A Survey on Radio Frequency Identification as a Scalable Technology to Face Pandemics

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(Invited Paper)

Abstract—**The COVID-19 pandemic drastically changed our way of living. To minimize life losses, multi-level strategies requiring collective efforts were adopted while waiting for the vaccines' rollout. The management of such complex processes has taken benefit from the rising framework of the Internet of Things (IoT), and particularly the Radiofrequency Identification (RFID) since it is probably the most suitable approach to both the micro (user) and the macro (processes) scale. Hence, a single infrastructure can support both the logistic and monitoring issues related to the war against a pandemic. Based on the COVID-19 experience, this paper is a survey on how state-of-the-art RFID systems can be employed in facing future pandemic outbreaks. The three pillars of the contrast of the pandemic are addressed: 1) use of Personal Protective Equipment (PPE), 2) access control and social distancing, and 3) early detection of symptoms. For each class, the envisaged RFID devices and procedures are discussed based on the available technology and the current worldwide research. This survey shows that RFID could generate an extraordinary amount of data so that complementary paradigms of Edge Computing and Artificial intelligence can be tightly integrated to extract profiles and identify anomalous events in compliance with privacy and security.**

Index Terms—**RFID, COVID-19, pandemic, social distancing, contact tracing, healthcare Internet of Things, personal protective equipment.**

I. INTRODUCTION

COVID-19 pandemic abruptly changed the way we live, starting from social interactions and healthcare, up to commerce, transportation and entertainment. The high spreading capabilities (even by asymptomatic individuals [1]) and the severe impact on public health [2] forced the Governments to adopt urgent restrictive countermeasures [3]. Although at the time of writing the emergency is mitigating, the earned experience so far has taught us that at least two consecutive phases must be promptly managed to proficiently face the future pandemics and allow a rapid recover of activities and daily life [4]: (*i*) social distancing with home confinement and/or lockdown until the availability of vaccines, (*ii*) technological support to mitigate the infection risk during reopenings, to manage COVID-19 patients in hospitals and at home, and to handle the logistics issues of the distribution of vaccines [5].

The pillars of countermeasures against a respiratory infectious pandemic can be identified as:

(*i*) the usage of Personal Protective Equipment (PPE), like facemasks and hygiene products, to reduce the spread of infecting particles;

(*ii*) social distancing and access control to avoid, or at least reduce, possible channels of infections among people, and contact tracing to identify recent interactions with infected people;

(*iii*) early detection of symptoms (e.g., fever, blood saturation, irregular breath, cough, in synergy with Nasopharyngeal/Oropharyngeal Swabs and serologic tests).

Furthermore, due to the scientific and clinical evidence of the presence of infectious droplets floating in the air for a long time, especially in indoor environments [6], the continuous verification of air quality and ventilation is recommended to reduce the risk of inhalation and of infection [7].

The fight against the spread of the infection can benefit from pervasive equipments that are currently adopted in daily life (i.e., smartphones and wearable devices), namely, the rising framework of the Internet of Things (IoT). This technology can be specialized in a fan of options sharing same infrastructures, standards, and expertise [8]. Different IoT protocols like Bluetooth Low Energy (BLE), Wireless Fidelity (Wi-Fi), Global Positioning System (GPS), have already gained popularity for providing solutions to pandemic-related challenges in both domestic and hospital scenarios [9]–[11]. The Radiofrequency Identification (RFID), that is nowadays one of the pillars of the Healthcare Internet of Things (H-IoT) [12], is probably the most suitable technological approach to be scaled up in order to support, by means of a single infrastructure, almost all the logistic and monitoring issues related to the war against a pandemic. RFID transponders [13] can be manufactured over large scale in any shape and material, including plastics, paper, elastomers, as well as dissolvable organics compounds. The tag can be embedded into things and can be attached onto the human skin as well. Readers can be rugged and multifunction, integrable into a smartphone and even into a smartwatch-like personal device. Not least, RFID relies on standard protocols and is intrinsically low-cost.

While the original purpose of RFID was the electronic labeling of goods, it is nevertheless quickly moving to the monitoring of objects, industrial processes, and people, by
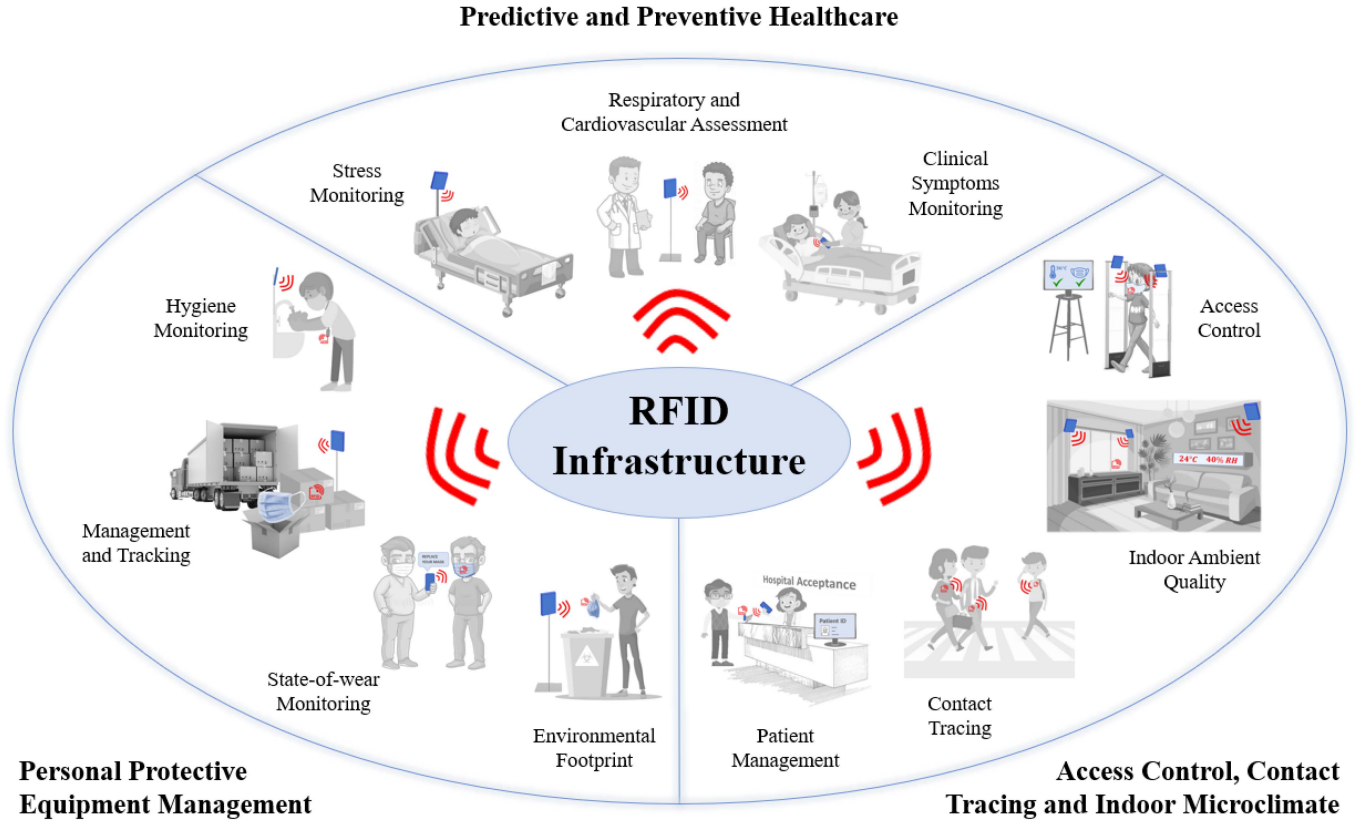
Predictive and Preventive Healthcare

Fig. 1.   Synopsis of applications of RFID technology to pandemic countermeasures.

empowering low-cost devices with sensing capabilities [13]. Measurement of temperature, pressure, humidity, just to list some, are now feasible with commercial-off-the-shelf (COTS) tags [14]. Advanced applications, involving chemical parameters (pH, chlorides) and biophysical signals (EMG, EKG, skin resistance), are under advanced investigation in worldwide research labs [15], [16]. Hence, there is a creative wealth of technology all around that could be usefully put in phase for application to pandemic emergencies.

The aim of this paper is, therefore, showing how the existing RFID devices (technology introduced in Section II) and the most advanced related research efforts could be synergically used to fight a COVID-19-like pandemic. Three macro-topics (as schematized in Fig. 1) are considered: PPE supply, usage and management (Section III), Access control, contact tracing and indoor ambient quality (Section VI), and Predictive and Preventive Healthcare (Section V). For each topic, the main issues and needs are resumed, and consequently the most appropriate RFID devices and processes are identified. In some cases, the technology has already been adopted in the proposed scenario. In other cases, applications are in different fields but could be employed in the fight against pandemics. To improve readability and enable a direct access to the required information and solutions, each of the three sections can be considered as a standalone chapter. For each application, a table lists the real-life problems and the possible solutions through RFID technology. References are accordingly grouped to directly find the source of the discussed topics.

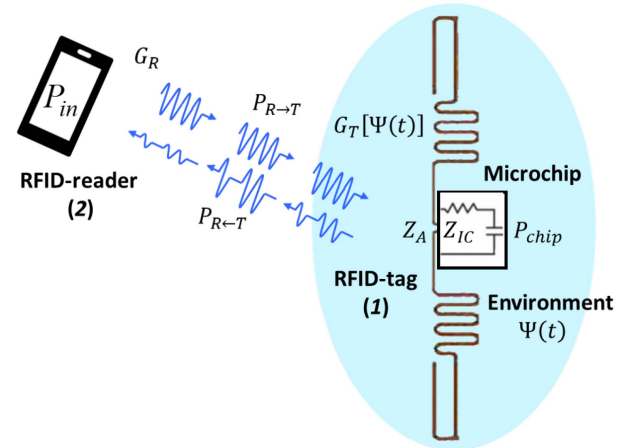The overall purpose of the paper is definitely to provide a survey on what could be immediately applied to

Fig. 2. A sketch of the RFID system. A reader (2) interrogates the tag (1), the behavior of which is influenced by a changing physical feature Ψ. Adapted from [13].

the pandemic-related problems, as well as to draw a picture of the open challenges for the finalization of current researches.

