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Wearable Biosensor Integration for Remote Chemotherapy Monitoring in Decentralized Cancer Care Models

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ABSTRACT

The shift toward decentralized cancer care has accelerated the demand for innovative technologies that enable continuous, remote monitoring of patients undergoing chemotherapy. Wearable biosensors have emerged as a promising solution, offering real-time tracking of physiological and biochemical markers critical to chemotherapy management. This review explores the integration of wearable biosensors into remote chemotherapy monitoring, examining their technological foundations, clinical applications, and impact on patient outcomes. It highlights how these devices enhance adherence, detect adverse effects early, and support timely clinical decisions in outpatient and home-based settings. Additionally, the paper addresses key implementation challenges, including technical limitations, patient usability, and regulatory considerations. Finally, it discusses future directions in sensor development, artificial intelligence integration, and policy adaptation to support scalable, personalized cancer care. Wearable biosensor technology holds transformative potential to redefine chemotherapy delivery within decentralized care models.

Keywords : Wearable, Biosensor, Integration, Remote. Chemotherapy, Decentralized cancer Models.

1. INTRODUCTION

1.1 Background: Evolution of Decentralized Cancer Care and Remote Monitoring

The global oncology landscape has witnessed a paradigm shift toward decentralized cancer care, driven by rising patient volumes, the need for personalized treatment, and the imperative to reduce the burden on centralized health systems. This transition has been accelerated by advancements in digital health and the increasing

adoption of telemedicine, especially following the COVID-19 pandemic. Decentralized care models enable patients to receive ongoing treatment and monitoring from their homes or local clinics, thus minimizing travel burden, improving quality of life, and increasing access to care for those in remote or underserved areas (Davis et al., 2022). Remote patient monitoring (RPM) technologies have emerged as key enablers of this shift. In particular, wearable biosensors provide continuous, real-time data on physiological parameters such as heart rate, temperature, blood pressure, and biomarkers relevant to chemotherapy side effects, such as neutropenia or cardiotoxicity. These technologies are not only helping clinicians detect adverse events early but also supporting proactive, data-driven care interventions (Offodile et al., 2023). The integration of wearable devices within oncology workflows reflects a growing emphasis on patient-centered and value-based care models, wherein digital tools extend clinical oversight beyond traditional settings (Bradley et al., 2021). As cancer therapies become increasingly complex, the ability to monitor patients remotely using wearable biosensors represents a significant advancement in both safety and personalization. This approach aligns with emerging healthcare delivery models that emphasize decentralization, real-time monitoring, and adaptive treatment strategies.

1.2 Emergence of Wearable Biosensors in Oncology

The integration of wearable biosensors into oncology care marks a significant step in the digital transformation of healthcare. These non-invasive devices continuously monitor physiological and biochemical signals, offering enhanced patient surveillance during chemotherapy. Originally developed for fitness tracking, they have evolved to clinical-grade standards, making them suitable for cancer care (Li et al., 2021). In oncology, wearable biosensors now monitor vital indicators such as heart rate variability, body temperature, blood oxygen saturation, electrodermal activity, and movement patterns—metrics that can detect early signs of chemotherapy-related complications like fatigue, infection, or cardiotoxicity. Their real-time data capabilities enable prompt clinical response, improving safety and treatment outcomes (Pecoraro et al., 2022). Advances in miniaturization, wireless connectivity, and data analytics have accelerated their adoption in oncology, aligning with the shift toward personalized medicine and decentralized care as shown in figure 1. This is especially important for patients receiving treatment at home, as wearable biosensors serve as a critical link between clinical supervision and home-based monitoring. These innovations not only expand the reach of cancer care but also support proactive, responsive, and individualized treatment strategies.

Figure 1 shows three different portable biosensor devices used for blood sample analysis. Figure (a) displays three compact devices including a handheld glucose meter. Figure (b) shows a smartphone-integrated electrochemical biosensor that collects a small sample. Figure (c) presents a pop-up paper-based glucometer designed for point-of-care diagnostics. These innovations mirror the shift in cancer care from centralized clinical environment's to decentralized, patient-centric models. As highlighted in the section, such biosensors enable real-time, non-invasive monitoring of critical health indicators, facilitating early detection of chemotherapy-related complications and promoting continuous patient oversight outside traditional healthcare settings. The image reinforces how miniaturization and digital integration have made high-quality, at-home monitoring feasible, paving the way for broader use of biosensors in oncology.

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Figure 1: Picture of Portable Biosensors for Blood Analysis (Gosai, 2022)

1.3 Rationale for Integrating Wearable Technology in Chemotherapy Management

Chemotherapy remains one of the most widely used yet complex treatment modalities in oncology, often associated with severe side effects and variable patient responses. Traditional models of care rely on intermittent clinical visits and patient self-reporting, which can lead to delayed recognition of adverse events, treatment non-adherence, and suboptimal outcomes. The integration of wearable biosensors into chemotherapy management offers a transformative solution by enabling continuous, real-time physiological monitoring, thereby closing critical gaps in surveillance and care delivery (Gupta et al., 2020). Wearable devices allow clinicians to remotely assess vital parameters and behavioral patterns—such as heart rate, physical activity, skin temperature, and sleep quality—that can serve as early warning signs for complications like febrile neutropenia, dehydration, or cardiotoxicity. Early detection through these biosensors supports timely clinical interventions, reduces emergency department visits, and enhances the safety of at-home chemotherapy administration (Sadoughi et al., 2022). Furthermore, objective physiological data collected through wearables can supplement or replace subjective self-reporting, improving the accuracy and reliability of symptom assessment, especially in older or high-risk patients. Beyond individual patient monitoring, wearable biosensors offer opportunities for data aggregation and advanced analytics, enabling clinicians and researchers to identify population-level trends, personalize treatment plans, and assess therapeutic effectiveness over time. In decentralized care models, these technologies help bridge geographic and logistical barriers by maintaining a continuous link between patients and their care teams. Thus, the rationale for integrating wearable technology into chemotherapy management lies in its potential to improve patient outcomes, optimize resource utilization, and support a safer, more responsive, and patient-centered approach to cancer care.

