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# A Review of the State of the Art for the Internet of Medical Things

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**Abstract:** The technological developments in the Internet of Things (IoT), data science, artificial intelligence, wearable sensors, remote monitoring, decision support systems, fog, and edge systems have transformed digital healthcare. Especially after the pandemic, there has been a rapid transformation of healthcare infrastructure from a conventional to a digital approach. Now, specifically, technologies such as the Internet of Things play a vital role in the transformation of the healthcare system. In this paper, an effort has been made to encompass the transformation of healthcare with a focus on the Internet of Medical Things (IoMT). In particular, it provides a detailed overview of the Internet of Medical Things whilst discussing the design goals and challenges, the resource constraints and limitations of the complex healthcare systems. The paper also provides a detailed account of the research initiatives as well as off-the-shelf wireless motes, internet-enabled sensors and open-source platforms. A thorough account of the next-generation digital healthcare technologies and future research opportunities is provided. This work not only covers the state-of-the-art but also offers critical insight into the digital healthcare challenges. The work attempts to summarise the extensive literature in the domain and present a new perspective on the internet of medical things, affiliate technologies and their role in healthcare.

**Keywords:** IoT; IoMT; data science; eHealth; medical technology

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## 1. Introduction

The Internet of Medical Things (IoMT) encompasses a network of medical devices and applications which enable advanced healthcare systems to function seamlessly. The IoMT plays a significant role in the evolution of healthcare technologies. The interconnected devices and systems in IoMT help enhance patient care, improve operational efficiency, and reduce healthcare costs [1]. These devices generate, collect, analyse, and transmit health data, facilitating real-time monitoring and management of patient health, enabling decision support systems and offering flawless operational efficiency of connected healthcare systems [2].

IoMT, while primarily dependent on the connected medical devices/sensors, has a much wider scope and thus encompasses sensing, connectivity, data collection and management, advanced analytics, user interfaces, web dashboards and decision support systems.

In IoMT, medical devices could broadly be divided into wearable, implantable and stationery devices. Wearable devices, such as fitness trackers, smartwatches, and biosensors, continuously monitor vital signs like heart rate, blood pressure, and glucose levels. These devices provide real-time health data, enable proactive management of chronic diseases, and promote healthier lifestyles [3]. Implantable Devices, such as pacemakers and insulin pumps, are surgically implanted to monitor and manage health conditions. These offer constant health monitoring, improve patient outcomes, and reduce the need for frequent hospital visits. Stationary medical equipment, such as MRI machines, CT scanners, and infusion pumps, is used in clinical settings to diagnose and treat patients. These devices enhance diagnostic accuracy, streamline treatment processes, and facilitate remote monitoring of in-patient data. IoMT's wireless communication capabilities enable seamless interaction between medical devices and healthcare systems. The connectivity is supported by several state-of-the-art technologies such as WiFi, Bluetooth, cellular networks, 6LowPAN, and WirelessHART [4], which ensure continuous data transmission, support real-time monitoring, and facilitate telehealth services. The connectivity also facilitates cloud-based services in IoMT, such as scalable storage and computing power for managing and analysing large volumes of health data. Some well-known examples of this include Amazon Web Services (AWS) HealthLake and Google Cloud Healthcare API [5]. Cloud services offer secure data storage, facilitate big data analytics, support interoperability between different healthcare systems, manage comprehensive patient records, support longitudinal health studies, and enable data-driven decision-making. Advanced analytics are also used in IoMT-enabled systems, which use machine learning (ML) and artificial intelligence (AI) to analyse health data, predict health trends, and provide clinical insights. Tools like IBM Watson Health, Google DeepMind Health and advanced ML and AI techniques improve diagnostic accuracy, enable personalised treatment plans, and enhance preventive care strategies. User interfaces and health dashboards are becoming an essential element of the wider IoMT ecosystem. User interfaces (MyFitnessPal, HealthKit, Medisafe) provide platforms for patients and healthcare providers to interact with IoMT systems, which empower the patients to manage their health, facilitate remote consultations, and improve medication adherence. Furthermore, healthcare dashboards offer healthcare providers real-time insights into patient data [6].

All these components enable IoMT to offer extensive benefits and serve as a catalyst for change in the legacy healthcare system. A graphical representation of the IoMT system is presented in Figure 1.

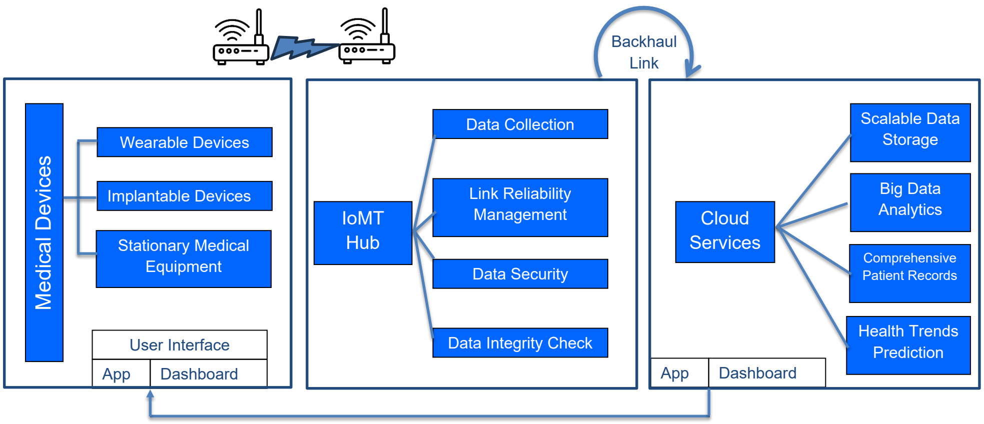


**Figure 1.** Internet of Medical Things (IoMT) enabled Healthcare infrastructure.

The IoMT, while essential in today's healthcare industry, is not the only solution, and several other legacy systems exist, such as traditional sensor networks, telehealth and telemedicine systems. It is, therefore, essential to evaluate the systems with the legacy systems and how IoMT differs from these. In Table 1, a comparison is provided which outlines the key differences between the Internet of Medical Things (IoMT), traditional sensor networks, and other similar solutions from the past. This comparison highlights aspects such as connectivity, data management, application areas, and the level of intelligence and integration [7].

**Table 1.** Comparison of IoMT with traditional sensor networks and similar solutions.

| Feature/Aspect | Internet of Medical Things (IoMT) | Traditional Sensor Networks | Similar Past Solutions (Telemedicine, Telehealth etc.) |
| --- | --- | --- | --- |
| Connectivity | Uses advanced connectivity technologies like Wi-Fi, Bluetooth, 6LowPAN, WirelessHART, 5G | Typically uses basic wireless technologies | Often limited to wired connections or basic telephony |
| Data Management | Advanced data analytics and machine learning for real-time insights | Basic data collection with limited processing | Data often processed manually or with basic software |
| Integration | Highly integrated with healthcare IT systems and EHRs | Limited integration capabilities | Integration mainly at the software level |
| Application Areas | Comprehensive healthcare monitoring, diagnostics, and treatment | Basic environmental or health monitoring | Primarily remote consultations and diagnostics |
| Level of Intelligence | High (AI and machine learning for predictive analytics) | Low to moderate (simple algorithms) | Low (basic decision support systems) |
| Security Measures | Robust security protocols to protect sensitive health data | Basic security measures | Basic security, often vulnerable to breaches |
| Patient Interaction | Real-time interaction and feedback | Limited interaction capabilities | Scheduled interactions via phone or video |
| Examples of Devices | Wearables, implantables, smart hospital equipment | Simple sensors for temperature, heart rate, etc. | Telemedicine kits, basic diagnostic tools |
| Cost Efficiency | Potential for high initial cost but long-term savings | Generally low cost | Varies, often high due to hardware and maintenance |
| Regulatory Compliance | Strict compliance with healthcare regulations (e.g., HIPAA) | Limited regulatory requirements | Varies by region and application |

Several recent survey articles have attempted to provide comprehensive reviews of IoMT, their applications and related challenges [8–11]. Ref. [8] provides an overall overview of fundamental concepts, underpinning architectures and application areas of IoMT and is limited to generic definitions and discussions without going into specifics of the reviewed topics. On the other hand, Prasad et al.'s work [9] focuses on the importance of data processing and supporting infrastructure in IoMT applications, proposing integration of the Federated Learning approach into IoMT. The data aspect of the IoMT and the use of lightweight AI is further explored in the most recent survey article by He et al. [10], with a strong emphasis on Explainable AI [11] also provides an in-depth review of the area with a systematic approach to organising the IoMT-related challenges into those with technical and social implications. While some of the work presented in our review overlaps with the work presented in the recent surveys, the added value of this paper is to evaluate the differences between legacy sensor network technology and current IoMT, as well as linking IoMT to Global Medical Devices Nomenclature (GMDN) Agency classification of medical devices. Furthermore, it takes a different approach to organising IoMT-related challenges, which are then linked to specific case studies and Off-the-shelf solutions.