II. UHF RFID TECHNOLOGY: BASIC PRINCIPLES AND LATEST ADVANCEMENTS

An RFID system (sketch in Fig. 2) comprises two components: (*1*) the *tag*, that is attached onto the object (or even on the person) to be labeled, comprising an antenna and a microchip transponder (Integrated Circuit, IC), and (*2*) the

local querying system (or *reader*), that energizes the tag from remote and collects data reflected back from it throughout backscattering modulation. The backscattering communication scheme applies for both short range (namely HF/NFC systems working at 13.56 MHz) and long range (working in the UHF 860-960 MHz frequency band) platforms [17]. In the former case the interaction with the reader is mostly one-to-one (inductive coupling), whereas in the latter case a single reader can simultaneously collect information from hundreds of tags, being the radiating elements conventional antennas operating in far-field conditions. Accordingly, the UHF band has the advantage to be tailored to control, within a unitary framework, both single items and complex processes [18], with extremely low power consumption and maintenance cost (passive and battery-less systems). This paper is therefore focused on systems working in the UHF frequency band, which currently provide the largest amount of COTS devices for any kind of material and are readable up to more than 15 m [17].

The tags can be passive, when they harvest energy from the interrogating system, semi-active (BAP: Battery Assisted Passive), when a battery is included to only feed the sensors and the internal memory, or fully active. In the latter case, a local source directly feeds both a microcontroller and the transmitting radio, such to sensibly increase the reading distance and enable autonomous operations.

In passive and BAP technology (see again Fig. 2), at the beginning of the reader-to-tag communication protocol, the reader first activates the tag by sending a continuous wave. It charges an internal capacitor, providing the required energy to the tag to perform actions. During the next steps of the communication, the tag receives commands from the reader, and finally sends back the data through backscattered modulation of the continuous wave provided by the reader itself. In this case, the tag's IC acts as a programmable switching device between a low impedance and a high impedance state, thus modifying the reflectivity of the responding tag itself, and hence the strength of the reflected power.

During a typical RFID communication, reader and tag share different types of data.

- *Electronic Product Code* (EPC) and *User memory*, that are the unique IDentification name assigned to the tag and up to 8k byte of data; both can be writable many times and password protected;
- *Received Signal Strength Indicator* (RSSI), that is related to the power backscattered by the tag toward the reader;
- *Turn-on power*, that is the minimum power the reader should emit to wake-up the tag at a given distance;
- *Phase*, that is the phase of the signal backscattered by the tag and related to the differential radar cross section *rcs* among the two modulating states.

The last three parameter are strictly related to the tag antenna operating features. Any variation of the surrounding environment Ψ, able to affect the antenna gain and input impedance, is transduced into a variation of the signals transmitted and received by the reader, and can be hence related to a sensing activity performed by the tag itself. This analog approach, denoted as *sensor-less sensing,* can be applied to every passive tag if properly designed [25]. Extremely low-cost wireless
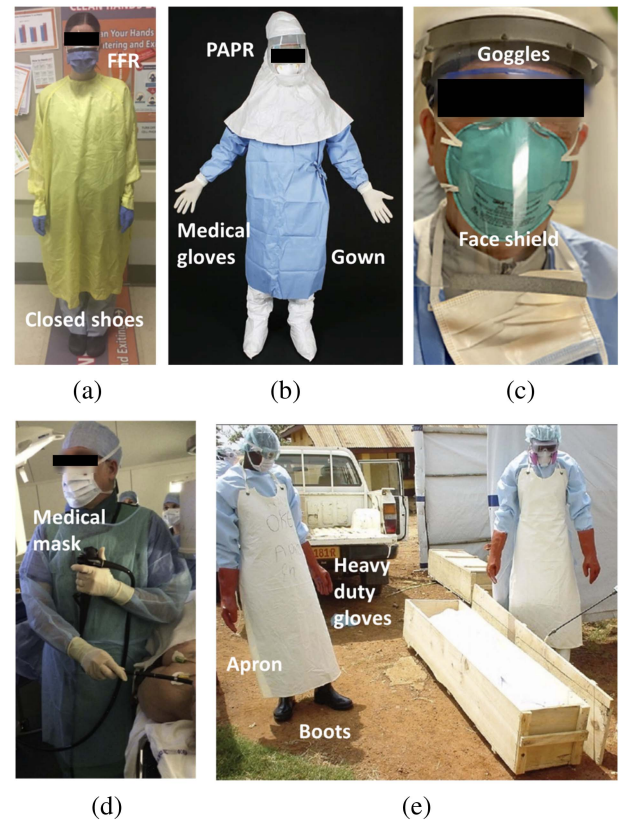

Fig. 3. Medical PPE used during the COVID-19 pandemic [19]. (a) FFR and closed shoes (adapted from [20]). (b) PAPR, medical gloves and gown (adapted from [21]). (c) Goggles and face shield (adapted from [22]). (d) Medical mask (adapted from [23]). (e) Heavy duty gloves, apron and boots (adapted from [24]).

sensors, namely disposable, can be obtained at the price of a modest accuracy [26].

Nowadays, off-the-shelf RFID ICs with augmented sensing capabilities are available [77]–[80]. They include high-speed non-volatile memory (EEPROM), typically integrate an embedded temperature sensor, and are provided with programmable I/O ports for connecting general-purpose microcontrollers and sensors. Sensing data are digitally encoded into the internal memory and transmitted through standard backscattering communication. If compared with the analog sensing, the collected physical information is definitively more specific and robust [13]. When provided with battery, such ICs can also act as data-loggers, and they can gather sensing data even without the need to receive energy from the reader. These devices can be considered as a convergence point among fully passive tags and the autonomous sensor nodes having local computational capability with already assessed applications in Industry [18] and Healthcare [81].

III. PERSONAL PROTECTIVE EQUIPMENT MANAGEMENT

According to the WHO guidelines [19], HealthCare Workers (HCWs) and general public must wear proper PPE depending on the activities to be performed and on the occupied spaces. The set of appropriate PPE to protect against pandemics (Fig. 3) comprises:

TABLE I
POSSIBLE APPLICATIONS OF TAGGED PPE DURING PANDEMICS

PPE problem	Possible RFID Application	Application examples	References
SUPPLY CHAIN MANAGEMENT	PPE shortages	Localization and tracking inside hospitals to reduce lost and stolen PPE	[27] [28] [29] [30] [31] [32] [33] [34]
	Optimization of HC supply chains	Supply chains of hospitals and pharmacies	[35] [36] [37] [38] [39] [40]
	Anti-counterfeiting	Supply chain integrity	[41] [42] [43] [44]
		Post-supply chain control through block-chain	[45] [46]
APPROPRIATE USE OF PPE	Check if the HCW is wearing the proper PPE	Gate-based check	[47] [48] [49] [50] [51] [52] [53] [54]
		A body-worn portable reader monitors the PPE worn by the worker	[55] [56] [57] [58]
PPE INTEGRITY	Correlate the PPE with sensed data about its conditions	Maintenance of respirators optimized through their life cycle data	[53]
		Pressure sensor to monitor the correct use of the PPE	[59]
		Embedded humidity-sensing to monitor the effectiveness of the filtering mask	[60]
PPE DISPOSAL	Monitor the disposal of the PPE (which is a medical waste)	Tracking the medical wastes to be disposed	[61] [62] [63] [64] [65]
	Improvements in the supply chain and in the reverse logistic of the PPE to reduce the environmental footprint	Environmental footprint reduction by adopting the RFID in supply chains and in the reverse logistic of medical wastes	[66] [67] [68]
HAND HYGIENE AND DISINFECTION	Ensure the compliance with the hand hygiene procedures	Identify the HCW who needs to perform the hand hygiene	[69] [70] [71]
		Monitor the correction of the hand hygiene procedure	[72] [73] [74] [75] [76]

- medical masks, filtration respirators (N95 or FFP2), cloth masks, higher filtering masks, and Powered-Air Purifying Respirators (PAPR) [82], [83];
- gowns;
- medical or heavy-duty gloves;
- eye protections (e.g., goggles or face shields);
- aprons;
- boots or closed shoes.

In addition to these requirements, a proper hand hygiene is mandatory [82].

The management of PPE requires:

1) an efficient supply chain and control of counterfeit products [84], [85], along with solutions to face their shortage, especially in the case of misuse and overuse [86];
2) to check the compliance of the HCWs with the PPE procedures and guidelines, which moreover can be time-consuming or even confusing [87], also considering the difficulty of working while wearing the PPE [88], [89];
3) to check the condition of PPE, as it overuse can cut down its effectiveness [90], [91];
4) the care of the environmental impact produced by the wasted PPE, in particular regarding their correct disposal [92].

Similar issues are related to the pharmaceutical chain, in particular to vaccines and life-saving drugs [5], whose supply and correct distribution is directly proportional to their effectiveness.

RFID systems that can be employed in the PPE management are resumed in Table I.

A. Supply Chain Management

RFID technology has been massively exploited for the supply chain in healthcare [35] and pharmaceutical [40], [43], [44] branches, with promising results in terms of cost reduction and patient safety [35].