1.4 Scope and Significance of the Review

This review explores the intersection of wearable biosensor technology and decentralized chemotherapy management, with a focus on how these innovations are reshaping cancer care delivery. The scope encompasses

an examination of sensor technologies applicable to oncology, their integration within remote monitoring infrastructures, and their practical implications in supporting patient-centered care models. It also addresses clinical use cases, implementation challenges, and future directions relevant to healthcare systems, clinicians, and technology developers. The significance of this review lies in its timely evaluation of a rapidly evolving field. As global cancer incidence continues to rise and healthcare systems strive for efficiency, the shift from hospital-based chemotherapy to home-based and outpatient models demands robust tools for remote monitoring (Wildiers et al., 2020). Wearable biosensors are uniquely positioned to fulfill this need by offering scalable, non-invasive, and real-time physiological tracking capabilities. Their ability to captures and transmit clinically actionable data not only enhances patient safety but also empowers oncologists to make more informed, data-driven decisions (Maddison et al., 2022). Furthermore, this review contributes to the ongoing discourse on digital transformation in oncology by highlighting the transformative role of biosensors in enabling decentralized care. It underscores how such technologies align with broader goals of improving access, reducing disparities, and advancing personalized medicine in cancer treatment (Topol, 2019). By synthesizing current evidence and identifying key trends and gaps, the review provides a comprehensive foundation for future research, policy-making, and clinical adoption of wearable biosensor systems in oncology.

2. TECHNOLOGICAL FOUNDATIONS OF WEARABLE BIOSENSORS

2.1 Overview of Relevant Theories

The integration of wearable biosensors into remote chemotherapy monitoring can be effectively understood through several theoretical lenses that explain technology adoption, patient engagement, and behavioural change in healthcare settings. Three prominent theories—**Technology Acceptance Model (TAM), Self-Determination Theory (SDT),** and **Health Belief Model (HBM)—**offer valuable frameworks for analysing the interaction between patients, clinicians, and digital health technologies. The ***Technology Acceptance Model (TAM)***, developed by Davis (1989), posits that two key factors—perceived usefulness and perceived ease of use—predict a user's intention to adopt and utilize new technology. In the context of oncology care, the acceptance of wearable biosensors by patients and clinicians hinges on how effectively these devices are perceived to support treatment outcomes, simplify monitoring, and integrate into daily life (Holden & Karsh, 2010). When users find wearables beneficial and user-friendly, sustained engagement and adherence are more likely. ***Self-Determination Theory (SDT)*** emphasizes autonomy, competence, and relatedness as critical drivers of intrinsic motivation (Deci & Ryan, 2000). In cancer care, wearable biosensors can empower patients by providing personalized feedback, fostering a sense of control over their health, and enhancing communication with care teams. This can contribute to greater patient engagement and self-management during chemotherapy, especially in decentralized care models where face-to-face interaction is limited. The ***Health Belief Model (HBM)*** offers insight into how patients perceive their susceptibility to adverse events and the benefits of adopting preventive health behaviors (Champion & Skinner, 2008). Wearable biosensors, by delivering real-time physiological feedback, may reinforce patients' understanding of health risks and encourage proactive behaviors—such as reporting early symptoms or adjusting activity levels—thus promoting adherence to treatment protocols and timely clinical response. Together, these theories underscore the complex interplay between technology design, user perception, and behavioral outcomes. Their relevance lies in guiding the development, implementation, and evaluation of biosensor-based monitoring systems in remote cancer care.

Table 1: Summary of Theoretical Frameworks Relevant to Wearable Biosensors in Remote Chemotherapy

Theory	Core Concept	Application in Cancer Care	Relevance to Biosensor Integration
Technology Acceptance Model (TAM)	Perceived usefulness and ease of use drive technology adoption	Patients and clinicians adopt biosensors when they simplify monitoring and improve outcomes	Guides user-centered design and implementation to enhance adoption and sustained use
Self-Determination Theory (SDT)	Motivation is driven by autonomy, competence, and relatedness	Wearables support autonomy and communication, empowering patients in self-management	Promotes patient engagement and motivation in decentralized care environments
Health Belief Model (HBM)	Health behavior depends on perceived risk and benefits of action	Biosensors reinforce awareness of health risks and benefits of adherence to treatment	Encourages proactive behavior, adherence, and timely clinical reporting through real-time feedback

2.2 Types and Functionality of Wearable Biosensors

Wearable biosensors are compact, non-invasive devices that continuously collect physiological or biochemical data, enabling real-time monitoring, early detection of adverse effects, and personalized interventions in decentralized chemotherapy care. These sensors vary in type and function. Physiological biosensors monitor core vitals such as heart rate, respiratory rate, blood pressure, skin temperature, and oxygen saturation. Devices like smartwatches, chest straps, and adhesive patches use photoplethysmography (PPG), electrocardiography (ECG), and temperature sensors to detect early signs of cardiotoxicity or infection (Wang et al., 2021). Biochemical biosensors detect glucose, lactate, pH, and electrolyte levels through interstitial fluid or sweat and are promising for tracking metabolic disturbances and drug responses during chemotherapy. These use enzymatic or electrochemical methods embedded in skin-worn patches or microneedle arrays (Kim et al., 2020). Motion and activity sensors utilize accelerometers and gyroscopes to measure posture, gait, sleep, and fatigue, providing insight into neuropathy, functional decline, or treatment-related side effects (Maddison et al., 2022). Multi-parameter integrated systems combine various sensors in smart textiles or wearable platforms, transmitting data wirelessly to cloud dashboards. These systems enhance clinical decision-making through AI-assisted analytics and real-time alerts (Stoppa & Chiolerio, 2014), contributing to early intervention, improved safety, and reduced hospitalizations in remote cancer care.

Table 2. Types and Clinical Functionality of Wearable Biosensors in Chemotherapy summarized.

