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*Review Article*

# Technological Features of Internet of Things in Medicine: A Systematic Mapping Study

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Nowadays, applications for the Internet of Things (IoT) have been introduced in different fields of medicine to provide more efficient medical services to the patients. A systematic mapping study was conducted to answer ten research questions with the purposes of identifying and classifying the present medical IoT technological features as well as recognizing the opportunities for future developments. We reviewed how cloud, wearable technologies, wireless communication technologies, messaging protocols, security methods, development boards, microcontrollers, mobile/IoT operating systems, and programming languages have been engaged in medical IoT. Based on specific inclusion/exclusion criteria, 89 papers, published between 2000 and 2018, were screened and selected. It was found that IoT studies, with a publication rise between 2015 and 2018, predominantly dealt with the following IoT features: (a) wearable sensor types of chiefly accelerometer and ECG placed on 16 different body parts, especially the wrist (33%) and the chest (21%) or implanted on the bone; (b) wireless communication technologies of Bluetooth, cellular networks, and Wi-Fi; (c) messaging protocols of mostly MQTT; (d) utilizing cloud for both storing and analyzing data; (e) the security methods of encryption, authentication, watermark, and error control; (f) the microcontrollers belonging to Atmel ATmega and ARM Cortex-M3 families; (g) Android as the commonly used mobile operating system and TinyOS and ContikiOS as the commonly used IoT operating systems; (h) Arduino and Raspberry Pi development boards; and finally (i) MATLAB as the most frequently employed programming language in validation research. The identified gaps/opportunities for future exploration are, namely, employment of fog/edge computing in storage and processing big data, the overlooked efficient features of CoAP messaging protocol, the unnoticed advantages of AVR Xmega and Cortex-M microcontroller families, employment of the programming languages of Python for its significant capabilities in evaluation and validation research, development of the applications being supported by the mobile/IoT operating systems in order to provide connection possibility among all IoT devices in medicine, exploiting wireless communication technologies such as BLE, ZigBee, 6LoWPAN, NFC, and 5G to reduce power consumption and costs, and finally uncovering the security methods, usually used in IoT applications, in order to make other applications more trustworthy.

## 1. Introduction

Connected "things" to the Internet have increased exponentially in recent years [1, 2]. The devices can be identified and controlled via a new Internet called IoT. This new Internet integrates physical and virtual world things to improve the quality of human life and provides better services [3–5]. Physical things, such as devices and tools, have abilities of sensing, actuating, and interconnecting while virtual things, such as multimedia content and software applications, can


Figure 1: Mapping study workflow [14].

be stored, processed, and accessed [6]. The things can be identified with the EPC (Electronic Product Code) and integrated via the Internet [7]. Today, thanks to widely available technologies such as communication technologies and smart portable devices, IoT has become one of the hottest topics in all areas [8], particularly in healthcare, which is estimated to engage 40% of IoT devices by 2020 [2].

Due to the prevalence of ICT (Information and Communication Technology) in healthcare industry, equal provision of healthcare services for patients has increased widely having enhanced the utilization of healthcare resources [5]. In healthcare, therefore, sensor and communication technologies, integrated by IoT, are attempting to enhance traditional communication with the patients to provide more efficient health services [9]. In most research studies, on the other hand, the use of IoT in the areas such as combining wireless physiological sensors and smart mobile devices in daily activities, health monitoring, locating and tracking health-related things, diagnosis, and collaboration is investigated [10]. In order to increase patient empowerment, IoT is attempting to move healthcare from being centralized to lateralization, i.e., to e-health. There is a trend to shift medical services from centers to homes, especially for the elderly or the disabled, in order to budget time and reduce medical costs [4].

However, the technological features which are commonly used in current medical IoT applications are not evidently clear to all. In other words, the available capabilities or shortages of the features of medical IoT applications have not yet been investigated. It is, therefore, necessary to shed light on the current technological features of IoT in medicine through scrutinizing the relevant medical IoT literature. Such study can illuminate the current advances as well as the gaps and opportunities for future progresses. A need is thus evident for a review study to find out the current technological features of IoT applications in medicine.

The present study is, thus, an attempt to systematically map the nature of the IoT technological features used in medical areas through analyzing the related literature. It has been designed to provide an overview of medical IoT research area through producing classifications and counting contributions in relation to the categories found in those classifications [11]. The results of this study can be beneficial for various medical IoT stakeholders, such as researchers intending to carry out primary or secondary studies in medical IoT-related fields, interested postgraduate candidates in medical sciences, and medical IoT developers. Pioneers in the field can also take advantage of the gaps inserted at the end of the current study.

## 2. Materials and Methods

This review study is systematic mapping in nature. A systematic mapping review is usually used to support further research, most commonly the systematic reviews, and is intended to classify the primary research studies in a specific field [12]. In other words, a mapping review study is the starting point for a researcher to conduct a related primary study or a systematic review by shedding light on the pursued knowledge. While a systematic review study, pertinent to ours, would be used to identify, evaluate, and interpret all relevant research [13], the present study, however, has systematically reviewed the relevant papers, published between 2000 and 2018, aiming at identifying and classifying the above-mentioned features in medical IoT applications and specifying knowledge gaps in the field. Figure 1 shows the processes followed in conducting this study.

*2.1. Research Questions.* As several technologies, protocols, and hardware/software components are involved in the development of IoT applications, ten research questions related to major features of IoT applications were chosen to be the focus of the current review study. The relevance between each research question and the related information provided in the previous review studies and the significance of our study pertinent to each question have all been presented below.

*2.1.1. Annual Publication Trend (RQ 1).* What is the annual trend of studies in medical IoT? The distribution of the relevant articles by publication year—from 2010 to 2016—was investigated [15]. We have extended the years and included medical IoT studies until the end of 2018.

*2.1.2. Wearable Technology (RQ 2).* How did medical IoT studies deal with wearable technology? Wearable IoT devices are used in medicine as sensors attached to the body to monitor the health of the patients [16]. Various sensors embedded in some of these devices can measure a variety of signals or parameters (physiological, environmental, or motion) [17–20]. Our purpose of probing this idea was to discover the extent of the presence of wearable IoT devices in medicine and, finally, how these devices are attached to the body.

*2.1.3. The Cloud (RQ 3).* How was the cloud involved in medical IoT? Purchase or design of system with high computational power would be extremely expensive and energy intensive. Some services such as storage and data processing are, therefore, performed via cloud. Cloud computing has virtually unlimited storage and processing capabilities, is a much more advanced technology, and has partially addressed most of the IoT issues [21]. Recent advances in IoT and cloud computing make it possible to develop a smart medical system that allows remote continuous monitoring of patients in a seamless and unobtrusive manner [22]. One review study has reviewed the use of cloud in medicine in real-time data capture and processing, data visualization, cloud service type, and data analytics [15]. Another study has conducted a qualitative analysis of the use of cloud in healthcare [20]. We have, nevertheless, explored the frequency of studies having used the available servers (such as Microsoft and Amazon) utilizing either storage or processing cloud service types.

*2.1.4. Wireless Communication Technologies (RQ 4).* How have wireless communication technologies been engaged in medical IoT? Wireless communication technologies, as an integral part of IoT, are used to connect IoT devices [2, 23]. Major forms of these technologies are RFID (Radio-Frequency Identification), NFC (Near-Field Communications), Infrared (IR), Z-Wave, ZigBee, 6LoWPAN,Wi-Fi, Bluetooth, GPS, and cellular networks [23, 24]. One review study has divided communication technologies into short-ranged and long-ranged ones and has reviewed their standards in healthcare IoT studies [20]. Another paper has presented the studies in terms of the existing wireless communication technologies without any classification [15]. However, we have detected the communication technologies and the frequency of their existing siblings in order to provide the required information for the interested scholars.

*2.1.5. Messaging Protocols (RQ 5).* Which messaging protocols have been used for medical IoT? When data are to be transferred between two devices via a data channel, each device must have an appropriate network interface to allow it to communicate across the channel. The devices and their network interfaces use a protocol to generate data that is transmitted over a channel so that it can be decoded by the receiver [25]. The most frequently used application-layer messaging protocols in IoT are, namely, MQTT (Message Queuing Telemetry Transport) and CoAP (Constrained Application Protocol) [26]. The limitation that we saw in the literature of IoT messaging protocols was that only one review study has illustrated the papers having used IoT protocols in healthcare until 2016 [15]. The current study has, therefore, endeavored to extend the search to 2018 while having tried to carry out a more rigorous search in medical area.

*2.1.6. Security Methods (RQ 6).* How has security been dealt with in medical IoT?

IoT devices are more vulnerable to different types of attacks on different layers of IoT architecture. There are studies concentrating on privacy and security issues and proposed solutions to address these issues [27–29]. Privacy and security are particularly important for the health sector because of the sensitive nature of human life data [30]. In most distinctive review studies, different features of IoT security and privacy are identified and analyzed [13, 20], the studies having developed security mechanisms for healthcare applications are gathered [18], and finally, medical IoT issues of privacy and data protection are reviewed [19]. We, nonetheless, have tried to show the protection methods used in medical IoT literature.

*2.1.7. Microcontrollers (RQ 7).* Which microcontrollers are used in medical IoT?

The microcontroller unit is a microchip containing the CPU, memory, and input/output peripherals. Enabling everything on the Internet to be accessible and controllable, microcontrollers are the key components for developing IoT applications [31]. Due to the high demands for IoT applications in medicine as well as the limitations of the present ones, the patients' desires are not fully satisfied. So, some of the customers have shown tendency to develop their own IoT application using open platforms. To fulfill these needs, there are various microcontrollers and development boards for different purposes [32]. Having not detected any previous review study dealing with this question, we attempted to report the most capable, appropriate, and frequently used types of microcontroller and their families in order to recognize the ones used in medicine.

*2.1.8. Development Boards (RQ 8).* What are the proportions of use of development boards in medical IoT?