1) Shortages of PPE: The shortages of PPE can be partly addressed by adopting RFID equipment-tracking system within the hospital environment to increase their utilization and reduce the number of lost and stolen items [27], [30]. RFID-based localization and tracking systems in healthcare scenarios are resumed in [33], [34], [94], [95]. For this purpose, RFID can also be hybridized with either 2D-barcodes [28] or with infrared localization [32].

2) Inventory of Vaccines: Even though hospitals still widely employ barcodes to label equipments, drugs and other medical items, RFID tags can be more effective thanks to the possibility to store additional data on the tagged objects [36], and, above all, for the potential upgrading to sensing capabilities. In particular, RFID systems have already been employed in the
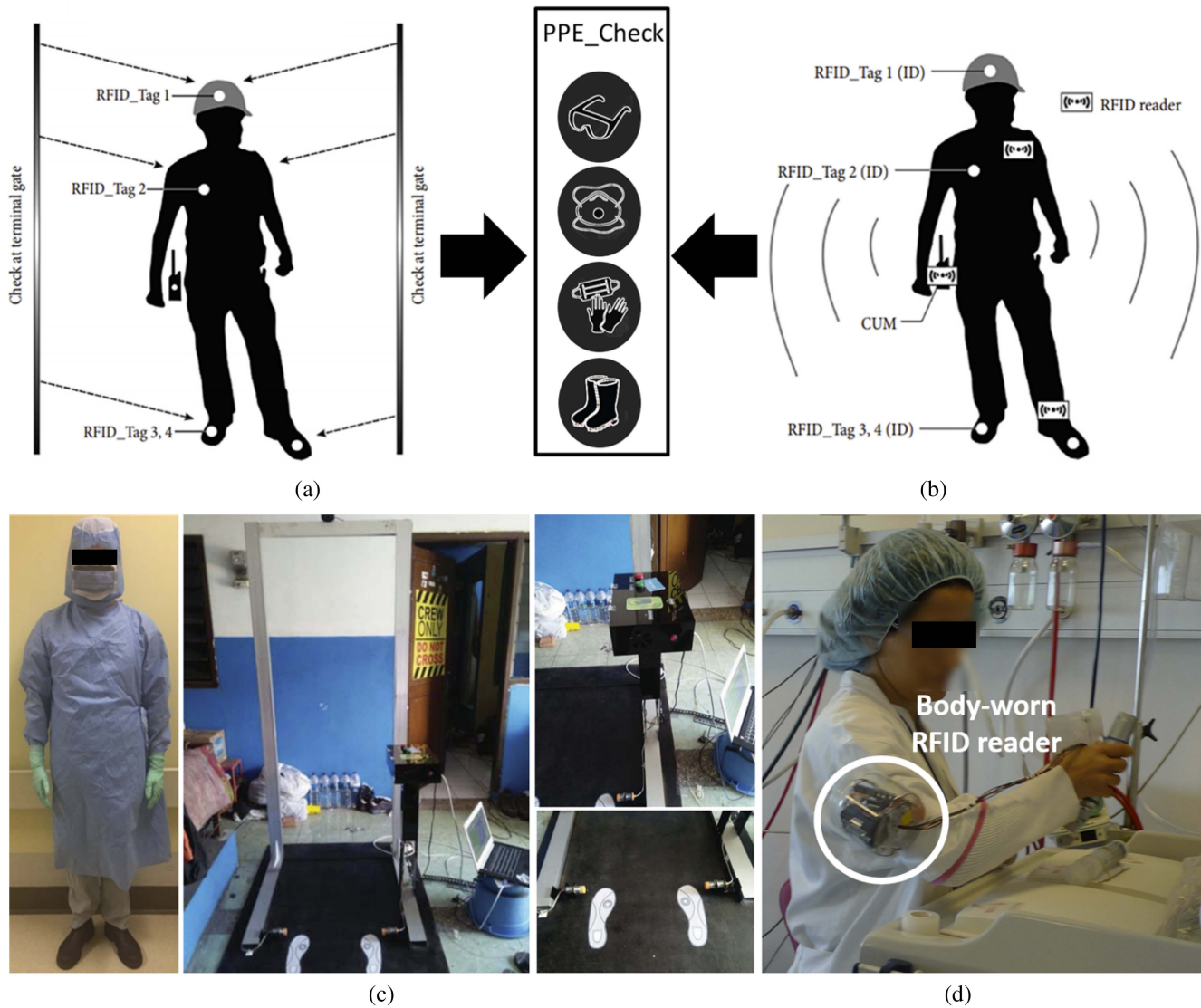
Fig. 4.   System's architecture to monitor the PPE worn by the workers (adapted from [47]): (a) terminals checking, eventually equipped with cameras, and (b) body-worn readers checking through communication with the Central Unit Microcontroller (CUM) embedded in the worker's Personal Digital Assistant. Examples of implemented systems: (c) a gate to monitor the compliance with the worn PPE (adapted from [20], [52]); (d) a portable RFID reader worn by a nurse (adapted from [93]).

supply chain of the transfusion blood [38], [39] and in cold chain operations [96]–[98]. Hence, they could be applied in the management of vaccines that need to be kept at controlled temperature [99].

3) Anti-Counterfeiting: RFID tags could also be adopted for anti-counterfeit purposes [41], [42], in both pharmaceutical and PPE sectors [43], [44]. The supply-chain integrity can be monitored by the synergistic action of RFID and blockchain systems [45], especially when an unambiguous ownership is missing [46], for example, in most of the single-use medical PPE.

B. Appropriate Use of PPE

PPE is often cumbersome and difficult to use; therefore, HCWs may not strictly follow the guidelines, consequently hindering the effectiveness of the equipment. If the PPE is provided with an RFID tag, a reader could check if the worker is wearing the proper pieces of equipment [48], [53]–[55]. A more robust PPE check can be achieved by combining ID and sensing data. For instance, tagged hardhats equipped with pressure sensors can ensure that the worker is effectively wearing the equipment and not just carrying it with him [59].

Overall, two kinds of architecture can be implemented (sketch in Fig. 4) to check if the workers carry their PPE: (*i*) check-points, i.e., readers on gates and terminals (Fig. 4.a), and (*ii*) portable/wearable readers (Fig. 4.b).

1) Gate-Based Check: Gate-based systems located in strategic points exploit RFID tags on the PPE to either control the presence of the PPE itself when entering dangerous areas [47]–[50], [53], [54] or to identify the worker while a camera checks for the PPE compliance through images processing [51], [52].

2) Body-Worn Readers: Since RFID gates cannot check if HCWs remove the PPE after the checkpoint, portable readers
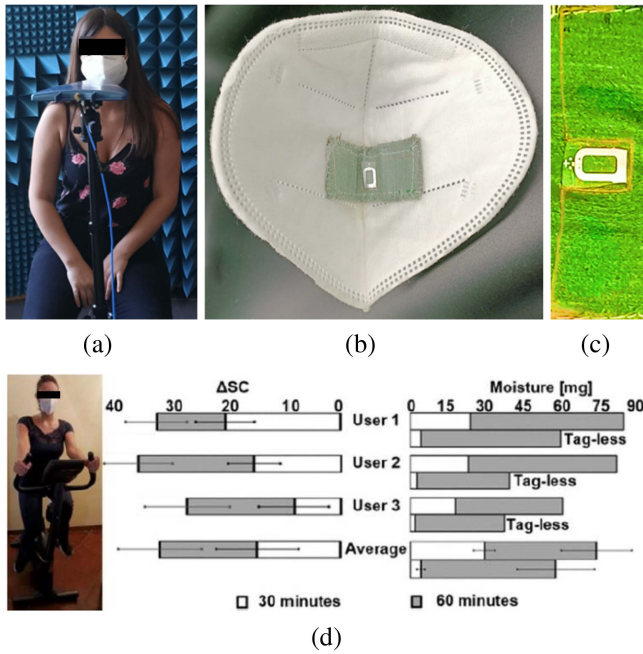
Fig. 5. Sensorized FFR. (a) Volunteer wearing a tagged facemask. (b) FFR-integrated humidity tag. (c) Zoomed-in view of the textile humidity-sensing tag. (d) Measured water moisture collected by the tagged and tag-less FFRs after 30 and 60 minutes of physical exercise with a stationary bike. Adapted from [60].
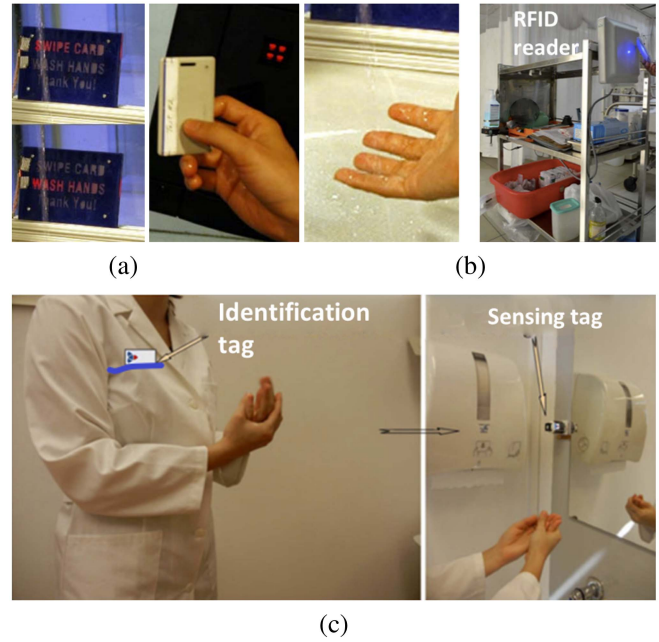

Fig. 6. RFID-based systems to monitor hand hygiene compliance. (a) A smart sink identifying the user through RFID badge (adapted from [69]). (b) A dispenser of hand sanitizer exploiting RFID badges (adapted from [71]). (c) A system to monitor dispenser activation, which couples the ID and the sensing information given by two different tags (adapted from [76]).

can be adopted for continuous monitoring of the workers. Readers could be either body-worn and connected to a Central Unit Microcontroller (CUM) [55], [57], or embedded in the workers' Personal Digital Assistants (PDA) [56]. Body-worn portable readers could also be used to recognize the activity carried on by the HCW [93], as the *iBracelet* in [58].