IoMT plays an essential role in the healthcare ecosystem and offers exceptional benefits over legacy systems. This article aims to provide a comprehensive overview of the technology, its architecture, applications, and stakeholders whilst also highlighting some case studies and off-the-shelf solutions, finishing by looking at the challenges. A detailed overview of the paper's contributions and novelty is discussed in the key contribution sections.

## 2. Internet of Medical Things

This section provides an overview of the Internet of Medical Things, how they are embedded into current healthcare architecture, its significance, and the benefits of IoMT in transforming conventional healthcare architecture.

### *2.1. Overview of IoMT*

Healthcare is reaping the benefits of the increasing pervasiveness of the Internet of Medical Things (IoMT) and its provision of new avenues for the continuous monitoring of health parameters. Today, IoMT is becoming a residing feature in all aspects of healthcare, from medicine, dentistry, pharmacy, midwifery, nursing, and optometry.

The Internet of Things (IoT) phenomenon has made way for IoMT. At the forefront of modern-day technology, IoT has become a reality [12] evolving from some experimental inter-connected appliances back in 2009 to nearly all common types of devices, including cars, TVs and fridges, all now extended to offer the 'connecting internet'. The journey has not been without challenges, but many have been overcome with the enablement of enhanced network capabilities, tools to manage and interpret data from IoT [13] and the vital creation of new standards. The ultimate challenge of gaining smooth interaction for IoT hardware and software from different vendors while new things are being invented and 'integrating the previous with the new' [14] has seen researchers and computing professionals seeking answers in the fight to maintain 'ubiquitous computing'.

IoMT wearable sensors monitor health parameters from blood pressure, epilepsy, diabetes, and heart and bowel conditions. Vital signals can now be monitored from sensors in infusion pumps, chest bands, finger pulse oximeters [15], wrist-worn accelerometers (to measure movement in Epilepsy patients) [16] and EEG sensors to measure brain activity. Interestingly, the impact of IoMT can be seen most notably when deploying IoMT in-home, on-body, in the community, and in-hospital [17].

The increasing number of connected medical devices can generate, collect, analyse and transmit data. The data, along with the devices themselves, are creating IoMT, a connected infrastructure of medical devices, software applications and health systems and services [18]. Prevalent examples of IoMT include the remote patient monitoring of patients with long-term and chronic conditions.

Old and/or conventional medical means and instruments that have been used in past decades are now being renovated and deployed for IoMT technology. For example, there is IoMT technology to identify patients location upon hospital admission and medication management trackers for patient medication prescription services [19].

Consequently, IoMT technology requires complex architecture and significant components, for example, the hugely scalable Cloud, thus, the connection of a medical device to the cloud opens a world of new possibilities for patient care [20]. Its infrastructure provides the resources that a vendor can use on demand and makes it simpler to unburden storage and manage tasks from IoT devices to cloud servers. Therefore, big data technologies are now accessible, affordable and, in essence, a compliment to IoMT.

### *2.2. How IoMT Embeds into Current Healthcare Architecture*

If more data is generated about a specific patient, then it stands to reason there will be improved patients' outcomes, traditionally, medical devices were designed for a specific application, if connectivity is added to a device, more meaningful data can be generated.

Traditional everyday medical devices are becoming smart-enabled, and the development of connected medical devices is underway. The medical technology (Medtech) industry produces a wide range of medical products that help to diagnose, monitor, and treat diseases and health conditions. The 500,000 medical technologies currently available have a beneficial impact on people's health and quality of life [18].

As observed by the Global Medical Devices Nomenclature (GMDN) Agency [21] (see Table 2 below), medical devices fall within 21 categories of Medtech products. The classifications are varied, showing small appliances such as plasters and syringes to laboratory instruments and implements used for surgery, monitoring/diagnostic devices and imaging machines [18].

Although there is an increasing number of connected medical devices on the market, it is interesting to observe that all the device classifications below also have the potential to be connected medical devices [18]. This is made possible because of the increase in hardware capacity enabling embedded sensors, continuous software advances, and IoT protocols with faster connectivity, such as Fifth Generation (5G) cellular networks provide key enabling technologies for ubiquitous deployment of the IoT technology [22].

**Table 2.** Classification of medical technologies as determined by the GMDN.

| Code | Classification | Example |
|---|---|---|
| 01 | Anaesthesia and respiratory devices | Oxygen mask, gas delivery unit, anaesthesia breathing circuit |
| 02 | Body fluid and tissue management devices | Haemodialysis devices and heart-lung machines |
| 03 | Body tissue manipulation devices | Liposuction devices |
| 04 | Cardiovascular devices | Cardiac stents and pacemakers |
| 05 | Complementary therapy devices | Acupuncture needles/devices, bio-energy mapping systems/software, magnets, moxibustion devices, suction cups |
| 06 | Dental devices | Dentistry tools, alloys, resins, floss, brushes |
| 07 | Disability-assistive products | Wheelchairs, walking frames, hearing aids |
| 08 | Ear/Nose/Throat (ENT) devices | ENT microscopes and workstations |
| 09 | Endoscopic devices | Gastroscopes, laryngoscopes |
| 10 | Gastro-urological devices | Specialised urology catheters |
| 11 | General hospital devices | Hospital beds |
| 12 | Healthcare facility products and adaptions | Gas delivery systems |
| 13 | In vitro diagnostic medical devices (IVDs) | Pregnancy test, genetic test, glucose strip |
| 14 | Laboratory instruments and equipment | Most IVD which are not reagents |
| 15 | Neurological devices | Implantable neurostimulators and CSF drainage catheters |
| 16 | Obstetrical/Gynaecological devices | Delivery forceps and vaginal speculums |
| 17 | Ophthalmic devices | Spectacles, contact lenses, intraocular lenses |
| 18 | Orthopaedic devices | Hip or knee joint replacement devices |
| 19 | Physical therapy devices | Heat therapy products |
| 20 | Plastic surgery and cosmetic devices | Breast implants |
| 21 | Radiological devices | CT scanners |

### *2.3. Healthcare Architecture Considerations & Challenges*

Current/traditional healthcare architecture is being gradually replaced with IoMT architecture and whilst it's paving the way forward, it brings with it a new complexity and many challenges as identified in Figure 2.

Linking datasets from multiple sources is advantageous, but achieving connectivity at larger scales requires interoperability: communication through a common language is needed so that healthcare organisations can link the varied data formats from different vendors, but currently, rendering devices is not interoperable [23].

Hence IoMT faces critical issues in connecting medical devices, whilst it strives to continually innovate, in turn, it struggles to keep pace with wireless technology, and moreover poses a significant risk to patient's privacy and safety [24].

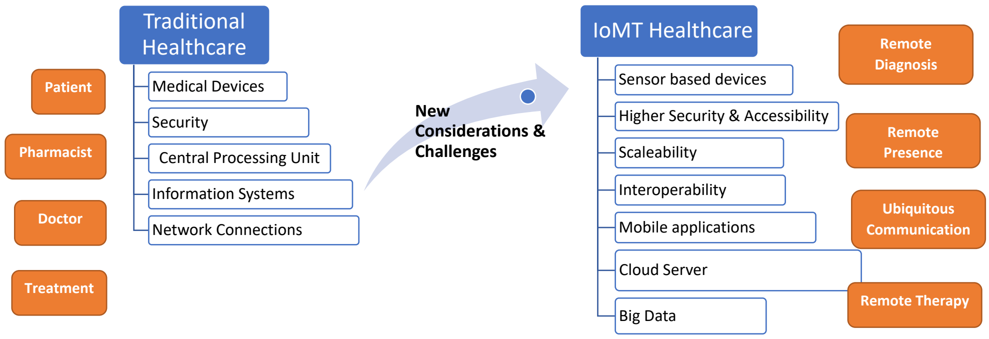


**Figure 2.** Considerations and Challenges.

*2.4. Benefits of IoMT in Transforming Conventional Healthcare Architecture*

Together with the development of IoMT the 4th industrial revolution (with the developments) of big data, AI, mobile applications, 3D printing, robotics are contributing to improved patient outcomes, drug management, improved diagnosis and treatment etc. Some of the main benefits can be seen in Table 3. Technology drivers such as smart diagnostic tools are having impact on the accuracy of medicines, whilst smart beds decrease cost and impact HC (Healthcare) staffing levels by automating changing patient pressure levels.

