



ARTICLE ID: BTS0426004

DIGITAL BIOMARKERS IN CLINICAL PHARMACY: REVOLUTIONIZING THERAPEUTICS WITH WEARABLES, MOBILE APPS, AND AI

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Received: 31 August 2025 | **Revised & Accepted:** 19 October 2025

Keywords: Digital biomarkers, Clinical pharmacy, Wearable devices, Artificial intelligence.

ABSTRACT

Digital biomarkers, which are defined as objective, quantifiable physiological and behavioral data captured through digital devices, are rapidly changing clinical pharmacy and therapeutics. Incorporating wearables, mobile health applications, and artificial intelligence (AI) into everyday practice means we can now monitor an individual's drug response, adherence, and safety in real-time and facilitates bridging the traditional biomarker realm with precision medicine. Wearables such as continuous glucose monitors, ECG patches and smartwatches are now collecting constant physiological data and mobile applications can acquire patient-reported outcomes, adherence to medication and behavioural data for relevant therapy optimisation. AI tools are able to extract relevant real-time insights from large scale data in digital health and adjust for bias associated with drugs or conditions, predict modelling, optimal drug or device efficacy, and anticipated patient outcomes associated with adverse drug reactions or dose adjustments. Clinical pharmacy is in the early stages of harnessing these innovations primarily in chronic disease management, oncology, psychiatry, and cardiovascular care where digital biomarkers can potentially improve therapeutic outcomes, and reduce healthcare burdens. Despite their promise, challenges such as data standardisation and data fidelity, along with privacy implications for information mining, regulatory frameworks, and electronic health records integration. This review highlights the important transition of digital biomarkers impacting clinical pharmacy, conferences about their role in personalized pharmacotherapy, drug development, and patient monitoring in practice and identifies future directions for advancement of patient-centred care.

1. INTRODUCTION

For many years, biomarkers can be described as objectively measurable indicators of biological processes, pathogenic processes, or pharmacologic

responses, and have been at the forefront of diagnosis, monitoring the course of disease, and inferring clinical decisions. Classic biomarkers such as blood pressure, blood glucose, and cholesterol are certainly valuable, however their

restrictive nature of using simply episodic measurements and primarily dependent on clinical visits limit their ability to detect the dynamic changes of patients' health; an increasingly important endeavor in the burgeoning era of personalized medicine. Digital biomarkers have emerged with the introduction of digital health technologies and are generally defined as objective, quantifiable physiological and behavioral data related to health collected through personal digital devices (e.g., wearable devices, mobile applications, implants, and/or sensors.). Unlike classic biomarkers that only facilitate episodic measurements, digital biomarkers enable continuous monitoring of virtual biomarker analogs such as rest, step count, heart rate variability (HRV), sleep quality, medication adherence, or cognitive function. In conjunction with artificial intelligence (AI)-machine learning (ML), these data can provide reasonable understanding on subtle health patterns, predict disease progression, and support opportunities for proactive interventions if necessary. This shift from classic biomarkers that only facilitate episodic measurements to acquisition of digital biomarkers that enable continuous, personalized health measurements can be viewed as a leap forward into the future of medicine providing a better vantage of patient health. Digital biomarkers allow for real-time measurements of therapeutic effectiveness, rapid detection of adverse drug events, and custom tailoring of treatment regimens. Digital biomarkers connect the patient's behaviour, their physiological response from the drug, and the pharmacokinetics and pharmacodynamics of the drug. Digital biomarkers contribute to evidence-based treatment decisions, provide better patient

safety, and enable more precision in providing health care. This review will walk through the history, contemporary use, and future applications of digital biomarkers in clinical pharmacy.^[0] This review will display the new monitoring avenues that exist using wearable's, mobile applications, and AI technology to enhance patient monitoring and adaptations of drugs in therapy. This review will also illustrate some overall barriers and challenges for digital biomarkers and ethical considerations regarding the use of digital biomarkers. Ultimately, this review aims to help researchers, clinicians, and policymakers become aware of how digital biomarkers could disrupt therapeutics and revolutionize personalized care for patients as shown in (Figure 1).^[2-3]