C. PPE Integrity

The PPE health conditions must be in optimal conditions to guarantee their effectiveness. As an example, since the filtering capabilities of the facemasks are reduced by the breath humidity [90], [91], the WHO advises replacing the masks as soon as they become damp [100], or at least after a specific use-time. An embedded humidity-sensing tag is capable of discriminating normally used Filtering Facepiece Respirators (FFRs) from abnormally wet ones (having more than 50 mg of moisture on the internal surface; Fig. 5) [60]. Moreover, RFID tags integrated inside the mask can monitor the health status of the wearer [101], as discussed next in Section V-B.

D. PPE Disposal

A used PPE is an infectious medical waste that must be properly disposed of, especially during pandemics [102]. The correct disposal of wastes through RFID has been a well-studied topic in civil and industrial sectors [103] to reduce the environmental impact [66]. RFID could be effectively exploited also for medical waste management [61], [65]. In such systems, the tags are read thrice [62], [63]: when leaving the hospitals, inside the trucks through truck-mounted readers, and when arriving at the disposal site. The RFID can also be exploited for the optimization of the route to collect the medical wastes [64], with benefits also in recycling procedures and reverse logistics [67].

E. Hand Hygiene and Disinfection

Hand hygiene is crucial to correctly wear and undress the PPE [163], [164]. Available RFID solutions are summarized in Fig. 6. RFID can identify the HCW suggesting to perform the hand hygiene with a given periodicity [69]–[71]. Then, the HCW RFID badge can activate the hand sanitizer dispenser [72]–[75]. Alternatively, a sensor tag can monitor the dispenser activation by measuring the propanol and ethanol concentration in the air [76], linked to the presence of the HCW ID in the same room.

IV. ACCESS CONTROL, CONTACT TRACING AND INDOOR AMBIENT QUALITY

During pandemic emergencies, to allow a safe interaction among people, especially in indoor spaces, three key strategies have been identified: (*i*) access control, (*ii*) contact tracing, and (*iii*) social distancing. Mobile applications [166] and/or wearable radios [137] can be employed for interactions monitoring. A specific case of access control and tracing is the management of patients and staff in hospitals, points of care, and nursing homes, especially in case of overwhelmed situations that could lead to delayed cures [167]–[169]. In addition, since infectious aerosols remain viable for up to 3 hours [6], the simultaneous presence of people within a restricted environment demands continuous air recycle. Moreover, if room temperature and humidity are not appropriate, the risk of inhalation and infection increases [7]. Hence, ventilation and

TABLE II
RFID APPLICATIONS FOR PATIENT MANAGEMENT, CONTACT CONTROL, ACCESS CONTROL AND THE INDOOR AMBIENT QUALITY VERIFICATION

Goal	RFID Application	Application examples	References
ACCESS CONTROL	Authorization verification	The individual entering a secured zone should be detected, and its trustfulness should be automatically verified	[104] [105] [106] [107] [108] [109] [110]
	Occupants limitation, Individuals flow, and Resident time	Entrance/exit reports should be recorded to keep track of the check-in or check-out status of each visitor	[107] [108] [111] [109] [110]
	PPE-based authorization	Properly placed gates and terminals deny access if the entering individual is not wearing the appropriate PPE	[53] [54] [48] [49] [50] [47] [51] [52] [60]
	Temperature-based authorization	Properly placed gates and terminals deny access if an anomalous body temperature is detected	[112] [113] [114]
PATIENT IDENTIFICATION AND MANAGEMENT	Labelling of the patient	Assigning an ID to the patient	[115] [116] [117] [118]
		Assign the patient's medical records to the tag	[119]
	Tracking of the patient	Univocally assign a reader to a room	[120] [121] [122] [123] [124] [125] [126] [127]
		Assign a tag to the location of the nearest reader	[128] [129]
		Hybrid system exploiting RFID and Wi-Fi	[130]
CONTACT TRACING AND INTERPERSONAL DISTANCING	Contact tracing	Readers in checkpoints	[131] [132] [133] [134]
		Tag-to-tag communication	[135] [136] [137] [138] [139] [140] [141] [142]
	Social distancing	Proximity detection	[143] [144]
		Estimation of the tags' orientation to monitor face-to-face contacts	[145] [146] [147] [148] [149] [150] [151]
INDOOR MICROCLIMATE	Room temperature	The monitoring of environmental temperature is carried out by deploying multiple sensor units to constitute a USN	[152] [153] [154] [109]
	Room relative humidity (RH)	The monitoring of environmental humidity is carried out by deploying multiple sensor units to constitute an USN	[155] [156] [157] [158] [159] [160] [161] [154] [109]
	Air exchange (windows opening)	The occurrence of windows opening is enabled by properly distributed light sensors and on-window transponders	[152] [162] [154] [109]

air quality management play a key role in preventing the spread of respiratory infections indoors [170], [171].
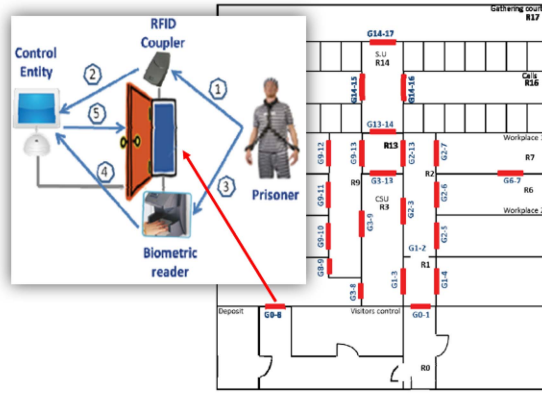
RFID-based access control, contact tracing and social distancing require that people wear an RFID tag within their badge or on PPE. Furthermore, since RFID tags empowered with sensing capabilities can enable the possibility to get also the "state" of the tagged entity, the monitoring of ambient quality becomes feasible too. Table II shows how RFID systems could be employed in the former scenarios, as detailed next.

A. Access Control

Access control systems can leverage the RFID technology [108]. Regarding public areas, such as shops, restaurants, workplaces, classrooms, and hospitals, access should be granted only if a set of criteria is simultaneously satisfied: (*i*) the person has the right privileges to enter the restricted area (Fig. 7.a); (*ii*) the number of people inside the venue does not exceed the maximum capacity limit [172]; (*iii*) the individual correctly wears the required PPE, which at least includes the protective facemask; (*iv*) the body temperature is below 37 °C [173].

1) Detection of People Density: RFID-based access control systems allow to count the number of people inside space and also to generate log reports to keep track of check-in and check-out status of each visitor [107], [108] (Fig. 7.c). RFID passive tags [110] can be integrated within the user badge and revealed by one or more readers at the
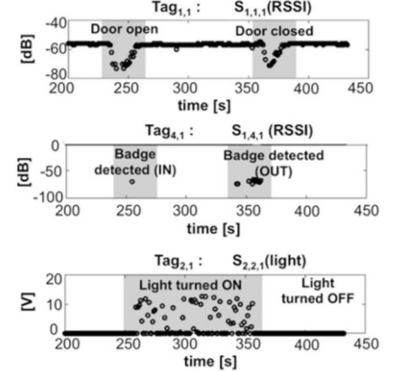
Fig. 7. (a) Access control system testbed on a prison floor, with details of biometric-based access control protocol (adapted from [106]). (b) Gate access control setup at the door, able to discriminate the flow of tagged individuals (adapted from [111]). (c) RFID card-based access control. Example of a summary of processed requests (adapted from [107]). (d) A subset of signals collected by an RFID sensors network in case of authorized access to a restricted area (adapted from [165]).

access gates for the automatic identification and the storage of entrance/exit records. In particular, the monitoring of people flow in closed areas can be achieved by applying phase-based methods [111] capable of discriminating incoming and outgoing tags (Fig. 7.b). By evaluating the time spent inside the venue, the risk of exposure to infection can be estimated accordingly.

In these applications, RFID tags can also be distributed in the environment to be controlled so that the interaction with people will cause a detectable change in their communication link to the reader. For instance, the RFID device in [154] is used as a perimeter sensor, placed on the floor and close to the access points, so that variations in the returned RSSI can be exploited to detect/identify the people passage. When deployed in a real-world application [109], [165], [174], the RFID network is able to reveal unauthorized access in critical areas (Fig. 7.d), such as hospital wards or vaccine storage warehouses.

2) Preventing the Access of Non-Compliant People: PPE-based access control systems should be implemented as a countermeasure to deny access if the individual does not wear the required tagged PPE (e.g., the facemask in Fig. 5, [60]). In addition, wearable tags with temperature sensing capabilities permit to accomplish another easy countermeasure to deny access to potentially ill individuals. The

wearable tags can be integrated into clothes (e.g., textile RFID tags [110], [112], [175], [176], Fig. 8.a) or even adhere directly on the skin (e.g., epidermal RFID tags [177], see Figs. 12, 13, 14). Such a temperature-based access control system enables the automatic detection of the anomalous temperature of the individuals during the crossing of a surveillance gate [113], [114], accordingly triggering an alarm and/or preventing the doors from opening (Fig. 8.b,c).

