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Smart Biomedical Devices for Medication Adherence: Can Engineering Improve Long-Term Treatment Outcomes?

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ABSTRACT

In chronic diseases that have complex and long-term treatments, adherence to the prescribed medication is a key factor for successful long-term treatment. Missed or incorrect doses can be caused by forgetfulness, complexity of treatment, side effects, lack of health literacy, cost, or lack of communication with health care providers. Self-report, pill counts, and refill records are often incomplete measures of actual medication use because they are based on a set of conventional methods. Improvements in biomedical engineering have facilitated the development of smart medication systems that include sensors, smart devices, automated dispensing, mobile applications, and data analysis to help and monitor adherence. They can be electronic pillboxes, smart blister packs, ingestible sensors, drug-connected inhalers, wearable devices, and smart systems for drug delivery. This review covers various aspects of the medication adherence challenge and how engineering can help by starting from a patient-centred device design, through real-time monitoring, automated reminders and personalised feedback. The review also takes into account the evidence of adherence and clinical outcome improvements. Research indicates that smart devices have the potential to enhance adherence to medication in certain patient sub-populations, yet they can be effective in only some cases and only to a certain extent, depending on the device's usability, its integration with the health system, patient engagement and the quality of the evidence. Barriers to consider are cost, interoperability, cyber safety, privacy, regulations and inequitable access to digital technologies. The future should see a marriage between artificial intelligence, biosensing, remote monitoring and adaptive interventions to bring more tailored medication support. In this regard, engineering has great potential to enhance treatments in the long term; however, smart devices should be used in addition to patient-centred clinical care.

Keywords: Medication adherence; Smart biomedical devices; Biomedical engineering; Digital health; Drug delivery; Wearable sensors; Artificial intelligence

1. INTRODUCTION

1.1 Background and Importance of Medication Adherence

Medication adherence refers to the extent to which the patient adheres to the plan for taking the medication. Adherence is crucial in long-term treatment since missed doses, suboptimal dosing, or premature discontinuation of appropriate treatment may render it ineffective (Gast and Mathes 2019; Kini and Ho 2018). This challenge is pertinent in chronic diseases that require long-term medication, such as diabetes, blood pressure problems, cardiovascular disease, asthma, HIV infection, and neurological diseases. Engineering technologies can be used to support adherence to medicines, including recording of medicine-related events, identification of medication patterns, and providing timely reminders or clinical follow-up (Gast and Mathes 2019; Kini and Ho 2018).

Compliance is crucial in chronic diseases like diabetes, hypertension, cardiovascular disease, asthma, HIV infection, and neurological diseases. Commonly, these conditions must be treated for a prolonged period despite the absence of symptoms. Adherence to medicines is therefore important in determining whether a clinically effective medicine does the job it is supposed to be doing. Engineering technologies may facilitate adherence by capturing medication-related events, detecting medication gaps, and providing reminders or clinical follow-up.

1.2 Burden and Consequences of Medication Non-Adherence

Treatment complexity, adverse effects, perceived lack of benefit, financial barriers, cognitive difficulties, and difficulties in medication management are all possible factors that can contribute to medication non-adherence (Kini and Ho 2018). These are all factors which vary from patient to patient and treatment to treatment, and adherence is a multifactorial issue rather than just a memory issue. The traditional assessment practices are also not well suited. All these are subjective; refill records do not reflect ingestion, and pill counts are not accurate in determining when and how a dose was consumed. This has resulted in the need for more time-accurate technologies (Mason et al. 2022). The potential clinical implications of nonadherence and the difficulties of assessing adherence are discussed in Section 2.

