Leveraging Emerging Technologies and the "Internet of Things" to Improve the Quality of Cancer Care

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Kevin Ashton coined the term "Internet of Things" in 2009 in the setting of supply chain management,[1] but since that time, the Internet of Things (IoT) has had an impact on many other markets. Over the past several years, advances in computing and sensing have sparked the emergence of the IoT for health care. The IoT refers to a connection of smart objects such as appliances, sensors, controllers, wearables, and medical devices to the Internet. Overall, the IoT health care market is predicted to grow from 32.4 billion in 2015 to 163 billion by the year 2020.[2] In 2015, there were already 25 billion Internet-connected devices, which is double the number of humans on Earth.[3] In addition, the number of IoT devices will have unprecedented growth and is expected to increase to more than 50 billion by 2020.[3] Within the IoT, wearable devices and sensors alone will grow to more than 118 million devices predicted to be sold by 2018.[4]

As health care moves away from traditional encounter- and office-based care paradigms to more continuous interactions between the patient and the health care system, there is an unparalleled opportunity to leverage emerging technologies to create an ecosystem with the patient at the center. It is now possible to track various types of data in the patient's own environment. Examples include accelerometer data (physical activity and intensity), temperature, heart rate and heart rate variability, blood pressure, sleep, caloric intake/expenditure, brain wave activity, pulse oximetry, glucose, and other biometric data. Wristbands and smartwatches currently predominate the fitness wearables market,[5] but there will be a shift toward smart garments by 2020.[6] There are also several ingestible and implantable sensors for tracking biometric data that already have or are currently undergoing US Food and Drug Administration approval. Beyond wearables, sensors can now be attached to appliances, objects, and the environment to detect carbon dioxide and carbon monoxide, particulate matter, ambient room temperature, light, and allergens such as pollen.

Information technology was cited as a key requirement for building a high-quality cancer care delivery system by the Institute of Medicine and also as the foundation for a learning health care system.[7] This vision for digitally capturing the health care experience for "real-time generation and application of knowledge for care improvement" has made substantial progress since that report in 2009. One exemplar is CancerLinQ,[8] which is an initiative of the American Society of Clinical Oncology for aggregating and analyzing data from electronic health records, clinical trials, and clinical practice guidelines. Recently, CancerLinQ and the Cancer Informatics for Cancer Centers announced a collaboration to apply big data methodologies to drive discovery in cancer care. Understanding health care delivery through

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real-time, large-scale monitoring and evaluation is an important step toward actualizing a true learning health care information technology system that targets the specific issues unique to cancer care.

Until recently, electronic health records have not incorporated patient-generated health data (PGHD) in cancer care. PGHD includes patient-reported outcomes, medical/wearable device data, and other sensor-generated data from within the patient's home environment. Because patients spend most of their lives outside the walls of the clinic and hospital, IoT technologies that generate PGHD provide an unparalleled opportunity to obtain a more holistic longitudinal view of the health of a patient with cancer. For example, one could envision that a patient with cancer who also has heart failure could have a smart home environment which has sensor-enabled doors, floors, refrigerator/freezer, pillboxes, toothbrushes, bed, and mirrors coupled with wearable sensors for continuous or intermittent monitoring of heart rate, electrocardiogram, pulse oximetry, respiratory rate, body temperature, galvanic skin response, hydration, weight, and gait (Fig 1). The patient's context within the IoT ecosystem could be further enhanced with data streams from social media, consumer data (purchases), and geographic information systems and from scanning the environment for audio and/or voice data. Advanced computational and mathematical analytic approaches could process and aggregate these data into actionable information to shape self-management or clinical decisions. In this IoT ecosystem, an oncologist could be notified if a patient has not been out of bed or out of their room or if their pillbox has not been opened for several days. These signals from within the IoT data would provide an opportunity for the oncologist to check in with the patient and have the patient answer an electronic patient-reported outcome questionnaire via the patient portal. The oncologist could also send a text message to the patient or caregiver to determine whether the patient is having intractable pain or their physical function has declined such that they are unable to get out of bed to reach the pillbox and have therefore missed doses of their oral chemotherapy medication.