B. Patient Identification and Management

1) Identification: Labeling of patients can be achieved by passive wristband tags, with the aim of identifying them along clinical paths and optimizing the clinical practices. RFID wristbands can be assigned before entering the hospital, e.g., when accepted on the ambulance [115] or during the triage [117]. RFID-wristband can also be applied to identify the pre-surgery patients as well as to manage their clinical records [116]. RFID systems, moreover, permit to optimize the waiting times of the treatments [118] and also to keep track of medications within the Intensive Care Units (ICUs). For instance, when an intravenous medication has to be administered to the patient, the nurse can be required to validate the process by reading together both the patient and the medication ID [119].
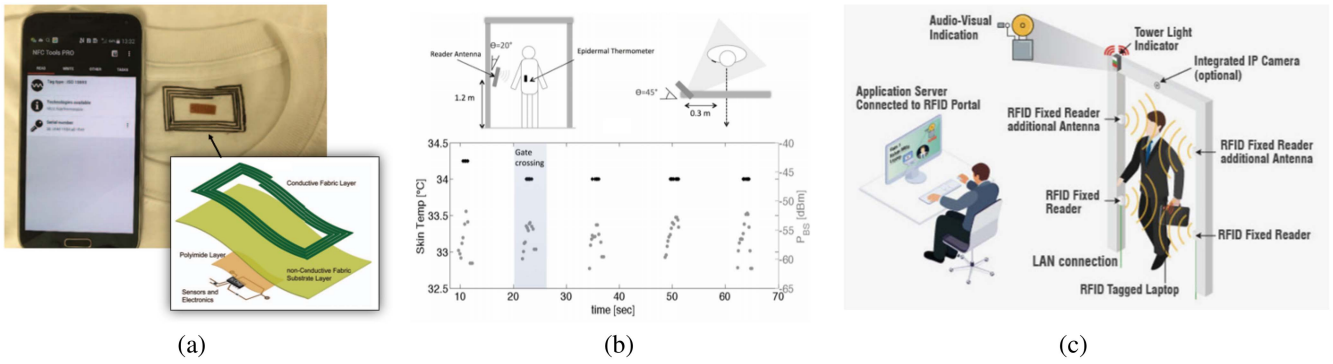
Fig. 8.   (a) Wearable fabric-based RFID skin temperature monitoring patch, glued on T-shirt (adapted from [112]). (b) RFID portal for the automatic temperature screening of crossing people wearing epidermal sensors (adapted from [113]). (c) Schematic drawing of the automatic detection of temperature data of people during the crossing of a surveillance gate (adapted from [114]).

2) Tracking: Patients tracking can be achieved by linking one (or more) reader(s) to one room so that the presence of the patients is retrieved from the corresponding detected on-body tags [124], [125]. In this case, each reader is assigned to a specific area. Alternatively, the assignment can be based on the maximum signal strength received by the readers [120] or by the tag [127], [128]. In any case, the last reader illuminating the tag of the patient can write its ID on the tag so that other readers can retrieve its last known position [123]. More accurate localization can be obtained by active RFID tags that also exploit Wi-Fi signals for the localization of the tagged individual [130].

C. Contact Tracing and Interpersonal Distancing

RFID-based contact tracing is based on (*i*) readers placed in checkpoints (Fig. 9.a), or (*ii*) tag-to-tag (T2T) interaction (Fig. 9.b).

1) RFID-Based Check-Points: This first architecture is similar to the standard people tracking strategy, wherein people are tagged, and properly placed readers monitor specific areas. Such RFID systems were successfully deployed in Taiwan and Singapore [131], [178] during the epidemic outbreak of the Severe Acute Respiratory Syndrome (SARS). In both cases, the systems were based on active UHF RFID tags and differed only for the people that were tagged: in Singapore everyone entering the hospital was tagged; instead, in Taiwan, only the medical staff. It is also possible to place a reader on each patient's bed to identify approaching nurses and physicians. This system can successfully track almost every interaction up to a range of 1.75 m and can prevent nosocomial infections [132], [179].

2) Face-to-Face Tracing: The current bottleneck of massive implementation of RFID-based contact tracing is the high cost of readers. This critical issue could be overcome by resorting to the architecture of Tag-to-Tag (T2T) communication [138], which uses a much simpler reader, namely a continuous wave generator. T2T communication is based on *reader tags* (also known as *talkers* [139]), capable of interrogating *listener tags* by backscattering the field generated by an RF source (the *illuminator* [138]). When tags of different items get in close proximity, they start interacting and sharing information, hence recording the meeting event.
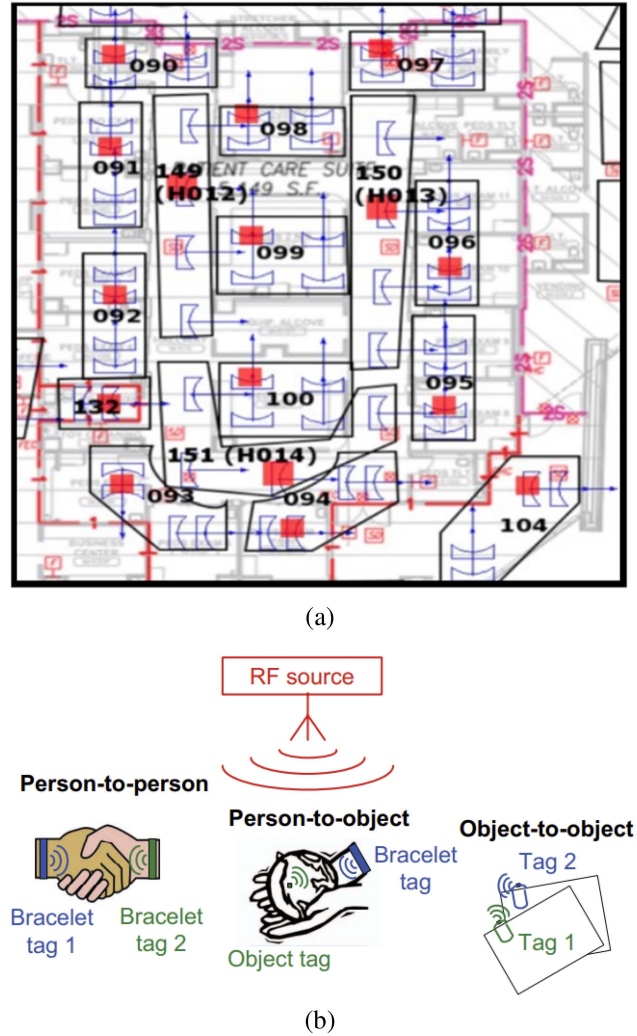

(a)

(b)

Fig. 9.   (a) Map of RFID readers (blue sketches) installed in an emergency department. The outlined boxes in the images are different areas (numbered as reported near to the red squares), and multiple readers per area are deployed (adapted from [129]). (b) Sketch of T2T systems, wherein an illuminator allows the communication between tags (adapted from [138]).

Although the T2T maximum achievable communication distance can be as low as 25 mm [138], [139], a demodulator capable of extending the T2T communication range up to 1.5 m has been developed [140]. A different kind of T2T
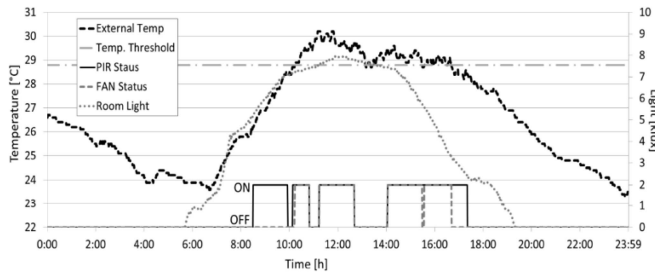
Fig. 10. RFID-enabled ambient control on the basis of local data and context data. Adapted from [162].

communication involves receiving-only RFID listeners, called *augmented RFID receiver* (ARR), creating an *augmented RFID system* that monitors the contacts of tagged people near the listener [141], up to a distance of 3 m [143]. A type of ARR named *Sense-a-Tag* can be embedded into a wristband to sense the interactions of the user with tagged objects [144] and possibly detect face-to-face contacts that are known to require extra-distancing between people to prevent airborne infections [180].

D. Indoor Microclimate

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) suggests doubling the outside air changes per hour with respect to the recommended ventilation rate before the pandemic (14 m^3/hr) [216]. Moreover, indoor temperature and relative humidity (RH) should be maintained within determined ranges (e.g., 20-24 °C and 40-60 % respectively) to mitigate the virulence of infectious agents [170], [171].

1) Windows Opening: RFID tags embedding light sensors can be used to monitor the windows opening to foster the exchange of air [152], [154], [162]. For instance, by sensing the light level, a fan located in an office room can be activated only when certain conditions are verified [162] (Fig. 10). More elementary strategies can involve passive tags disposed on the windows, whose opening/closure is retrieved by processing the RSSI from the tags [165].

2) Indoor Temperature and Humidity: The microclimate of a room, namely the temperature and humidity (Fig. 11.a), can be monitored by sensor-oriented tags, thus providing a further indication about critical environmental conditions that require air recycling. Environmental temperature can be monitored by means of battery-less UHF RFID transponders provided with a temperature sensor [152], [153]. Humidity sensors can be instead designed providing the RFID tag with a material having a high ability to absorb moisture and changing its dielectric properties accordingly [155]–[161] (Fig. 11.b, c, d). The same reader infrastructure deployed for the access control can be used for the interrogation of the above environmental sensors.

V. PREDICTIVE AND PREVENTIVE HEALTHCARE

The health monitoring of suspected or confirmed infected people can be referred to three different and often consecutive phases: (I) Preventive early diagnosis, (II) Domestic disease monitoring, (III) Hospitalization.