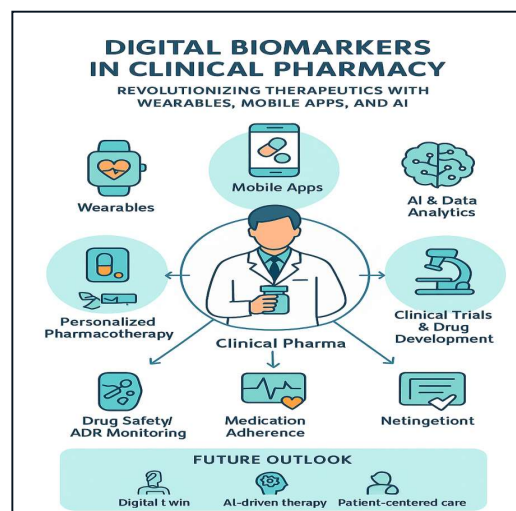


Fig (1): Importance of digital biomarkers in modern clinical pharmacy

2. DIGITAL BIOMARKERS: CONCEPT AND FRAMEWORK

2.1 Definition and Characteristics of Digital Biomarkers

Digital biomarkers are objective, measurable physiological, behavioural, or biochemical data collected via digital means such as using wearable sensors, mobile applications, and implantable monitoring devices. They represent continuous and real-time information about an individual's health state, disease progression, or response to therapy. Digital biomarkers have critical characteristics of longitudinal tracking, high-detail data collection, reproducibility, clinical relevance, and the possibility to interact with AI (artificial intelligence) and ML (machine learning) for predictive analytics, allowing for interventions. Digital biomarkers differ from traditional biomarkers as they are recorded in real-world environments, providing more comprehensive data for understanding patient health. ^[4]

2.2 Classification of Digital Biomarkers

Digital biomarkers can be classified into distinct categories based on the type of health information they capture and the method of collection as shown in (Figure2).

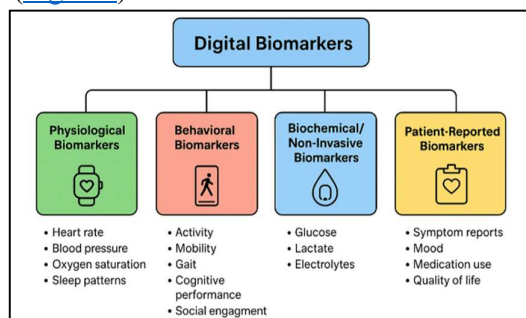


Fig (2): Classification of Digital Biomarkers

2.2.1. Physiological Biomarkers

This category of biomarkers includes objective indicators of vital signs and

bodily functions, such as heart rate, blood pressure, respiratory rate, blood oxygen saturation, and sleep-wake cycles. Many wearable devices can obtain such measurements ultimately using smartwatches or chest straps that can continuously capture various vital signs for tracking a person's cardiovascular, respiratory, or metabolic health.

2.2.2. Behavioral Biomarkers

Behavioral biomarkers can indicate patterns of activity, mobility, cognitive performance, and social engagement. An example of behavioral biomarkers is step counts, analyses of gait from phone sensor data, phone call and use patterns, and reaction times tapped from mobile apps that also determine an individual's lifestyle, mental status, and functional loss.

2.2.3. Biochemical/Non-Invasive Biosensor Biomarkers

These biomarkers may involve measuring biochemical analytes that are considered biomarkers themselves (like glucose, lactate, electrolytes, and other biomarkers associated with stress), by using biosensors that are minimally invasive or non-invasive. Continuous Glucose Monitors (CGMs) and sweat sensors are examples in this area that allow for metabolic tracking in real-time.