Type of Biosensor	Key Parameters Monitored	Example Devices	Clinical Application
Physiological Biosensors	Heart rate, respiration, temperature, SpO_2	Smartwatches, chest straps, skin patches	Early detection of infection, cardiotoxicity monitoring
Biochemical Biosensors	Glucose, lactate, pH, electrolytes	Microneedle arrays, sweat analyzers	Monitoring metabolic status and drug response

Motion & Activity Sensors	Activity level, posture, gait, sleep patterns	Accelerometer bands, wearable fitness trackers	Assessing fatigue, physical function, and treatment tolerance
Multi-parameter Integrated Systems	Combined physiological, biochemical, and activity metrics	Smart vests, textile-integrated patches	Comprehensive remote monitoring and real-time clinical decision support

Figure 2: Picture of Clinical Biosensors for Chemotherapy Monitoring

Figure 2 illustrates diverse clinical biosensors aligned with the types described in this subsection, highlighting their role in chemotherapy monitoring. The wearable patch reflects physiological biosensors that track vital signs in real time, while the implantable chip parallels biochemical biosensors that monitor drug levels and metabolic responses. The handheld biosensor represents point-of-care biochemical detection, and the smart bandage integrates motion or biochemical sensing for post-treatment care. Together, these examples explains the functional diversity and real-world application of wearable biosensors in supporting continuous, personalized oncology care.

2.3 Data Collection, Transmission, and Analytics Infrastructure

Remote chemotherapy monitoring relies on the integration of data collection, transmission, and analytics infrastructure to deliver accurate, real-time insights critical for decentralized oncology care. Wearable biosensors equipped with technologies such as photoplethysmography (PPG), electrochemical sensors, accelerometers, and thermistors monitor physiological and biochemical parameters like heart rate, skin temperature, glucose levels, and motion. Biochemical biosensors, including microneedle patches and sweat analyzers, enable non-invasive monitoring of treatment efficacy and toxicity biomarkers (Heikenfeld et al., 2018). Collected data undergo onboard preprocessing—noise reduction, drift correction, and artifact elimination—to ensure clinical accuracy in ambulatory settings (Pantelopoulos & Bourbakis, 2010). The refined signals are transmitted via BLE, Zigbee, or Wi-Fi to mobile devices or hubs, then securely relayed to cloud systems using encrypted networks as shown in figure 3. To maintain continuity, buffering and recovery protocols mitigate data loss, and compliance is ensured through end-to-end encryption under HIPAA and GDPR guidelines (Patel et al., 2012). In the cloud, AI and ML tools analyze multivariate data to predict adverse events and support clinical decisions, with findings displayed on clinician dashboards or patient apps (Lee et al., 2021). Integration with EHRs and innovations like edge computing and federated learning (Xu et al., 2021) enhance scalability, privacy, and responsiveness in remote cancer care.

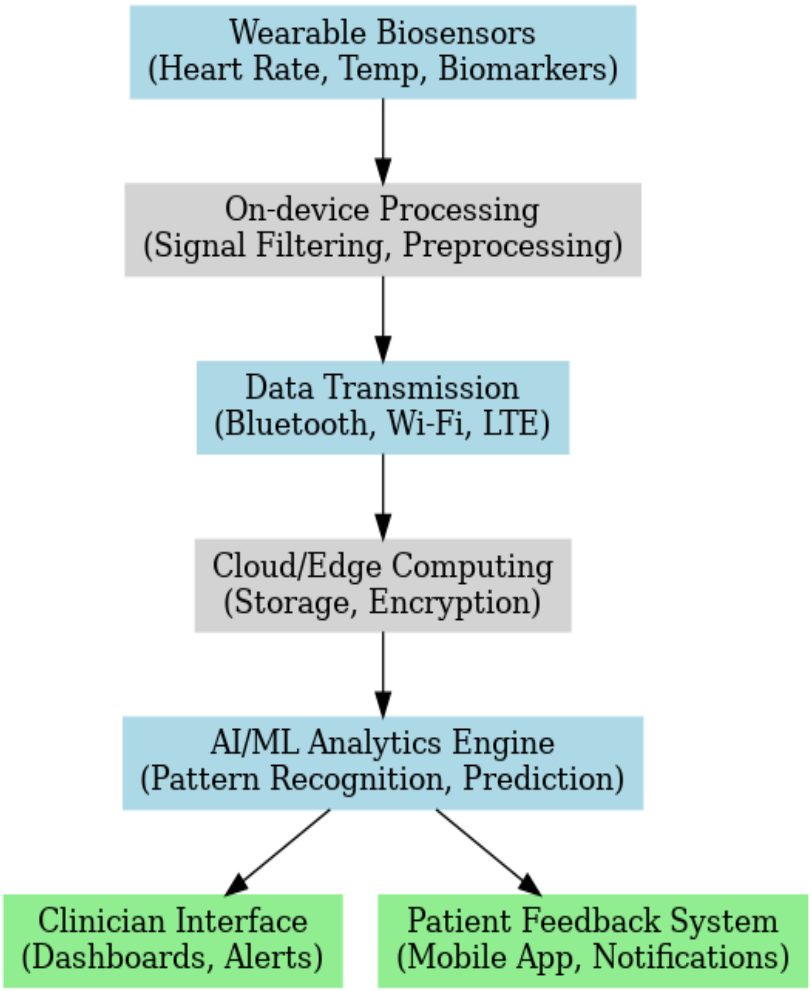

Figure 3: Data Collection, Transmission, and Analytics Infrastructure for Wearable Biosensors

Figure 3 illustrates visually reinforces this section by mapping the entire biosensor data pathway—from collection through transmission and cloud-based AI analysis to output delivery. It illustrates how wearable sensors gather physiological and biochemical data, which are locally preprocessed and wirelessly transmitted. These data streams are then analyzed by AI/ML platforms, and the resulting insights are presented to clinicians and patients via dashboards and mobile apps, enabling timely interventions and collaborative care in remote oncology settings.

2.4 The Interoperability with Electronic Health Records and Telehealth Platforms

The effectiveness of wearable biosensors in remote chemotherapy monitoring is amplified by their interoperability with electronic health records (EHRs) and telehealth platforms. Seamless data integration enables real-time, patient-generated health data to enter clinical workflows, improving care coordination and facilitating timely, data-driven interventions in decentralized oncology settings. Integration with EHRs, provides clinicians with a longitudinal view of patient health, supporting the monitoring of treatment responses and early detection of adverse events such as cardiotoxicity or dehydration. This is often achieved through standardized data exchange protocols like HL7 FHIR, which ensure secure and structured transmission of data across platforms (Mandel et al., 2016). EHR-linked dashboards and predictive tools enable providers to act on early warning signs—for instance, combining declining activity with elevated heart rate to detect fatigue or infection. Telehealth platforms further extend care by enabling remote consultations informed by biosensor data, enhancing patient engagement and reducing hospital visits—particularly vital for immunocompromised patients (Bashshur et al., 2020). Developers must adhere to data governance and privacy standards, including HIPAA and GDPR, while leveraging open APIs to overcome interoperability barriers (Adler-Milstein & Jha, 2017). As standards evolve, such integrations promise more scalable, personalized cancer care across diverse healthcare environments.

