoring, Horne et al. (Horne et al., 2020) presented an ultra-low-power UHF RFID ECG system. An ECG frontend MAX30001 and microcontroller MSP430FR5969 interface with an EM4325 RFID chip in BAP mode. The design achieved < 2 mW consumption, produced clean PQRST waveforms (Figs. 7.6–7.7), and achieved 3–4× lower energy compared to BLE-based ECG, extending operation beyond 120 h with a 120 mAh cell (Bhuiyan et al., 2018).

The lightweight RFID systems, using piezoelectric sensors and active band-pass filters, detect heartbeat peaks devoid of any external batteries. This minimalist approach therefore allows for low-cost, disposable monitoring solutions.
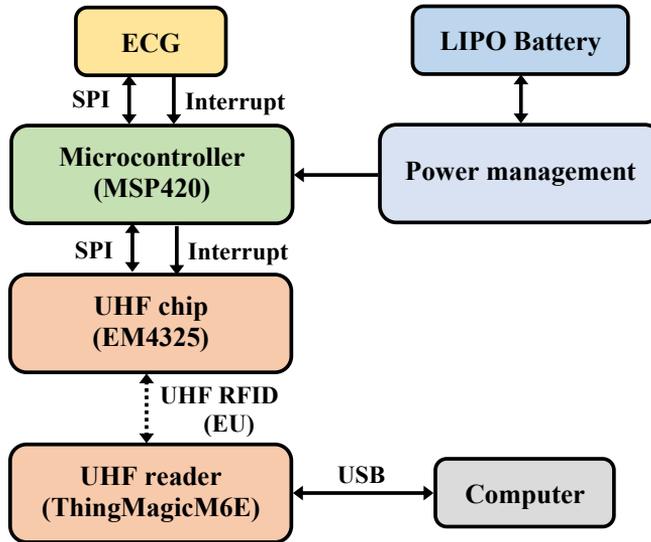

Fig. 7.6 System block diagram of the ECG device proposed by Horne et al.
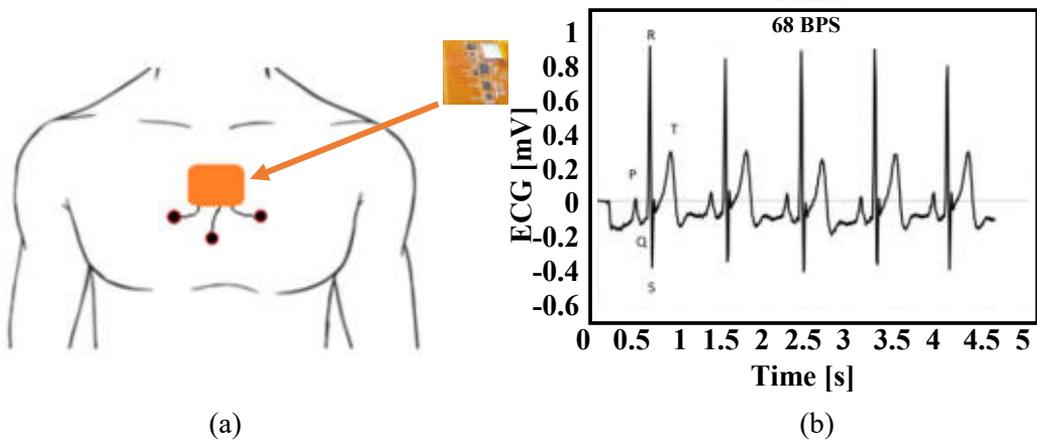

| (a) | (b) |

Fig. 7.7 (a) Placement of the device on the torso, and (b) recorded Electrocardiogram (ECG) signal showing characteristic P wave, QRS complex, and T wave.

At the minimalist extreme, piezoelectric RFID heartbeat identifiers couple a piezo sensor with a low-power active band-pass filter (ABF), where the RFID reader's field biases the ABF and eliminates both an external battery and amplifiers (Stornelli et al., 2009). The peaks in heartbeat modulate the tag's antenna/transfer function, providing robust backscatter events that yield accurate rate estimation Fig. 7.8 (Leoni et al., 2020). Such designs represent ultra-low-cost wearables for screening and home monitoring.
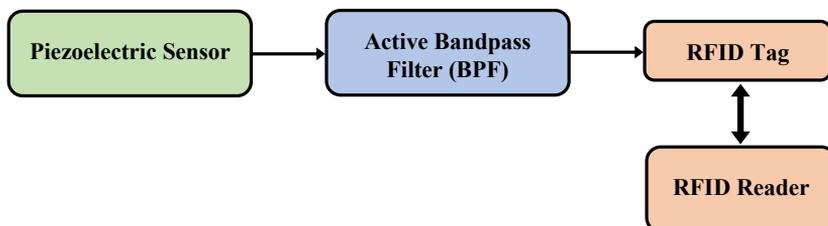

Fig. 7.8 Conceptual diagram of the heart rate monitor.