2.2.4. Patient-Reported Digital Biomarkers

These are structured data captured from patients by digital means such as symptom severity reports, medicines use reports, mood assessment reports, and reports related to quality of life indicators. Mobile apps and electronic diaries are examples of ways to capture comments and patient-reported outcomes. ^[5]



2.3 Distinction Between Digital and conventional Biomarkers

The main difference is measurement mode, frequency, and context. Traditional biomarkers are usually measured in a clinical setting at a certain point in time, to provide a limited and static view of health at that time. Digital biomarkers are providing constant, real-world monitoring of the health experience, reflecting dynamic and relational changes in physiology, behavior, and health that may not be captured with traditional approaches. Furthermore, digital biomarkers produce a very large longitudinal dataset that can often be

coupled with artificial intelligence (AI) and machine learning (ML) and in turn support predictive modeling concerning disease trajectory, treatment response, and medication adherence, allowing for personalized health and treatment and optimized therapies.^[6]

3. TOOLS AND TECHNOLOGIES IN DIGITAL BIOMARKER COLLECTION

The collection of digital biomarkers relies on advanced tools and technologies that capture, process, and interpret patient health data in real time as mentioned in ([Table1](#)).

Table1: Tools And Technologies in Digital Biomarker Collection

Application	Role of Digital Biomarkers	Benefits
Drug Development & Clinical Trials	Remote and continuous monitoring with wearables and apps	Improves safety, reduces hospital visits, speeds up drug evaluation
Personalized Pharmacotherapy	Collects physiological and behavioral data; AI predicts outcomes	Optimizes drug and dose, enhances efficacy, minimizes side effects
Medication Adherence & Compliance	Smart pill bottles, reminders, electronic tracking	Detects non-compliance early, improves adherence, better therapeutic outcomes
ADR Monitoring	Real-time monitoring of vital signs and patient-reported outcomes	Early detection of toxicity, improves safety, reduces hospitalization

3.1 Wearable Devices

Wearable devices are becoming an increasingly important source of digital biomarkers because they are a continuous and real-time source of data obtained in natural environmental settings. Smartwatches and fitness trackers help collect information about moderate to vigorous physical activity, heart rate, oxygen saturation, and sleep.^[7] ECG patches and continuous glucose monitors measure cardiac rhythm and fluctuations in

glucose to provide insight into chronic disease management. About gait, motor

function, and sleep assessments, a variety of motion sensors and sleep trackers help elucidate patient lifestyle, and combined with clinician decision-making, this type of data opens a window into patient feedback loop that goes beyond self-reported health status.^[8,9]

3.2 Mobile Health Applications



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mHealth apps convert smartphones into a means of biomarker collection and patient engagement. They support medication adherence through reminders, pill diaries, and smart pillboxes. Some apps track symptoms (e.g., mood), while other apps and digital diaries capture pain or effects of treatment (side effects). Some mHealth apps link with Electronic Health Records (EHRs), which enable analysis of real-world data. Real world data can be helpful for clinicians and pharmacists interested in optimizing treatment plans.^[10,11]

3.3 Artificial Intelligence and Data Analytics

AI and advanced analytics play critical roles in analyzing a wide array of source data emerging from wearables and mobile applications. AI and advanced analytics are utilized to seek novel digital biomarkers, uncover hidden patterns,

researchers can leverage predictive modeling to predict drug responses and optimize dosages for personalized therapy.^[12] Additionally, machine learning can be used to identify risk of adverse drug reactions earlier to improve patient safety. When combined with the knowledge and experience of clinical pharmacists, AI insights transform raw data into evidence-based clinical decisions to support pharmacists in providing world-class precision and efficiency in pharmacy practice.^[13,14]

4. APPLICATIONS IN CLINICAL PHARMACY

Digital biomarkers are transforming clinical pharmacy by supporting drug development, optimizing individualized therapy and improving medication adherence as mentioned ([Table 2](#))

Table 2: Applications Of Digital Biomarkers in Clinical Pharmacy

Tool / Technology	Function / Purpose	Examples / Applications
Wearable Devices	Capture real-time physiological and behavioral data outside clinical settings; monitor patient habits and health status	Smartwatches, fitness trackers, ECG patches, continuous glucose monitors, motion sensors, sleep trackers; used for cardiovascular health, Parkinson's, insomnia, metabolic tracking
Mobile Health Applications	Collect patient-reported outcomes, improve engagement, monitor adherence, integrate with EHRs	Medication reminders, digital pill diaries, symptom trackers, digital patient diaries; supports therapy optimization and chronic disease management
Artificial Intelligence & Data Analytics	Analyze large datasets, identify patterns, predict drug response, detect ADRs, personalize therapy	AI algorithms, predictive modeling, machine learning for ADR detection, cardiotoxicity/hepatotoxicity prediction; transforms raw patient data into actionable insights for pharmacists and clinicians