**Table 3.** IoMT Benefits.

| Technology Driver | Benefit | Impact |
|---|---|---|
| Remote Monitoring | Improving Patient outcomes | Patient |
| Smart Diagnostic Tools | Accuracy of medicines | Medicine |
| Vital Signs Monitoring | Improved diagnosis treatment | Patient |
| Smart Beds | Decreased Costs | HC Staffing levels |
| Smart Pill Bottles | Improved drug management | Patient and HC staff |
| E-Prescriptions | Decreased Costs | Patient and HC staff |
| Patient Education | Enhanced Patient experience | Patient |

Interestingly (in 2014) it was even predicted that 'Technology itself will become a treatment', as evidenced by the new generation of mobile apps increasingly appearing in treatment guidelines—initiatives like point-of-care testing to improve the diagnosis of sepsis [25].

Yet although there are many benefits of IoMT there still resides resistance to use IoMT in the healthcare industry: one study highlighted this scepticism towards IoMT, yet observed the resistance rationality could lead to improved managerial policies for introducing and successfully implementing IoMT technologies in hospitals [26].

It is the scientists that can benefit from IoMT by utilising 'the massive amount of medical data generated in the IoMT systems' [27] as Machine Learning opens analysing capabilities which focus on medical data over a long period to find patterns that could detect early signs of chronic diseases such as heart disease [28].

## 3. Architecture

IoMT applications are built on various architectures based on well established layered model, Figure 3 [11]. This typically involves IoT or things (bottom) layer, Fog (middle) Layer and Cloud (top) layer. For IoMT applications to be reliable, secure and efficient they must be built on architecture that enable those properties. This study explores and evaluates available architectural models and their suitability for reliable IoMT applications. It considers reference models offering layered structure with the key components and characteristics of each layer, as well as application specific designs and their benefits.

In a basic reference architecture, IoMT, known as IoT devices can be characterised as devices with limited capabilities such as limited power or processing abilities. Although, some of the devices that act as IoMT, such as smart phones, smart watches, etc., can offer greater capabilities. By definition, IoT and hence IoMT devices are able to, either directly or through switches or other devices, connect to internet enabled systems. IoMT devices are operating at the bottom layer of the layered architecture, most recently referred to as edge layer. Depending on the functionality, role and capability of devices they connect to that form middle layer, applications might be utilising Edge/Fog/Cloud architecture or Edge/Cloud set up where fog layer is not available.

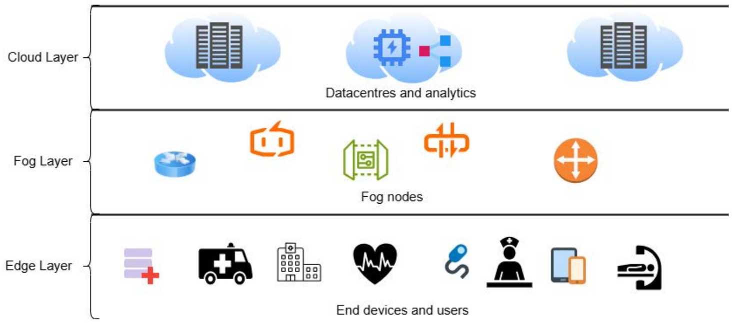


**Figure 3.** A layered architecture for IoMT.

Since its introduction in 2011 [29], Cloud Computing has become a major enabler of IoT and IoMT, which require resource-intensive computation power and scalable storage. Cloud enables capturing and storing row IoMT data through its data lakes, storing cleaned data in its servers as well as providing powerful data analytics tools, data analysis and visualisation. It also allows running of computationally have machine learning models that are very often deployed for monitoring, prediction or/and prevention of diseases and health conditions. While cloud is a major enabler of IoMT applications in a two-layer architecture where IoT devices are directly interacting with cloud services Quality of Service and reliability of life critical applications can be challenging. Location of cloud servers and speed of the networks connecting IoMT devices to cloud based services can introduce delays in decision making applications that are used, for instance, for monitoring epileptic seizures, predicting heart failure, or even falls in assisted living scenarios [30]. These challenges have been addressed by introducing fog computing that is based on multi-layer architecture bringing computational and other data related resources closer to the edge devices addressing the delay related challenges in Cloud-edge two-tiered architecture [31]. It has been observed that cloud/fog/edge architecture has become a recommended reference architecture for reliable and secure IoMT applications [32–35].

## 4. Applications

The rapid revolution of the internet in recent decades enables a fast and efficient connection between different devices that work for various purposes, and one of which is medical purpose IoMT. IoMT has been applied in wide range of healthcare areas—from health monitoring to diagnostics; from patient's home to hospital's operation room; from biomarkers to robotics. IoMT bridges the gap between patients and healthcare professionals, overcoming geographical and physical barriers. This section reviews the different application areas of IoMT.

### 4.1. Assistive Living

In 2021, World Health Organization (WHO) reported that the world's population of people aged 60 years and older will reach 2.1 billion by 2050, and the number of persons aged 80 or older is expected to be 426 million by then. Despite this increase in life expectancy, ensuring a high quality of life for the elderly remains a significant challenge. How to ensure a quality long-term care, not just for elderly but for all individuals, becomes a major challenge for the healthcare and social system of all countries [36].

Ref. [37] reported a HABITAT (Home Assistance Based on the Internet of Things (IoT) for the Autonomy of Everybody) project aimed to develop and experiment an IoT based platform for assistive and reconfigurable space. This platform considers a range of end users, such as the elderly, the patient, the professionals and the family or caregivers, and utilises User-Centred Design (UCD) methodologies to ensure the product can be customized to meet the specific need of the elderly. These needs are typically categorised in two groups: self and non-self supports, as listed in Figure 4. The functions classified under self-supports are for the elderly or patient to take the actions themselves independently, while those under non-self-supports are for the care providers to intervene in case of accidents or when professional assistance is required.

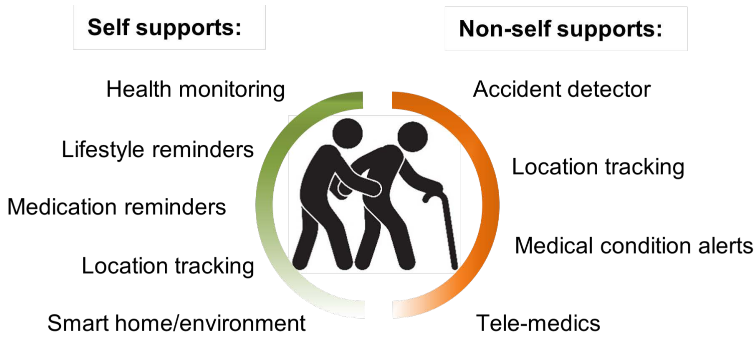


**Figure 4.** IoMT applications in assistive living.

Syed et al., 2019 [7] explored an ambient assisted living system that used IoMT, big data analytics and machine learning algorithms to predict the physical activities of the subject (either the elderly or the frail patient) in order to give them the assistance of healthy living.

Maskeliunas et al., 2019 [38] provideds an overview of IoMT technologies, their impact and challenges in the assistive living domain. They analysed several successful or unsuccessful systems in the area and emphasized the importance of psychological consideration in the development of IoMT gerontechnology. These psychological considerations are closely linked to the acceptance and effective implementation of the technology in the area.