1.3 Emergence of Smart Biomedical Devices

Smart biomedical devices are physical devices that are equipped with sensing, computing, communicating, and feedback functions. These include electronic pillboxes that track whether the pillbox has been opened and automated dispensers that dispense scheduled doses. The smart packaging can record access to the medicine, and ingestible sensors can directly identify medicine intake. The drug-administration events can also be recorded with connected delivery devices. Recent reviews have shown that this field is developing with many types of commercial products and prototypes involving various alarm, sensor, mobile application, cloud storage, and remote monitoring combinations (Faisal et al. 2023; Turjamaa et al. 2020).

The idea of reminding is taking a step beyond. In a modern system, it will be possible for it to identify that a dose has been missed, to alert a smartphone, to analyse the adherence pattern, and to provide an

individualised intervention. Caregivers or health care professionals can also be provided information if appropriate.

1.4 Role of Engineering in Improving Medication Adherence

There are three ways that engineering can support adherence: by making the management of medicines easier, by making the behaviour of taking medicines measurable, and by linking the information on adherence with timely interventions. Biomedical engineers are able to place sensors inside packaging or delivery systems, design low-power communications systems, build sensor-friendly user interfaces, and develop algorithms to interpret the raw sensor data to provide useful information. These capabilities enable adherence support to be more responsive and individualised.

However, behaviour and social determinants of non-adherence will not go away with engineering. If a device is too expensive, cumbersome, intrusive, or inconvenient to use, or doesn't fit seamlessly into a patient's lifestyle, it will likely fail to work. Engineering solutions should combine technical effectiveness with patient-centred design and clinical usefulness (Mason et al. 2022).

1.5 Rationale and Scope of the Review

The review explores smart biomedical devices and their potential as engineering solutions for the medication adherence problem in the long term. It explains design principles, key device types, key enabling technologies, evidence of effectiveness, limitations, and prospects. Special focus is placed on whether new technology for monitoring and delivery of medication leads to a significant improvement in adherence and clinical outcomes.

2. MEDICATION ADHERENCE: CHALLENGES AND CLINICAL SIGNIFICANCE

2.1 Definition and Dimensions of Medication Adherence

Adherence to medication is a multi-faceted process that consists of initiation, implementation, and persistence. Initiation refers to the patient's initiation of treatment. Implementation refers to adherence to the prescribed treatment, and persistence refers to the duration of the treatment. A patient might, therefore, start a medicine but forget to take doses or take doses at the wrong time, or stop a medicine too early.

Pharmacy dispensing or refill records may provide information on whether the medication was accessed, but not when it was taken. Electronic medication monitoring devices can document events like opening of a container or access to a blister pouch, but are only indirectly indicative of ingestion. While ingestible sensors offer a more direct source of evidence of ingestion, there are also added concerns around privacy, informed consent, acceptability, cost, and data security. (Mason et al. 2022; Chai et al. 2022).

2.2 Patient-Related Factors Affecting Adherence

Patient-related factors include forgetfulness, beliefs about medicines, perceived need for treatment, concerns about side effects, health literacy, cognitive impairment, depression, social support, and daily routine. Medication management may be more complicated in patients of various ages, especially those with multiple chronic conditions, due to the risk of polypharmacy. Elderly individuals might be at further disadvantage due to a decrease in visual function, diminished motor control, or cognitive function. Simultaneously, younger and more tech-savvy patients are not necessarily engaged; if they receive a lot of notifications and are burdened by the devices, they may not be.

2.3 Treatment-Related and Healthcare-Related Factors

Use of multiple medications and complicated dosing regimens, especially multiple medications administered more than once a day, can add to treatment burden. This burden can be increased by side effects, inconvenient dosing regimens, and long treatment duration. As the number of medications increases, it may be hard to determine what drug to take at a given time. Healthcare barriers include poor counselling, fragmented care, lack of follow-up, and poor communication.

While some treatment burdens can be mitigated by dose organisation, automation of treatment, and engineering, it cannot address unaffordable treatment or inappropriate prescribing itself. The most useful application of smart devices is when they're integrated into a care pathway where the clinician can take action based on information about adherence.

