Editorial

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The internet of things for combatting antimicrobial resistance

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According to the Oxford English Dictionary, the internet of things (IoT) is “a proposed development of the internet in which many everyday objects are embedded with microchips giving them network connectivity, allowing them to send and receive data” [1]. A recent report dated February 2020 states that “The global internet of medical things (IoMT) market is expected to swell to a $158 billion valuation in 2022, up from $41 billion in 2017” [2]. Additionally, in a recent report from *Research and Markets* “The entire healthcare industry is poised to undergo an unprecedented transformation as a result of technology advances and healthcare access concerns due to the recent coronavirus pandemic” and “We see substantial growth in the healthcare industry largely propelled by IoT technology” [3]. Therefore, although the majority of IoT devices are unlikely to be specifically designed for microbiology-based purposes, there is still scope for the use of IoT in helping to combat antimicrobial resistance (AMR). This short *Expert Opinion* article provides a few insights.

Essentially, for medical applications, IoT would comprise (web-enabled) smart devices that are potentially embedded in wearables, medical devices, edibles and smartphones. The devices would comprise IoT-interlinked sensors together with processing and communication software. However, crucial to this medical transition is the development of durable, reliable, safe, secure and low-cost (point-of-care) sensors, including self-powered sensors and devices [4]. Such devices and sensors could be used in Diagnosis, Treatment and Infection Prevention strategies against AMR, as well as in holistic Healthcare Information collection programs. Further, their area of impact would not be limited to medical institutions such as hospitals, care homes, general practitioner offices etc., but could be expanded to include farms and farm animals, ecosystem monitoring and the patient’s own home.

Diagnosis

The implementation of (self-powered) IoT-connected diagnostic devices would allow for the potential real-time monitoring of biomarkers in and on the human (or animal) body e.g., sweat, urine, blood etc., including the potential ability to distinguish between viral and bacterial infections. In real time, such information could impact on ‘yes/no/wait’ antibiotic prescribing decisions and provide more accurate and timely information regarding potential ‘infection’ versus ‘sterile’ inflammation disease processes [5,6]. Further by collecting real time data on individual patients, IoT could be utilized to develop personalized predictive algorithms for identifying infection, sterile inflammation or the possibility of relapse, up to hours before visible physical signs are observed [7]. Also, the reaction of the patient to antibiotic treatment could be monitored more closely, indicating if the patient is actually responding to antibiotic therapy and possibly indicating that antibiotic resistance may be present, allowing clinicians to consider adapting their ‘first line’ treatment therapy in a timely manner.

Treatment

The correct use of antibiotics could be promoted by IoT embedded in pill dispensers or smartphone apps that remind care providers or patients when the next antibiotic tablet is due to be taken and provide visual and/or auditory reminders to ‘remember to take the whole course’ and ‘medicines are to be used only by the patient’ [8]. This type of system could be suited for larger care centers, for example, nursing homes and even be available for discharged patients for use at home. Information could also be recorded and included in information retrieval systems. Additionally, when combined with surveillance, (IoT) diagnosis and prescribing information, the prevalence/incidence of AMR could be related back to the epidemiology of disease, antibiotic usage data and patient compliance, generating a more holistic overview of the development of AMR at regional, national and international levels [9]. It is also possible that IoT sensors could be embedded in individual tablets, which when combined with patient monitoring of biomarkers and/or antibiotic levels in body fluids, could provide more accurate information on antibiotic compliance and the efficacy of treatment on a personalized level, helping steer the correct prescribing dosage and dose period for individual patients [10].

Infection Prevention - IoT devices may not only useful in measuring biological parameters *per se*, but may also be useful in monitoring the behavior of care givers. As abundantly made obvious during the current COVID-19 epidemic, the usefulness of hand washing has been shown to be an effective measure to prevent the spread of viral (and antibiotic resistant) microorganisms. Sensors attached to handwashing dispensers, or standalone devices could be connected to continually monitor handwashing compliance even in Low and Middle Income Countries (LMICs) [11]. Alternatively, using smartphone location or other IoT services, care givers could be warned when they move from one patient to another, or from one room to another, and have not washed their hands. Such systems could also warn caregivers and patients if they have come into contact with potentially infected individuals during nosocomial AMR outbreaks [12] and could be based on systems proposed for COVID-19 such as 'the Cognitive Internet of Medical Things (CIoMT)' [13]. This type of monitoring could be considered intrusive, but the development of a smartphone app. that only registers movement (and contains no personal information) may help with protecting the civil rights of caregivers [14]. Monitoring medical air disinfection parameters using IoT could also be useful in infection prevention strategies aimed more specifically at hospitals [15].

Security and privacy issues regarding IoT and healthcare applications should not be forgotten, and though not specifically aimed at IoT for AMR, such issues are essential for promoting the use and trust in IoT in general. These issues include: 1) emphasizing built-in security solutions and *General Data Protection Regulation* (GDPR) considerations [16], 2) future-proofing devices to meet the security challenges of tomorrow, 3) access control and device authentication, 4) reducing the amount of personal data collected by IoT devices and 5) rendering compromised data useless without destroying the IoT infrastructure [17]. Of course, such issues may be amplified if data from AMR IoT devices is being collected from (inter) national networks and being scrutinized by artificial intelligence (AI) or machine learning (ML) systems [18]. *Block Chain*-based IoT technology may be useful in maintaining cyber security at patient history and patient treatment (including antibiotic treatment) levels. The *Block Chain* is "a growing list of records (blocks) where the records are connected to each other using a cryptographic method called hashing. Each record contains a cryptographic hash of the previous record, which will chain the records together and make them resistant to modifications" [19]. Block chain technology could help secure the manufacture and distribution of medicines (including antibiotics and vaccines) against inferior counterfeit medicines, whilst also helping safeguard the medical records of patients.

Finally, the roll out of 5G networks potentially provides a new impetus with regard to IoT-based connectivity and (e-)healthcare systems. Such continuing technological advancements will help embed IoT devices into everyday life generating smart hospitals, smart vehicles (including emergency vehicles) and even smart homes to monitor and protect our health via biosensors, apps, telemedicine, wearables, data acquisition and data processing hardware and software [20]. The fight against antimicrobial resistance may never be won, but the implementation of IoT technologies will add an extra set of tools to help the world control the emergence and spread of antimicrobial resistance at local, national and international levels.

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