### 4.2. Fitness Tracking

The benefits of physical activity have been well studied and documented across wide scopes: from children to the elderly, from women to men, and from physical health to mental health [39–41]. Maintaining adequate physical activity not only benefits the individual health, but also contribute to the overall well-being of society and reduces the burden on national healthcare service. With the widespread adoption of smartphones in recent years, there has been a significant increase in the availability of personal wearables on the market. These wearables, such as smartwatches, wristbands, smart belt, smart shoes, etc, are fitted with various types of sensors, which are used to collect physical activity data like numbers of steps taken, calories burned, and time exercised. The collected data are then transmitted to the applications of smartphones or computers to help individuals keep track of their physical activity levels. These data are further analysed by the smartphone apps to provide some general suggestions on future activity plan. Despite the large number of wearable fitness trackers being purchased and used by consumers every year, there is still limited evidence that proves how these IoMTs motivate individuals' perception and further influence their habits of physical activities in the long term [42].

In addition to the monitoring of physical activities, the fitness trackers and applications also allow users to keep a record of body weight, which can be realized by manual input or via the gadgets like Wi-Fi-enabled scale. These functions provide a promising assistance in weight management [43].

### 4.3. Smart Hospital

Hospitals are one of the most important elements of health service and provision, and their quality and efficiency significantly reflect that of the national or regional healthcare system. A smart hospital is a healthcare facility that leverages optimised and automated processes and advanced technology, particularly Information and Communication Technology (ICT) and internet of things (IoT), to improve existing patient care procedures, introduce new capabilities, and improve overall efficiency. The migration from traditional hospital to smart hospital sees the improvement of healthcare service from different viewpoint, as illustrated in Figure 5.

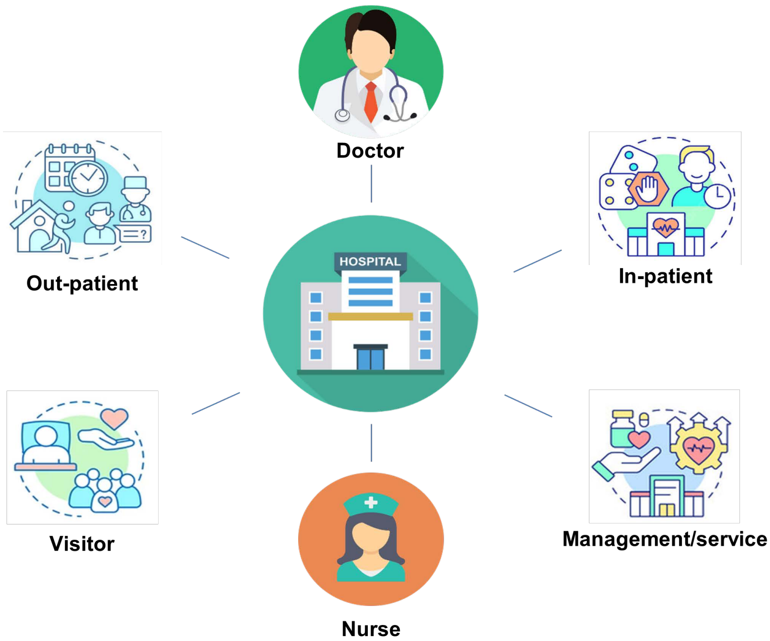


**Figure 5.** Potential Hospital-based IoMT Agent Integration.

#### 4.3.1. Doctors and Nurses

Robots such as the 'Nao Robot' [44] can be used to 'talk' to patients after the medical data are analysed, to discuss the potential risk of some diseases, and also to give patients some advice on adopting a healthier lifestyle. This frees doctors from such general tasks and allows them to focus their expertise and time on more specialised tasks. This consequently improves the efficiency of hospital service.

The application of robotics technology in the operating theatre also strengthens the capability of replicating the hand motion of experienced surgeon while minimising any hand tremor that might affect the surgery outcome. This also makes the remote tele-surgery feasible in reality [45]. The quality of surgery is further improved by enhanced tissue recognition and real-time diagnosis facilitated by high-definition images and videos.

Smart medication, employing ingestible IoMT sensors, provides an advanced level of healthcare service by monitoring biomarkers, antibiotic levels and antibiotics compliance, etc. Doctors can study and analyse the data to offer patients more personalised, accurate and effective treatments.

#### 4.3.2. Hospital Management and Service Team

Hospitals have a wide range of assets including building, facilities, medical equipment, information systems, and data. IoMT applications offer enhanced efficiency and effectiveness in managing these assets compared to traditional methods. For example, autonomous robots are deployed for various routine tasks such as delivering medicine, food or medical supplies, as well as managing biomedical waste and conducting disinfection procedures. This diminishes the need for human intervention, which was a particularly important aspect during the pandemic [45]. This can also reduce the waste of hospital resources and ultimately lower the cost of healthcare service.

#### 4.3.3. Patients

Patients are consistently the focal point of healthcare services. The ultimate goal of smart hospitals is to provide top-tier patient care, which can be achieved through: (a) accessing essential expertise promptly, irrespective of geographical constrains; (b) leveraging large dataset for diagnosis assistance and optimal treatment option; (c) reducing waiting times and the duration of hospital stays; and (d) offering convenient real-time health monitoring and seamless data sharing with healthcare professionals.

#### 4.3.4. Hospital Visitors

The implementation of an automated information desk is a key improved services that a smart hospital can provide to all visitors. This allows visitors access to all up-to-date hospital information, including ward location, café and elevators positions, navigation routes, and more. This type of service not only reduces the need for human intervention, but also conserves the hospital staff resources for tasks directly related to patient related.

Robots integrating visual, audio, ultrasound, laser and mechanical sensors have also been used to assist hospital visitors in collisions avoidance. One such example is Guido's design [46], which has been developed specifically for visually impaired person to navigate in the hospital environments safely.

### *4.4. Remote Monitoring*

The applications of IoMT expand the scope of traditional hospitals and enable the medical care to extend beyond the hospital premise. Medical devices such as implantable, wearable and other mobile devices provide real-time patients monitoring. These devices are built in with various types of sensors, such as cardiac activity sensors, respiratory function sensors, foot drop detection sensors, etc. [47,48]. Figure 6 illustrates some examples of remote measurements achievable with such devices. Healthcare providers can review these data on a regular basis and schedule close check-ups based on the analysis. Additionally, they can promptly provide urgent medical attention in response to any warning raised from the monitoring data. Thus, the healthcare providers can restrict hospital admissions to those cases deemed necessary, leading to a more efficient allocation of healthcare resources [49].

### *4.5. Healthy Living*

The NHS advise on health living, emphasising a balanced diet and regular and adequate exercise, as these are the key factors that contribute to maintaining a healthy weight. IoMT simplifies the management of these factors, offering ease and convenience. Sensor-based wearable fitness trackers like Fitbit can monitor the physical activity, commonly tracking steps, distance, intensity, and estimated energy expenditure. Additionally, some wearables can track sleeping data, such as duration and quality. Wi-Fi enabled scale like the

Fitbit Aria can measure body weight and estimate body composition. All the data collected by these devices are transferred to the apps associated to the devices and used for analysis of health conditions and lifestyles patterns.

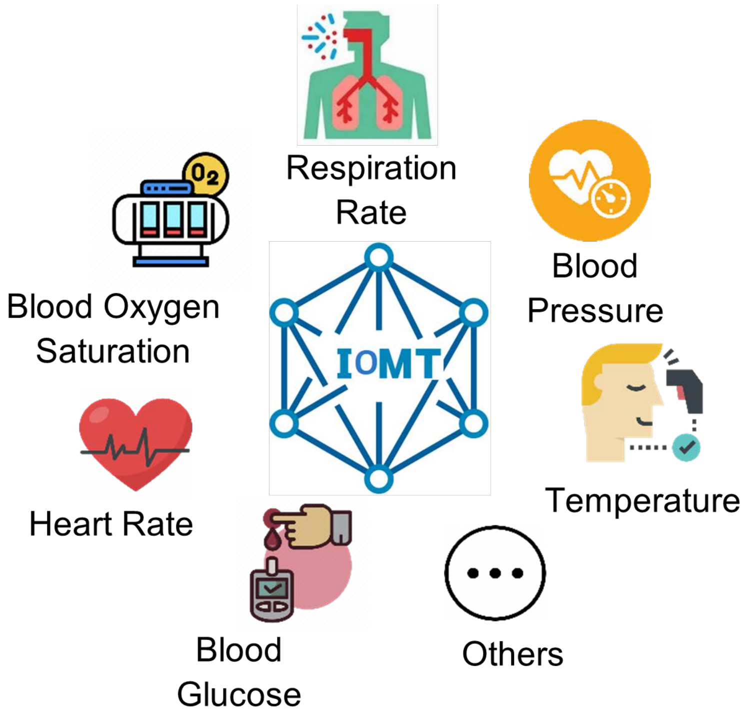


**Figure 6.** IoMT applications in remote monitoring.

Presently, IoMT's function for promoting healthy eating relies on users manually inputting data. Users can record their foods and beverages intake by selecting the items from a comprehensive database, which includes numerous common food and drink items, and their corresponding calories counts per unit weight. Moreover, individuals can input personal recipes, although analysing these recipes is considerably more complex and often requires approximation based on existing information within the database [43].

