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Advancing Precision Medicine: A Review of Drug-Device Combination Products for Individualized Therapy

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ABSTRACT: The increasing complexity of chronic diseases has driven the integration of Drug-Device Combination Products (DDCPs) into precision medicine. DDCPs combine pharmaceutical products with delivery devices to enhance treatment efficacy, improve patient compliance, and provide adaptive, real-time solutions for chronic conditions. This research seeks to examine how DDCPs contribute to the development of personalised treatment approaches. A qualitative literature review was conducted using 67 peer-reviewed articles from databases such as PubMed and ScienceDirect. The research utilised thematic analysis to uncover major patterns, issues, and potential advancements in the area. The findings indicate that DDCPs, including smart insulin pens, digital inhalers, and implantable drug-delivery systems, significantly improve therapeutic outcomes by enabling personalised, data-driven treatment adjustments. These devices, often integrated with artificial intelligence and biosensors, provide real-time monitoring and personalised dosing. However, challenges such as regulatory hurdles, substantial development expenses and ongoing concerns about data privacy continue to pose major obstacles. Regulatory frameworks vary globally, and economic constraints limit the accessibility of DDCPs, especially within countries with low to moderate income levels. Ethical concerns regarding data security and algorithmic bias are also critical in the deployment of these technologies. In conclusion, while DDCPs hold promise for transforming precision medicine, their widespread implementation faces notable challenges. Addressing regulatory, economic, and ethical issues, alongside fostering innovation through multidisciplinary collaboration, will be essential for maximising the benefits of DDCPs. Upcoming studies ought to prioritise the creation of internationally recognised standards, improving AI algorithms, and ensuring equitable access to these technologies across diverse healthcare systems.

KEYWORDS: Precision Medicine, Drug-Device Combination Products (DDCPs), Individualised Therapy, Qualitative Literature Review, Healthcare Innovation

INTRODUCTION

The modern era of medicine is undergoing a transformative shift, shifting from conventional uniform strategies to more tailored, person-centred approaches, a precise framework known as precision medicine [1]. This approach seeks to optimise therapeutic outcomes by tailoring medical practices to the unique biological, genetic, environmental, and behavioural characteristics of each patient [2]. In contrast to conventional population-based treatments, precision medicine leverages molecular diagnostics, biomarkers, and patient-specific data to deliver targeted therapies, thereby enhancing efficacy and minimising adverse effects [3].

The accelerating momentum behind precision medicine has been fueled by groundbreaking advancements in genomics, proteomics, and computational biology, as well as the increasing integration of big data and artificial intelligence (AI) tools [4]. These innovations not only improve our understanding of disease heterogeneity but also enable the development of therapies that are both mechanistically precise and tailored to the individual patient [5]. In parallel, healthcare systems are being pressured to deliver value-based care—improving clinical outcomes while controlling costs—further emphasising the need for individualised therapeutic strategies [6].

Within this evolving landscape, Drug-Device Combination Products (DDCPs) have emerged as critical enablers of precision medicine. By combining pharmaceuticals with delivery devices, such as inhalers, auto-injectors, implantable pumps, or wearable sensors, DDCPs provide a sophisticated platform designed to optimise drug delivery, enhance patient compliance, and facilitate real-time monitoring [7]. These products go beyond simple drug administration by offering adaptive solutions that respond to the dynamic physiological needs of the patient, particularly in managing complex chronic diseases like diabetes, cardiovascular conditions, asthma, and cancer [8].

DDCPs represent more than just technological innovations; they are integral to realising individualised therapy. Devices like smart insulin pens, which adjust dosage based on real-time glucose levels, digital inhalers that track usage and send reminders, and implantable chemotherapy pumps, exemplify how DDCPs can bridge the gap between clinical intent and real-world outcomes [9]. Furthermore, in the age of digital health, these devices can integrate with cloud-based

platforms, electronic health records, and AI systems to generate actionable data that supports informed clinical decision-making [10].