3. CLINICAL APPLICATIONS IN REMOTE CHEMOTHERAPY MONITORING

3.1 Monitoring Physiological and Biochemical Parameters During Chemotherapy

Monitoring physiological and biochemical parameters during chemotherapy is vital for evaluating treatment efficacy, minimizing toxicity, and ensuring patient safety. Chemotherapy can induce adverse effects across cardiovascular, renal, and hematologic systems, necessitating close surveillance (Barton et al., 2018) as shown in figure 12. Physiological indicators such as heart rate, blood pressure, temperature, and respiratory rate are key for detecting early complications. For instance, anthracyclines may cause cardiotoxicity, requiring continuous cardiac monitoring to prevent severe outcomes (Pettit et al., 2019). Similarly, elevated temperature may signal febrile neutropenia—an urgent complication in immunocompromised patients (Jackson et al., 2021). Biochemical monitoring includes complete blood counts, renal and liver function tests, and electrolyte levels. Chemotherapy-induced myelosuppression can reduce white blood cells, red blood cells, and platelets, increasing the risk of infection, anemia, and bleeding. Regular CBCs help guide timely interventions like growth factors or transfusions (Williams et al., 2020). Nephrotoxic agents like cisplatin require monitoring of serum creatinine and BUN, while hepatotoxic drugs such as cyclophosphamide necessitate liver enzyme evaluation (Liu et al., 2019). Electrolyte imbalances, including disturbances in sodium, potassium, and calcium, must also be corrected to avoid arrhythmias or seizures (Green et al., 2020). Advances in wearable and remote monitoring technologies now allow real-time, home-based tracking, enhancing early intervention and improving patient outcomes.

Figure 4 depicts a clinical scenario where healthcare professionals are closely monitoring a chemotherapy patient's physiological and biochemical parameters to ensure treatment safety and efficacy. The patient, seated and partially exposed to allow access to a central venous catheter or port-a-cath, is under the attentive care of

two clinicians—one actively performing a procedure, possibly drawing blood or administering medication, while the other oversees the intervention. This reflects critical practices such as monitoring for chemotherapy-induced cardiotoxicity, nephrotoxicity, and myelosuppression. The presence of central line access suggests the need for frequent laboratory evaluations, including complete blood counts (CBCs), liver and renal function tests, and electrolyte panels to detect complications like febrile neutropenia, anemia, or metabolic disturbances. The setup, including medical equipment and sterile technique, reinforces the importance of real-time clinical surveillance in mitigating risks associated with cytotoxic regimens and aligns with modern chemotherapy protocols that prioritize continuous assessment to improve therapeutic outcomes and patient safety.

Figure 4: Picture of clinicians monitoring a chemotherapy patient via central line access to ensure safe and effective treatment (Friedl, E., 2017)

3.2 Enhancing Adherence, Safety, and Early Detection of Adverse Events

Optimizing chemotherapy outcomes requires a strong focus on adherence, patient safety, and early detection of adverse events. Poor adherence can reduce therapeutic efficacy and increase the risk of disease progression or treatment failure (Shah et al., 2023). Factors such as complex regimens and distressing side effects can hinder compliance, but personalized care plans, effective communication, and digital health tools—like mobile apps and reminders—can improve adherence (Liu et al., 2021). Mobile health interventions have shown success in supporting real-time medication tracking and provider-patient communication, leading to better adherence (Smith et al., 2020). Safety is another priority due to the cytotoxic nature of chemotherapy agents. Regular assessments, lab tests, and real-time monitoring technologies help detect adverse effects early. Integrating pharmacogenomics into treatment decisions can reduce risk by personalizing drug selection and dosing (Wilson et al., 2020). Safety protocols, including checklists, also help prevent administration errors (Bates et al., 2019). Early detection of adverse events—such as neutropenia or organ toxicity—is enabled by tracking blood counts, biomarkers, and imaging data (Yoon et al., 2021; Zhou et al., 2020). Wearable biosensors as shown in figure 5provide continuous data on vital signs, supporting rapid interventions for complications like cardiotoxicity or respiratory distress (Smith et al., 2020).