It is also conceivable that, in the near future, most of the data to inform clinical care will be collected outside clinical settings and will potentially provide richer details about the patient. For frail and elderly patients with cancer, remote monitoring using PGHD and the IoT could help keep patients out of the hospital so they can instead remain in their homes and still have any adverse symptomatic events or acute exacerbations managed effectively. With the IoT, providers could identify variance or deviations from baseline measures and alert the patient or caregiver to check in or to seek emergency care.

Integrating the IoT to improve the quality of cancer care faces several challenges, including security and privacy, data standards and interoperability, data provenance and ownership, and workflow integration into clinical care. As the number of Internet-connected devices and objects increases, the number of potential entry points for cyberattacks increases. Streaming sensitive health data from IoT devices presents an attractive target for data thieves. Ensuring the security and privacy of these data will be paramount. In an extreme case, a medical device or sensor could be hacked in real time, which could have potentially fatal consequences. In another case, data from a device could be stolen, thus potentially revealing sensitive health information.

There are a number of challenges regarding data standards and interoperability. The accuracy of data from consumer devices is variable, and some devices perform better than others for physical activity and heart rate.[9,10] In the case of physical activity data, the raw accelerometer data generally are processed by proprietary algorithms that can vary by device and are often updated without notice to the user. Standardizing the outputs of these data across devices and performing validation studies in various patient populations will improve the use of these data across patient populations. There are also numerous standards and ontologies, which make mapping data from different data streams extremely difficult. Moreover, there will likely be numerous types of devices and sensors within the IoT health ecosystem that need to exchange and interpret data shared with each other and with electronic health record systems. Thus, interoperability on a foundational, structural, and semantic level will be paramount.

Data provenance and ownership is another broad concern identified by patients, providers, health care systems, and policy makers. The ability to demarcate patient-generated data from data generated during clinical encounters is key for bringing these types of data into the health care setting in a way that physicians can differentiate them.[11] In terms of data ownership, there is much debate about whether PGHD is owned by the patient or by the health care system if the data are synchronized to the electronic health record system or patient portal. Ultimately, data ownership issues have important downstream effects. If patients own their data, they have an opportunity to contribute the data for