Individuals can utilise this data to monitor and manage their own healthy lifestyle or make corresponding adjustment to their habits following the suggestions provided by the apps, which are based on the analysis of collected data and background database. On the other hand, healthcare providers can use the data to provide individuals an evidence-based behaviour change plan aim at promoting healthy living and helping them achieve their wellness goals.

The applications of IoMT have delivered benefits to individuals, communities, clinics, hospitals and national healthcare system, though this rapid evolving field is still experiencing various challenges. The future development of IoMT applications foresees a close and comprehensive integration of technologies like cloud computing, artificial intelligence, deep learning and big data analytics.

## 5. Stake Holders

As with all systems, it is imperative that the stakeholders are considered when developing any solutions, as failure to do so can undermine the efficiency and effectiveness of the implementation [50]. Unlike historical perspectives, it is no longer sufficient to only consider the human factors of stakeholders; but instead, the impacts of technological factors must also be considered, such as AI/machine learning/data analytics and so on [1,51–59].

### 5.1. Hospitals and Medical Facilities

Hospitals and medical facilities will be the first and main users of IoMT to improve the services to patients. This can be as simple as monitoring as patients for a specific condition/component, such as blood pressure, all the way to having a patient live in a custom smart environment that monitors them much more in- depth, allowing for greater control over the diagnosis.

### 5.2. Patients

Alongside the hospitals, the patients are the other main stakeholders, as they will be the ones who are using the devices daily. So whilst the hospital might want a specific type of IoMT installation, it will be done to the patients and their acceptance of the approach to see what can be used. This acceptance of the techniques used will be a major consideration as if the patient does not accept techniques, then it is irrelevant how good it is; it is not fit for purpose. Development must keep in mind concepts such as the technology acceptance model.

### 5.3. Policymakers

This is mainly down to either organisations or governmental institutions that make policies for either specific hospitals/medical environments or for governments making much broader decisions that can cover nations. This will also include organisations involved in the funding of healthcare, either public or private and the mentality for this will dramatically change from country to country.

### 5.4. Old Age and Recovery Centres

Certain countries have a history of using some assistive technologies, mostly with things such as panic buttons. These are normally used with old age homes, warden-controlled environments. As one of the main causes of many medical conditions is age, the inclusion of organisations and services that are specifically aimed at supporting the elderly will be imperative. It is also important to normalise the techniques being used as this elderly demographic is traditionally one of the ones most adverse to using new techniques.

### 5.5. Health Research Institutes

The final set of stakeholders would be health researchers, as they would be able to make use of the data being provided by the IoMT devices for research purposes; however, again this would have to be carefully monitored and all legal and ethical factors would have to be considered.

## 6. Case Studies

### 6.1. The FreeStyle Libre System

The Freestyle Libre is a continuous glucose monitoring system that transmits glucose readings every minute directly to the user's smartphone, facilitating prompt action to prevent hypoglycemia (low blood sugar). The system features a compact, water-resistance sensor worn beneath the skin on the underarm for 14 days. It records glucose levels around the clock, ensuring comprehensive monitoring throughout the day and night [60].

Freestyle Libre enables individuals to access minute-by-minute readings by simply scanning the sensor with their smartphone. This functionality assists users in real-time identification of hypoglycemia (when their blood sugar levels are too low) or hyperglycemia (when their blood sugar is too high), eliminating the need for frequent finger prick tests. The Libre-free system includes an alarm that notifies users of high or low blood sugar levels, allowing prompt action if their levels deviate from the target range. Additionally, this alarm can alert users in the event of a signal loss between the sensor and its reader. Freestyle Libre is suitable for individuals with both type 1 and type 2 diabetes [60].

The monitor measures the interstitial fluid, which is the amount of glucose in the fluid surrounding the body cells. Precision is measured through mean absolute relative difference, which calculates the average discrepancy between the glucose values obtained from a flash glucose monitoring sensor and the relative values used for testing. A lower percentage signifies a stronger correlation between the results from the individual's flash glucose monitoring sensor and the reference values.

### 6.2. The Cardionica

The Cardionica is an IoMT device, designed for daily use. The device automatically detects episodes of atrial fibrillation, tachycardia and bradycardia when placed on the thorax by an adhesive electrode. It can be used in connection with a Bluetooth smartphone, via an app which displays the electrocardiogram (ECG trace) and the response of the analysis. The app allows the patient to download the data of tests performed and share this information [61].

### 6.3. The Oura Ring

The Oura ring is an IoMT health tracker equipped with advanced sensors capable of monitoring various health metrics. This device can track activity, body temperature, sleep patterns, recovery, stress levels, and heart rate. The ring is equipped with red, infrared, and green light sensors, allowing it to directly capture data from finger arteries. It leverages infrared Photoplethysmography (PPG) to monitor biometric information during sleep, utilises green light sensors to keep tabs on heart rate throughout the day and during workouts, and harnesses red and infrared light sensors to measure oxygen saturation. The PPG sensors in the Oura ring resemble the ones used in hospital equipment designed for heart rate monitoring. This PPG system operates by emitting light through LEDs and then collecting it with a photodiode. This process allows the device to measure how pluses of light, as they pass through the arteries, reflect the activity of the heart. It also measures skin temperature.

The Oura ring calculates readiness score by factoring in the lowest overnight heart rate, body temperature, previous day's activity, heart rate variability (HRV), and sleep quality. It considers activity levels over the last 14 days compared to the last two months to gauge if the person is significantly exceeding or falling short of their body's accustomed activity. A score exceeding 70 is considered favourable, with 85 being the highest achievable score. This score serves as a valuable indicator to guide a person's daily activity levels, where lower scores suggest a need for rest, and higher scores signal readiness for more demanding challenges. Consistently receiving a low readiness score may indicate the necessity for improved recovery practices, as it could signify overtraining or insufficient sleep and recovery time [62].

While on sleep, the Oura ring gauges bloods oxygen levels, utilising these measurements to evaluate the body's oxygen circulation and absorption efficiency, potentially uncovering any breathing-related issues during sleep. Subsequently, it generates a hypnogram, a graph that categorises sleep stages into three distinct categories: light, deep and Rapid Eye Movement (REM). This data is then utilised to calculate a sleep score on a scale of 0 to 100. A score exceeding 85 indicates optimal sleep quality, while a score between 74 and 84 signifies good sleep, and a score below 70 highlights the need for improvements in sleep patterns [62].

The ring captures an individual's activity score by analysing daily activity, step count, training frequency, and various other metrics. It employs a 3D accelerometer, which is a compact device of technology discretely integrated into the ring, to gather and process these metrics. The 3D accelerometer allows the ring to gauge the physical activity (hand movement), step count (leg movement), providing estimates for overall body activity. It employs metabolic equivalents (METs), which refers to the ratio of the working metabolic rate in relation to the resting metabolic rate. A MET value of two, indicates that an individual is burning calories at a rate double that of what they would expand during a state of rest [62].

## 7. Off-the-Shelf Solutions

### 7.1. Wireless Motes

This section provides a comparative analysis of the key aspects of wireless motes, considering design, connectivity options, wearability, bandwidth, communication protocols, energy consumption, and other factors relevant to their suitability for different applications, particularly in IoT and environmental monitoring contexts. A comparison is presented in Table 4.

#### 7.1.1. Design and Connectivity

The design and connectivity options vary widely among motes, with each suited to specific applications. For instance, the Helium Atom and PYCOM PYLIFE integrate multiple wireless connectivity options like LoRa, Wi-Fi, and Bluetooth, making them versatile choices for IoT applications. In contrast, motes such as TELOSB and MICAZ use IEEE 802.15.4 [63] for communication, which limits their application scope but is ideal for low-power, short-range communications typical in agricultural and environmental monitoring.