4.1 Drug Development and Clinical Trials

Digital biomarkers facilitate remote and continuous observation using wearables and apps provide high-quality, real-time data outside the traditional clinical environment. This type of situation could be beneficial for participant safety, reducing hospital visits, and complementing real-world data by providing a window into the trajectory of the patient. By helping to track participants and anticipate potential issues, we can adopt an adaptive design and increase the speed of drug evaluation and efficacy. The use of digital biomarker insights can help the regulatory process and ease drug development.^[15]

4.2 Personalized Pharmacotherapy

Digital biomarker enables personalized treatment by using continuous data capture to collect information on both physiological activity and behavioral activity. In this way, clinicians can mediate drug, dose, and parameters to optimize efficacy while being aware of side effects. The use of AI facilitation for predictive analytics and forecasting outcomes can optimize the clinician's decision-making tree and increase the likelihood of the right drug and dose, eventually contributing to precision medicine.^[17,18]

4.3 Medication Adherence and Compliance

Digital interventions, such as smart pill bottles, mobile reminders, and electronic adherence tracking allow patients to be more compliant with prescribed medications and gives clinicians useful data. When clinicians can notice adherence patterns earlier, they're in a better position to intervene, which is especially relevant

for the management of chronic diseases, to get better therapeutic outcomes.^[19,21]

4.4 Adverse Drug Reaction (AdR) Monitoring

Digital biomarkers provide healthcare professionals with real-time monitoring of vital signs, biochemical markers, and patient-reported outcomes in order to monitor for drug toxicities. In high-risk therapies such as chemotherapy or biologics, digital biomarkers support early identification of toxicities and interventions, improving safety, decreasing the likelihood of hospitalization, and improving precision in ADR management.^[22,23]

5. CHALLENGES AND LIMITATIONS

5.1 Data Privacy, Security, And Ethical Concerns

Ongoing collection of digital biomarkers will eventually result in extensive and sensitive patient information. These biomarker collections, usually considered protected health information, will lead to questions about privacy, consent, ownership and misuse. Compliance with regulating agencies, such as HIPAA and GDPR, are crucial tasks to develop the framework to protect patients. Organizations will require substantial safeguards, encryption measures and security against breaches to maintain client confidence.^[24,25]

5.2 Lack of Validation and Standardization

Digital biomarkers as emerging health technologies lack standardized validation practices leading to hybridization: different sensors, collection of data and analysis using various algorithms. Further, digital biomarkers lack reliability, accuracy, and clinical meaning. To



separate digital biomarkers from other health measurements, standardized, reproducible, and validated metrics against meaningful clinical endpoints is needed. [26]

5.3 Regulatory Barriers

Emerging regulations also raise issues for the widespread uptake of digital biomarker as they do require premarket approvals around safety, efficacy, and reliability. Clinical trials usually encounter substantial concerns regarding complex software, ongoing app updates, volume and variance of data. These obstacles, in tandem with the costs and timeframes of digital biomarkers, take time to build into clinical practice. [27]

5.4 Integration into Clinical Workflow

Integrating digital biomarkers into clinical workflow presents its own set of challenges, including technical, operational, and logistical barriers. For instance, the data may be inconsistent, too much, and/or inconsistent with the EHR systems already in place, potentially causing confusion instead of clarity. If standardized protocols, training, and seamless integration are not in place, there's a risk that digital biomarkers could add a layer of complexity instead of achieving improved care outcomes. [28]

6. FUTURE PERSPECTIVES IN CLINICAL PHARMACY

6.1 Digital Twins in Pharmacotherapy

Digital twins are digital representations of patients created based on real-time data and computational modeling. Digital twins can utilize already developed digital biomarkers and data from other sources, such as genomics, lifestyle factors, and metabolomics, to simulate responses to

drugs and the progression of disease. Digital twins thus allow clinicians to "trial" therapeutic strategies in a simulated environment, empowering the potential of enabling changes to a regimen to achieve personalized therapy and precision medicine, although regulatory (GxP) concerns may prevent their potential use at this stage. [29]