IoT development boards include microcontrollers or processors, memory, programmable input/output, and communication components. No study on this research question was found. We were thus interested in learning about the more preferred development boards applied in medical IoT to grasp the reasons behind the choices. In order to meet the requirements of any IoT functions, choosing the right development board to prototype an IoT application, project, or product is a vital step [32].

*2.1.9. Mobile/IoT Operating Systems (OSs) (RQ 9).* How has mobile/IoT OS been employed in medical IoT?

Mobile/IoT OS works as a management and interface agent for smart portable devices such as smartphones, smart watches, and IoT devices that can be used for interfacing sensors to measure health parameters. Android, iOS, and Windows are mobile OSs for smartphones, tablets, smart watches, and other mobile devices. Things in IoT have an embedded OS that could be run on low-powered IoT devices. A study was found reviewing different IoT OSs such as TinyOS, ContikiOS, RIOT, MbedOS, Zephyr, and Brillo [33] but is not focused on medical IoT devices. We found it essential to identify the mobile/IoT OSs used more frequently in medicine. Thanks to possessing unique addresses, displays, sensors, and wireless communication technologies that enable mobile devices to be used as hubs or access centers, smartphones enjoy a distinctive status among other IoT applications [32].

*2.1.10. Programming Languages (RQ 10).* What are the usage proportions of the programming languages in medical IoT? A wide range of programming languages, such as C, Python, C++, and Java, can be used for the development of IoT applications. Since each language plays a specific role in the development and management of the applications, it seems that

Table 1: Search strategy for each database.

| Research database | Search strategy |
|---|---|
| Web of Science | TS = ((IoT OR "Internet of Things") AND (medic∗ OR health∗ OR hospitals OR clinic∗ OR diseases)) |
| Scopus | TITLE-ABS-KEY ((IoT OR "Internet of Things") AND (medic∗ OR health∗ OR hospitals OR clinic∗ OR diseases)) |
| PubMed | (IoT [TIAB] OR "Internet of Things" [TIAB]) AND (medic∗[TIAB] OR health∗ [TIAB] OR hospitals [TIAB] OR clinic∗ [TIAB] OR diseases [TIAB]) |
| IEEE Xplore | ("IoT" OR "Internet of Things") AND (medic∗ OR health∗OR hospitals OR clinic∗ OR diseases) |

the use of the right language for specific purposes has become a matter of concern [32]. This question shows which programming languages are more involved in the development and use of medical IoT applications. Concerning the absence of a review study in this regard, it was intended to identify the type(s) of the programming language(s) which are more frequently used in medical IoT applications in order to pinpoint the more compatible ones in this filed.

*2.2. Inclusion-Exclusion Criteria.* The articles were included based on specific criteria as follows: (1) the articles in English related to implementation and deployment of IoT in medicine addressing a specific disease or a medical field and (2) the articles in English pursuing validation and evaluation research methods among several research facets in software engineering such as solution proposals, validation research, evaluation research, and experience articles in medical subfields. However, the papers having the following criteria were excluded from the study: (1) the articles having focused on sensor issues and energy saving in IoT systems, (2) the articles related to IoT in nursing, nutrition, fall detection, ambient assisted living (AAL), drugs, and emergency care, (3) review and conference articles on medical IoT, and (4) the medical IoT articles for which the full texts were not available.

*2.3. Search Strategy and Data Sources.* Our search for the relevant papers consisted of the activities of identifying the keywords, formulating the search strategy, and selecting data sources. The keywords were identified, and the required search strategy was developed using the content of the main research questions. After a preliminary search, the keywords were refined. In several iterations, we combined some keywords until we found an appropriate set of keywords. Keywords and synonyms were grouped into two sets and the search strategy was formulated as follows: [(Set1) AND (Set2)] that Set1 is [medical OR medicine OR medication OR health OR healthcare OR hospital OR clinical OR clinic OR disease] and Set2 is ["Internet of Things" OR IoT].

Due to the introduction of IoT at the beginning of the 21st century, the published papers between 2000 and 2018 were included in our study. As an interdisciplinary subject matter, IoT topics were searched in high-quality journals related to both engineering and medicine. To find the relevant papers, we searched the related ones published in major online academic databases including IEEE Xplore, Web of Science, Scopus, and PubMed. In each database, searches were performed in the title, abstract, and keywords (Table 1).

*2.4. Collection of Studies.* To answer the research questions, we collected the related studies. The flow diagram in Figure 2 shows the identification and selection processes in our study. Due to our wide research questions, which is a natural feature of this type of study [34], the number of the extracted papers was found to be relatively large, i.e., 3679 ones. We used Mendeley as reference management software to organize the papers. After identifying and removing duplicate papers, 2009 papers remained among which the selection process began. Study selection consisted of two screening steps. In the first step, two of the present authors independently reviewed the titles and the abstracts to identify more relevant papers against our inclusion/exclusion criteria. Only when an article received two negative votes, it was excluded from the study. In this step, 1808 papers were excluded. Then, the authors read the full text of the remaining papers based on inclusion/exclusion criteria and excluded the irrelevant papers ($n = 112$). Finally, 89 papers were included in our study.

*2.5. Data Extraction.* In this section, the full text of the selected articles was studied in order to gather the data needed to answer each research question. To collect the data, we designed an extraction form in Microsoft Excel. The data extracted from 89 selected studies was collected manually by two of the authors and inserted in the extraction form (Table 2).

## 3. Results

The results of each question were classified, analyzed, and then illustrated as tabular or visual representations. Various types of plots and diagrams were used to map the findings to better understand the trends of field studies.

*3.1. Annual Publication Trend (RQ 1).* Figure 3 shows the annual trend of medical IoT studies between 2000 and 2019. From 2000 to 2013, almost a plateau was observed in the production of medical IoT research. However, there is an exponential increase in publication between 2013 and 2019. Figure 4 shows the distribution of the selected studies in this field between 2011 and 2018. There is a sharp increase in publications ranging from 3 to 44 between 2015 and 2018.

*3.2. Wearable Technology (RQ 2).* The results showed that more than half of the papers (46 out of 89) had contributed to wearable technology in medicine. Based on the findings in Table 3, the most frequently investigated types of wearable sensors were related to accelerator, ECG, and thermometer

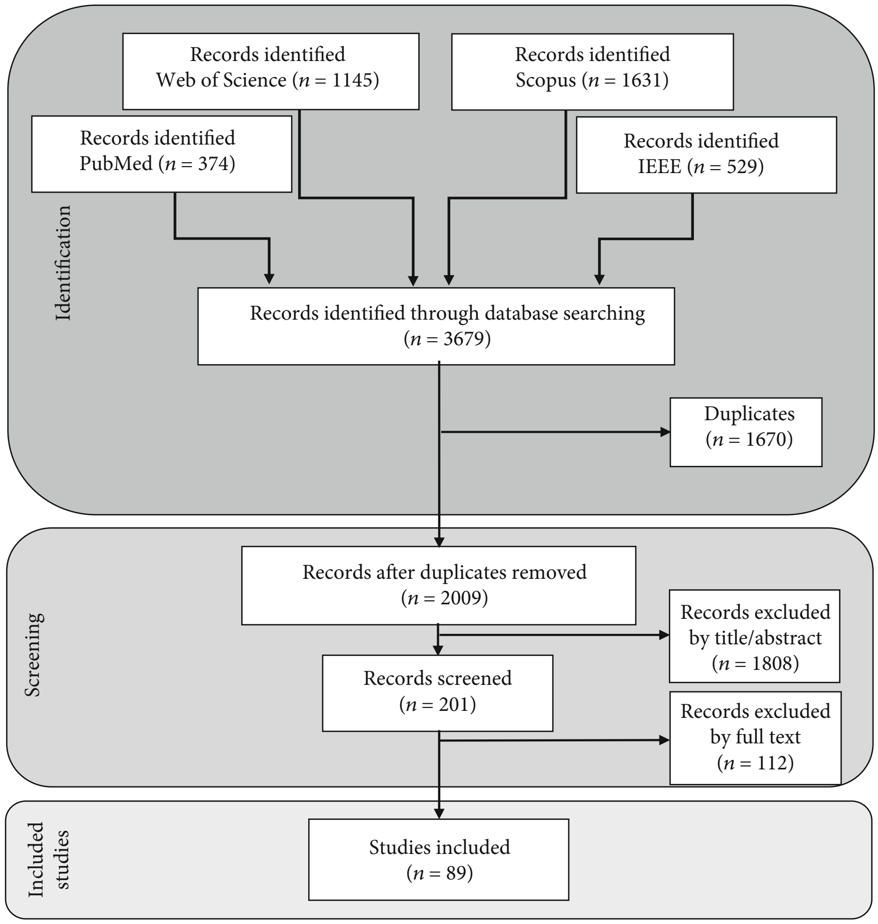


Figure 2: The flow diagram of study selection processes.

which were studied in 14, 11, and 7 papers, respectively. Apart from some articles having missed to state both their sensor types and the measuring parameters ($n = 5$), it is observed that, totally, 21 IoT sensor types have been studied in medicine. However, as the parameters being measured were not clear in two papers, a general term, i.e., physiological sensor, has been assigned to them (Table 3).

Due to the importance of wearable IoT applications, Figures 5 and 6 have been prepared to reveal details about these devices in medicine. In Figure 5, in a hierarchy plot from inner to outer layers, focus starts from the sensor types in the innermost layer, the body parts in the middle layer, and the wearable devices in the outer layer. Figure 6 demonstrates the wearable sensors and devices which can be attached to or embedded in the body parts. It is also observed that the most commonly used body parts of the body used by IoT sensors were the wrist and the chest being examined in 25 and 18 selected studies, respectively. The most commonly used sensors were accelerometers and ECG, while the former has been used prominently in the wrist (in 7 out of 18 studies) and the latter has been adopted in the chest (in 9 out of 12 studies).

The wearable IoT applications, designed for different purposes, are accordingly placed in specific parts of the body. Figure 6 shows that these applications are either placed on the body—such as a heart rate sensor set in a smart watch—or are implanted inside the body such as internal or external bone fixators. Some wearable IoT devices can be positioned in various parts of the body to measure the same parameter. For example, heart rate sensors can be placed either on the wrist or on the chest. Among these IoT types, accelerometers have shown to be adequately flexible of being used in several parts of the body.