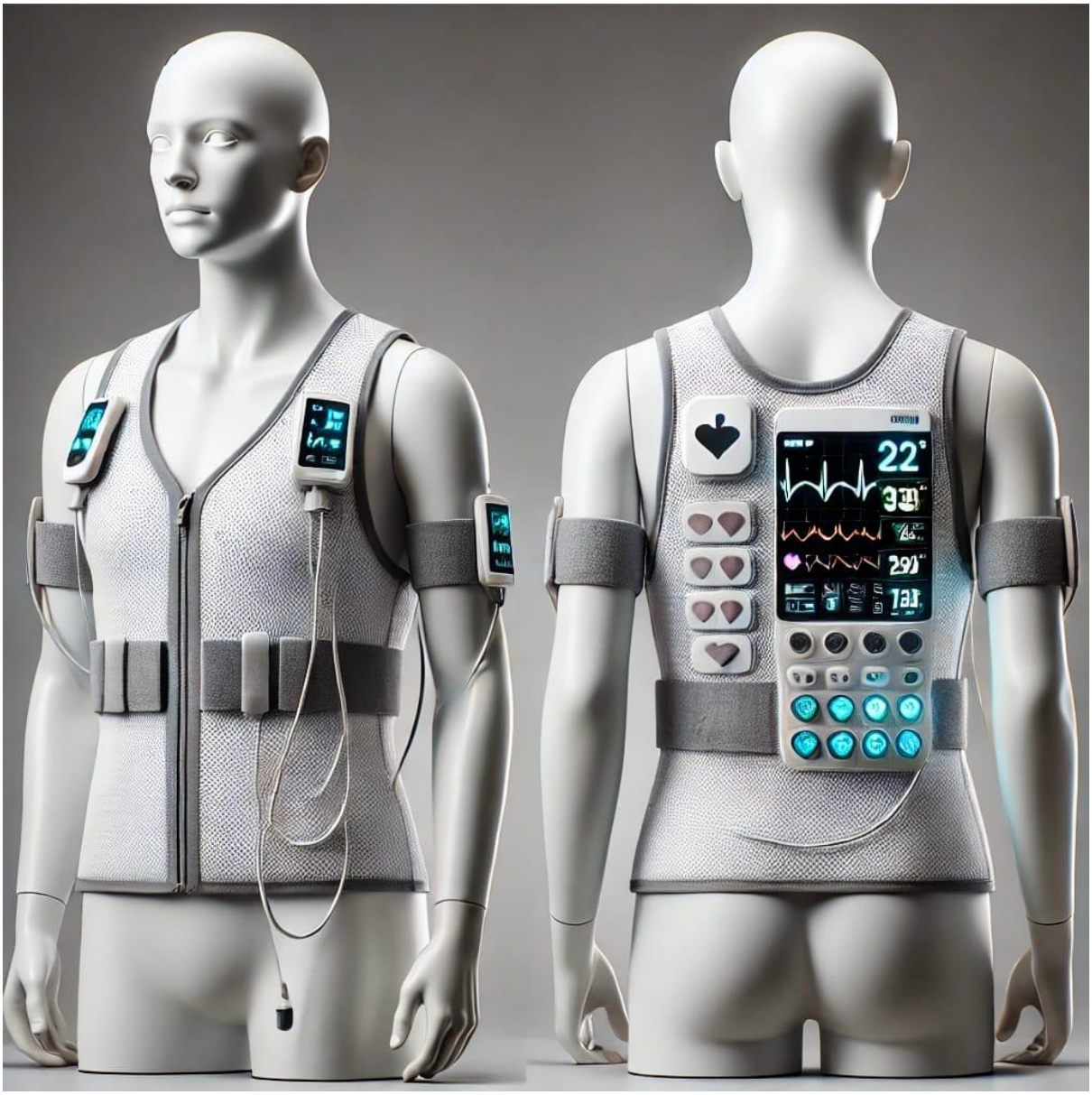

Figure 5 : Picture of Smart Monitoring Vest for Enhancing Adherence, Safety, and Early Detection in Chemotherapy Care

figure 5 is a smart monitoring vest which continuously tracks vital signs such as heart rate, respiratory rate, and temperature, supporting early detection of adverse chemotherapy effects. Integrated digital displays and wearable sensors help ensure patient safety by providing real-time clinical data. The vest promotes adherence by minimizing the burden of frequent hospital visits through remote monitoring. Alerts and biometric feedback empower both patients and providers to respond quickly to complications. Such wearable technologies represent a major advancement in optimizing chemotherapy outcomes.

3.3 Case Examples of Wearable Integration in Cancer Care Settings

Wearable devices are revolutionizing cancer care by enabling continuous monitoring, early detection of side effects, and personalized treatment. These technologies—ranging from fitness trackers to advanced biosensors—track vital signs, activity, and even biochemical data, offering real-time insights that improve outcomes and adherence. One example is a pilot study where chemotherapy patients wore smartwatches to track heart rate and activity. This data, sent to clinicians in real-time, allowed early detection of fatigue and cardiac issues,

enabling prompt treatment adjustments and reducing hospital visits (Smith et al., 2020). Another trial used wearable ECG monitors to detect early signs of anthracycline-induced cardiotoxicity. Machine learning analysis of heart rhythm data helped providers intervene before significant damage occurred, enhancing patient safety (Johnson et al., 2021). Wearables have also aided in managing chemotherapy-induced peripheral neuropathy (CIPN). Sensors tracking nerve function and limb movement allowed clinicians to adjust treatment, minimizing neuropathy's impact (Taylor et al., 2020). During the COVID-19 pandemic, remote monitoring using wearables helped maintain care continuity, with devices tracking sleep, activity, and vital signs to guide treatment (Perez et al., 2021). Additionally, wearables offer emotional support, with some allowing mood tracking integrated into care plans, improving holistic cancer management (Bergstrom et al., 2020).

Table 3: Summary of Representative Use Cases of Wearable Devices in Oncology Care Settings

Device/Wearable	Function/Monitored Parameter	Clinical Setting/Use Case	Reported Benefit
Smartwatch (e.g., Apple Watch)	Heart rate, physical activity, sleep	Outpatient cancer rehab	Improved monitoring and patient engagement
Patch biosensors (e.g., Vital Patch)	Temperature, respiration, ECG	Chemotherapy monitoring	Early detection of adverse reactions
Continuous glucose monitors (e.g., Freestyle Libre)	Glucose levels	Cancer patients with diabetes	Reduced hospital visits, better metabolic control
Smart pill bottles/reminders	Medication adherence tracking	Home-based oral chemotherapy	Increased adherence and timely intake

4. CHALLENGES AND CONSIDERATIONS IN IMPLEMENTATION

4.1 Technical Barriers: Accuracy, Battery Life, and Connectivity

Despite their promise in cancer care, wearable devices face technical barriers that limit their reliability and clinical utility. Key challenges include data accuracy, limited battery life, and inconsistent connectivity—each of which can affect patient monitoring and safety. Accuracy remains a major concern, as many wearables struggle to match the precision of clinical-grade equipment. Factors such as sensor misplacement, user error, and device calibration can result in unreliable readings of heart rate, oxygen levels, or activity—potentially leading to false alerts or missed complications like cardiotoxicity (Zhang et al., 2020). Enhancing sensor technology and refining algorithms are necessary to improve data validity. Battery life also limits continuous monitoring. Wearables often require frequent recharging, which can be burdensome for cancer patients dealing with fatigue or complex treatment schedules. This may reduce device usage and result in incomplete data. Innovations in energy efficiency and solutions like wireless or solar charging could mitigate this issue (Li et al., 2021). Connectivity is another challenge. Wearables depend on stable Bluetooth or Wi-Fi connections to transmit real-time data to healthcare systems. Inconsistent connectivity—especially in remote or underserved areas—can delay critical decisions or result in lost information. Ensuring seamless integration with healthcare platforms and building resilient infrastructure are vital for dependable data flow (Nguyen et al., 2020). Overcoming these

barriers requires ongoing innovation, better collaboration between developers and clinicians, and a focus on patient-centered design to ensure wearables can truly enhance cancer care.