6.2 Blockchain for Secure Data Exchange

Blockchain can create decentralized digital systems for applications related to digital biomarkers which can safely and securely manage health data associated with multiple parties who may require data access at different points in time. These applications are tamperproof and enable transparency in data-sharing, patient-determined consent, and protection against unauthorized access of sensitive data allowing for the trust between patients, pharmacists and clinicians. Block chain can protect the integrity of the supply chain and preserve regulatory compliance, whilst also allowing greater accountability of patients in a digital health ecosystem. [30]

6.3 Ai-Driven Closed-Loop Therapeutic Systems

Conversely, AI-enabled closed-loop therapeutic systems automate the processes for monitoring patients and modifying therapy. AI is capable of interpreting the digital biomarkers while the patient interacts with the digital health intervention; as such, it is reasonable to expect a smart drug delivery device to adapt its dosing based on digital biomarker data, or a smart wearable to detect adverse reactions and automatically inform the patient's healthcare team to adapt their program and/or therapies. Digital insulin



pumps are a positive indicator of the potential future of closed-loop systems, and there seems to be significant promise to better, safer, effective, and no-error care across other therapeutic areas.^[30]

6.4 Expanding Role of Pharmacists In Digital Health

As digital biomarkers advance from the fringes to mainstream implementation, the role of pharmacists is similarly evolving from medication management and dispensing to additionally encompass data interpretation, digital health device validation, patient and caregiver training, and integration of digital biomarkers from the patient into health care.^[32] This creates an opportunity for pharmacists to extend their roles into key intermediators to ensure the patient is engaged in safe, effective, and ethically sound care in a technology-enabled health care environment as shown in (Figure3).

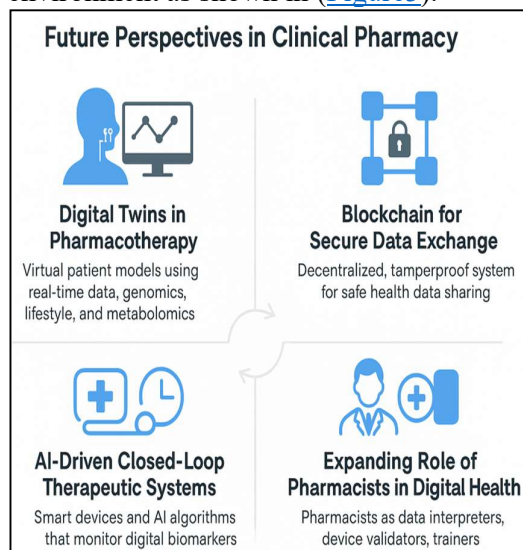


Fig (3): Future Perspectives in Clinical Pharmacy

CONCLUSION

Digital biomarkers are revolutionizing Clinical Pharmacy with the potential for

providing access to continuous and personalized patient health information. The evolution of wearables, mobile apps, and artificial intelligence (AI) already augments drug development, optimizes pharmacotherapy, enhances adherence recommendations, and provides real-time assessments of serious adverse reactions. Digital biomarkers have already demonstrated great promise in the areas of cardiovascular, metabolic, neuropsychiatric, and oncological care, while products associated with digital human twins, blockchain, and closed-loop systems also allow for a more integrated intelligent care continuum. Nevertheless, the development and widespread implementation of digital biomarkers also have a number of challenges with respect to data protection and privacy, validation, regulation, and clinical workflow integration. However, Clinical Pharmacists continue to be a trusted link between the emerging and integrating technologies, patient transparency, predictive analytics and actual health behaviours through data informed interpretation, health education, and therapeutic advising. Overall, digital biomarkers transform Clinical Pharmacy into a patient-centred, digital-enabled, point-of-access delivery model that accelerates precision medicine and improves health globally.