2.4 Consequences of Poor Medication Adherence

The impact of non-compliance is different for each disease and medication. Failure to adhere to chronic disease medications can result in inadequate symptom control, risk of disease progression, failure of treatment, and preventable healthcare utilisation. In infectious diseases, inconsistent treatment can impact the effectiveness of the treatment and could have implications for public health. Diabetic individuals may end up with hyperglycemia and glycemic variability if they miss out on a dose of insulin.

2.5 Limitations of Conventional Adherence Strategies:

Counselling methods include education, counseling, shortened regimens, pill reminders, pill containers, family support, and follow-up. These are still important for adherence as human behaviour and social context affect adherence. But there are many methods that rely on patient self-report and only give intermittent information between clinical visits. The use of technology can take adherence support beyond the clinic and offer the benefit of time-stamped data, which could help the clinician determine if there are ongoing adherence issues or isolated issues (Mason et al. 2022).

3. DESIGN AND FUNCTIONAL PRINCIPLES OF SMART MEDICATION DEVICES

3.1 Patient-Centered Design and Ease of Use

The smart medication device should fit into the patient's routine. Some key design features are ease of use, easy-to-read labels, and compact size, as well as adequate battery life, easy medication loading, and well-defined instructions. Accessibility for older adults might include easy-to-open compartments and tactile and audible alerts, as well as large text.

Usability isn't just about convenience. Patients can become frustrated with a complex device and therefore not use it, potentially increasing the technical apparatus and not having a beneficial impact. The use of smart medication systems has been highlighted for the ease of learning, portability, convenience, and integration with everyday life as key evaluation criteria for the technologies (Mason et al. 2022).

3.2 Medication Tracking and Dose Verification

Switches, optical sensors, weight sensors, motion sensors, pressure sensors, or electronic event markers can be used in smart devices to monitor use or administration of medication. These methods can produce an event log of medicines that includes a timestamp. An important difference between detection of access to a medicine and confirmation of medicine ingestion, however, exists. Just because the pill box is opened, it does not mean the right dose was taken, nor does an event of the pill box in the electronic blister-pack system mean that the correct pill was swallowed.

Ingestible sensors offer a more direct way to detect ingestion by sensing ingestion after the sensor has reached the gastrointestinal environment through the generation of a signal. These types of systems can thus be used to solve a key problem of container-based monitoring (Chai et al. 2022).

3.3 Reminder, Alert, and Feedback Mechanisms

These range from alarms or indicators flashing to alerts on a Smartphone, voice prompts, and caregiver alerts. For more sophisticated systems, adherence information can be fed back to the system to either adjust the timing or the strength of the reminders. Adherence summaries, progress indicators, or messages can be used to give feedback and encourage the patient to take action.

But too many reminders can result in alert fatigue. Therefore, the patient's preferences, the severity of a missed dose, and whether repeated alerts are beneficial should be taken into account in the design process. Do not be critical or condemning when providing feedback.

3.4 Personalisation and Adaptability to Patient Needs

Personalisation enables systems to take into account the person's medication plan, schedule, accessibility needs and past adherence patterns. For instance, an algorithm could determine that missing doses is a regular occurrence at a specific time of day and tailor the intervention to that time. Adherence history might be integrated with other information such as physiology or context in future systems to help

differentiate a single failure to take the medication from a growing adherence issue. In the design and use of smart medication systems, patient autonomy and freedom of choice need to be considered fundamental. These technologies should help patients to manage their medication, not force them to follow a prescription. Informed consent should be obtained before adherence monitoring begins, and patients should be informed what information will be collected, how the information will be used, and who will have access to the information. Patients should also be given suitable control over the sharing of their adherence data and, if clinically appropriate, the ability to refuse and/or opt out of adherence monitoring. These factors are relevant to technologies like ingestible sensors that can provide accurate information regarding when a medication has been taken and hence are more concerning in terms of privacy and surveillance. Smart medication systems should thus strike a balance between the therapeutic potential of adherence monitoring and informed consent, privacy, patient control, and respect for individual treatment choices (Chai et al. 2022; O'Sullivan et al. 2022).