#### 7.1.2. Wearability

Certain motes, like the STM32 BlueNRG-Tile and Zigduino, feature compact designs and Bluetooth Low Energy (BLE) support, making them suitable for wearable applications. Their small form factors and onboard sensors (such as accelerometers and gyroscopes) are advantageous for indoor localization and fitness tracking.

#### 7.1.3. Bandwidth and Communication Protocols

Bandwidth and protocol choices range across LoRa, Zigbee, Wi-Fi, and cellular IoT, influencing the motes' range, power consumption, and data throughput. For example, LoRa-based motes like Helium Atom and SenseCap Wireless Sensor offer long-range communication, which is suitable for remote monitoring but has lower bandwidth compared to Wi-Fi or cellular IoT options like nRF9160 Feather.

#### 7.1.4. Energy Consumption and Power Management

Most motes prioritize low power consumption, with some providing ultra-low-power operations, like the nRF9160 Feather and Digi XBee3. These motes are equipped with power-saving features to extend battery life, a critical factor for applications in remote or hard-to-access areas where frequent charging or battery replacement is impractical. Modular designs, such as in the Libelium Waspmote Plug & Sense, allow users to optimize power usage based on application needs by enabling or disabling specific components.

#### 7.1.5. Charging and Network Lifetime

Extended network lifetime is a recurring feature among motes intended for IoT and environmental monitoring. The SenseCap Wireless Sensor and Meshlium focus on long battery life and low-power designs. However, charging options are limited across these motes, and solutions often involve external power sources or replaceable batteries rather than built-in rechargeable options.

**Table 4.** Wireless IoMT Characteristics.

| Wireless Mote | Wireless Connectivity | Microcontroller | Sensors/Features | Power Use | Additional Features | Example Applications |
|---|---|---|---|---|---|---|
| Helium atom | LoRaWAN, Wi-Fi | ESP32 | - | Low power | Built-in LoRaWAN and Wi-Fi connectivity, Helium Network compatibility | IoT applications, smart city projects, asset tracking |
| Pycom Pylife | Wi-Fi, LoRa, Bluetooth | Espressif ESP32 | - | Low power | Integrated LoRa, Wi-Fi, and Bluetooth connectivity, Pybytes cloud integration | Smart agriculture, environmental monitoring, asset tracking |
| nRF9160 Feather | Cellular IoT (LTE-M/NB-IoT) | Nordic Semiconductor nRF9160 | - | Low power | Integrated cellular modem, Ultra-low power operation | Asset tracking, remote monitoring, industrial IoT |
| AirLift Breakout | Wi-Fi | ESP32 | - | Low power | Built-in Wi-Fi connectivity, Feather-compatible design | IoT applications, home automation, smart devices |
| Sensecap wireless sensor | LoRaWAN | - | Various (High precision) | Low power | High precision sensors, Long battery life, Plug-and-play installation | Agriculture monitoring, environmental monitoring, smart farming |
| Libelium Waspmote Plug & Sense | Zigbee, LoRa, 3G/4G | - | Various (Sensor options) | Low power | Modular design, Open-source API and development platform | Smart cities, air quality monitoring, precision agriculture |
| Pycom FiPy | Wi-Fi, LoRa, Bluetooth | Espressif ESP32 | - | Low power | MicroPython support, Multi-network connectivity | Smart agriculture, asset tracking, environmental monitoring |
| LoPy4 | Wi-Fi, LoRa, Bluetooth | Espressif ESP32 | - | Low power | MicroPython support, Multi-network connectivity | Smart agriculture, asset tracking, environmental monitoring |
| Meshlium | Wi-Fi, Zigbee, LoRa, Bluetooth | - | Various (Sensor options) | Low power | Gateway and router functionality, Multi-protocol support | Smart cities, environmental monitoring, urban infrastructure |

**Table 4.** *Cont.*

| Wireless Mote | Wireless Connectivity | Microcontroller | Sensors/Features | Power Use | Additional Features | Example Applications |
|---|---|---|---|---|---|---|
| TelosB | IEEE 802.15.4 | MSP430 | Temperature, Light | Low power | Small form factor, Open-source software (TinyOS) | Smart agriculture, environmental monitoring, industrial automation |
| MicaZ | IEEE 802.15.4 | Atmel ATmega128L | Temperature, Humidity | Low power | Compact size, Compatible with TinyOS | Structural health monitoring, wildlife tracking, home automation |
| Zigduino | ZigBee | Atmega128RFA1 | None | Low power | Arduino-compatible, USB connectivity, Onboard LEDs and buttons | Home automation, energy management, wearable devices |
| Waspmote | ZigBee, LoRa, Bluetooth | ARM Cortex-M3 | Various (Modular design) | Low power | Support for various protocols and APIs, Modular design | Smart cities, precision agriculture, industrial IoT |
| Arduino Wireless | Wi-Fi, Bluetooth | Arduino-compatible | Various (Sensor/shield options) | - | Easy to program, Wide range of sensor and shield options | Home automation, IoT prototyping, remote monitoring |
| Raspberry Pi Zero W | Wi-Fi, Bluetooth | Broadcom BCM2835 | None | Low power | HDMI and USB ports, GPIO pins for sensor integration, Linux OS | Home automation, media center, IoT gateway |
| Zigbee Mote | Zigbee | - | None | Low power | Zigbee wireless communication protocol, Mesh networking capabilities | Smart home automation, building energy management, asset tracking |
| LoRa Mote | LoRa | Semtech SX1276/78 | ARM Cortex-M3 | Low power | Long-range wireless communication, Support for LoRaWAN protocol | Smart agriculture, remote monitoring, smart city infrastructure |

**Table 4.** *Cont.*

| Wireless Mote | Wireless Connectivity | Microcontroller | Sensors/Features | Power Use | Additional Features | Example Applications |
|---|---|---|---|---|---|---|
| Particle Photon | Wi-Fi | Particle P0 | Various (Sensor/shield options) | Low power | Cloud integration (Particle Cloud), Onboard RGB LED | Internet of Things (IoT) projects, home automation, data logging |
| Digi XBee3 | Zigbee, Wi-Fi, Cellular | Digi XBee3 module | None | Ultra-low power | Scalable and flexible design, OTA firmware updates | Industrial IoT (IIoT), asset tracking, remote sensor networks |
| STMicroelectronics BlueNRG-Tile | Bluetooth Low Energy (BLE) | STM32 | Built-in sensors (e.g., accelerometer, gyroscope) | Ultra-low power | Mobile app integration, Onboard sensors | Indoor localization, wearable devices, fitness tracking |
| ESP8266 | Wi-Fi | Tensilica L106 | None | Low power | Integrated TCP/IP protocol stack, Small form factor | IoT devices, home automation, wireless sensor networks |
| Particle Argon | Wi-Fi, Mesh | Nordic Semiconductor nRF52840 | None | Low power | Particle Cloud integration, Mesh networking capabilities | IoT projects, smart home automation, remote monitoring |
| Heltec LoRa32 | LoRa, Wi-Fi, Bluetooth | Espressif ESP32 | None | Low power | Onboard OLED display, Integrated LoRa antenna | IoT applications, LoRaWAN development, remote sensing |
| ZigFi | Zigbee | - | None | - | Zigbee wireless communication protocol | Home automation, building management, industrial control - |
| Seeeduino LoRaWAN | LoRaWAN | Atmel SAMD21G18A | Various (Sensor options) | Low power | - | - |

#### 7.1.6. Additional Features and Applications

Many motes include unique features tailored to specific applications. Particle Photon and Heltec LoRa32 integrate cloud compatibility and remote firmware updates, adding flexibility in industrial IoT and home automation applications. Seeeduino LoRaWAN and Libelium Waspmote support modular sensor options, enhancing adaptability for precision agriculture and environmental monitoring by allowing users to customize sensors based on specific monitoring needs.

### *7.2. IoT Devices*

Similarly, a comparative analysis of IoT devices is presented in this section, focusing on their connectivity options, microcontroller specifications, sensor capabilities, power consumption, unique features, and application use cases. This is shown in Table 5.