REFERENCES

1. Kalali A, Richerson S, Ouzunova E, Westphal R, Miller B. Digital biomarkers in clinical drug development. In: Handbook of behavioral neuroscience. 2019. p. 229–38. <https://doi.org/10.1016/b978-0-12-803161-2.00016-3>
2. Aungst TD, Franzese C, Kim Y. Digital health implications for



ARTICLE ID: BTS0426004

- clinical pharmacists services: A primer on the current landscape and future concerns. JACCP JOURNAL OF THE AMERICAN COLLEGE OF CLINICAL PHARMACY. 2020 Dec 28;4(4):514–24. <https://doi.org/10.1002/jac5.1382>
3. Guthrie NL, Carpenter J, Edwards KL, Appelbaum KJ, Dey S, Eisenberg DM, et al. Emergence of digital biomarkers to predict and modify treatment efficacy: machine learning study. BMJ Open. 2019 Jul 1;9(7):e030710. <https://doi.org/10.1136/bmjopen-2019-030710>
 4. Alonso AKM, Hirt J, Woelfle T, Janiaud P, Hemkens LG. Definitions of digital biomarkers: a systematic mapping of the biomedical literature. BMJ Health & Care Informatics. 2024 Apr 1;31(1):e100914. <https://doi.org/10.1136/bmjhci-2023-100914>
 5. Wright JM, Regele OB, Kourtis LC, Pszeny SM, Sirkar R, Kovalchick C, et al. Evolution of the digital biomarker ecosystem. Digital Medicine. 2017 Oct 1;3(4):154–63. <https://doi.org/10.4103/digm.digm.35.17>
 6. Babrak LM, Menetski J, Rebhan M, Nisato G, Zinggeler M, Brasier N, et al. Traditional and digital biomarkers: two worlds apart? Digital Biomarkers. 2019 Aug 16;3(2):92–102. <https://doi.org/10.1159/000502000>
 7. Chen X, Kim DH, Lu N. Introduction: Wearable devices. Chemical Reviews. 2024 May 22;124(10):6145–7. <https://doi.org/10.1021/acs.chemrev.4c00271>
 8. Nahavandi D, Alizadehsani R, Khosravi A, Acharya UR. Application of artificial intelligence in wearable devices: Opportunities and challenges. Computer Methods and Programs in Biomedicine. 2021 Nov 17;213:106541. <https://doi.org/10.1016/j.cmpb.2021.106541>
 9. Hughes A, Shandhi MMH, Master H, Dunn J, Brittain E. Wearable devices in cardiovascular medicine. Circulation Research. 2023 Mar 2;132(5):652–70. <https://doi.org/10.1161/circresaha.122.322389>
 10. Zhao J, Freeman B, Li M. Can mobile phone apps influence people's health behavior change? An evidence review. Journal of Medical Internet Research. 2016 Nov 2;18(11):e287. <https://doi.org/10.2196/jmir.5692>
 11. Nussbaum R, Kelly C, Quinby E, Mac A, Parmanto B, Dicianno BE. Systematic Review of Mobile Health Applications in Rehabilitation. Archives of Physical Medicine and Rehabilitation. 2018 Aug 29;100(1):115–27. <https://doi.org/10.1016/j.apmr.2018.07.439>
 12. Raikar GS, Raikar AS, Somnache SN. Advancements in artificial intelligence and machine learning in revolutionising biomarker discovery. Brazilian Journal of Pharmaceutical Sciences. 2023 Jan 1;59. <https://doi.org/10.1590/s2175-97902023e23146>
 13. Huss R, Raffler J, Märkl B. Artificial intelligence and digital biomarker in precision pathology guiding immune therapy selection and precision oncology. Cancer Reports. 2023 Feb 22;6(7). <https://doi.org/10.1002/cnr2.1796>