4. SMART BIOMEDICAL DEVICES FOR MEDICATION ADHERENCE

4.1 Smart Pill Dispensers and Electronic Medication Boxes

Smart pill dispensers have compartments where the medicines can be organised and can dispense/expose the correct medicine at the correct time. Sensors are used for access detection, and alarms & mobile notifications for reminders. Some systems will alert the caregiver if a dose has not been picked up.

The most significant benefit is that these gadgets provide organisation, reminders, and monitoring. They may be especially helpful for those who have to take multiple drugs at different times. The 2023 scoping review identified 114 smart medication adherence products, and there were significant differences in the number of pills they could hold, their alarms, sensing, connectivity, security and cost (Faisal et al. 2023). This difference underscores the importance of standardised evaluation and not equating the same clinical benefit from all smart dispensers.

A large share of dispensers keep track of a proxy for ingestion. Data from dispensing should not be regarded as definitive evidence of intake, as the user can open a compartment without taking medicine and/or can remove several doses at once.

4.2 Ingestible Sensors and Digital Pills

Digital pills are swallowable sensors that are either part of or attached to a pill. Once ingested, the sensor may emit a signal that is picked up by an external sensor (either wearable or receiver) to be able to provide a record that can be time-stamped and track the ingestion event. This method is a direct way to measure adherence, as opposed to the technologies used to open containers.

The technology has been evaluated in psychiatric care, HIV prevention and treatment, and other chronic diseases. Reviews focus on technical feasibility and take into account acceptability, privacy, and implementation (Aungst and Patel 2020). Digital pills are especially relevant if information on when the pill was swallowed has clinical relevance.

Direct monitoring may pose more privacy risks than traditional reminders, especially if adherence data is passed on to clinicians, caregivers or others. Digital pills should therefore only be used when the clinical benefit is warranted, and their use would add value to the monitoring effort and be meaningful to the patient.

4.3 Smart Wearable Devices and Medication-Reminder Systems. Reminders can be given by wearable devices, and they can take physiological or contextual data. A patch that can be worn could be a communications link between a smartwatch sensor and a wearer, and a smartwatch or a mobile phone could provide medication reminders. Wearables can also contribute to adherence indirectly by being correlated with medication events, behavioral or sleep, or other behavioral data.

The main benefits they offer are their portability. Wearables can be incorporated into the patient's digital habits, eliminating the need for patients to constantly interact with the dedicated medication device. But the challenges of skin irritation, charging the device, connectivity, notification overload, and engagement over the long term remain. Wearable systems should thus be designed to require the least monitoring that is necessary to accomplish the desired clinical purpose.

4.4 Connected Drug-Delivery Devices and Smart Injectors

Smart drug-delivery devices are not just reminders to take a medicine, but are able to record drug administration. Dose information and/or dose timing data can be recorded with connected injection pens. This is especially true when using insulin therapy, since there is a direct correlation between the time when it is administered and the effectiveness of the treatment.

Introduction of the device in a real-life study of a connected insulin pen was found to significantly improve the time in glucose range and reduce bolus omission by 43% (Adolfsson et al. 2020). These results show that the value of adherence technology might be greatest when combined with trusted dosing information and a pre-existing clinical management pathway.