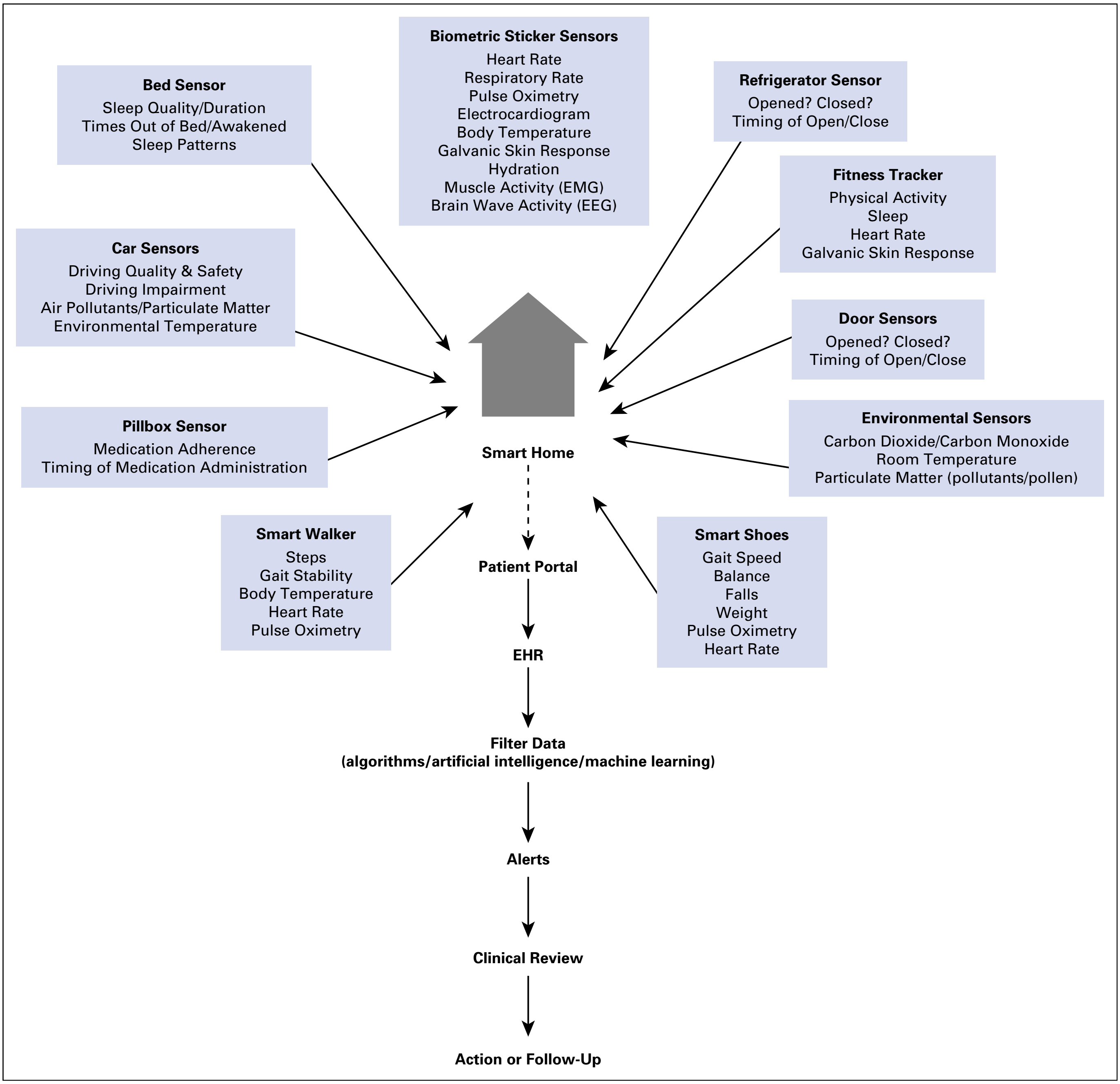

FIG 1. Conceptual model of an "Internet of Things" ecosystem for health. EEG, electroencephalogram; EHR, electronic health record; EMG, electromyogram.

research purposes. Citizen science is making progress through organizations such as PatientsLikeMe and the Patient-Centered Outcomes Research Institute, which serve as the infrastructure for contributing PGHD to research on a larger scale. If patients do not retain ownership of their data, scaling citizen science efforts will be difficult. Currently, little is known about the patient experience in populations not captured within cancer trials. Thus, the IoT could provide an opportunity to better understand these populations, their outcomes, and the influence of contextual factors on their health and could move beyond the information currently streamed from consumer fitness wearables.

Integration of IoT and PGHD into clinical care processes is challenging because the evidence base is evolving. First, it is unclear which types of patients with cancer would benefit most from being monitored by using IoT technologies, which types of data will be necessary to accurately capture the quality of care and improve patient outcomes, and how frequently data should be sampled (continuously *v* intermittently). Second, while a recent national survey showed that patients are quite willing to exchange information about vital signs and symptoms over a mobile phone or tablet,[12] little is known about whether patients would be willing to be continuously monitored with IoT technologies that might be perceived as being more obtrusive. Third, providers who are already inundated with data are wary about the impact of additional data on their workflows and workload.[11] Finally, there is little guidance regarding how frequently these data should be brought into electronic health record systems as part of the medical record and how they should be presented to providers to facilitate clinical decision making. In some instances, bringing in continuous streams of IoT data without appropriate alerts and notifications to inform providers about abnormalities in real time could present safety issues. For example, a patient with breast cancer who is receiving anthracycline, which is potentially cardiotoxic, could develop a life-threatening arrhythmia that could be detected by using a continuous heart rate sensor. If her data were not monitored in real time with an alert generated to notify the physician on call, missing that event could have serious consequences.

As the IoT ecosystem expands over the next few years, there will be new opportunities to quantify, evaluate, and monitor a patient's biometrics, home, and environment. This will provide researchers and oncologists with an exceptional opportunity to better understand how a patient's unique ecosystem contributes to their overall health and long-term outcomes during and after cancer treatment. Although there are known environmental exposures that contribute to cancer risk, IoT data may be able to enhance our understanding of the microenvironment's contribution to an individual's cancer risk. Overall, these insights will allow for greater precision and tailoring of clinical recommendations and treatment options and ultimately improve the patient's experience longitudinally. JOP

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