*3.3. Wireless Communication Technologies (RQ 3).* Figure 7 shows that the main wireless communication standards such as Bluetooth, cellular networks, and Wi-Fi probed in 47, 40, and 33 papers, respectively, have been used more than the other ones in medical IoT applications. Among the short-ranged communication standards, the classic Bluetooth ($n = 33$) has been employed considerably more than the other ones. Among the cellular networks, 3G and 4G have been used more than others probably due to their faster data transition speeds [122].

*3.4. Messaging Protocols (RQ 4).* According to Figure 8, the number of 14 papers has been involved with messaging protocols of which seven and six papers have used MQTT and REST, respectively. Only one article has employed CoAP.

*3.5. The Cloud (RQ5).* More than half of the included studies (54 out of 89 studies) have presented the deployment of

Table 2: Data extraction results.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5G-smart diabetes: toward personalized diabetes diagnosis with healthcare big data clouds | 2018 [35] | ECG, pulse oximeter, and thermometer | | 5G | | | | | | |
| 2 | Arduino based IoT platform for remote monitoring of heart attacks and patients falls | 2018 [36] | Accelerometer and heart rate sensor | ThingSpeak cloud | GSM | | | | Arduino UNO and Arduino NANO | Android | |
| 3 | Behavior analysis through multimodal sensing for care of Parkinson's and Alzheimer's patients | 2018 [37] | Accelerometer, gyroscope, and magnetometer sensor | | WSN | | | | | | |
| 4 | Cloud and IoT based disease prediction and diagnosis system for healthcare using fuzzy neural classifier | 2018 [38] | Wearable sensor | | | | | | | | Java |
| 5 | Cloud computing-based non-invasive glucose monitoring for diabetic care | 2018 [39] | — | Mobile cloud computing | Bluetooth, Wi-Fi, 2G/3G/4G | MQTT/JSON | Secured with Transport Layer Security (TLS) standards. Android 7.0 allows for file-based encryption (FBE) with independent keys, encryption, and user authentication to prevent unauthorized access. | | | Android | Python |
| 6 | Cognitive IoT-cloud integration for smart healthcare: case study for epileptic seizure detection and monitoring | 2018 [40] | EEG sensor | | NFC, RFID, ZigBee, Bluetooth, Z-wave, and LoWPAN | | | | | | |
| 7 | Congestive heart failure risk assessment monitoring through Internet of Things and mobile personal health systems | 2018 [41] | _ | | Bluetooth | | Biometric solution (combination of face and voice recognition). Data stored locally in a 256-bit AES encrypted SQLite database using the SQLCipher security extension | | | Android | |
| 8 | Design and study of a smart cup for monitoring the arm and hand activity of stroke patients | 2018 [42] | — | | NFC, Bluetooth, Wi-Fi | | | | Arduino, Raspberry | | |
| 9 | Designing an Internet-of-things (IoT) and sensor-based in-home monitoring system for assisting diabetes | 2018 [43] | Wearable sensor | Microsoft Azure or Amazon AWS | Bluetooth, Wi-Fi, SMS, LR-WPANs | | | | | TinyOS | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | patients: iterative learning from two case studies | | | | | | | | | | |
| 10 | Development of IoT-based impedometric biosensor for point-of-care monitoring of bone loss | 2018 [44] | — | ThingSpeak cloud | Wi-Fi | | | | Arduino Uno | | |
| 11 | Development of sleep support system using electroencephalogram for person with developmental disorders | 2018 [45] | — | | Wi-Fi | | | | Arduino | | |
| 12 | Edge computing with cloud for voice disorder assessment and treatment | 2018 [46] | — | Edge computing and cloud computing | | | | | | | |
| 13 | Electrooculography by wearable graphene textiles | 2018 [47] | EOG sensor | | | | | ATmega328 AVR | | | MATLAB |
| 14 | ePhysio: a wearables-enabled platform for the remote management of musculoskeletal diseases | 2018 [48] | Inertial devices (accelerometer, gyroscope, and magnetometer sensor) | Edge | Bluetooth, Wi-Fi, BLE, LR-WPANs | | | | Raspberry Pi 3 | Android/ContikiOS | C |
| 15 | Fog-cloud based cyber-physical system for distinguishing, detecting and preventing mosquito borne diseases | 2018 [49] | — | Fog-cloud | RFID, GPS, mobile networks | | | | | | |
| 16 | Integrated IoT intelligent system for the automatic detection of cardiac variability | 2018 [50] | ECG sensor | | Bluetooth | | | ATmega328P AVR | Arduino UNO | Android | C, C ++, MATLAB |
| 17 | An integrated IoT-Wi-Fi board for remote data acquisition and sharing from innovative immunosensors. Case of study: diagnosis of celiac disease | 2018 [51] | | ThingSpeak | Wi-Fi | RESTful API | | | | | MATLAB |
| 18 | Intelligent hybrid remote patient-monitoring model with cloud-based framework for knowledge discovery | 2018 [52] | — | | Wi-Fi, 3G, general packet radio service (GPRS), Bluetooth, LR-WPANs, and ZigBee | | | | | | MATLAB |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | An interface for IoT: feeding back health-related data to Parkinson's disease patients | 2018 [53] | Accelerometer | | Mobile networks | | | | | Android | |
| 20 | Internet of Things for sensing: a case study in the healthcare system | 2018 [54] | — | | S-band (microwave based IEEE 802.11) | | | | | | MATLAB |
| 21 | An IoMT based cyber training framework for orthopedic surgery using next generation Internet technologies | 2018 [55] | — | | | | | | | | C#, JavaScript |
| 22 | An IoT solution for online monitoring of anesthetics in human serum based on an integrated fluidic bioelectronic system | 2018 [56] | — | | Wi-Fi, Bluetooth | | HyperText Transfer Protocol Secure (HTTPS) | ATxmega32E5 | Raspberry Pi | Android | |
| 23 | IoT-based cloud framework to control Ebola virus outbreak | 2018 [22] | Blood pressure and thermometer sensor | Amazon EC2 cloud | RFID, Wi-Fi, Bluetooth, 3G/4G | | | | | Android | |
| 24 | IoT-based wireless polysomnography intelligent system for sleep monitoring | 2018 [57] | — | | Bluetooth | | | TI MSP430 | | | Java, MATLAB |
| 25 | An IoT-enabled stroke rehabilitation system based on smart wearable armband and machine learning | 2018 [58] | EMG sensor | | BLE | | | | Arduino Mega 2560 | | MATLAB |
| 26 | MagicSox: an E-textile IoT system to quantify gait abnormalities | 2018 [59] | Accelerometer, flex sensor, gyroscope, and pressure sensor | | BLE | | | | Arduino 101 | Android | |
| 27 | Wireless ECG monitoring system using IoT based signal conditioning module for real time signal acquisition | 2018 [60] | ECG sensor | IBM Watson cloud | Wi-Fi | MQTT/HTTP | | | | | Python |
| 28 | Wearable sensor devices for early detection of Alzheimer disease using dynamic time warping algorithm | 2018 [61] | Accelerometers and gyroscope | | | | | | | | |
| 29 | Using Internet of Things and biosensors technology for health applications | 2018 [62] | — | | Wi-Fi, Bluetooth, RFID | | | | | | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Use of Internet of Things to provide a new model for remote heart attack prediction | 2018 [63] | ECG sensor | | Wi-Fi | MQTT/HTTP | | | | | |
| 31 | An ultra-low power smart headband for real-time epileptic seizure detection | 2018 [64] | EEG sensor | | BLE | | | | | | |
| 32 | Technology integrated health management for dementia | 2018 [65] | – | | Bluetooth, GPS | | | | | | |
| 33 | A technical note on the PainChek™ system: A web portal and mobile medical device for assessing pain in people with dementia | 2018 [66] | – | Amazon Elastic Compute Cloud (Amazon EC2) | Wi-Fi, Bluetooth | | | | | Android/iOS | |
| 34 | System for monitoring and supporting the treatment of sleep apnea using IoT and big data | 2018 [67] | Step counter and heart rate sensor | Fog and cloud computing | 6LoWPAN, ZigBee, BLE | | Security/privacy | STM32 | Mini Arduino, Raspberry Pi 2 Model B | Android/ContikiOS | Python, C++ |
| 35 | Spatial blockchain-based secure mass screening framework for children with dyslexia | 2018 [68] | | Cloud and fog (Amazon S3) | | | Blockchain and off-chain-based decentralized framework | | | Android/windows | JavaScript, Python |
| 36 | Real-time monitoring of bone fracture recovery by using aware, sensing, smart, and active orthopedic devices | 2018 [69] | Conductivity, contact, force/torque, and thermometer sensor | | GPS | | | | | | |
| 37 | Rapid detection of urinary soluble intercellular adhesion molecule-1 for determination of lupus nephritis activity | 2018 [70] | — | | 2G | | | | | | |
| 38 | A proposal of a usability scale system for rehabilitation games based on the cognitive therapeutic exercise | 2018 [71] | Wearable sensor | | | | | | | | |
| 39 | A proposal for a sleep disorder detection system | 2018 [72] | | | | | | | | | |
| 40 | Personalizing the fitting of hearing aids by learning | 2018 [73] | Wearable sensor | | BLE | | | | | iOS | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | contextual preferences from Internet of Things data | | | | | | | | | | |
| 41 | Online obstructive sleep apnea detection on medical wearable sensors | 2018 [74] | ECG sensor | | BLE | | | STM32L151RDT6 | | | C |
| 42 | A novel three-tier Internet of Things architecture with machine learning algorithm for early detection of heart diseases | 2018 [75] | | Apache Hbase | RFID, 5G | | | | | | Java |
| 43 | Monitoring vital signs and postures during sleep using Wi-Fi signals | 2018 [76] | | | Wi-Fi | | | | | | |
| 44 | A novel cardiac auscultation monitoring system based on wireless sensing for healthcare | 2018 [77] | | | BLE | | | 8051 | | Android | Java |
| 45 | Real-time signal quality-aware ECG telemetry system for IoT-based health care monitoring | 2017 [78] | ECG sensor | | Bluetooth/Wi-Fi/cellular networks | | | | Arduino | Android | MATLAB |
| 46 | Robot assistant in management of diabetes in children based on the Internet of Things | 2017 [79] | _ | | Bluetooth/Wi-Fi | | Encryption and decryption process (by using device ID and security token number), HTTPS | | | | C++, Python |
| 47 | Sleep information gathering protocol using CoAP for sleep care | 2017 [26] | Localization and physiological sensor | | 4G/5G/Wi-Fi | CoAP/HTTP | HTTPS encrypt the session data through SSL (Secure Sockets Layer) or TLS (Transport Layer Security) protocols. CoAP also provides security-enhanced CoAPS through DTLS (Datagram Transport Layer Security). | | Raspberry Pi 3 | | JavaScript |
| 48 | Smart health solution integrating IoT and cloud: a case study of voice pathology monitoring | 2017 [80] | — | | Bluetooth | | Watermark | | | | |
| 49 | Ultra-low power, secure IoT platform for predicting cardiovascular diseases | 2017 [81] | ECG sensor | | | | Encrypt and authenticate the communication using the ECG-generated key | | | | MATLAB |
| 50 | Usability test of exercise games designed for rehabilitation of elderly patients after hip | 2017 [82] | _ | | | | | | Raspberry Pi | | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | replacement surgery: pilot study | | | | | | | | | | |
| 51 | Wearable IoT sensor-based healthcare system for identifying and controlling chikungunya virus | 2017 [83] | Localization and thermometer | Fog | GPS/RFID | | Three fragments of varying levels of security | | | | MATLAB |
| 52 | Wearsense: detecting autism stereotypic behaviors through smartwatches | 2017 [84] | Accelerometer sensor | | Bluetooth | | | | | Android | |
| 53 | GluQo: IoT-based non-invasive blood glucose monitoring | 2017 [85] | — | ThingSpeak cloud | Wi-Fi | | | | Arduino/Intel Edison | Android | C |
| 54 | Healthcare IoT m-GreenCARDIO remote cardiac monitoring system-concept, theory of operation and implementation | 2017 [86] | ECG sensor | | GPRS/LTE/Bluetooth | | | STM32F107 | MCBSTM32 | | C |
| 55 | Development of a new ICT-based multisensor blood pressure monitoring system for use in hemodynamic biomarker-initiated anticipation medicine for cardiovascular disease: the national IMPACT program project. | 2017 [87] | Accelerometer, thermosensor, and barometer sensor | | Wi-SUN, LTE/Bluetooth low energy (BLE)/Wi-Fi | | | | | | |
| 56 | Development of Parkinson patient generated data collection platform using FHIR and IoT devices. | 2017 [88] | Foot pressure sensor | Heroku cloud (PaaS) | Bluetooth | RESTful API/FHIR | Removing the quasi-identifier and generated a random string of 14 digits consisting of integers from 1 to 9 and letters a to z as an identifier for the anonymous user (ISO/TS 25237:2008 health informatics-pseudonymization) | | | Android | |
| 57 | DJINNI: a novel technology supported exposure therapy paradigm for SAD combining virtual reality and augmented reality | 2017 [89] | Camera, localization and physiological sensor | | iBeacon/Wi-Fi/iGPS/iBeacons, RFID, Infrared, ultra-wideband | | | | | | |
| 58 | An IoT platform for epilepsy monitoring and supervising | 2017 [90] | Accelerometer and heart rate sensor | MANET MobiCloud | BLE/Wi-Fi/4G | RESTful web services/HTTP | | | | Android | |
| 59 | An innovative speech-based user interface for | 2017 [91] | — | | Infrared (IR) | | | | Raspberry Pi | Android | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | smarthomes and IoT solutions to help people with speech and motor disabilities | | | | | | | | | | |
| 60 | An intelligent and secure system for predicting and preventing Zika virus outbreak using fog computing | 2017 [92] | — | Fog and Amazon EC2 cloud | Wi-Fi/4G/GPS | | Two-stage process to prevent unauthorized access to data | | | | MATLAB |
| 61 | An international study on the determinants of poor sleep amongst 15,000 users of connected devices | 2017 [93] | Accelerometer and thermometer sensor | | | | | | | | |
| 62 | An Internet of Things framework for remote monitoring of the healthcare parameters | 2017 [94] | ECG sensor | Fog | Bluetooth/GSM (GPRS/2G/3G)/USB | MQTT/HTTP | Central server authentication (based on username and password) and data distribution service (DDS) security specification | STM32F107 | | Android | |
| 63 | A novel wearable device for continuous non-invasion blood pressure measurement | 2017 [95] | Light based sensor | | Bluetooth | | | | | | |
| 64 | A QRS detection and R point recognition method for wearable single-lead ECG devices | 2017 [96] | Heart rate sensor | | Bluetooth | | | | | Windows | C++ |
| 65 | A smart toy to enhance the decision making process at children's psychomotor delay screenings: a pilot study | 2017 [97] | — | | Wi-Fi | RESTful web services/HTTP | AES/CBC with 128-bit key | ATmega328P AVR | Arduino/Raspberry Pi | Android/iOS | JavaScript |
| 66 | A wearable health monitoring system for posttraumatic stress disorder | 2017 [98] | Accelerometer, altimeter, and optical heart rate sensor | | Bluetooth | | | | | Android/iOS | |
| 67 | A wireless health monitoring system using mobile phone accessories | 2017 [99] | ECG sensor | | Bluetooth/GPS | | | | Rfduino | Android/iOS | |
| 68 | ALZUMERIC: a decision support system for diagnosis and monitoring of cognitive impairment | 2017 [100] | — | | | | HTTPS | | | | MATLAB |
| 69 | An automatic health monitoring system for | 2017 [101] | — | | | | | | | | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | patients suffering from voice complications in smart cities | | | | | | | | | | |
| 70 | Optimized deep learning for EEG big data and seizure prediction BCI via Internet of Things | 2017 [102] | | Amazon cloud | | MQTT/HTTP | Authentication and registry and the device registry to store the certifications | | | | |
| 71 | A context-aware, interactive M-health system for diabetics | 2016 [103] | — | | GPRS/GPS | MQTT | | | | Android/iOS | |
| 72 | A new telerehabilitation system based on Internet of Things | 2016 [104] | EMG sensor | saas | Wi-Fi | RESTful web services | | ATmega328P AVR | Arduino Uno | | |
| 73 | A non-invasive method for blood glucose detection in diabetes patients with IoT application | 2016 [105] | — | | | | | | | | MATLAB |
| 74 | An IoT-based mobile gateway for intelligent personal assistants on mobile health environments | 2016 [106] | Optical heart rate sensor | AMBRO | Wi-Fi/BLE/2G, 3G, 4G, and LTE/GPS | RESTful web services/HTTP | Security and authentication module | | | Android | |
| 75 | An IoT-cloud based wearable ECG monitoring system for smart healthcare | 2016 [107] | ECG sensor | | Bluetooth, ZigBee/Wi-Fi/GPRS/LTE | MQTT/HTTP | | STM32F103RC | | | |
| 76 | Cloud-assisted industrial Internet of Things (iiot)-enabled framework for health monitoring | 2016 [108] | | | Bluetooth | | Watermarking and authentication | | | | Java |
| 77 | Efficient health care monitoring and emergency management system using IoT | 2016 [109] | — | ThingSpeak cloud | IEEE 802.15.4 GPRS/GSM Wi-Fi | | | | Intel Galileo Gen2 (Intel® Quark™ SoC X1000) | | |
| 78 | Enabling breakthroughs in Parkinson's disease with wearable technologies and big data analytics | 2016 [110] | Accelerometer sensor | | Bluetooth | MQTT | | | | | |
| 79 | Low power personalized ECG based system design methodology for remote cardiac health monitoring | 2016 [111] | — | | Bluetooth low energy/ZigBee/Wi-Fi | | | LPC1768 ARM Cortex-M3 | | | C |
| 80 | Low-power wearable ECG monitoring system for multiple-patient remote monitoring | 2016 [112] | — | | ZigBee/Bluetooth/Wi-Fi | | Secure access manager and secure TCP/IP packet | | | Android | |