#### 7.2.1. Connectivity and Microcontroller Specifications

Many IoT devices utilize Wi-Fi and Bluetooth for connectivity, balancing range and power efficiency for in-home applications. Devices like the Nest Cam and Wyze Video Doorbell Pro primarily rely on Wi-Fi for continuous monitoring, while others, like the Apple Airtag, utilize Bluetooth for short-range, low-power tracking. Devices with multi-protocol support, such as the Ring Alarm Pro (Zigbee, Z-Wave, Wi-Fi), expand compatibility across various smart home devices, enhancing user flexibility and integration options.

#### 7.2.2. Sensor and Feature Set

Most devices in this category are equipped with specific sensors suited to their use cases. Security cameras like the Nest Cam and Ring Video Doorbell include cameras and motion sensors for enhanced surveillance, while devices like the Fitbit Versa 3 offer heart rate and sleep tracking for health monitoring. Smart assistants, such as the Amazon Echo Dot and Google Nest Mini, integrate microphones and speakers, enabling voice control and smart home management. The Nest Learning Thermostat stands out with its temperature and humidity sensors, enabling adaptive climate control.

#### 7.2.3. Power Consumption

These devices are predominantly designed for low-power consumption, enabling prolonged usage without frequent charging or battery replacement. Fitness trackers like the Fitbit Charge 2 and Versa 3 prioritize battery efficiency to allow continuous monitoring. Security devices, including the Nest Cam (Battery), Ring Stick Up Cam, and Arlo Video Doorbell, also optimize power consumption to extend operational time, particularly important for wire-free setups.

#### 7.2.4. Unique Features

Many IoT devices include standout features tailored to specific environments. For example:

- Apple Airtag leverages Apple's Find My network for precise location tracking.
- Ring Alarm Pro supports professional monitoring with multi-protocol functionality, improving smart home security.
- Nest Protect incorporates smoke and carbon monoxide detection with smartphone alerts and voice warnings for real-time home safety.
- Amazon Echo Show 5 and Google Nest Hub add visual displays for enhanced smart home control and multimedia functionality.
- These additional features make them versatile choices for both specialized and integrated IoT solutions.

**Table 5.** IoMT Devices.

| Iot Device | Connectivity | Microcontroller | Features | Power Use | Additional Features | Applications |
|---|---|---|---|---|---|---|
| Apple airtag | Bluetooth | - | Location tracking | Low power | Integration with Apple Find My network | Asset tracking, Lost item retrieval |
| Nest Cam (Battery) | Wi-Fi | ARM Cortex-A7 | Camera, Motion sensor | Low power | Smartphone alerts, Video recording capabilities | Home security, Surveillance |
| Ring Alarm Pro | Zigbee, Z-Wave, Wi-Fi | ARM Cortex-A8 | - | Low power | Professional monitoring service, Multi-protocol support | Home security, Smart home automation |
| Wyze Video Doorbell Pro | Wi-Fi | - | Camera, Motion sensor, Doorbell | Low power | Smartphone alerts, Video recording capabilities | Home security, Surveillance |
| Apple HomePod Mini | Wi-Fi, Bluetooth | Apple S5 | Speaker, Microphones | Low power | Siri voice assistant, Smart home integration | Voice control, Home automation |
| Google Nest Hub (2nd Gen) | Wi-Fi, Bluetooth | - | Display, Speaker | Low power | Google Assistant, Smart home control | Smart home control, Entertainment |
| Sonos Roam | Wi-Fi, Bluetooth | - | Speaker, Microphones | Low power | Portable design, Auto Trueplay feature | Portable audio, Home entertainment |
| Amazon Echo Dot (4th Gen) | Wi-Fi, Bluetooth | - | Speaker, Microphones | Low power | Alexa voice assistant, Smart home integration | Voice control, Home automation |
| Fitbit Versa 3 | Bluetooth, Wi-Fi | - | Heart rate, Activity tracker, Sleep monitoring | Low power | OLED display, Smartphone integration | Fitness tracking, Health monitoring |
| Ring Video Doorbell 3 | Wi-Fi | - | Camera, Motion sensor, Doorbell | Low power | Smartphone alerts, Video recording capabilities | Home security, Surveillance |
| Ecobee SmartCamera | Wi-Fi | ARM Cortex-A8 | Camera, Motion sensor, Speaker, Microphones | Low power | Smart person detection, Voice control | Home security, Surveillance |
| Google Nest Mini | Wi-Fi, Bluetooth | - | Speaker, Microphones | Low power | Google Assistant, Smart home integration | Voice control, Home automation |
| Amazon Echo Show 5 | Wi-Fi, Bluetooth | - | Display, Speaker, Camera, Microphones | Low power | Alexa voice assistant, Video calling | Smart home control, Entertainment |
| Sonos One (2nd Gen) | Wi-Fi, Bluetooth | - | Speaker, Microphones | Low power | Alexa voice assistant, Smart home integration | Voice control, Home automation |
| Arlo Essential Wire-Free Video Doorbell | Wi-Fi | - | Camera, Motion sensor, Doorbell | Low power | Smartphone alerts, Video recording capabilities | Home security, Surveillance |

**Table 5.** *Cont.*

| Iot Device | Connectivity | Microcontroller | Features | Power Use | Additional Features | Applications |
|---|---|---|---|---|---|---|
| August Wi-Fi Smart Lock | Wi-Fi | - | Door lock | Low power | Smartphone app control, Auto-locking feature | Home security, Access control |
| Ring Stick Up Cam Battery | Wi-Fi | - | Camera, Motion sensor | Low power | Smartphone alerts, Video recording capabilities | Home security, Surveillance |
| Google Home Mini | Wi-Fi, Bluetooth | - | Speaker, Microphones | Low power | Google Assistant, Smart home integration | Voice control, Home automation |
| Sonos Play:1 | Wi-Fi, Ethernet | - | Speaker | Low power | Multi-room audio, Smartphone app control | Home entertainment, Audio streaming |
| Belkin WeMo Switch | Wi-Fi | - | Power switch | Low power | Smartphone app control, Scheduling features | Home automation, Energy management |
| Nest Learning Thermostat (3rd Gen) | Wi-Fi | - | Temperature, Humidity, Motion sensor | Low power | Learning algorithms, Smartphone app control | Home climate control, Energy efficiency |
| Fitbit Charge 2 | Bluetooth | - | Heart rate, Activity tracker, Sleep monitoring | Low power | OLED display, Smartphone integration | Fitness tracking, Health monitoring |
| Google OnHub Router | Wi-Fi | - | Router | Low power | Automatic network optimization, Smartphone app control | Home network management, Internet access |
| Apple HomeKit | Wi-Fi, Bluetooth | - | - | Low power | Smart home control, Integration with Apple ecosystem | Home automation, Smart device control |
| Belkin WeMo Light Switch | Wi-Fi | - | Light switch | Low power | Smartphone app control, Scheduling features | Home automation, Lighting control |
| Nest Protect | Wi-Fi | - | Smoke, Carbon monoxide detector | Low power | Voice alerts, Smartphone alerts | Home safety, Smoke detection, CO detection |
| Canary All-in-One Security Device | Wi-Fi | - | Camera, Motion sensor, Air quality sensor | Low power | Smartphone alerts, Video recording capabilities | Home security, Surveillance |
| LIFX LED Light Bulb | Wi-Fi | - | Light, Color | Low power | Smartphone app control, Voice control | Smart lighting, Ambiance control |
| Withings Wi-Fi Body Scale | Wi-Fi | - | Weight, Body composition | Low power | Smartphone integration, Health metrics | Health monitoring, Fitness tracking |

7.2.5. Example Applications and Market Release

The versatility of these devices is seen across home automation, security, health, and entertainment applications:

- Home automation devices like the Belkin Wemo Switch and Nest Learning Thermostat simplify energy management and provide climate control.
- Health monitoring devices like the Fitbit Versa 3 and Withings Wi-Fi Body Scale cater to personal wellness with seamless smartphone integration for tracking fitness metrics.
- Smart lighting options like the LIFX LED Bulb offer ambiance customization through colour control and voice command compatibility. has context menu

## 8. Challenges

The uptake and acceptance of IoT devices have been steadily increasing despite numerous concerns over data privacy. According to [3] 65% of users were concerned with the data privacy issues surrounding IoT devices, and this data came from an international survey including the UK, France, Japan, Australia and the USA as participants. Despite these concerns, the usage of IoT devices has grown by 18% in 2022 and 16% in 2023 [64] showing that the public acceptance of the devices is greater than their concerns about the technology.