Injectable treatments have also been looked at for electronic auto-injectors. Interferon beta-1b is a disease-modifying drug that can be used in patients with clinically isolated syndrome or relapsing-remitting multiple sclerosis (MS). Electronic auto-injectors can facilitate drug administration and create an objective record of drug administration, since they are given by injection. BETACONNECT is a new electronic auto-injector that will help make interferon beta-1b easier to inject and keep track of how often it is used. Farej et al. (2022) assessed 146 adults with relapsing-remitting MS or clinically isolated syndrome in a prospective, observational, multicenter study for 6 months. Of the 91 participants who finished the study, the mean adherence rate was 82.5%, and among them, 65.9% maintained an adherence rate of at least 80%. Moreover, patients' satisfaction with the device was also reported to be high, as the study also showed. But since the study was observational with no randomized comparison to show that the adherence was actually improved due to the introduction of the BETACONNECT, the results should be interpreted as evidence of an association between device use and high adherence, and not as proof of a causal improvement in adherence (Farej et al. 2022).

4.5 Smart Packaging and Electronic Blister Packs

EMPackaging (electromedication packaging) refers to packaging that is equipped with sensors or electronics within the container or blister packs. These record package activity, provide reminders, and transmit adherence information.

Electronic packaging is less intrusive and more likely to be incorporated into a patient's normal drug delivery system as compared to ingestible systems. It is still a measure of access, though. Previous systematic and scoping reviews have revealed that packaging interventions have been associated with improved adherence in certain settings (in particular when combined with monitoring and feedback, or when integrated with a healthcare system) (Kurup et al. 2020; Checchi et al. 2014).

4.6 Mobile-Integrated Medication Management Devices

In addition to being mobile, the hand-held devices are also capable of handling medications. The mobile hand-held devices can also manage medications.

Medication devices, patients, caregivers, and healthcare professionals can be linked via a smartphone. Schedules can be shown; data from sensors can be received; reminders can be sent, and self-reported data can be collected; adherence summaries can be provided.

We carried out a systematic review and meta-analysis of randomised trials to assess the effectiveness of medication-adherence apps; results revealed variable effectiveness, dependent on the behaviour change techniques that were included in the intervention (Armitage et al. 2020). This implies that an app shouldn't be assessed as a virtual reminder. It will only be of value if it can provide an effective behavioural and clinical intervention**.**

5. ENGINEERING TECHNOLOGIES ENABLING SMART MEDICATION DEVICES

5.1 Biosensors and Physiological Sensors

The building blocks of sensors are the conversion of the behaviour of medicines to measurable data. Mechanical switches, optical sensors, weight sensors, pressure sensors, accelerometers, or biosensors are all possible sensors for a system, depending on the application. Wearable systems can also be used to take physiological parameters that can contextualise medication use. Specialised sensors are a more specialized type that can, in addition to detecting medication events, detect ingestion events. New research in engineering has been shown to be viable for low-power systems that integrate ingestible sensors, wearable sensors, mobile and web interfaces (Weeks et al. 2018). Future developments will require the system to be smaller, lower power, low-cost fracturing complexity and be low cost and reliable in measurement.

5.2 Internet of Things and Wireless Communication

Medication devices can communicate with smartphones, gateways, the cloud, and clinical systems using the Internet of Things. Time-stamped medication data can be sent via Bluetooth, Wi-Fi, cell phone communications,, and other wireless technologies for monitoring and analysis.

Connectivity facilitates remote care, but introduces reliance on connectivity and interoperability. Different data formats can pose a challenge for the integration of eHRs, and there is a need for proper fall-back and data exchange standards.

5.3 Artificial Intelligence and Machine Learning

AI can sift through the massive volume of adherence information and identify patterns that may be challenging to identify manually through large longitudinal datasets. Machine-learning models can help predict risk for future non-adherence, pinpoint high-risk moments, and inform targeted interventions. AI can also be used to analyse adherence patterns and identify patients who might need more counselling.

But AI is not necessarily better than simpler algorithms. Medication adherence data are often incomplete, biased, or noisy. The model developed during training on one population might not work as well with another population. Clinical systems need to be validated, transparent, monitored for bias, and supervised by humans.

5.4 Mobile Applications and Cloud-Based Platforms

The adherence information can be stored, visualised, and shared across devices via mobile and cloud technologies. A patient might be given a daily summary of their adherence; a health care professional might be given a more extended summary. Cloud systems can also have the ability to back up software updates and incorporate multiple data sources.