Table 2: Continued.

| Ref. No. | Article title | RQ 1 Year/Ref. | RQ 2 Wearable sensor | RQ 3 Cloud-based technology 2 | RQ 4 Communication technologies | RQ 5 Messaging protocol | RQ 6 Security | RQ 7 Microcontroller | RQ 8 Development board | RQ 9 Mobile OS | RQ 10 Programming languages |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 81 | Real-time heartbeat rate monitoring system using Raspberry Pi | 2016 [113] | — | | Bluetooth | | | ATmega168 AVR | Raspberry Pi B | | Python |
| 82 | Smart toys designed for detecting developmental delays | 2016 [114] | — | | | | Symmetric encryption system called Fernet (Fernet is part of the Python cryptography library) that is built on top of AES on CBC mode with a 128-bit key. It also uses HMAC with SHA256 for authentication. | ATmega328P AVR | Arduino/Raspberry Pi | | Python |
| 83 | Assigning UPDRS scores in the leg agility task of parkinsonians: can it be done through BSN-based kinematic variables? | 2015 [115] | Accelerometer, gyroscope, and magnetometer sensor | | Bluetooth/ZigBee | | | TI MSP430 | | | |
| 84 | Assisting physical (hydro)therapy with wireless sensors networks | 2015 [116] | Accelerometer, magnetometer and pulse oximeter | | ZigBee | | TinySec, ContikiSec, and OpenSSL version (1.0.1g) | | Arduino Uno | TinyOS | C# |
| 85 | An emerging technology-wearable wireless sensor networks with applications in human health condition monitoring | 2015 [117] | Thermometer and heart rate sensor | | | | | | | | |
| 86 | IoT-based smart rehabilitation system | 2014 [118] | — | | Wi-Fi/Bluetooth/RFID/GPS | | | | | | |
| 87 | The architecture of an automatic eHealth platform with mobile client for cerebrovascular disease detection | 2013 [119] | — | | RFID | | | | | Android/Windows | ASP |
| 88 | MIOTIC study: a prospective, multicenter, randomized study to evaluate the long-term efficacy of mobile phone-based Internet of Things in the management of patients with stable COPD | 2013 [120] | | | 3G/Wi-Fi/USB/Bluetooth | | | | | Android | |
| 89 | An Internet of Things-based personal device for diabetes therapy management in ambient assisted living (AAL) | 2011 [121] | — | | 6LoWPAN/RFID/NFC | | Symmetric-key encryption AES-CBC (256-bit key), SHA256 and CRC16- ITT. 3DES (triple data encryption standard) cryptography | | | | Java |