In the former phase, preventive testing programs, both viral (swabs) and physical, should be performed. Examples are temperature monitoring [173], cardiovascular and respiratory screening (i.e., cardiac rate, cough and altered respiration [217], and oxygen saturation [218]), especially in case of individuals belonging to controlled and restricted communities, such as hospitals, nursing homes, assisted living facilities, factories and workplaces in general, schools and prisons [219].

In the second and third phases, the health status of isolated individuals should be continuously monitored to intervene in a timely manner in case of rapid worsening. For instance, the domestic monitoring of symptoms of COVID-19 positive patients for signs of deterioration has demonstrated to effectively decrease the mortality rates [220] and the hospital loads in China.

Wearable and epidermal RFID sensors [177] exhibit a great potential to enable a comfortable, easy-to-use and wireless monitoring of a significant set of physiological parameters, such as temperature, breath anomalies, electrophysiology, and biomarkers in sweat, through small devices to be applied directly over the skin [221], [222]. Table III summarizes the possible applications of RFID platforms versus some symptoms of the infectious disease [223].

A. Body Temperature

During the fight against the SARS emergency in 2006, UHF active tags with an embedded thermometer, employed for the Location-based Medicare Service (LBMS) project at the Taipei Medical University Hospital [178], demonstrated that the automatic and real-time temperature taking reduces the risk of staff infections by limiting the contact with patients. This system, moreover, improved patients safety by detecting fever events in a timely manner.

RFID epidermal thermometers are suitable to be directly attached to the human skin by means of bio-compatible transpiring membranes [190] (Fig. 12.a). Over the years, they have become increasingly more flexible, conformable [113] (Fig. 12.b), [183] (Fig. 12.c), and small [181] (Fig. 13), also paying attention to their reusability to reduce fabrication costs and pollution [188]. New pioneering studies [182] look in the direction of multichip RFID temperature sensors to strengthen the correlation between the skin and core body temperature (Fig. 12.e).

Passive RFID epidermal thermometers can be read up to 1.5-2 m [224], hence being compliant with an automatic and on-the-fly reading through gates and check-points to enable the unsupervised detection of anomalous temperature peaks [114] (Fig. 12.d). Moreover, envisaged applications are also in clinical and domestic settings by means of fixed remote antennas (e.g., continuous overnight temperature monitoring). In this sense, these thermal sensors have already been experimented on a hospital ward [187] and have been deemed robust and reliable. If placed in the armpit region (Fig. 13), they are well correlated with a standard axilla electronic thermometer (Pearson's coefficient $p = 0.78$) with a difference of less than 0.6°C in the 95% of measurements [181].

(a)

(b)   (c)   (d)
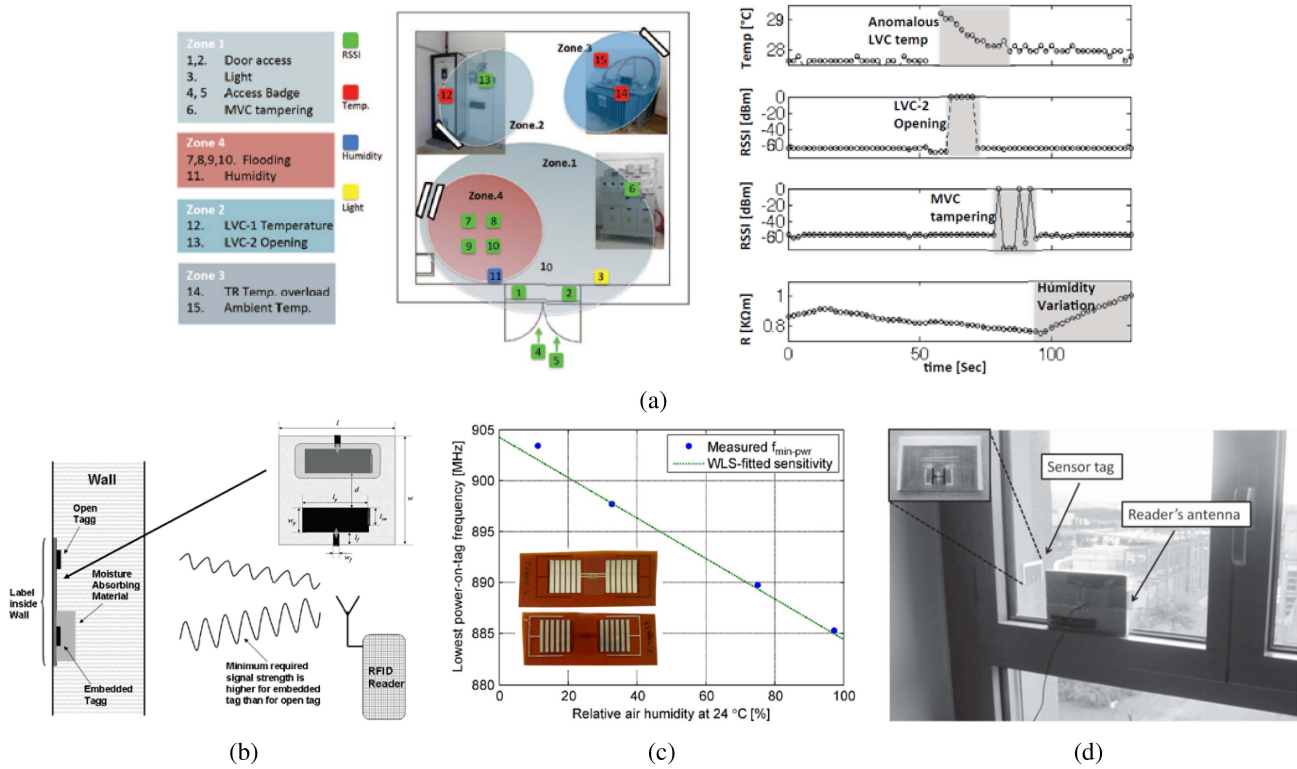
Fig. 11.   (a) Architecture of an RFID sensors network for both ambient monitoring and access control, with a subset of the measured electromagnetic signals (adapted from [109]). (b) Moisture sensing label incorporating two RFID tags to be integrated over walls (adapted from [156]). (c) Calibration curve of the humidity inkjet-printed sensor tag (adapted from [157]). (d) Measurement setup for the overnight humidity exposure with a doped tag placed outside an external wall and interrogated by an RFID reader from the inside (adapted from [158]).

(a)   (b)   (c)

(d)   (e)

Fig. 12.   On-skin temperature RFID sensors. (a) Worn prototype of the epidermal RFID temperature sensor (adapted from [190]). (b) Flexible epidermal RFID thermometer (adapted from [113], [187]). (c) Flexible and conformable RFID thermometer (adapted from [183]). (d) i-TEK's body temperature monitoring system (adapted from [114]). (e) Dual-chip flexible epidermal RFID temperature device (adapted from [182]).

Continuous sampling of the skin temperature can also be achieved by exploiting BAP RFID tags [185] (Fig. 14) working as data-loggers. Their validity was demonstrated in [186] for
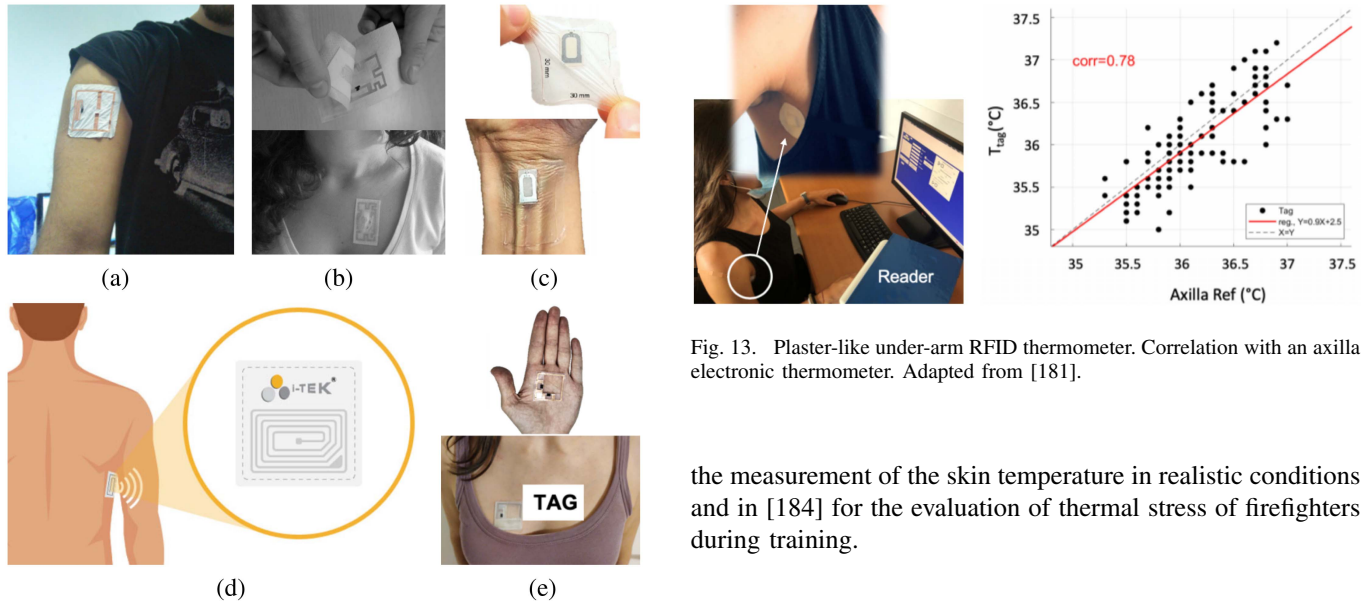

Fig. 13.   Plaster-like under-arm RFID thermometer. Correlation with an axilla electronic thermometer. Adapted from [181].

the measurement of the skin temperature in realistic conditions and in [184] for the evaluation of thermal stress of firefighters during training.

