Wearable Sensor Integration and Personalised Reminder Intelligence: Real-Time AI Systems for Medication Adherence Monitoring and Management

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1. Introduction to Medication Adherence and its Challenges

Medication adherence can be defined as the degree to which patients take the prescribed dose of medication within the agreed interval and follow a described regimen. Patient non-adherence to medications can have a significant impact on health outcomes and health costs; patients who were not adherent to their medication were more likely to have poor outcomes than those who were adherent. Numerous different barriers to adherence to medications have been identified. These range from complex issues based on beliefs about medications, such as concerns about taking long-term medication, which aligns with the concept of the necessity of medications, to patient-related issues such as socioeconomic status, health literacy, and cognition (either related to advanced age or cognitive or mental health-related diagnoses). Furthermore, lack of social support, for example, not having a caregiver to remind them to take their medication, has been shown to impact adherence to medication.

While various prescribing interventions have been trialed, many of these are costly to deliver and fail to show clear benefits in terms of improving adherence. The challenges that need to be addressed to help support medication adherence, however, have to be defined in further detail to develop and implement effective solutions. Moreover, in order to understand the benefits of improving rates of medication adherence, it is also important to understand the impact of patient non-adherence on the clinical effectiveness of medications, the health service in terms of the cost of treating patients who are non-adherent (especially with potentially preventable hospital admissions), and public health in terms of disease progression and potential transmission.

2. The Role of AI in Improving Medication Adherence

Artificial intelligence (AI) has the potential to revolutionize the field of medication adherence. It engages patients through personalized education and interventions while helping to establish simpler medication regimens. AI can also help analyze complex patterns to maneuver historical data, making it easier to identify patients who may benefit from proactive interventions. Some tools are enhanced communication strategies that use logic engines and natural language processing, app-based reminder systems based on a patient's electronic medical record, or may encourage behavior analytics by integrating with third-party apps or other wearable technologies. In fact, some of the most informative AI solutions can capture up to 3,000 various data points.

In capturing this data, patients with the highest probability of non-adherence can be identified for further follow-up. Moreover, these AI engine interactions based on this collected data can be performed automatically and/or manually depending on the workflow and customizable settings by practices and providers. Since AI engines can give personalized feedback to each patient, the patient and their clinical teams can have a more unique patient-specific conversation using the collective data to aid in the discussion. Additionally, these AI capabilities can be integrated with other applications to save time, provide a more useful sharing of data, and support the delivery of personalized health care. This care should be considered in the context of how such highly personalized interventions can be integrated into the clinical workflow. Similarly, data from the AI – after identifying patients needing follow-up for non-adherence – should further assist in determining the approach to integrating an adherence tool or selecting from a myriad of adherence tools. Integrating AI into clinical care is a key part of developing and enhancing health care delivery. Such tools are technology-enabled, and integration allows for the sharing of clinical and patient data for seamless transition across healthcare settings, which will be increasingly critical in the age of value-based care.

2.1. Machine Learning Applications in Healthcare

Machine learning is evolving to find applications, especially in the healthcare domain. I can categorize models used in healthcare into two categories: predictive analysis models and systems providing decision support. For example, ML algorithms allow the creation of non-invasive diagnostic systems for detecting risk factors for Parkinson's disease.

They help in personalized therapy by predicting the medications a patient should take and at what time. Integrating long-term, in-the-wild sensor data with information about the patient's status and changing personal factors, inferred from wearables, can offer the next generation of self-adapting autonomous health management systems. In particular, when patient models and behaviors are analyzed at once in an iterative procedure.

The importance of the ML model is only as strong as the data used to train the models. Data used to train these models need to be diverse and of high enough quality; the bigger the dataset and higher the dimension of the data, the better the prediction the model will be able to make. Depending on the task assigned to the model, caveats need to be taken in pruning the training features to shrink the data to the most important feature signals and prime results. The machine learning model the practitioner decides to use is task-dependent and needs hyperparameter tuning, as the cost function for optimization is also task-dependent. The model needs to be robust and precise regardless of its complexity. Results of the model over the testing set are the key performance indicators. Throughout the years, healthcare has been a frontrunner in using machine learning models in analytics and decision support. Algorithmic monitoring and feedback inform decision strategies in medication and monitoring implementation. For example, predicting medication non-adherence or predicting future health-related or medication-taking behavior in simulation of therapy management failure. The information could be used to trigger intervention in patients at immediate risk of failing treatment, in support of maintaining long-term patient physiological and drug adherence, and to track patients' treatment progression in low-compliance settings.