3.3 Medication Tracking and Anti-Counterfeiting

As shown in Fig. 7.9 Counterfeit medicines continue to be one of the major health problems worldwide. RFID-tagged packaging of pharmaceuticals can introduce serialization, traceability, and tamper detection functionalities, as required or suggested by regulatory frameworks such as the EU Falsified Medicines Directive (FMD) and the US Drug Supply Chain Security Act (DSCSA) (Omar et al., 2022).
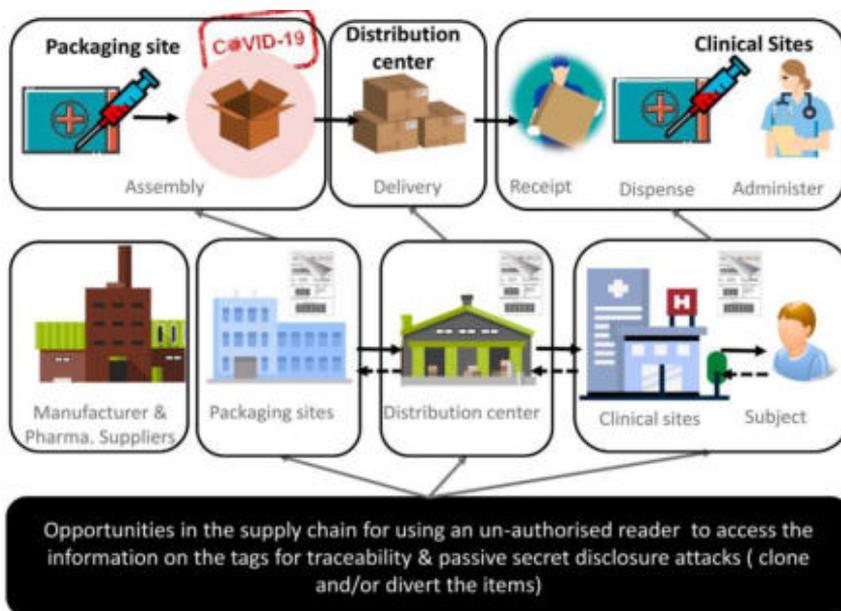

Fig. 7.9 Potential vulnerabilities and attack points in the pharmaceutical or medical device supply chain, proposed by Safkhani et al.

Supply chain integrity: Passive UHF tags in drug packaging support bulk scanning and non-line-of-sight verification. The blockchain integration further secures the chain, as depicted in the study by (Safkhani et al. 2020), who integrated RFID with the Authenticated Encryption (AE) cryptosystems for authentication at two different layers.

Smart pillboxes and adherence monitoring: RFID-enabled dispensers can record events related to pill removal and automatically notify caregivers when doses have been missed. Li et al. presented a wearable RFID-based medication adherence system consisting of a smart pillbox, a custom wristband, and a computer application (Li et al., 2014). The user or caregiver has the opportunity to input the schedule of the medication through this system, which reminds the user of the dosage in time; it monitors hand gestures during medication intake via RFID proximity sensing and tracks the status of compartments of the pillbox to trigger an alert for refilling. See Ref. for a thorough review of monitoring medication adherence (Aldeer et al., 2018).

3.4 Asset and Equipment Management

Ultra-high-frequency RFID-based RTLS has transformed asset tracking in healthcare facilities by offering a continuous, automated, and accurate way of tracking mobile medical equipment such as infusion pumps, wheelchairs, portable monitors, and surgical instrument sets. These systems guarantee significant returns on investment through better use of equipment, reduced times spent searching, minimal losses, and enhanced infection control through better sterilization workflow consolidation. The problem of misplaced or underutilized equipment forces many hospitals to spend more money buying new equipment rather than utilizing the available capacity, which sometimes results in delays to patient care. UHF RFID RTLS offers room-level or zone-based location visibility across big campuses.

In SPDs (Sterile Processing Departments), RFID allows traceability of surgical instrument trays during decontamination, packaging, sterilization, and storage. Each tray is equipped with a durable, autoclave-resistant RFID tag capable of sustaining high temperatures and moisture. Furthermore, erroneous instruments in surgical sets may create procedural delays. With an RFID-enabled counting system, such as that tested by Bourouah et al., verification of all contents within a surgical kit, including between 35 and 40 instruments, can be completed automatically in a few seconds, reducing manual counting errors by 100% (Bourouah et al., 2015).

Contextual insights are provided through the integration of modern RFID RTLS with hospital asset management software and electronic health records. Examples include:

– Equipment use data informing procurement and maintenance schedules;

– Alerts triggered if a device is overdue for servicing;

– Integration with nurse call systems allowing for automated assignment of equipment to rooms.

4 Standards and Regulatory Considerations

The deployment must agree with the RF, safety, interoperability, and privacy frameworks. Up to now, various deployments related to RF and air-interface compliance of ISO/IEC 18000-63 (e.g. EPC Gen2, UHF, and ISO/IEC 14443/15693) are standard in healthcare. For electromagnetic (EM) safety and EMC, it follows the IEC 60601 series with regard to medical electrical equipment. Generally, data exchange with hospital systems is done through HL7/FHIR interfaces, while controls on privacy and security obey current legislation (HIPAA/GDPR). Spectrum use is according to regional rules. For example, ETSI in the EU and FCC in the US. These constraints influence the band choice, the reader power, and acceptable device proximity to clinical equipment.

Conclusion

To date, RFID technology has transitioned from a logistics enabler to a versatile tool for healthcare, exclusively bridging between identification and sensing in the IoT prototype. As revealed in this chapter, RFID sensors can support:

- Patient-centered monitoring in vital signs and cardiovascular care, both as wearables and implantable.
- Pharmaceutical integrity and adherence, through end-to-end supply chain traceability and smart packaging.
- Operational efficiency by facilitating asset tracking, surgical set management, and workflow optimization.
- Environmental safety, including cold chain integrity for vaccines, sterility, and conformity with regulatory requirements.
- Elderly care and chronic disease management, where RFID integrates smoothly into everyday objects and spaces.

Notwithstanding these developments, some challenges persist: technical issues include restricted read range in lossy environments; advanced sensing also requires higher energy, while susceptibility to environmental interference is another issue. At the system level, fee, portability, and integration with hospital information systems regulate the degree of diffusion, while data security & privacy concerns fall under relevant regulations. Among them, we notice HIPAA and GDPR as examples.

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