B. Respiratory Function and Cough

1) Cough: The presence and the dynamics of coughing can be monitored by wearable RFID devices sewed into clothes on the chest region (Fig. 17.c), exploiting the backscattered power in combination with motion inertial sensors [110]. Another simple mean to count cough events is based on sensorized facemasks that enable the detection of cough's periodicity and duration by detecting the temperature spikes produced by cough shots [225] (Fig. 15).

TABLE III
WEARABLE RFID SENSORS FOR THE MONITORING OF POSITIVE OR SUSPECTED INFECTED INDIVIDUALS

| Clinical Evaluation of COVID-19	Measured Parameters	Wearable RFID Sensors Potentials	References	Phases
CLINICAL SYMPTOMS MONITORING	Body Temperature	• Comfortable on-skin plaster-like devices • Continuous or periodic measurements of body temperature • Fever detection	[114] [181] [182] [183] [184] [185] [186] [187] [188] [113] [189] [190] [178]	I, II
	Cough	• Fabric-integrated devices • Coughing fit detection • Indirect breath monitoring (RSSI variations)	[110]	I, II
RESPIRATORY ASSESSMENT	Respiratory Rate, Respiratory Depth, Respiratory Cycle, Breath Effort	• Comfortable facemask or on-skin plaster-like devices, or fabric-integrated devices • Abnormal respiration patterns detection (e.g. apnea, tachypnea, ...) • Direct (breath temperature or humidity) or indirect (phase or RSSI variations) breath measurements	[191] [192] [193] [194] [195] [196] [197] [198] [199] [200] [201] [202] [203] [204]	I, II
	Blood Oxygen Saturation	• Continuous pulse oximetry monitoring • Very low power consumption	[205]	II
CARDIOVASCULAR STATUS	ECG, Hearth Rate	• Comfortable on-skin or fabric-integrated devices • Continuous or periodic hearth rate and multichannel ECG monitoring • Very low power consumption	[206] [207] [200] [208] [189] [209] [210] [211]	II
	Cuffless Blood Pressure	• Fabric-integrated devices • Continuous blood pressure monitoring in static condition (in care facilities)	[200]	II
PSYCHO-PHYSICAL STRESS MONITORING	Sweat	• Comfortable on-skin plaster-like devices or fabric-integrated devices • Continuous or periodic sweat pH, biomarkers and compound measurements • Psycho-physical stress detection • Direct (sweat chemicals) or indirect (RSSI variations) sweat measurements	[15] [185] [212] [175]	I
	Sleep Disorders	• Fabric-integrated and ambient tags • Continuous overnight sleep quality evaluation • Overnight body movements detection • Possible integration with other RFID sensors (e.g. body temperature, sweat compound, ...)	[204] [195] [201] [113] [213] [214] [215]	I, II
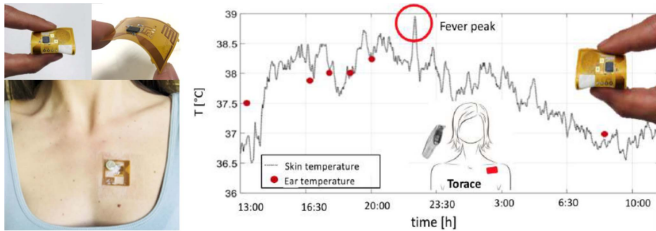
Fig. 14. Small-size flexible RFID BAP epidermal sensor board and continuous temperature monitoring against sporadic tympanic sampling. Adapted from [185], [186].

2) Breath: RFID devices for breath monitoring can allow the avoidance of intrusive nasal probes and chest bands [226].

The first category of devices relies on *direct* measurement of the human breath through RFID temperature or moisture sensors to be attached under the nose or over the facemask. A flexible RFID sensor was demonstrated in [196] and [198] (Fig. 16.a) for integration into a facemask or directly stuck on the face and provided with a graphene-oxide electrode to monitor the moisture emitted during breathing. This sensor is able to detect the inhalation/exhalation cycles and abnormal patterns of respiration like apnea, tachypnea, etc. (Fig. 16.c). Simpler and lower-cost breath detection [197] can only involve a temperature sensor (even integrated into the RFID IC itself). In this case, the overall device is smaller and suitable to be
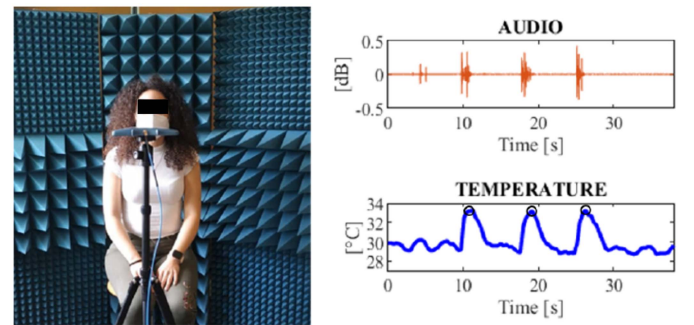

Fig. 15. RFID-enabled cough evaluation system through detection of temperature spikes. Adapted from [225].

directly applied close to the nostrils as an epidermal patch (Fig. 16.b). It measures the temperature gradient of the air flux that is correlated to the inhalation and exhalation rhythm and depth. To obtain better accuracy, bilateral breath measurements can be achieved by dual-chip sensor tags as in [192].

An *indirect* breath monitoring avoiding sensors on the face can be instead based on the measurement of the torso expansion and contraction by placing regular RFID tags on the abdomen, or even on the bed [204], for overnight monitoring. Breath identification is based on the measurements of the variations of RSSI [195], [199], [200] and phase [191], [194], [201]. Sleep respiration rate and sleep

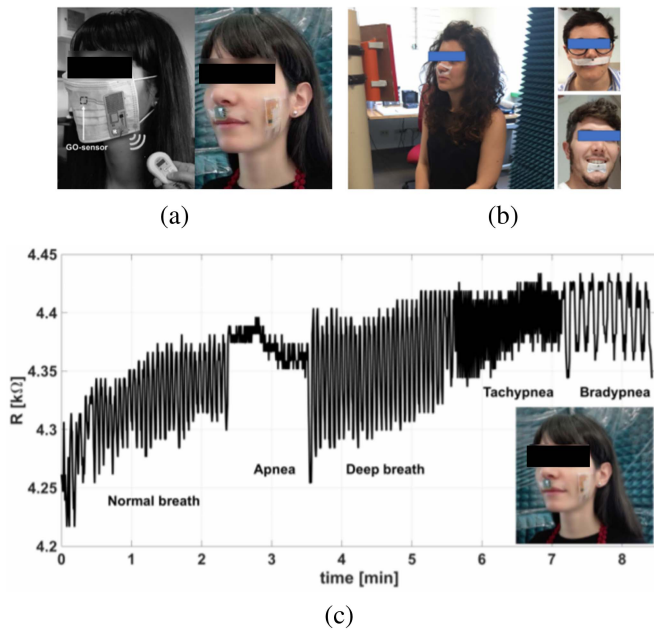(a)   (b)

(c)

Fig. 16. RFID sensors for *direct* respiratory function assessment. (a) RFID breath humidity sensors for integration into a facemask (left) and over the skin (right) (adapted from [196], [198]). (b) Different prototypes of RFID skin-attachable breath temperature sensors (adapted from [197]). (c) Recording of a respiratory pattern (adapted from [196]).

(a)   (b)

(c)   (d)

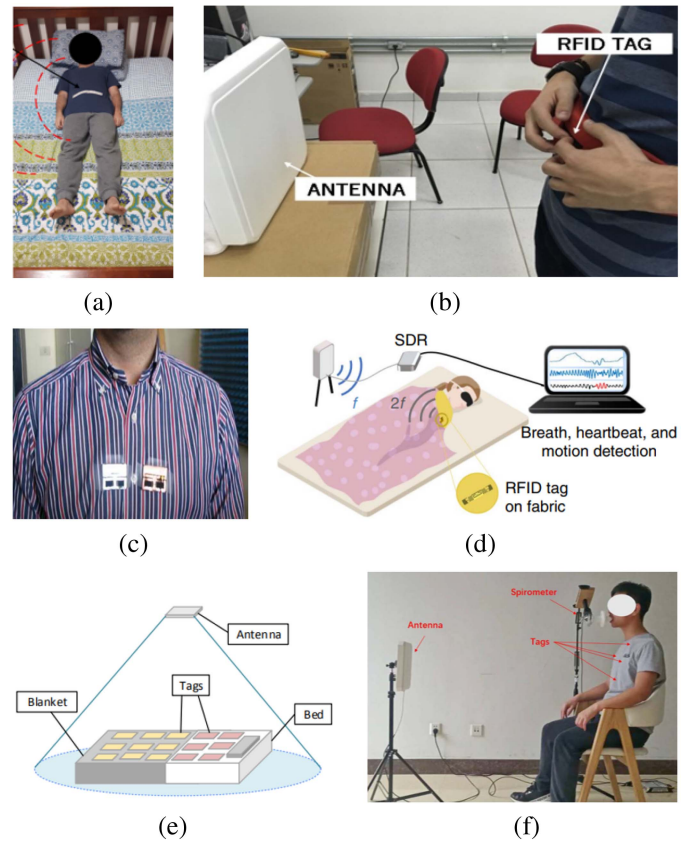(e)   (f)

Fig. 17. RFID sensors for *indirect* respiratory function assessment. (a) Sleep respiration monitoring system with passive COTS RFID tags (adapted from [195]). (b) RSSI-based respiratory monitoring system with passive RFID tags (adapted from [199]). (c) Motion inertial based cough monitoring RFID sensor (adapted from [110]). (d) Fabric-integrated RFID tag for respiratory assessment during sleep (adapted from [201]). (e) Non-invasive sleep monitoring system based on bed-integrated RFID (adapted from [204]). (f) Measurement setup of the RF-RVM system (adapted from [191]).

apnea can be detected through a fixed reader antenna at the bedside, and RFID tags can be attached [195] (Fig. 17.a) or fabric-integrated [201] (Fig. 17.d) at the abdomen level. For instance, the *TagBreathe* platform in [194] resorts to an array of COTS RFID tags to enhance the measurement robustness. Similarly, the respiratory volume can be retrieved by collecting the temporal phase information from tags attached to the chest and abdomen [191] (Fig. 17.f). Moreover, by placing the RFID tag on the abdomen, the respiratory rate in a medical examination-like situation [199] (Fig. 17.b) can be evaluated too.