3. Real-Time Monitoring of Medication Adherence

Interventions and support systems for managing medication adherence often require close monitoring and patient-specific tailoring. Real-time monitoring by providers allows early intervention responses when non-adherence is detected, suggesting that interventions can be delivered specifically when patients need them the most. Real-time feedback also differs from spontaneous or interval-based feedback in that it requires more accountability at the time of delivery. In addition to automated monitoring solutions and applications with time-based medication reminders, several new and innovative tools have been developed, supporting real-time demographic tracking via mobile technologies, inhalation monitoring with outcome prediction for respiratory

diseases, and home-based monitoring of behavioral illness. In general, a variety of data sources and factors can be associated with patient non-adherence. The ability to provide automated real-time feedback to various providers is also desirable for a more comprehensive view of patient non-adherence.

There are several ways to engage and monitor patients in real time, although many current interventions involve contact with a health professional either face to face or by telehealth, such as by phone. The increasing sophistication of electronic devices has created a wealth of patient and provider-generated data which can be used for smarter monitoring systems ensuring actual patient behavior. These devices can incorporate real-time communication services or receive and store data for future upload. However, the application of new technology in real time is not without its challenges. First, electronic devices may not be immediately available or could be prohibitively expensive for some groups of patients. Second, some patient groups may not be familiar with new technologies, or may lack confidence or interest in using them. Third, monitoring large numbers of patients can create a large amount of data that must be interpreted by a healthcare provider, which may not always be feasible. Managing real-time data from patients will be important in terms of what can be delivered and ensuring that healthcare professionals have the right skills and resources to act on it. Managing non-adherent patients in real time requires the ability of a health provider to respond in an informed and timely manner, and to engage with patients in a way that will affect their beliefs and actions.

3.1. Sensors and Wearable Technology

The most direct way of understanding whether a medication is adhered to is to document the actual ingestion of a pill. As a result, there is a growing interest in the use of various sensors that can measure medication-taking. The majority of these sensors are integrated into wearable devices to collect continuous health data alongside detectable events if medication has been taken or placed upfront for access by a prescribed time. The wearable devices act as patient-centric wearables that both collect direct data around medication use and monitor overall patient engagement. The wearable devices themselves are designed to allow for ease of use, with user-friendly interfaces that minimize impact on daily patient activities.

Many types of sensors integrated into wearable devices have been studied in real-world settings in order to validate prescribed adherence. They have been developed to treat a wide range of chronic and acute conditions and can transmit medication ingestion data wirelessly to an unpaired mobile device. Patients and physicians can see this data on an app. Specific medications that have approved members for the system include several antiretrovirals, an atypical antipsychotic, and a digital version of the schizophrenia drug. Employing sensor technology can potentially help empower patients by providing them with personalized and actionable insights to help them better understand their adherence behaviors and connect with prescribers to share data about their medication use.

Although wearable devices can play an important role in addressing medication adherence, it is critical to deal with controversial issues around the collection of personal health information, such as security, privacy, and data ownership. Developers and clinicians must work to ensure the trustworthiness and safety of wearable devices to receive information about patients' daily lives. They must also be transparent when it comes to who owns the data and how it can be used. Devices should be simple to use, especially for people who are not familiar with technology.

4. Predictive Analytics for Patient Compliance

Predictive analytics becomes one possible way to identify these non-adherent patients. This advanced analytic approach uses historical data to develop a model that predicts the future value or behavior a patient will have. In the case of medication adherence, the prediction would be if a patient would take their medication(s) as prescribed on future occasions. The majority of predictive models used to identify adherent and non-adherent patients were created on large commercial prescription datasets and typically used hundreds of variables in the algorithm and a large number of patients. Patient claims data can answer questions such as: When did patients go to the doctor or fill a prescription? Did they fill the prescription? Did they stop filling the prescription early? Those who use predictive analytics strategies frequently do so to monitor, track, and proactively intervene with patients identified as high risks. Most adherence intervention studies rely on data from 12 to 18 months prior to the intervention to 'predict' the need. As patient care changes, these predictive models need to be refined and updated to take into account the impact of educational and support services designed to address those at

high risk of not keeping their illness in check. This could be due to changes in patient communication preferences, changes in healthcare delivery approaches, changes in care coordination, etc.