Table 4: summary of Technical Challenges Associated with Wearable Biosensors in Cancer Care

Technical Barrier	Description	Example in Cancer Care	Proposed Solution
Accuracy	Variability in readings due to motion artifacts, skin conditions, or sensor misplacement.	ECG or heart rate monitors giving inconsistent readings during patient movement.	Use of machine learning algorithms to filter noise and calibrate data in real-time.
Battery Life	Frequent recharging limits usability, especially in continuous monitoring devices.	Patients undergoing chemotherapy forgetting to recharge wearable patches.	Development of energy-efficient components, wireless charging, or solar-powered sensors
Connectivity	Intermittent or failed data transmission due to poor Bluetooth/Wi-Fi connections.	Data loss during remote monitoring sessions using home-based wearables.	Implementation of 5G technology and edge computing for stable, high-speed data transfer.
Data Integration	Difficulty syncing data with EHR systems and clinical dashboards.	Wearable-generated vitals not appearing in oncologist's EMR.	Use of standardized health data protocols (e.g., HL7 FHIR) for seamless integration

4.2 Patient-Centric Challenges: Usability, Privacy, and Equity

The adoption of wearable devices in cancer care is limited not only by technical factors but also by patient-centric challenges. Usability, data privacy, and health equity are critical concerns that influence how effectively patients can benefit from these technologies. Usability is a major barrier, especially for patients undergoing demanding cancer treatments. Wearables with complex interfaces, difficult setup procedures, or uncomfortable designs can be challenging for patients, particularly those who are elderly or have limited digital literacy (Imoh, & Idoko, 2023). Without proper guidance or training, patients may misuse devices or abandon them altogether, leading to poor data quality or noncompliance. To improve usability, developers must prioritize intuitive design, clear instructions, and accessible support systems that accommodate the needs of diverse patient populations (Thompson et al., 2021). Privacy concerns also hinder patient trust and acceptance. Wearables collect sensitive health data, and without strong data protection protocols, patients may fear unauthorized access or misuse—such as for commercial purposes without consent. This is especially critical in oncology, where patient vulnerability is high. Ensuring transparency in data use, implementing robust cybersecurity measures, and complying with health privacy regulations like HIPAA are essential to protect patient information and build trust (Zhou et al., 2020). Equity is a growing concern as wearables risk deepening healthcare disparities. Socioeconomic barriers—such as the cost of devices, lack of internet access, and limited digital infrastructure—can exclude low-income, rural, or underserved populations. Without equitable access, the benefits of wearable health technologies may not reach those who could benefit the most. Solutions include subsidizing device costs, expanding broadband access, and designing inclusive systems that account for socioeconomic and geographic

diversity (Garcia et al., 2020). In summary, for wearable devices to fulfill their potential in cancer care, developers and healthcare systems must address usability, privacy, and equity. By ensuring devices are user-friendly, data is securely managed, and access is inclusive, these technologies can enhance patient engagement, support continuous monitoring, and improve clinical outcomes for all patients.

Table 5 : summary of *Patient-Centered Barriers to Wearable Adoption in Oncology*

Barrier	**Nature of the Challenge**	**Affected Population**	**Implications for Care**
Usability	Complex interfaces, small screens	Older adults, low-tech literacy	Lower adoption and usage
Privacy Concerns	Complex interfaces, small screens	All demographics	Reluctance to use wearables
Health Equity	Cost, internet access, device access	Rural or low-income	Limited access and care disparities

4.3 Clinical and Regulatory Hurdles in Decentralized Models

The integration of wearable devices into decentralized cancer care models—where patients are monitored remotely outside traditional healthcare facilities—presents a series of clinical and regulatory challenges that must be resolved to ensure safety, efficacy, and scalability. Decentralized healthcare models, including telemedicine and remote monitoring, depend heavily on continuous and reliable data from wearable technologies as shown in figure 6. However, for wearables to contribute meaningfully to clinical decision-making, they must first undergo rigorous clinical validation. Unlike hospital-grade devices, many commercially available wearables lack the stringent testing required to confirm measurement accuracy (Imoh, & Idoko, 2022). Inaccurate data, especially in oncology, can lead to delayed interventions or mismanagement of treatment-related side effects. Clinicians must also be trained to interpret wearable data correctly, and standardized protocols must be developed to guide how and when such data should influence care (Johnson et al., 2021).

Regulatory barriers also pose a substantial obstacle. While agencies like the FDA and EMA provide pathways for medical device approval, wearable technologies often outpace these frameworks due to their rapid innovation cycles. Many wearables fall into a gray zone—neither clearly consumer electronics nor certified medical devices—leading to delays in approval and uncertainty about their use in clinical settings. Updated, streamlined regulatory processes are necessary to match the pace of wearable development and ensure patient safety without stifling innovation (Morris et al., 2020). Another persistent issue is data interoperability. Most wearables are not built to interface directly with electronic health records (EHRs), making it difficult for clinicians to incorporate wearable-generated data into patient care workflows. This disconnect slows the flow of information, particularly in time-sensitive situations like chemotherapy monitoring. Developing unified standards for data formats and communication protocols between wearables and clinical information systems is critical to enabling seamless integration (Baker et al., 2020). Furthermore, global regulatory inconsistencies hinder the broader deployment of wearables across borders. Devices approved in one region may be restricted in another due to differing standards, delaying access and undermining the scalability of decentralized care models. Harmonizing

international regulatory frameworks would help ensure that innovative wearable solutions can be adopted more uniformly and efficiently around the world.