By adding other RFID tags, for example, at the wrist area, additional physiological parameters can be simultaneously collected, such as heart rate, blood pressure, and respiration rate [200].

3) Oxygen Saturation: The oxygen saturation in the blood can be captured by a wearable RFID device [205] comprising a reflective oxygen probe and the standard CMOS technology, whereas an active RFID tag is used to store and stream the data.

C. Cardiovascular Evaluation

ECG data can be collected and streamed in real-time by means of an ultra-low-power RFID BAP device to be placed at the center of the chest, where standard clip electrodes collect the ECG signal [206], [210] (Fig. 18.a). The Heart Rate Variability (HRV) can be quantified as well [207] with an array of COTS RFID tags attached to the chest area within the clothes (Fig. 18.b), exploiting the processing of the RSSI as described above for breath. Although the RFID reader captures the RF signal reflected from both the heart movement due

to heartbeat and the tag movement caused by respiration, the estimated HRV is comparable to existing wired techniques. Hearth Rate monitoring for infants can be achieved too by sewing an ECG-enabled RFID sensor [209], comprising fabric electrodes, onto the front bodice of a baby onesie [208] (Fig. 18.c). Multi-electrode RFID sensors (Fig. 18.d) have been experimented too, for a more accurate ECG recording without the use of an on-board battery [211].

D. Psycho-Physical Stress Monitoring

A pandemic may also impact the psychological sphere of patients and operators [227]. For example, the onset of dehydration, elevated biochemical stress, and increasing overnight sweat loss are critical indicators associated with COVID-19 [228].

1) Sweat Analysis: Early signs or precursors of psychological diseases can be identified by the chemical analysis of the sweat [229]. The pH index, which is correlated with the presence of altered electrolytes, can be wirelessly monitored through a flexible RFID device (Fig. 19.a) [15] equipped with an electrochemical printed iridium-oxide sensor. Measurements can be taken on the fly in battery-less mode
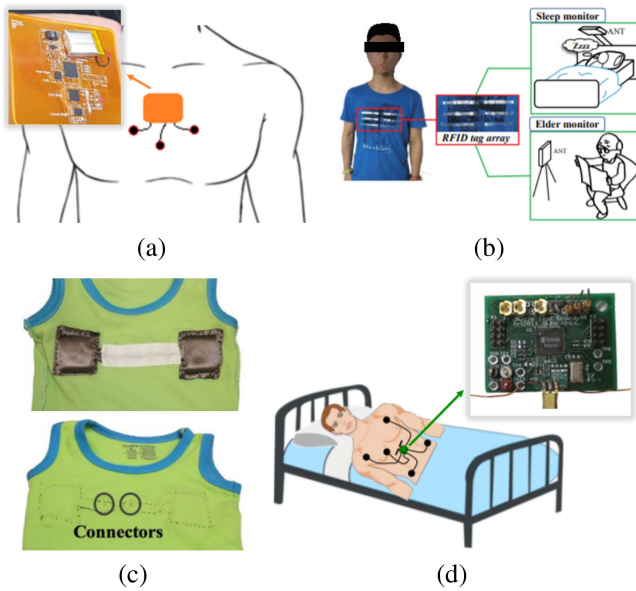
Fig. 18. RFID sensors for cardiovascular evaluation. (a) Epidermal ECG RFID device (adapted from [206]). (b) RF-ECG system with an array of COTS RFID tags (adapted from [207]). (c) Fabric-integrated hearth rate RFID device (adapted from [208]). (d) Battery-free multichannel ECG sensor (adapted from [211]).
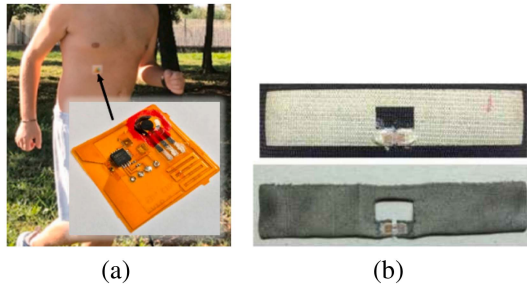

Fig. 19. RFID sensors for sweat monitoring. (a) Epidermal RFID device for pH sweat monitoring (adapted from [15]). (b) Textile-integrated RFID sweat rate sensor tags (adapted from [175]).
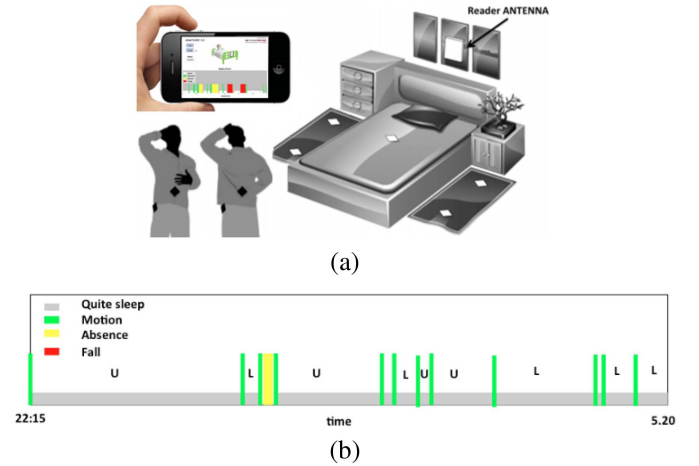

Fig. 20. (a) *NightCare* system for sleep monitoring (adapted from [213], [214]). (b) Classification of sleep quality and different body postures (adapted from [214]).

from a distance up to 1 m or continuously, provided that the device works in battery-assisted mode [185]. Hence, monitoring can be executed even during motion [212], as in the case of nurse activity in a hospital. Sweat RFID sensors can also be integrated into textiles (by carving electro-textiles or by screen-printing onto regular threads, Fig. 19.b), exploiting the change in the tag's substrate when it absorbs sweat [175].

2) Quality of Sleep: COVID-19, and in general emergency conditions, also affects the quality of sleep. As suggested by [9], measurements during sleep might provide a significant insight on the health status, and in some cases, it may be the only way to monitor a worker's health effectively. For instance, the *NightCare* system [213]–[215] (Fig. 20.a) can quantitatively evaluate the quality and phenomenology of the sleep through a set of wearable passive tags placed onto the sleeper's clothes and by also exploiting ambient tags placed over the bed and onto the nearby carpets (Fig. 20.b). Finally, the sleeper can be provided with wearable temperature sensor tags to additionally detect anomalous temperature transients during the night [113].

VI. CONCLUSION

The presented analysis suggests that an RFID-based country-level infrastructure could provide valuable support to the management of pandemics. The availability of devices is rich and currently increasing. Research outcomes from laboratories could quickly move to proof of concepts and then to products.

When applied over the large scale to a pandemic-like scenario, RFID frameworks are expected to generate an unprecedented amount of data. Hence Edge Computing [230] is needed to mitigate the data stream, whereas Artificial Intelligence [231] should be used to extract profiles and identify anomalous events out of the sea of data.

Furthermore, even more worrying issues for the social and industrial acceptance of the RFID-centric approach to the pandemic war are (*i*) the implementation costs of RFID systems and (*ii*) the privacy. Regarding the implementation, although the costs of RFID systems in hospital is not negligible [36], the estimated return of investment would be worth the initial cost [29], [37] since the same system can be used for multiple purposes (e.g., for the tracking staff and equipment [121], [126], even across different hospitals [31]). Then, concerns about the privacy and safety related to the RFID labeling of humans can lead to oral and practical forms of resistance, as the tampering or the misuse of the systems [232]. To preserve the anonymity of users, a *Crowd System* [233] can be employed, wherein the tags inside "crowd zones" repeatedly swap their identifiers. To secure the contact tracing, RFID readers can exploit a blockchain architecture through the Internet [133] so that a person wearing the RFID tag can be notified if he/she has encountered a confirmed infected person without disclosing his/her identity. Moreover, in all the cases, the coverage of the reading infrastructure needs to be optimized with ad-hoc network design methodologies [234]–[236], in compliance with the electromagnetic compatibility issues [237]. Despite these open issues, studies on technology adoption predict that the RFID

will be increasingly accepted and widespread in healthcare settings [238].

The main limitations of UHF RFID remain the limited read distance and the need for a continuous remote power source to activate tags. The latter problem could be mitigated through energy harvesting [239], [240], e.g., photovoltaic cells for environmental and on-object tags [241], or piezoelectric [242], vibration [243] and body-heat [244] powering for on-body sensors. Promising opportunities would also arise by exploiting commodities signals to implement backscattering communications among passive tags and routers, access points and even smartphone and wearable devices. Finally, emerging 5G infrastructures [245] will provide a further boost to improve interoperability, coverage efficiency and bit-rate.

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