4.1. Data Collection and Analysis Techniques

Given the previous discussion, data forms the base for many methods to measure and assess adherence to prescribed pharmacological treatments. It is important to highlight that objective quantitative measures of medication adherence using electronic monitoring and other novel technologies have been developed. Moreover, qualitative techniques have been developed in recent years. However, the use of new technologies allows for the incorporation of the patient's perspective probably better than direct questioning about adherence. Yet this might be complemented with other objective measures of exposure or therapeutic effects in order to obtain a more complete picture of medication adherence. Consequently, data sources are important for any index generation or other analysis. It is also more powerful to compare and combine the quantitative and qualitative data to gain maximum insight into a patient's adherence behaviors.

To gain knowledge of detailed patient behaviors and intentions, many quantitative tools have been developed. Data captured via electronic pillboxes and mobile applications can include date and time of drug container opening or closure, characteristics of the patient being entered, and characteristics of the regimens given and the disease being treated. These devices are usually used by an unselected group of patients and have data of objective measures of adherence and clinical outcomes collected from a large heterogeneous group of people. The criticism for these analyses and comparisons is the inherent limitations in the interpretation of the captured data: the extent of the association between behavior and adherence is generally not known and varies with different interventions, time since the intervention has started, doses or regimens given to the patient, therapeutic effects, cost associated with the therapeutic benefits, and the risk of study withdrawal. Clearly, accurate and precise ways to measure adherence are required to build effective and user-friendly adherence support systems. Besides self-reports, adherence can be monitored through direct measures or indirect measures. Currently, the vast majority of systems for adherence support are based on indirect measures. To interpret the amount and kind of data collected, a wide range of tools can

be systematically applied. Tools such as basic statistics, function representation and modeling, process mining, and advanced analytics using machine learning and predictive inferences provide the caregiver with more detailed insights. To enable an optimal analysis and interpretation of raw adherence-related data, appropriate visualization of data is necessary. Systems for adherence support must take into account context determinants that influence patients' adherence, such as patients' personal characteristics, specific environmental factors, and perception of diseases in general, as well as the specific disease and medication.

5. Interventions and Feedback Mechanisms

Because medication adherence results from the behavior of many actors, complex, multi-pronged approaches have been suggested to enhance it. These include educational programs, pre-prescription attention to the potential hindrances to adherence, reminders, adherence contracts with patients, efforts to simplify the regimen or foster its integration into daily life, and supportive care and counseling. Technological solutions, ranging from simple monitors to advanced wireless-enabled hardware combined with digital communications capabilities and machine-learning decision support, have also been suggested and are being widely implemented in order to enable frequent and low-effort adherence monitoring. One common and important adherence-enhancing strategy is to supply timely and relevant biomedical feedback to patients. This feedback may be of at least three types: (1) Self-efficacy feedback to drive growth cognitions, whereby a person receives information about the execution of a task or behavior, which has been documented to boost self-efficacy for that task and can raise the patient's belief in their ability to continue to perform well in the future; (2) Control outcomes feedback, informing a person about their performance relative to a norm; and (3) Success feedback, in which the patient is informed of a positive or adverse health state or outcome arising from their actions. Current expert opinion is that the provision of a combination of self-efficacy, control outcomes, and/or success feedback can result in positive behaviors.

Directly personalizing adherence-enhancing opportunities based on current adherence and where a patient falls on the 'Adherence Feedback Loop' has been considered to be an efficient way to optimize limited adherence resources. However, this practice requires the regular tracking and frequent updating of the adherence status of individual patients. To maintain the improvements in adherence and persistence beyond

the period of support, it is essential that the reasons for the improvements continue, and that any residual challenges are manageable by the patient alone. This may require sustained interventions. Behavioral health levels of support are designed to provide counseling, behavioral change, and lifestyle change support to those with psychosocial behavioral and mental health challenges and concerns. Ideally, patient data would indicate which level of support is needed to objectively assess the person as a coherent whole and address physical, emotional, and social issues. Some interventions propose a collaborative role for the healthcare professional. The expert healthcare professional still has an important role to play in helping patients to make sense of complex, accumulating, and obscure scientific information, and to understand and decide the benefits and risks of medications. Either through plain language or through more sophisticated dialogue, shared and informed decision-making and negotiation of patients' medical regimen are improvement-enhancing tasks assigned to the expert healthcare professional.