ARTICLE ID: BTS0426004

14. Seliverstov PV, Kutsenko VP, Gorelova VG, Magomedova ShA, Akhmedov SR, Nurmyradov YuN. USING ARTIFICIAL INTELLIGENCE FOR BIOMARKER ANALYSIS IN CLINICAL DIAGNOSTICS. *Molekulyarnaya Meditsina (Molecular Medicine)*. 2024 Nov 6;31–40.
<https://doi.org/10.29296/24999490-2024-05-04>
15. Kraus VB. Biomarkers as drug development tools: discovery, validation, qualification and use. *Nature Reviews Rheumatology*. 2018 May 14;14(6):354–62.
<https://doi.org/10.1038/s41584-018-0005-9>
16. Saeed A, Alajlan SA. Exploring the role of digital biomarkers and artificial intelligence in precision therapeutics. In: *Advances in computational intelligence and robotics book series*. 2025. p. 169–88. <https://doi.org/10.4018/979-8-3693-6270-9.ch006>
17. Chen IM, Chen YY, Liao SC, Lin YH. Development of digital biomarkers of mental illness via mobile apps for personalized treatment and diagnosis. *Journal of Personalized Medicine*. 2022 Jun 6;12(6):936.
<https://doi.org/10.3390/jpm12060936>
18. Van Boven JFM, Fonseca JA. Editorial: Digital Tools to measure and Promote Medication adherence. *Frontiers in*
19. Medical Technology. 2021 Sep 27;3.
<https://doi.org/10.3389/fmedt.2021.751976>
20. Özdemir V, Endrenyi L. A new approach to measure adherence to medicines using biomarkers and sensors. *OMICS a Journal of Integrative Biology*. 2019 Jun 14;23(7):334–7.
<https://doi.org/10.1089/omi.2019.0092>
21. Litvinova O, Yeung AWK, Hammerle FP, Mickael ME, Matin M, Kletecka-Pulker M, et al. Digital Technology Applications in the management of Adverse Drug Reactions: Bibliometric analysis. *Pharmaceuticals*. 2024 Mar 19;17(3):395.
<https://doi.org/10.3390/ph17030395>
22. Sharma ND, Farid NFB, Ferdouszaman NMD, Khan NT. Advances in molecular biomarkers for pharmacovigilance: Early detection of drug toxicity. *World Journal of Biology Pharmacy and Health Sciences*. 2025 Feb 10;21(2):071–81.
<https://doi.org/10.30574/wjbphs.2025.21.2.0142>
23. Patel DM. Ethical considerations in biomarker research and application. In: *Elsevier eBooks*. 2025. p. 275–83. <https://doi.org/10.1016/b978-0-443-29279-8.00013-2>
24. Ford E, Milne R, Curlewis K. Ethical issues when using digital biomarkers and artificial intelligence for the early detection of dementia. *Wiley Interdisciplinary Reviews Data Mining and Knowledge Discovery*. 2023 Feb 19;13(3).
<https://doi.org/10.1002/widm.1492>
25. Horvatovich PL, Bischoff R. Current technological challenges in biomarker discovery and validation. *European Journal of Mass*



ARTICLE ID: BTS0426004

- Spectrometry. 2010 Jan11;16(1):101–21.
<https://doi.org/10.1255/ejms.1050>
27. Landers M, Dorsey R, Saria S. Digital Endpoints: definition, benefits, and current barriers in accelerating development and adoption. *Digital Biomarkers*. 2021 Sep 13;5(3):216–23.
<https://doi.org/10.1159/000517885>
 28. Zhao Q, Zhang C, Zhang W, Zhang S, Liu Q, Guo Y. Applications and challenges of biomarker-based predictive models in proactive health management. *Frontiers in Public Health*. 2025 Aug 18;13.
<https://doi.org/10.3389/fpubh.2025.1633487>
 29. Mariam Z, Niazi SK, Magoola M. Unlocking the future of drug development: generative AI, digital twins, and beyond. *BioMedInformatics*. 2024 Jun 6;4(2):1441–56.
<https://doi.org/10.3390/biomedinformatics4020079>
 30. Fatoum H, Hanna S, Halamka JD, Sicker DC, Spangenberg P, Hashmi SK. Blockchain Integration with Digital Technology and the Future of Health care Ecosystems: Systematic review. *Journal of Medical Internet Research*. 2021 Apr 3;23(11):e19846.
<https://doi.org/10.2196/19846>
 31. Nimri R, Phillip M, Clements MA, Kovatchev B. Closed-Loop control, Artificial Intelligence–Based Decision-Support systems, and data science. *Diabetes Technology & Therapeutics*. 2024 Mar 1;26(S1):S-89.
<https://doi.org/10.1089/dia.2024.2505>
 32. Martin A, Brummond P, Vlasimsky T, Steffenhagen A, Langley J, Glowczewski J, et al. The evolving frontier of digital health: Opportunities for pharmacists on the horizon. *Hospital Pharmacy*. 2017 Nov 3;53(1):7–11.
<https://doi.org/10.1177/0018578717738221>