This is a common modality for IoT-based provision, however when you further add medical applications to any computing scenario the expectation and associated concerns grow as there are still many demographics that distrust medical technologies, e/m-health associated factors. This leads to the first of the challenges which is user acceptance.

### *8.1. User Acceptance*

Regardless of the potential positive impact an IoMT device might have it will always be limited by the willingness of the user to accept and utilise the technology [56,65,66]. This acceptance issue will always be prevalent in any technology-based scenario, however, there are methods to minimise the negative impact one of which is to make use of robust novel security approaches such as biometric security and blockchain [5,67].

### *8.2. Time Constraints*

Time constraints cross multiple purview's with IoMT, firstly they can address the time it takes for the device to complete its purpose; it can be the time in which it takes the data to be sent to the appropriate sources; the time taken to act upon the data by the approved medical professional; time synchronization and the impacts therein when multiple devices are being used [22,68]. This is especially important when it comes to the choice of the sensors being used, are they wearables or are they static, and finally what is the requirement for the specific system, is it general monitoring or is it emergency recognition and response monitoring [4,56,64–66]? These factors will drastically change the impact of time within an IoMT application.

### *8.3. Reliability*

All computing systems are required to be reliable and work efficiently, however, when working within a medical environment this reliability factor is one of the most important features due to the potential consequences that could occur. It would be very rare that current IoMT systems can provide active medical intervention to a patient, as this should always be left specifically to a trained medical professional, with the risk of incorrect medical procedures being too high. However, there are a variety of techniques in which the monitoring of a patient can take place and the reliability of the system will denote to what level of complexity this monitoring can attain. As Pazienza et al., 2020 [69] highlights there is a massive difference in complexity between the users monitoring their well-being after an exercise session compared to a hospitalised patient at risk of medical deterioration. This also leads to another challenge which would be the complexity of the data processing and the scalability of the process

### 8.4. Data Processing and Scalability

Along with the general complexity of implementing an IoMT environment, the amount of data being processed also needs to be considered. The amount of data will depend dramatically on the role the IoMT is being used for. For example, if the users are being monitored in real-time for a range of conditions/illnesses, then the data can include general things such as gait, weight, temperature, blood pressure and so on [45]. However, if the system is focusing on a specific condition, then the data gathered might be quite narrow for example, when considering just monitoring epilepsy [12]. This is not the only consideration, however, as whilst some systems may only be monitoring a single condition, that condition complexity might be such that the data gathered is inherently complex and requires more processing, whilst a situation that is doing general ad hoc monitoring might have quite simple data to deal with, but there is a lot of it. This brings forth the requirement that all systems are scalable so that the data can be processed in an efficient way, minimising errors or anomalies. This could be simply creating a scalable data processing plan or having redundancies in place in case of point failures [70,71].

### 8.5. Interference

Again, depending on the scenarios involved, the types of data being gathered and the devices being used, interference can become a major problem. In an ideal scenario, the IoMT environment would be completely controlled and would be easily adapted where needed. This is often not the case, and dealing with any wearable IoMT would minimise the advantages of it being wearable. Therefore, it is imperative to consider what type of interference can occur and how can be minimised. One obvious issue is that these devices need to be in contact with the internet to work correctly; however, if they drop connectivity for whatever reason, what will happen [31]? Is the data backed up and updated when the connection is restored? Is the data lost? How much data can the device store within a connection [4]? How easy is it to resynchronize with the servers when the connection is restored and so on? Alongside this issue, there are interference problems with certain sensors that must be considered; for example, glucose monitoring devices need to be small enough to not interfere with the patient as they are providing continuous data [72]. This can also be an issue for more hardware-centric sensors such as EEG and ECG tests that can potentially be impacted by the location of powerlines and heavy industry [73].

### 8.6. Wearability

This links directly to the next challenge, which is the wearability of the devices. Usually, these devices are split into two main areas: physiological and ambient sensors. Physiological focus on gathering data about the patient, whilst ambient gathers data on the environment and surroundings. Most of the physiological sensors are wearables, such as skin conductivity, blood glucose, pulse and ECG [11]. Whilst ambient looks at surrounding data such as light, sound, and temperature [72]. Normally these devices will be in the location the patient is; however, this would require a dedicated smart environment set up to facilitate this, and whilst that would be ideal in many scenarios, it is rarely possible due to financial, logistical or personal reasons [11]. This is why the focus is useful on what can be gathered with normal wearables such as smartwatches and monitors.

### 8.7. Security

As with all computing devices, the impact of security is of utmost importance; this is doubly so for any data being gathered that is personal/medical in nature. This data must be secure throughout its processing. This means that the physical security on the IoMT devices is robust, as are the data transference, storage, and applications. This is the same as any other security system dealing with medical data, and when choosing the appropriate sensors/architecture, the appropriate security considerations must be regarded [24,47,52,59,74–76]. As well as the normal security approaches that any system needs to consider, the other main concern for IoMT is the continuous data collection and access to patient records; these factors make the impact of a security breach potentially devastating. This is because, whilst medical data is important to protect, if the data is older (months/years), it will not have the same potential to negatively impact the users. It still can do this; however, the continuous, dynamic gathering of data has much more potential [77].

## 9. Discussion

This review has provided an in-depth exploration highlighting both the advances and challenges in the current state of IoMT. Considerable progress has been made in recent years in the technological medical world and IoMT is a chief in today's healthcare industry, the review has uncovered its exponential growth and evolution from traditional healthcare systems. IoT has been the game changer in this growth, and the challenges to embed the IoMT new paradigms into traditional healthcare architecture are prevalent. This review has highlighted the benefits of IoMT and how stakeholders including hospitals, researchers and policymakers are contending in the race to encompass IoMT to reduce costs, enhance precision and productivity.

IoMT devices have been discussed in this review. Despite bringing ease to the process of data collection and analysis for both personal and health- care provider use, and offering insights for personal lifestyle adjustments and evidence-based behaviour change plans other challenges remain. User acceptance, can be hindered by data privacy concerns and distrust of medical technologies. Although adoption has grown, public acceptance is outpacing privacy worries. The technology's effectiveness is also dependent on the reliability, scalability, and synchronicity of data processing, which becomes much more complex when dealing with multitudes of health conditions and broad data sets. Alongside this data security is a major concern due to the continuous, real-time nature of health data collection, necessitating robust security measures to prevent breaches.

Whilst the challenges of the Internet of Medical Things (IoMT) in promoting a healthy lifestyle and managing health-related data remain, the fast rate of IoMT device development, particularly driven by AI, adds further hurdles and requires developers to keep pace with the ever evolving IoMT devices. As wearable fitness trackers and Wi-Fi-enabled scales allow users to monitor physical activity, sleep, and body composition, helping individuals maintain a balanced diet and exercise regimen, the abilities of AI in improving the functionality, personalising patient care, detection accuracy, and automating decision-making, is coming round and must be embraced.

One significant finding with IoMT is its wide-reaching capability of remote monitoring allowing increased flexibility and improved efficiency with data-driven insights. This together with its tailored 'patient centred' ability is shifting the healthcare industry toward a more compassionate one, and if a seamless integration of IoMT architecture can come about it may be that IoMT is the key in the long term for more healthy living.

## 10. Conclusions

The increasing integration of the Internet of Medical Things (IoMT) is significantly transforming healthcare by enabling continuous monitoring of health parameters across various disciplines including medicine, dentistry, and nursing. The Internet of Things (IoT) has evolved from experimental connected devices to being a pervasive part of everyday objects, facilitating the establishment of IoMT. This shift has been made possible through enhanced network capabilities, data management tools, and new standards to ensure smooth interaction between different IoT devices and systems.

IoMT technologies, such as wearable sensors and monitoring devices, allow for the collection and analysis of health data from patients with conditions like diabetes, epilepsy, and heart issues, both in-home and in-hospital settings. These connected medical devices form an integrated infrastructure that includes software applications and health services, exemplified by remote monitoring of chronic conditions.

Traditional medical tools are being upgraded with IoMT capabilities, such as patient location tracking in hospitals and medication management systems. The deployment of IoMT requires a complex architecture, utilising scalable cloud solutions to facilitate data storage and processing. Big data technologies complement IoMT by making extensive data resources accessible and affordable, thus opening new possibilities for patient care. Future IoMT development aims to integrate technologies like AI and big data analytics further, though challenges related to acceptance, data management, and security remain pivotal.

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