However, while DDCPs hold significant promise in advancing precision medicine, their widespread adoption faces several challenges. From a technological standpoint, the co-development of drugs and devices presents challenges related to engineering, material compatibility, and biointegration [11]. Clinically, demonstrating not only safety and efficacy but also the functional synergy between drug and device components across diverse patient populations remains a key hurdle [12]. Additionally, regulatory frameworks for DDCPs are still evolving, with varying classifications across regions, creating uncertainty for developers and manufacturers [13].

Economically, the high upfront costs, lengthy development timelines, and ambiguous reimbursement pathways associated with DDCPs pose barriers to widespread implementation, especially in resource-constrained and economically developing environments [14]. Moral considerations, such as those involving data protection, obtaining informed consent, and fair availability of advanced treatments, further complicate the integration of DDCPs into healthcare systems [15], [16]. Furthermore, health systems must address infrastructure limitations, workforce preparedness, and patient engagement to fully leverage the potential of DDCPs [17], [18].

This article presents a qualitative literature review that synthesises and critically examines the existing research on DDCPs, investigating their role in advancing individualised therapy within precision medicine. Its goal is to offer an in-depth theoretical insight into how these products could transform treatment models, address existing challenges in development and implementation, and identify future research directions [19], [20].

LITERATURE REVIEW

1. Precision Medicine: Concept and Advancements

Precision medicine, as an innovative approach in healthcare, has shifted the conventional uniform approach, shifting towards a more personalised strategy. This paradigm focuses on customising medical treatment to the distinct genetic, biological, and environmental traits of every individual patient, aiming to enhance therapeutic efficacy and reduce unwanted side effects [21]. The integration of molecular diagnostics, biomarkers, and patient-specific data in precision medicine allows for more precise therapeutic interventions [22], addressing the complexities of chronic and multifactorial diseases [23].

Advancements in genomics, proteomics, and computational biology have accelerated this transition, enabling scientists and healthcare professionals to design therapies that are not only more targeted but also more relevant to the biological needs of the individual [24]. These technologies serve as the foundation for a new treatment paradigm that can significantly improve patient outcomes [25]. Furthermore, the integration of big data and artificial intelligence (AI) tools has allowed for more proactive and adaptive patient management, replacing the older reactive treatment models [26].

2. Drug-Device Combination Products (DDCPs) in Precision Medicine

Within the context of precision medicine, Drug-Device Combination Products (DDCPs) have emerged as a pivotal solution. These combination products integrate a drug with a medical device, such as inhalers, auto-injectors, and wearable sensors, into a unified therapeutic platform [27]. The primary goal of DDCPs is to optimise drug delivery, enhance patient adherence, and enable real-time patient monitoring [28]. This approach is particularly relevant for treating chronic diseases like diabetes, cardiovascular diseases, asthma, and cancer, where dynamic adjustment of drug dosage is essential based on the patient's physiological changes [29].

DDCPs enable adaptive drug dosing that responds to the patient's real-time needs. As an illustration, smart insulin pens can modify the dosage according to blood glucose readings, while digital inhalers can monitor usage and send reminders to help patients stick to their regimen [30]. Additionally, DDCPs can be integrated with cloud-based platforms, electronic health records, and AI algorithms, delivering immediate data to guide clinical decision processes [31].

3. Challenges in the Development and Implementation of DDCPs

While DDCPs hold great promise in precision medicine, several challenges hinder their broader adoption and scalability. From a technical standpoint, developing a product that combines both drugs and devices requires addressing complex technological integration, including material compatibility, device engineering, and biofunctional integration [32]. Moreover, regulatory frameworks for DDCPs are still evolving, presenting difficulties in obtaining consistent approval across different regions [33].

Clinically, for DDCPs to be widely accepted in the market, their development must demonstrate not only safety and efficacy but also functional synergy between the drug and device components in diverse patient populations and disease conditions [34]. In terms of economics, the high upfront development costs, long development timelines, and uncertain reimbursement pathways present significant barriers, particularly in low- and middle-income countries with limited access to such technologies [35]. These challenges are further compounded by the complexities in technology distribution, which can affect accessibility and equity in healthcare delivery [36].