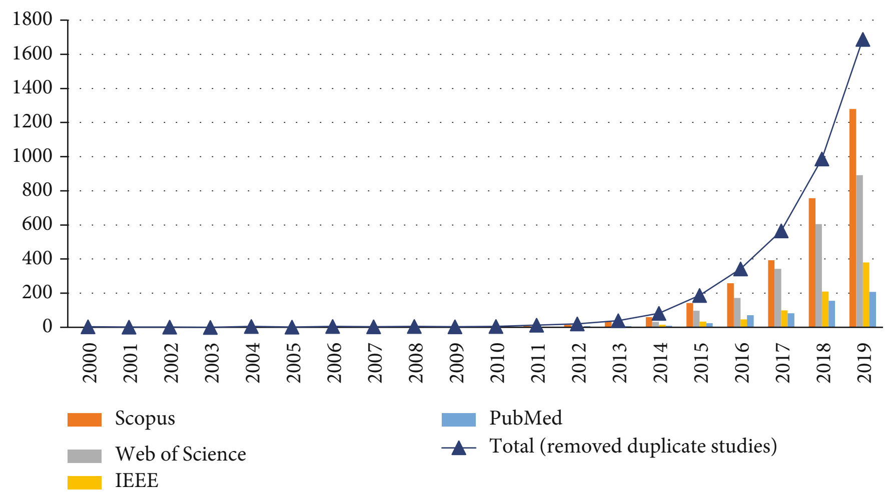


FIGURE 3: Publication trend in four databases (2000-2019).

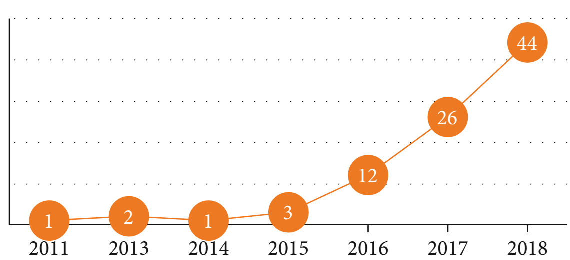


FIGURE 4: Annual publication trend of IoT in medicine.

medical IoT applications in cloud, but 39 studies have not specified the servers they have utilized. Moreover, the majority of these studies ($n = 33$) have taken advantage of both data storage and analysis in cloud (Table 4). Our review of the articles also showed that 8 articles used edge/fog computing as storage and computing systems allow data produced by IoT devices to be stored and processed close to IoT devices.

*3.6. Security Methods (RQ 6).* Of the 21 papers having referred to security in IoT applications, five ones have not stated the security method they have applied. In Figure 9, the squares in the inner layer show the reference numbers of the articles. The outer layer, i.e., the rectangles, accounts for 17 security methods used by the IoT applications in the articles. Arrows showed the relationship between the articles and the security methods they used. Some articles have applied more than one security method. It is also seen that the HTTPS as a transferring protocol and CoAPS as messaging protocols, being used in five and one articles, respectively, have provided security in six articles as well.

It was also observed that the security methods, explained in the papers, have had different security functions including encryption, authentication, watermarking, and error control. The colors of the rectangles have been associated with the types of the security functions performed. There are papers in which the simultaneous functions of authentication and encryption have been performed by the security methods (the green rectangles). In Figure 9, it is also seen that the encryption function (the yellow rectangles) has been utilized more than the other functions in the IoT uses presented in the selected papers. According to the figure, AES/CBC security method (with two different versions of 128- and 256-bit keys) is the most frequently used type of security method employed in four selected papers.

*3.7. Microcontrollers (RQ 7).* Figure 10 shows the microcontrollers and their companies. ATmega328P from the megaAVR family and STM32F107 from the ARM Cortex-M3 family were the most common microcontrollers used in IoT applications in medicine.

*3.8. Development Boards (RQ 8).* Figure 11 shows the development boards used in medical IoT applications. It was found that in the 28 selected studies, Arduino and Raspberry were the most preferred development boards in medical IoT applications.

*3.9. Mobile/IoT OS (RQ 9).* In this study, 32 of the 89 papers reported the mobile/IoT operating systems employed in medical IoT applications. It was found that Android, iOS, and Windows have been identified as the major mobile OS and TinyOS and ContikiOS have been employed for medical IoT applications. Figure 12 shows that some of the medical IoT applications are based on one or two mobile operating systems. Multiple operating systems may be used in some applications, for example, five papers employed iOS and Android, two papers used Windows and Android, and two papers used ContikiOS and Android for their IoT applications.

*3.10. Programming Languages (RQ 10).* Figure 13 shows programming languages and their contribution in medical IoT. It was found that MATLAB was the most widely used programming language in the papers ($n = 13$). The other most favored languages in terms of the magnitude of their frequency use were shown to be Python, C, and Java, being used 7, 6, and 6, respectively.

Table 3: Wearable sensors.

| Wearable sensor types | Another term | Measuring parameters | Count |
|---|---|---|---|
| Accelerometer | | Acceleration | 14 |
| ECG sensor | Electrocardiography | Electrical and muscular functions of the heart | 11 |
| Thermometer | Temperature sensors | Temperature | 7 |
| Heart rate sensor | | The number of heart beats per minute (bpm) | 5 |
| Gyroscope | Angular rate sensors | Orientation and angular velocity | 5 |
| Unspecified∗ | | Unspecified∗∗ | 5 |
| Magnetometer | | Magnetism | 4 |
| Localization sensor | Position sensor | Indoor and outdoor locations | 4 |
| Pressure sensor | Force sensor | Pressure/force/torque on a rotating system | 4 |
| Optical heart rate sensor | Photoplethysmography (PPG) | Heart rate | 3 |
| EMG sensor | Electromyography | Electrical activity produced by skeletal muscles | 2 |
| Pulse oximeter | | Oxygen saturation | 2 |
| EEG sensor | Electroencephalography | Electrical activity generated by the brain | 2 |
| Physiological sensors | | Unspecified∗∗ | 2 |
| EOG sensor | Electrooculography | Corneoretinal standing potential that exists between the front and the back of the human eye | 1 |
| Actigraphy | Actimetry sensor | Human rest/activity cycles | 1 |
| Altimeter | Altitude meter | Altitude of an object above a fixed level | 1 |
| Blood pressure sensor | | Blood pressure | 1 |
| Conductivity sensor | | Electrical current | 1 |
| Flex sensor | Bend sensor | The amount of deflection or bending | 1 |
| Step counter sensor | Step detector sensor | Steps | 1 |
| Barometer | | Air pressure | 1 |
| Camera | Image sensor | Photographs of daily living | 1 |

∗The sensor type was not specified. ∗∗The measuring parameters were not specified.

## 4. Discussion

The results of the current study, aimed at finding out the current features of IoT applications in medicine by means of answering 10 research questions, were previously mapped into the tables and figures in Results.

*4.1. Medical IoT Model.* A synthesized model of our findings has been presented in Figure 14 due to the depth of the details. Having rearranged the results of the study, this figure has divided the recognized IoT features in medicine into four layers, namely, devices and sensors, networks, cloud servers, and applications.

*4.1.1. Device and Sensor Layer.* Our findings on IoT devices in medicine consisted of a variety of wearable devices that can be used in the diagnosis, treatment, and control of patients' activities. These devices, which are noninvasive in nature, are either implanted inside the body—such as the fixators mounted on the bones—or are mostly attached on the body parts, chiefly on the wrist or the chest. As the data derived from the sensors is raw and unintelligible, it is gathered by the sensor nodes and then transmitted to the computing server by means of smartphones, development boards, and microcontrollers.

Arduino and Raspberry have been the most investigated development boards while Raspberry Pi is used as a single-board computer in complex projects, but Arduino is a microcontroller motherboard. According to a comparison made among the cutting-edge development board models, Raspberry Pi 3, apart from its greater power consumption, is less expensive than Arduino and enjoys larger memory as well as more supportive communication and connectivity capabilities [32].