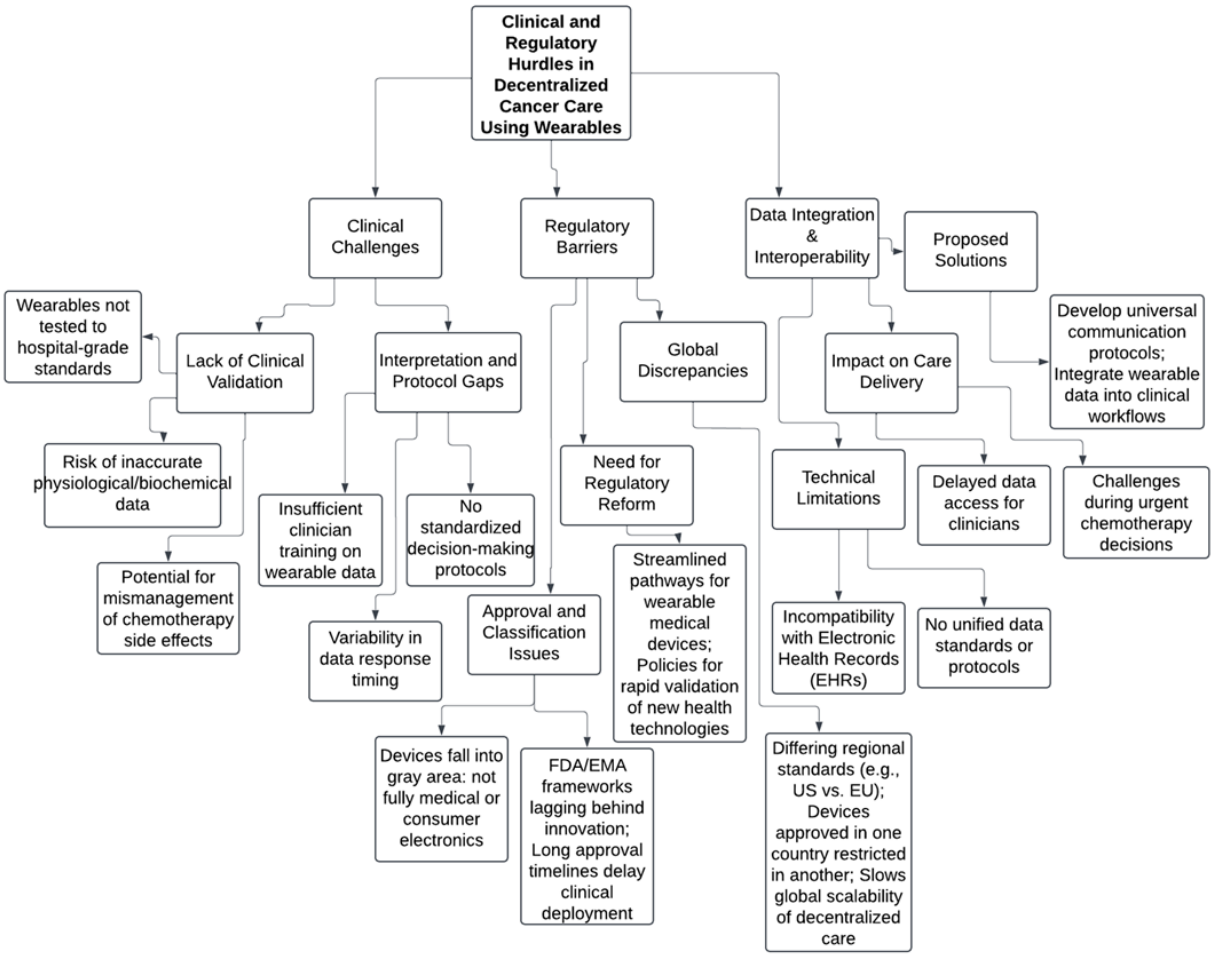

Figure 6: Diagram illustrating the clinical, regulatory, and data integration challenges hindering the effective use of wearable technologies in decentralized cancer care models.

Figure 6 visually organizes the key challenges into three main branches: clinical challenges, regulatory barriers, and data integration issues. The first branch outlines clinical concerns, highlighting that many commercially available wearables lack the rigorous clinical validation needed for reliable use in oncology, leading to potential misinterpretation and delayed interventions. It also emphasizes the absence of standardized protocols and limited clinician training in interpreting wearable data. The second branch addresses regulatory hurdles, noting that wearable technologies often fall outside traditional medical device classifications, resulting in delayed approvals due to outdated regulatory frameworks from agencies like the FDA and EMA. It also points out inconsistencies in global regulations, which hinder the cross-border deployment of validated wearable solutions. The third branch focuses on data interoperability, highlighting the inability of most wearables to integrate seamlessly with electronic health records (EHRs), which impedes clinical workflows, especially in time-sensitive chemotherapy monitoring. The diagram concludes with proposed solutions such as universal data standards and improved communication protocols to bridge the gap between wearable data and clinical decision-making systems, ensuring safer and more scalable decentralized cancer care models.

5. FUTURE DIRECTIONS AND INNOVATIONS

5.1 Advances in Sensor Technologies and Real-Time Analytics

Advancements in sensor technologies and real-time analytics are reshaping wearable healthcare, especially in cancer care. Modern sensors have become more precise, compact, and energy-efficient, allowing wearables to track complex biomarkers like glucose, lactate, and even tumor indicators (Miller et al., 2020). Multi-sensor integration as shown in figure 7 enables simultaneous monitoring of various physiological parameters—such as heart rate, respiration, hydration, and metabolism—providing a comprehensive view of a patient's condition (Li et al., 2021). This is crucial in oncology, where continuous, accurate monitoring supports early detection of side effects like cardiotoxicity or organ dysfunction.Complementing these sensor innovations, real-time analytics—powered by machine learning and AI—can instantly process data to identify health anomalies. These systems generate early alerts, allowing healthcare providers to intervene before complications worsen (Zhang et al., 2020). Integration with cloud-based platforms further enhances remote monitoring, enabling clinicians to track patient status in real time, even outside clinical settings. This continuous data stream supports personalized treatment strategies, adjusting care based on individual responses and health trends (Abiodun, et al., 2023). Overall, combining advanced sensors with real-time analytics enhances the precision, responsiveness, and personalization of cancer care, making wearable technologies essential tools for improving patient outcomes and enabling more proactive, data-driven healthcare delivery.