The engineering challenge is balancing the need for functionality with security and simplicity, implemented through data minimisation, authentication, encryption, and access controls, as well as secure software development.

5.5 Data Analytics and Real-Time Feedback

Data Analytics transforms data from device events to clinically meaningful data. A system can work out adherence percentages, missed-dose frequency, adherence persistence, and changes across time, instead of showing hundreds of individual timestamps. This can then be followed by a reminder or escalated, if it's the right time.

Analytics need to be accurate; otherwise, you will be frustrated by false alerts and reassured by missed alerts. Therefore, all of these aspects, namely sensitivity, specificity, completeness, usability, and clinical relevance, are relevant for assessment (Mason et al. 2022).

6. EFFECTIVENESS OF SMART BIOMEDICAL DEVICES IN IMPROVING TREATMENT OUTCOMES

6.1 Evidence for Improved Medication Adherence

The effectiveness of smart medication technologies is inconsistent depending on the type of technology, patient population, adherence measurement employed, and length of follow-up. There have been some studies that show improvements in medication-taking behaviour and some systematic reviews that show that the size and reliability of these improvements are different for different interventions.

One instance in which drug-delivery data can be tied to clinical care is connected drug-delivery devices. Adolfsson et al. (2020) assessed a connected insulin pen in individuals with type 1 diabetes who were using basal-bolus insulin and CGM. In the last 94 patients (target group), the time spent in the target glucose range was higher by 1.9 hours/day from baseline to follow-up. For those who were included in the missed-dose analysis, the number of missed bolus injections reduced by 43%. The study was thus able to show improvements in insulin-dosing behaviour and glycemic outcomes after the introduction of the connected pen. The study was observational, however, and the results do not show that the device led to these improvements by itself (Adolfsson et al. 2020).

Auto-injectors that can be programmed electronically have also been employed as an objective log to track the administration of injected drugs. Farej et al. (2022) studied interferon beta-1b adherence in patients with clinically isolated syndrome (CIS) and relapsing-remitting multiple sclerosis (MS) and found that adherence to interferon beta-1b was investigated using the BETACONNECT electronic auto-injector in patients with clinically isolated syndrome (CIS) and relapsing-remitting multiple sclerosis (MS). The mean adherence to the six-month observational study was 82.5% among those who finished the study. These results indicate that eAuto-injectors can provide objective longitudinal information on medication administration. The authors noted that the study was observational, and not a randomized controlled trial, so the device alone cannot be responsible for the adherence results (Farej et al. 2022).

Electronic medication packaging evidence is more of a mixed bag. Reviews of electronic packaging systems have been published, and these systems can be used to contribute to medication adherence monitoring by recording package access events; in some interventions, this monitoring includes reminders or feedback. However, opening a container or blister compartment is a proxy for medication intake, and various differences between patients, devices, adherence measures, and study methods limit the ability to assume that all electronic packaging systems provide the same adherence benefit (Checchi et al. 2014; Kurup et al. 2020).

Mobile apps are another example of the possibilities and challenges of digital adherence interventions. Armitage et al. (2020) did a systematic review and meta-analysis of nine randomized controlled trials that were designed to support medication adherence with mobile applications. The trials involved 1,159 people who had cardiovascular diseases, depression, Parkinson's disease, psoriasis, and multimorbidity. The pooled analysis revealed that app-based interventions were more likely to be associated with greater self-reported medication adherence than comparator interventions (OR 2.12, 95% CI 1.64–2.75). Six of

the nine studies, however, used self-reported adherence measures, and the individual studies were relatively small; intervention effects were inconsistent across studies. Caution is needed in the generalisability of findings to other populations and caution in interpreting the findings as evidence of sustained medication-taking behaviour due to the limitations (Armitage et al. 2020).