5.1. Personalized Recommendations

Personalized recommendations play an important role in medication adherence, as making suggestions to specifically suit the needs of the patient increases the effect of the adherence strategy. No two patients are alike, even in the case of a shared disease, which is why it is essential to gather as much information as possible to ensure that successful individualized recommendations can be made, such as understanding the patients' lifestyle, preferences, health conditions, and taking habits. Data analytics support in extracting pertinent segments of the patient population to build adherence plans, based on segmentation using key indicators defined by the healthcare provider. Other types of personalized adherence promotion approaches are therapeutic coaching or therapeutic patient education. They are based on discussing the therapy with the patient, promoting a better understanding of the proposed therapy, and facilitating therapeutic decision-making based on the patient's personal history, habits, and expectations. Studies reported the positive impact of personalized recommendations on medication adherence in real life. It has been shown that specifying the amount of physical activity necessary could significantly reduce non-adherence to recommended walking restrictions in coronary patients.

The time and effort spent on personalized advice increases the impact of any action by taking into account the patient's lifestyle and disease manifestations. Automated outputs exist which can be based on appraisals and thus formalize individualized advice even more, generating individual recommendations in response to patient information. An important limitation, as always in adapting to individualized recommendations, is to ensure that the population for whom these are defined is also able to learn about and use these recommendations in their treatment process. A patient-healthcare provider co-construction process is essential to share personalized recommendations to co-construct a personalized adherence plan adapted to the individual concerns addressed by the recommendations. These personalized recommendations are the cornerstone of patient-centered approaches in adherence.

6. Ethical and Privacy Considerations in AI-Powered Medication Adherence Systems

An increasing number of healthcare solution providers are developing AI-powered medication adherence systems, leveraging data such as patients' vital signs, as well as their behavioral patterns collected by electronic systems, mobile phones, and experiential technologies. These technologies rely on a continuous collection of large volumes of patient data and use a wide range of algorithms for purposes that span from monitoring compliance and diagnosing non-adherence to prescribing and reassessing therapies based on a predictive assessment of non-adherence. Associated with the gathering and analysis of such data are a number of ethical and privacy issues that require careful consideration and mitigation.

In essence, the ethical considerations are inherently linked to data security and patient consent, autonomy, and privacy. A delicate balance between the desirable use of patient data for the continuous improvement of care, often pursued by the providers of such systems, and the need for patient consent and continuous privacy protection measures is necessary. In addition, we are witnessing the rise of ethical discussions about algorithmic biases; that is, the risks of having an AI-prescribed treatment that discriminates against, for instance, gender or skin color. Streamlining interpretability, accountability, and transparency are also key, particularly in establishing levels of trust between healthcare providers and their patients. A number of guidelines are being developed, showcasing both the technological potential of AI systems and the possible ethical implications. Caution is advised. Assured ethical standards are needed to ensure

that the leveraging of AI does not result in added risk to patient safety and greater deleterious impact on patients who have already been actively disadvantaged.

7. Conclusion

Conclusion. Medication non-adherence is recognized as a major challenge in healthcare practices that address substantial health and economic burdens. To combat poor adherence and improve patient outcomes, several approaches have been introduced. Of particular note in this essay is the progression of AI-based technologies that not only empower patients to remain adherent but also strengthen healthcare professionals to overcome barriers preventing effective treatment. This report has accumulated evidence on the prospective and successful deployment of AI in medication adherence. Specifically, AI excels at real-time tracking, longitudinal monitoring, bottleneck identification, predictive analytics, and offering tools for personalizing interventions.

The need for ethical and legal guidelines that shed light on the safe collection, storage, and manipulation of intimate information in medication adherence contexts cannot be ignored. The future will witness collaborative initiatives between technology companies, healthcare workers, and patient organizations to provide real-time adherence solutions. In the years to come, these novel strategies will form a cornerstone for further person-centered care and predictive healthcare tactics. A demonstration of the clinical validity and economic feasibility of personalized non-adherence intervention predictions is important. High-quality intervention research will also be contributory. Comprehensive R&D on digital health combined with AI applying biomedical techniques for advancing healthcare will contribute to achieving this essential step.