Microcontrollers, having appropriate hardware and computing capabilities for processing data and controlling the devices, are the integral part of IoT devices. According to the results, the most common microcontrollers used in medical IoT applications are ATmega328p microchip and STM32F107 from megaAVR and Cortex-M3 families, respectively, owing most probably to the high performance and low energy consumption of the former and low-power demand of the latter. It is worth mentioning that microcontrollers belonging to AVR Xmega family possess all the features related to those of megaAVR family, with even more competencies, including delivering the best possible combination of real-time performance, high integration, and low power consumption for 8/16-bit MCU applications [123]. As only one of the selected studies has worked on AVR Xmega microcontroller family, it seems that the advantages of these family members are not clearly known to the

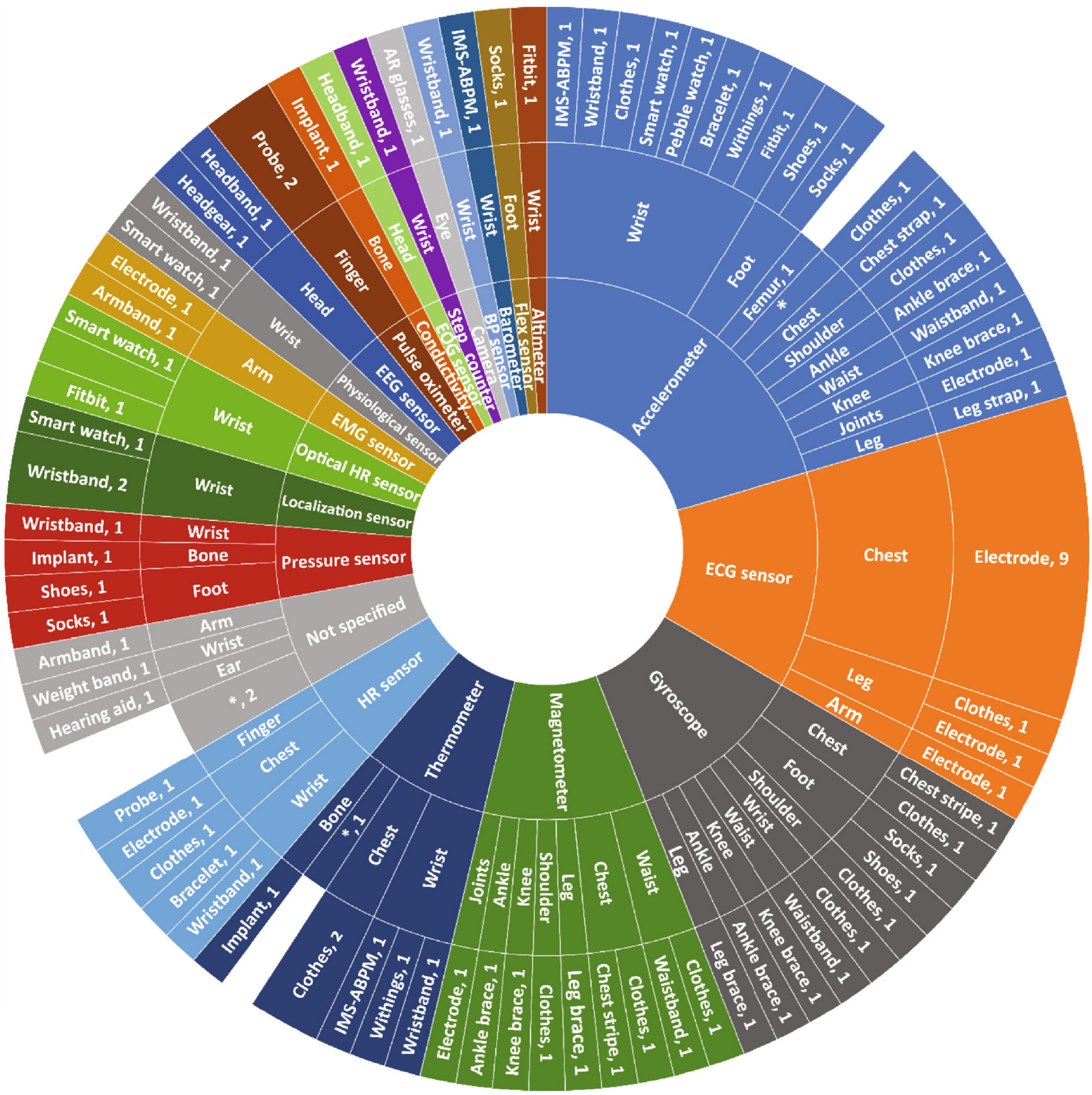


Figure 5: Hierarchy diagram (from inside to outside) of the sensor types, the engaged parts of the body, and the wearable devices.

producers. Another important finding was that although both Cortex-A and Cortex-M microcontroller families are appropriate for IoT applications, especially for the wearable devices [124], our results show that the selected papers in our study have used only from Cortex-M family microcontrollers.

End users can develop their IoT applications by programming the embedded microcontrollers and development boards or software of the applications using programming languages that have been found to be significantly MATLAB, Python, Java, and C. This finding can be attributable to MATLAB as a multiparadigm numerical computing environment with a proprietary programming language and its other distinguishing features, namely, multipurpose functionality and a variety of available tools. On the other hand, Python is an interpretable, interactive, object-oriented programming language with prettier syntax and more readability without compromising the size [125]. Nevertheless, taking some surveys into account, their findings are not in line with ours, as C and Java have shown to be used more frequently [126, 127] so much so that in IoT developer survey [126], MATLAB was not investigated as a programming language at all. Of the languages mentioned above, Python is the fastest growing language with the contribution rate of 1.5 [128].

Proposing various wearable devices in more than half of our selected papers testifies the fact that their use for continuous monitoring of physical and psychological behavior of the patients in order to efficiently improve the quality of care [129] has recently been recognized medically and socially. The magnitude of our selected articles working on wearable devices compared to those in the related literature [17, 18,

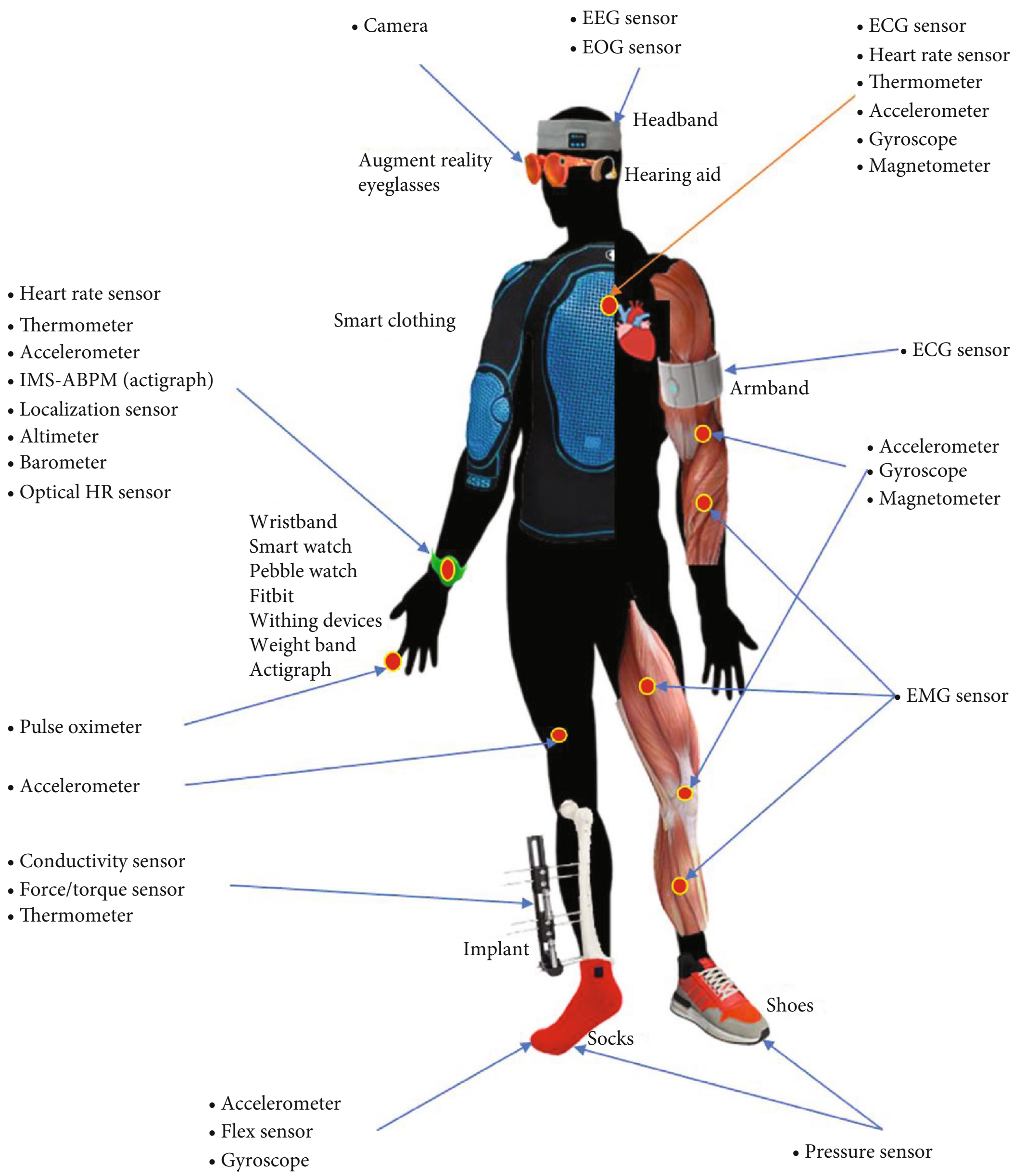


Figure 6: Wearable sensors and devises attached to or implanted in the body.

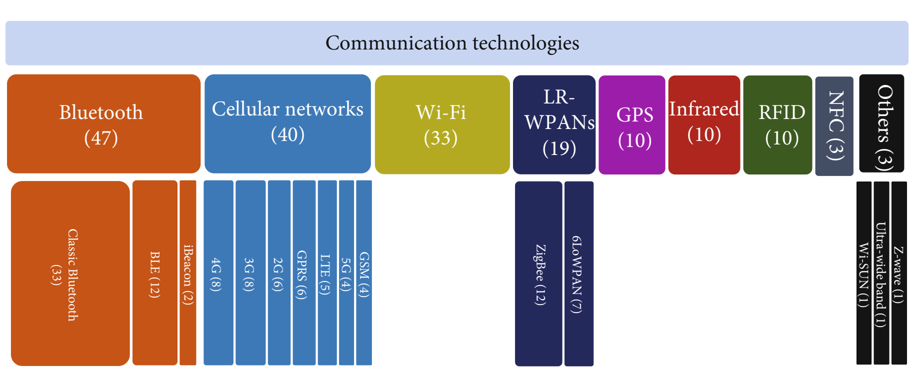


Figure 7: Frequency and classification of communication technologies.

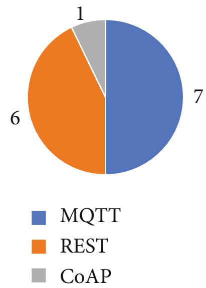


Figure 8: Messaging protocols used in the related studies.