All of these results suggest that smart medication technologies are not a "one size fits all" intervention. The various types of connected insulin pens, electronic auto-injectors, smart packaging and mobile apps affect the medication-taking behaviour in different ways. Some technologies appear to be effective for improving or subjectively documenting adherence, but in most cases, these technologies perform best in specific clinical settings, with accurate measures of adherence, patient engagement, intervention design, and adherence information integration into clinical care. Thus, assessment of the effectiveness of smart medication systems should be not only whether adherence changed, but also how adherence was measured, the magnitude/length of change, and whether this increase in adherence led to any clinically meaningful outcomes.

Smart devices have been shown to have the potential for effectiveness, but this does not mean that all are effective. Studies on medication-adherence technologies show numerous different methods employed, such as the use of electronic pillboxes, blister packs, ingestible sensors, mobile apps, and monitoring systems (Mason et al. 2022). Some studies improve adherence, and others do not improve adherence or do not consistently improve adherence.

The principal problem of smart pharmaceutical products is the heterogeneity. Adherence is defined differently in products, and there are variations in the type of product, patient population, monitoring, intensity of intervention, and definition of adherence. A recent survey (2023) revealed that the technological and functional attributes (Faisal et al. 2023) varied as well, and there was an increasing diversity of products. The term “smart medication device” does not mean one type of medication that has a known outcome.

6.2 Influence on Clinical Outcomes

For better adherence to be clinically useful, it must lead to better disease control. While there is more evidence of the link between smart devices and adherence behaviour, there is less evidence for the link between smart devices and clinical outcomes. In the insulin-dosing behaviour study, they connected an insulin pen with the outcomes of glucose levels and saw that improvement in insulin dosing behaviour led to better glucose outcomes (Adolfsson et al. 2020).

6.3 Comparison with Traditional Adherence Interventions

Smart technologies should be used in addition to traditional technologies. Education, counselling, regimen simplification, and financial assistance are non-technological solutions to the causes.

7. LIMITATIONS AND CHALLENGES

7.1 Technical and Engineering Challenges

One of the central challenges of medical engineering is being able to maintain the generation of reliable and clinically interpretable adherence data over the long term on the smart medication device. Medication-event records can be missing or inaccurate due to battery depletion, sensor failure, mechanical failure, connection problems, and software errors. Therefore, a missed dose may sometimes be due to a technical problem and not necessarily due to nonadherence. On the other hand, if a medication was taken as prescribed, it does not mean that a recorded device event was made.

Another factor in measurement validity is the type of measurements that the measurement system is designed to measure. Electronic pillboxes and smart packaging typically only monitor access to the medicine or drugs, while connected injectors can monitor an administration event and ingestible sensors can provide more direct evidence of ingestion. These measures should not therefore be considered as interchangeable measures of adherence (Mason et al. 2022). The evaluation of devices should include what is being measured, how accurately and completely data are recorded, how often devices will break down, and what strategies are used to deal with missing or uncertain events. The reliability of adherence information is of special concern when used to inform clinical decisions, since misinformation could result in unnecessary interventions or overlook true non-adherence.

7.2 Cost, Accessibility, and Healthcare Infrastructure

Adoption can be hindered by hardware, subscription, connectivity, and technical support. There is significant variation in smart medication products' price and availability, as discussed in the reviews (Faisal et al. 2023).

Then there is the issue of infrastructure to interpret and act on the incoming data; if monitoring is not well integrated into a healthcare system, it can add to the workload.

7.3 Data Privacy and Cybersecurity

Health-sensitive information is created on connected medication devices. Information can be anything from a medication schedule, adherence to medications, physiological data, geographic information, and identification. Medical devices that are connected to the internet may be susceptible to unauthorised access, insecure communication, software weaknesses, and attacks on connected networks (Khatiwada and Yang 2022).