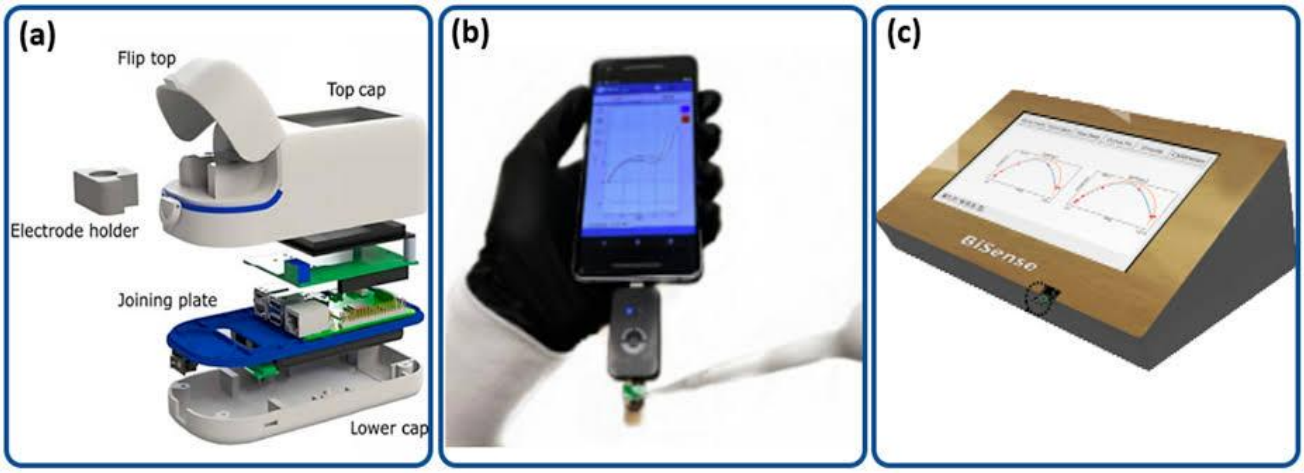

Figure 7: Picture of Advanced Designs of Biosensor Systems (Bhardwaj et al., 2022).

Figure 7 illustrates three advanced biosensor system designs that align with the integration of sensor technology and real-time analytics in cancer care. In (a), the exploded view of a compact biosensor highlights the internal components that enable miniaturization and multifunctionality—essential for wearable applications. Figure (b) shows a smartphone-connected handheld biosensor, demonstrating how mobile integration allows real-time health monitoring outside clinical settings. Figure (c) features a stationary biosensor reader (BISense), representing devices capable of more complex analytics, ideal for clinical environments. These designs collectively support the subsection's focus on continuous, personalized monitoring through smart, connected biosensor systems.

5.2 Integration with AI and Predictive Modeling for Personalized Care

The integration of Artificial Intelligence (AI) and predictive modeling with wearable technologies is transforming personalized cancer care. AI can analyze real-time data from wearables—such as heart rate, oxygen saturation, and physical activity—to detect subtle health changes and predict complications like neuropathy or sepsis (Patel et al., 2020). These insights allow healthcare providers to intervene early, improving

outcomes. Predictive modeling enhances this by using historical and genetic data to forecast treatment responses and side effects, helping clinicians tailor therapies more effectively. AI-powered wearables support proactive care by continuously learning from patient data. As the system adapts, it refines its ability to detect risks and recommend interventions. For example, it can differentiate between irregular heart rates caused by treatment or underlying cardiac issues, offering precise, context-aware alerts (Yang et al., 2021). This continuous learning process ensures evolving, personalized recommendations for each patient. Additionally, AI-enabled wearables facilitate remote monitoring, allowing clinicians to oversee patient health outside hospital settings. This reduces the need for frequent visits and lowers healthcare costs by preventing emergency admissions (Smith et al., 2020). Ultimately, combining AI and predictive analytics with wearable technology supports a shift toward truly individualized, data-driven cancer care.

Table 6: summary of *AI-Driven Enhancements in Wearable Cancer Care Systems*

AI Functionality	Wearable Application	Impact on Care	Real-World Example
Predictive Analytics	Forecasting adverse events	Proactive intervention	Early fever detection in chemotherapy patients
Pattern Recognition	Detecting abnormal vitals automatically	Reduced manual oversight	Continuous ECG analysis
Personalized Feedback	Adjusting alerts based on user behaviour	Increased adherence and comfort	AI-driven medication reminders

5.3 Implications for Policy, Reimbursement, and Health System Integration

The adoption of wearable biosensors in oncology care brings significant implications for healthcare policy, reimbursement models, and system-wide integration. Effective use of these technologies requires regulatory clarity to distinguish medical-grade wearables from consumer devices and ensure safety, efficacy, and data interoperability. Without well-defined frameworks, adoption in clinical settings may remain fragmented. Additionally, reimbursement remains a critical barrier; many wearable devices lack insurance coverage, which limits access and discourages provider integration despite their potential to enhance monitoring, reduce hospitalizations, and improve treatment adherence. To support sustainable use, healthcare payers and policymakers must recognize the long-term value of wearables and create appropriate reimbursement pathways. Furthermore, successful system integration demands robust data infrastructure capable of harmonizing wearable inputs with electronic health records and telehealth platforms. Ensuring that clinicians are trained to interpret biosensor data and that systems support equitable access will be essential in maximizing the benefits of wearable technology in decentralized cancer care.

5.4 Summary and Conclusion

The integration of wearable biosensors into remote chemotherapy monitoring marks a significant advancement in decentralized cancer care. This review explored the foundational technologies behind these devices, including precision sensors and real-time analytics, as well as their clinical applications and supporting digital infrastructure. Wearable biosensors allow for continuous monitoring of key physiological parameters—such as heart rate, temperature, hydration, and biomarker levels—which is especially critical in oncology, where timely detection of side effects like cardiotoxicity or organ dysfunction can significantly affect outcomes. These systems not only enhance early intervention but also improve patient adherence and engagement by enabling care to

extend beyond hospital walls. Furthermore, the interoperability of biosensors with electronic health records and telehealth platforms facilitates more coordinated, data-driven decision-making. Patients and providers can benefit from real-time updates and personalized treatment adjustments, enhancing the overall quality and efficiency of care. Despite these advantages, challenges remain, including concerns over data security, device reliability, standardization, and seamless integration with existing health IT systems. Addressing these issues is vital to ensuring the widespread and equitable adoption of wearable technologies in oncology. As the healthcare landscape evolves toward more patient-centric and decentralized models, wearable biosensors are poised to become essential tools in delivering responsive, personalized, and effective chemotherapy management in both clinical and home settings.

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