Table 4: Cloud services and servers.

| Cloud services | Count | Cloud servers | Frequency |
|---|---|---|---|
| Storage and analysis cloud | 33 | ThingSpeak cloud | 4 |
| | | Amazon EC2 | 2 |
| | | Amazon AWS | 1 |
| | | Amazon cloud | 1 |
| | | Apache Hbase | 1 |
| | | Microsoft Azure | 1 |
| | | MANET MobiCloud | 1 |
| | | IBM Watson cloud | 1 |
| | | Servers not mentioned | 21 |
| Storage cloud | 21 | Heroku cloud | 1 |
| | | Amazon S3 | 1 |
| | | AMBRO | 1 |
| | | Servers not mentioned | 18 |
| Total | | | 54 |

20] can be attributable, on the one hand, to the systematic mapping design of our study which normally necessitates a large data and, on the other hand, to the absence of any limitation in our included sensors. Unlike our study, Scarpato et al. [19] have scrutinized only the wearable sensors related to heart rate monitoring, diabetes, and oxygen saturation pulmonary disease and Baker et al. [20] have focused only on nonobtrusive and noninvasive sensors. Although Islam et al. [18] have not mentioned any limitations in their study, the number of the sensors studied was much less than those in our study. Neither of these studies has examined the implantable sensors. Qi et al. [17], while having classified the sensors as wearable and ambient, have studied only 11 sensors.

*4.1.2. Network Layer.* In our synthesized findings, a variety of short-ranged and long-ranged communication technologies and standards are available to provide wireless connections between and among the sensors and the IoT devices. Due to the limitation of storage and processing of mobile phones, the data collected is transferred to the cloud via gateways through short-ranged communication technologies such as Bluetooth or Wi-Fi and long-ranged communication such as cellular networks. About one-third of the papers pointed to security. Some of the papers have proposed solutions for security issues because privacy and security are important concerns that IoT applications in healthcare need to pay serious attention to [15, 18, 27, 28]. Based on the IoT developer survey, security, interoperability, and connectivity are the top three concerns of IoT [126].

According to our findings, the HTTPS and CoAP messaging protocols are also seen as security methods. To justify this capability, HTTPS is actually a secured form of HTTP that uses Transfer Layer Security (TSL) or Secure Sockets Layer (SSL) protocols to encrypt data sessions [26]. On the other hand, CoAP uses Datagram Transport Layer Security (DTLS) as a security protocol for automatic key management, data encryption, integrity protection, and authentication [130].

Our findings related to the outnumbering of the encryption function of the security methods in the selected medical IoT papers can designate the importance of confidentiality in medicine witnessing that unauthorized users are unable to access the patient health information. On the other hand, the findings denoting the outnumbering of AES over other security methods used in the papers can also stand for the attention is usually paid to health data because this method was firstly published by the U.S. National Institute of Standards and Technology (NIST) to encrypt sensitive data [131].

The reason why, in medicine, classic Bluetooth is a more frequently investigated short-ranged wireless communication technology compared to Wi-Fi can be attributable to the more availability and accessibility as well as the existence of a more personal area network for the former over the latter. On the other hand, exchanging data in IoT by Bluetooth mostly occurs by means of smart watches and mobile phones probably making this technology the most debated form of IoT in the literature. Unlike this finding in our study, in Ahmadi et al. [15], Wi-Fi was found to be focused more frequently in their selected studies compared with classic Bluetooth. This difference could be the result of the smaller number of selected papers in their study ($n = 60$) compared with those of ours ($n = 89$). Yet, regarding long-range wireless communication technologies, Ahmadi et al. [15], similarly, found that cellular network was the most frequently probed one. Our finding on 4G, as the most explored network in medical IoT applications, can be indicative of its higher speed and bandwidth in transferring a variety of data including texts, images, and audio/video files.

*4.1.3. Cloud Server Layer.* Storage and computing functionalities are moving from end devices to centralized data and computing centers. High capacity of cloud in both computing and storage of data can illuminate the reason why in our study about 60% of the selected studies have used cloud for both storage and computing. This finding agrees with that of Ahmadi et al. [15] showing that the majority of their selected papers have used cloud for the same purposes. This finding can stand for the ubiquitous use of this technology due to its multifunctional features. The fact that in a considerable number of the selected studies the cloud servers were not mentioned may be regarded as a flaw because the more

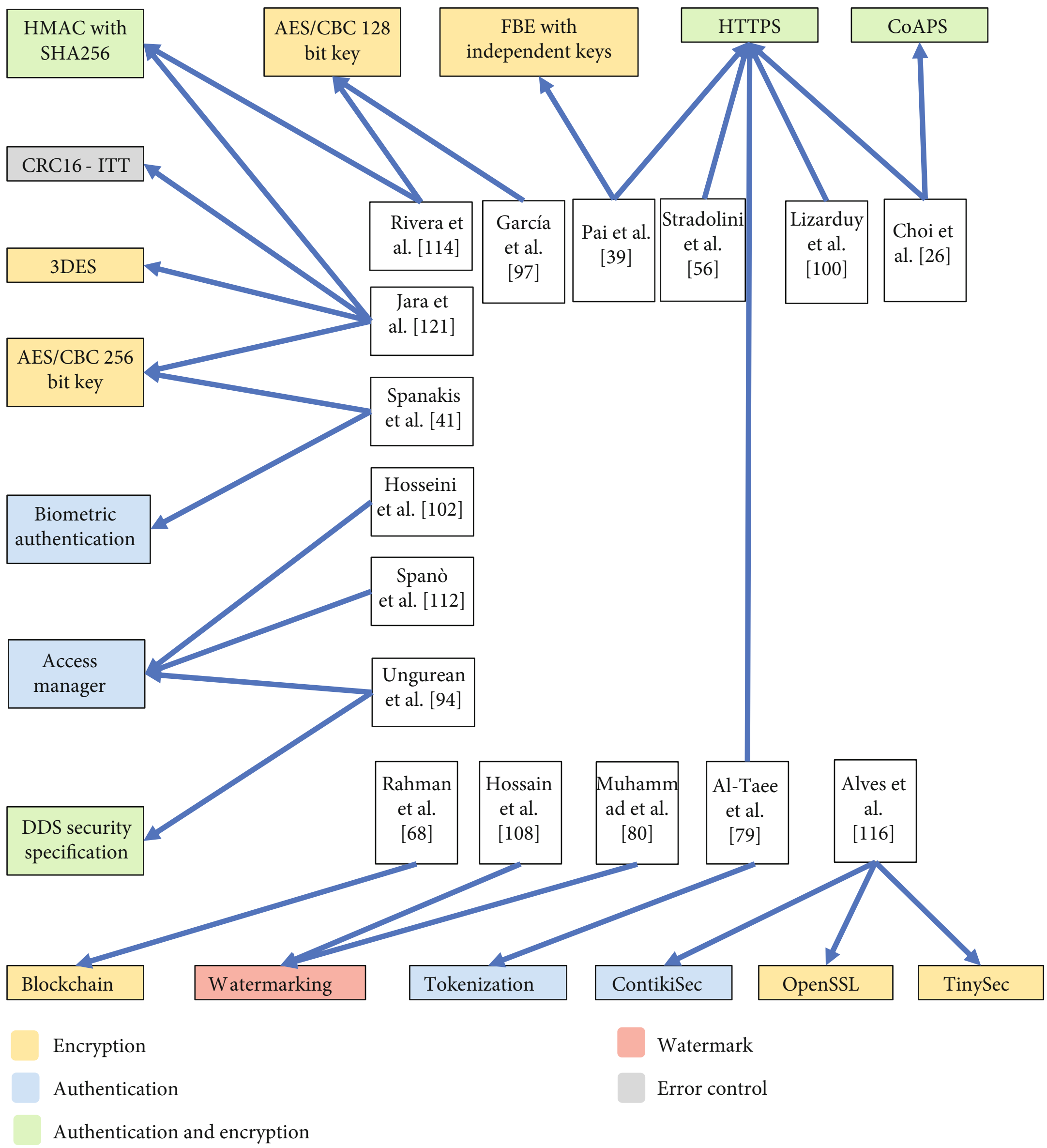


FIGURE 9: Security methods used in studies [26, 39, 41, 56, 68, 79, 80, 94, 97, 100, 102, 108, 112, 114, 116, 121].

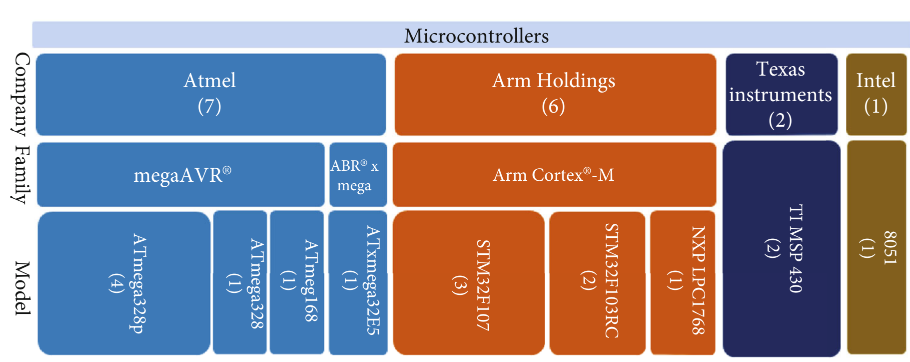


FIGURE 10: The microcontrollers used in medical IoT in and their manufacturing companies.

information we provide about the methodology of the research, the better understanding and appreciation as well as easier replicability occurs on the part of the readers.

The cloud has some shortcomings in handling big data such as response delays and network loads [132]. Due to the exploding volume of data collected from IoT devices, it

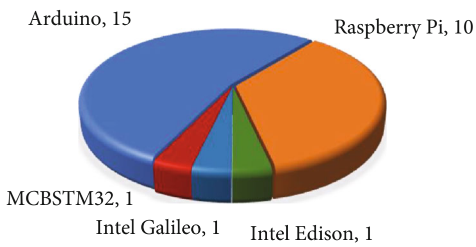


Figure 11: Development boards.