Digital pills, in particular, are of interest in terms of privacy as they are used to directly monitor pill-taking. There has been some concern about the shift from supportive care to surveillance as a result of ethical analyses where the patient is not in control of the use of their data (O'Sullivan et al. 2022). All these features should thus be embedded in the design of the device, using strong encryption, authentication, access control, secure updates, data minimisation, and transparency as features that are embedded in the design.

7.4 Ethical Considerations

Patients should be informed on the following: what is being monitored, why it is being monitored, and who would have access to the information. Technologies do not need to be intrusive, and should not be used in penalising ways with adherence data. Additionally, informed consent, issues of data ownership, algorithmic bias, and the potential for algorithmic decisions to affect clinical care without proper oversight and control by humans need to be taken into account for ethical implementation.

7.5 Patient Acceptance and Usability

Perceived usefulness, convenience, trust, privacy, and compatibility with daily life are the factors contributing to acceptance. More long-term studies are required, as their enthusiasm in the short-term may not translate to long-term use.

8. FUTURE PERSPECTIVES

8.1 Personalised and Adaptive Medication System

The future is likely to take a step toward adaptive reminders as a shift from fixed reminders. Rather than alerting a patient at the same level each day, an intelligent system could learn the habits of the patient and remind them only when they are likely to forget to take their medication. Personalisation might include patient medication schedules, preferred modes of communication, and daily activities and goals set by the patient.

8.2 Integration of AI, Biosensors, and Digital Health

Closed-loop medication-support systems are possible with the combination of biosensors and AI, smartphones and connected drug delivery devices. This could include adherence events and physiological information, which could be used to detect clinical events. There are several emerging examples of the use of AI for risk prediction, patient-specific reminders and medication management, but clinical validation is required.

To enable the transfer of adherence information securely between devices, applications and clinical systems, there will be a need for interoperability.

8.3 Predictive Medication Management

In the case of non-adherence, predictive analytics can cut down on the number of missed doses, if not prevent them altogether, by identifying patients who are at risk in advance. Instead of a low-intensity intervention (like a personalised reminder or pharmacist message) being considered a viable option to keep someone persistently adherent, the system could be used to send patients a low-intensity intervention. Additional interventions may be offered to those patients with persistent risk.

These systems need to be thoroughly tested, as a result of errors in prediction may result in unnecessary interventions or failure to provide necessary support. AI should not replace clinical judgment in patient care but work in tandem with it.

8.4 Opportunities for Home-Based and Remote Healthcare

Smart medication devices can enhance healthcare outside of the hospital and clinic. Longitudinal monitoring can be conducted remotely and can provide adherence information to the clinician; it can also be helpful for clinicians in the setting of telemedicine, home-based chronic disease management, and pharmacist-led interventions. This may be especially useful for those who might have trouble making regular visits to the doctor.

The digital divide should not be created by the use of remote care. For future engineering, low-cost materials, low-power communication, offline capability, usability, and the ability to work across various healthcare settings should be considered.

9. CONCLUSION

Non-adherence to medication is an ongoing problem, and smart biomedical devices are one of the technological solutions. These technologies can work together to make medication-taking behaviour more measurable and to deliver needed support at an appropriate time, outside of the clinical context. There are various examples of how engineering can help solve the real-life issues related to long-term treatment, such as electronic pillboxes, smart packaging, ingestible sensors, wearable systems and connected injectors.

There is potential evidence that there are benefits, but not all smart devices are shown to enhance adherence or clinical outcomes. The effectiveness of these depends on design, on the accuracy of monitoring, on the acceptance of the patient, on clinical integration and on the patients' reaction to missed doses. Techno-ability is not enough.

Interoperability, personalisation, security, cost-effectiveness, and clinically relevant outcomes should be vital future components of systems development. The use of AI and biosensors could help create more predictive and adaptive support for medication, but needs to be thoroughly validated and protected by ethical guidelines. Smart devices are most likely to impact outcomes when combined with an effective regimen, behavioural support, and responsive health care services.

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