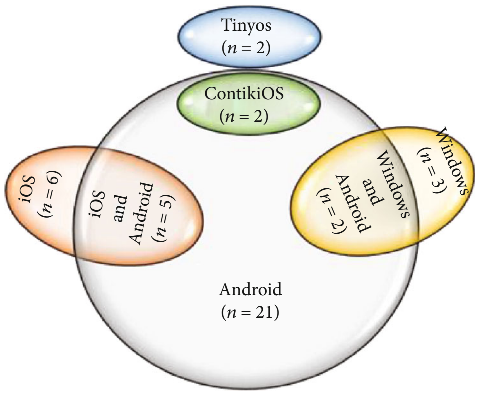


Figure 12: Usage share of mobile operating systems.

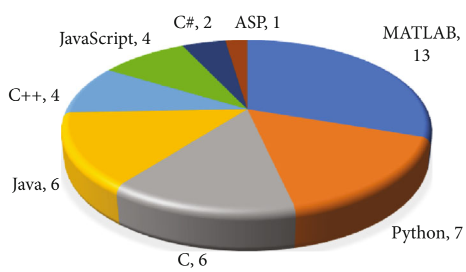


Figure 13: Programming languages.

is necessary to use fog/edge computing to extend the cloud by performing intermediary functions at the edge of the network. Fog/edge computing reduces latency problems by minimizing dependence on cloud-based services to analyze data. Because medical IoT applications require a rapid processing of medical data as well as storage, fog/edge computing provides IoT developers with real-time analysis of medical data. The results of this study showed that 9% of the studies were based on fog/edge computing. Based on the role of fog/edge computing in alleviating some of the problems of cloud-based IoT applications, IoT developers should be more involved with these technologies.

*4.1.4. Application Layer.* MQTT, REST, and CoAP protocols have been used to transfer data among IoT devices. To use these protocols, brokers (servers) that are primarily located in the cloud are needed. The more tendency or need for conducting research on HTTP compared with the other transfer protocols might be due to its popularity in the web. Largeness of messages in HTTP has caused this protocol to require high bandwidth while it is crucial for IoT applications to communicate with low bandwidth. On the other hand, IoT needs a long-lived connection. To fulfill these requirements, MQTT and CoAP have been presented in IoT with less latency of data transmission and communications overheads.

These protocols are very useful for large data or low bandwidth [26, 107] or, especially, for continuous real-time monitoring [107]. Nevertheless, CoAP has some advantages over MQTT as the latter works based on publish/subscribe mechanism, while the former uses the two mechanisms of request/response and publish/subscribe and is usually used when the application has limitation in energy consumption. Moreover, CoAP can be translated into RESTful web and HTTP by using proxies in order to be able to work on the web. CoAP uses URI (Universal Resource Identifier), and unlike MQTT and HTTP, CoAP works on UDP (User Datagram Protocol) which enables the application to connect to unlimited number of networks [26].

However, despite providing less message size, message overhead, power consumption, resource requirement, bandwidth, and latency while offering better support for security and additional services, CoAP has been used less than MQTT in IoT [26]. Our finding concerning the trivial research attention made on using CoAP messaging protocol verifies the same tendency of the users.

The fact that more than half of our selected papers have used Android as their operating system could be due to the fact that Android is an open source platform with high customization and low cost capabilities [133]. The 40% market share of Android uses [133] is in line with our finding. The next popular operating system, iOS, is, however, a close and limited platform. Contiki is widely used by IoT researchers or developers for memory-constrained and low-power IoT devices. TinyOS is an embedded operating system for low-power wireless devices and wireless sensor networks (WSN) [33].

*4.2. Annual Publication Trend.* The dramatic increase in medical IoT papers from 2015 to 2018 shows that publication has steadily increased every year. As a result of the emergence of more IoT applications, an increase is seen in the number of publications ranging from 987 to 1688 papers between 2018 and 2019. Our findings generally call attention to the fact that IoT in medicine is still a hot topic with various aspects which entail more scrutiny.

*4.3. Limitations of Our Study.* We encountered two limitations in our study. (1) Quality assessment was not carried out for the selected papers for two reasons: (a) this step is optional in systematic mapping studies, not compulsory; (b) we did not want to miss any attempts having been made on studying the technological aspects of medical IoT development. (2) Manual searching in the reference lists of the selected articles was not carried out, and (3) working on this study started in 2018 and the time spent on its preparation and publishing lasted over one year. Thus, the 2019 related articles were not included since we had already reached the results and prepared the tabular and graphical illustrations.

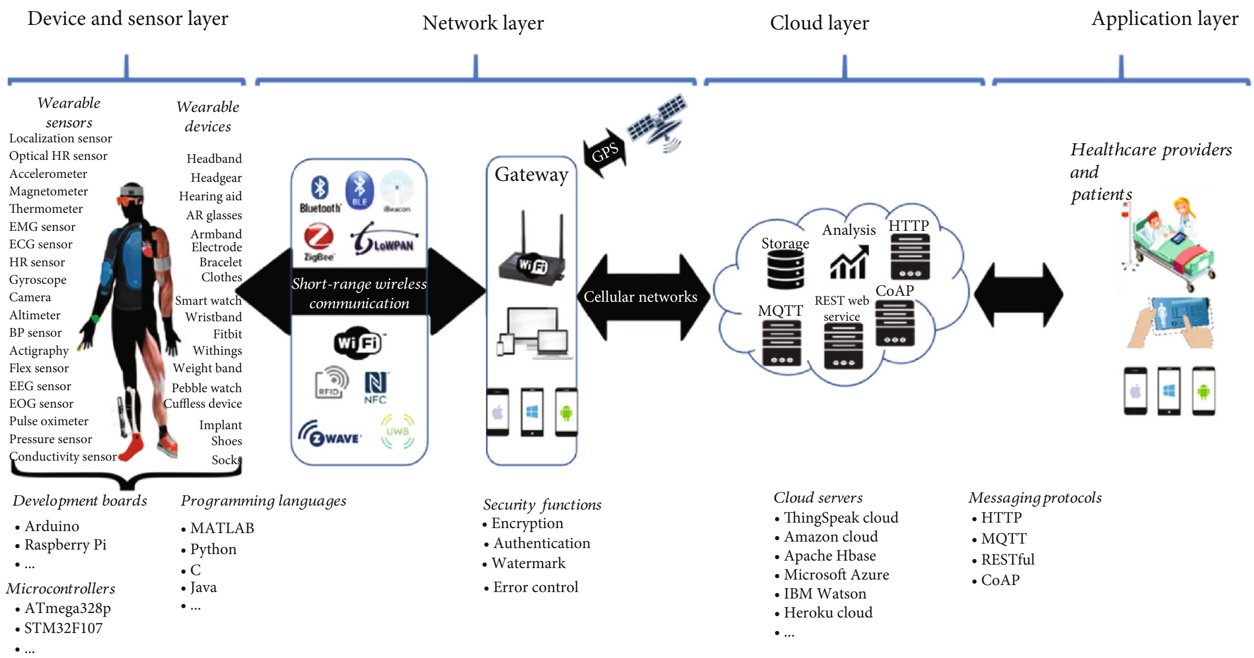


FIGURE 14: A synthetized model to show the relationships among the study outcomes.

## 5. Conclusions

From the findings of our study, the following various gaps were noticed which could be the inspiring areas of research and activity for the interested scholars or the IoT developers in the field.

(1) Security is of the utmost importance both in IoT devices and in medicine. As a tradeoff exists between security of an IoT device and its performance, more than one security method is occasionally used to enhance the IoT's safety provided that this does not cause performance reduction. Despite the significance of the security methods, only 16 papers out of 89 have clarified this feature of the IoT(s) they have presented. This shortage can affect our general trust and reliance in a given IoT performance. We suggest that incorporation of the security method used in the description of any IoT development be inevitable. (2) Concerning different advantages of utilization of CoAP over MQTT discussed above, it is needed to scrutinize the reasons or find the ways to make more publicity on the former. (3) At least half of the medical IoT applications are cloud-based, showing that storage and computing are changing into centralized data centers. However, due to some problems attributed to the cloud, such as high latency and network overload, medical IoT applications are unable to run real-time analytics. Edge and fog computing are two potential solutions, but few studies have used these technologies in medical IoT applications. (4) Apart from TinyOS and ContikiOS—two major IoT operating systems for memory-constrained and low-power wireless IoT devices—that have been underused in medicine, other operating systems, such as RIOT, MbedOS, Brillo, and Zephyr, are not yet employed in medical IoT applications. (5) It is expected that IoT in medicine undergoes more substantial enhancements in the near future as increasing developments in wireless communication technologies are under way to reduce power consumption and costs. This can be fulfilled by increasing the use of newer technologies such as BLE, ZigBee, 6LoWPAN, NFC, and 5G. (6) Programming languages such as MATLAB, Python, Java, and C are being used for IoT developments in medicine. MATLAB is mainly used for scientific and technical computing in validation research. But Python language with its capability of being used both in evaluation and validation research enjoys even further advantages, namely, having substantial power and speed in information analysis and community and library support as well as being easy-to-learn, easy-to-debug, embeddable, extensible, interpretable, portable, and being a free and open source. (7) Last but not least, two almost unnoticed facts about microcontrollers are worthwhile to mention here: firstly, AVR Xmega family delivers the best possible combination of real-time performance, high integration, and low power consumption for 8/16-bit MCU, and secondly, apart from Cortex-M microcontroller family used in our selected papers, Cortex-A is also suitable for IoT uses. More considerations of these electronic chips are, therefore, recommended.

## Conflicts of Interest

The authors declare no conflicts of interest.


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## Supplementary Materials

Supplementary table includes supplemental material (extracted data of the 89 articles) related to the research questions. The bibliographic data (title and year of publication) and the technological features used in the articles are clustered in the table. *(Supplementary Materials)*

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