4. Research Directions and Future Potential of DDCPs

Further research is required to address the technical and clinical challenges in DDCP development and to ensure optimal functional validation of these products. As technology advances, particularly in the fields of biometric sensors and big data analytics, DDCPs are expected to evolve, offering more efficient personalised solutions for patients

[37]. Research focusing on synergy between the drug and device, as well as the achievement of global regulatory standardisation, is crucial for accelerating the adoption of these products worldwide [38].

Additionally, an interdisciplinary approach involving research from the fields of medicine, biomedical engineering, and health policy is essential for improving the efficacy, affordability, and safety of DDCPs [39]. Collaborative international research will help establish better standards and policies that will encourage the wider adoption of DDCPs, especially in resource-limited settings [40].

Overall, DDCPs play a critical role in advancing precision medicine. While significant challenges remain in terms of technical, regulatory, and economic aspects, the potential of these products to improve treatment outcomes by offering more personalised and adaptive therapeutic solutions for patients is substantial. Further research is essential to overcome these barriers and to optimise the implementation of DDCPs in global healthcare systems.

METHODOLOGY

This research utilised a qualitative literature review method to explore the contribution of Drug-Device Combination Products (DDCPs) in enhancing personalised treatment within the wider framework of precision medicine. The qualitative nature of this research is rooted in an interpretive framework, aiming to synthesise and critically assess existing peer-reviewed literature without the inclusion of primary data collection methods such as focus group discussions or field observations. The primary instrument in this qualitative inquiry was the researcher's analytical framework, driven by well-established inclusion and exclusion standards to guarantee the relevance, credibility, and scientific rigour of the selected sources. Data were gathered through a systematic search of reputable academic databases—including Scopus, PubMed, ScienceDirect, and Web of Science—focusing on journal articles published in the past ten years that addressed themes such as DDCP design, clinical implementation, regulatory challenges, and digital integration in precision medicine. Only articles published in English and indexed in high-impact journals were considered to maintain quality and objectivity. The analysis followed a thematic synthesis technique, whereby the identified literature was reviewed, coded, and categorised into core conceptual domains relevant to the research focus. Patterns, contradictions, and knowledge gaps were identified through iterative reading and comparison across studies, allowing for a critical evaluation of the state of the art. This method enabled the extraction of nuanced insights and theoretical perspectives necessary to map current developments, highlight key challenges, and inform future directions in the integration of DDCPs within precision medicine frameworks.

RESULTS

This qualitative review integrated findings from 67 peer-reviewed studies published from 2015 to 2024. The articles were retrieved using targeted search strategies across databases such as PubMed, Scopus, Web of Science, and ScienceDirect, employing Boolean operators with terms like "drug-device combination," "precision medicine," "digital therapeutics," and "individualised therapy" [41]. Analysis was conducted through thematic coding and comparative synthesis to identify recurring trends, key enablers, and systemic barriers in the deployment of Drug-Device Combination Products (DDCPs) for precision care.

1. Integration of Smart Technology and Targeted Therapeutics

The literature strongly supports the role of smart drug-device integrations in enhancing therapeutic precision. A systematic review covering 45 clinical trials found that smart insulin pens with Bluetooth connectivity improved patient compliance by 26% and reduced hypoglycemic episodes by 31% [42]. Similarly, digitally enabled asthma inhalers decreased rescue inhaler use by 34% and improved asthma control test scores by 18% over six months in a randomised trial involving 1,200 patients [43].

In oncology, implantable micro-reservoirs capable of on-demand drug release triggered by pH or temperature cues have been shown to reduce tumour relapse rates by up to 40% compared to standard infusion therapies [44]. These devices, such as the Daré ADVA implant, provide continuous release of anticancer agents over several months, improving patient quality of life and lowering treatment burden [45].

2. Role in Chronic Disease Management and Disease-Specific Customisation

Drug-device integration is especially impactful in chronic disease contexts. In cardiovascular medicine, bioresorbable vascular scaffolds (BVS) that deliver antiproliferative agents like everolimus demonstrate similar efficacy to metal stents but reduce long-term restenosis risks by up to 27% in post-marketing surveillance data [46]. In diabetes, closed-loop insulin delivery systems, often referred to as artificial pancreas, keep blood glucose levels within the target range 72% of the time, compared to 54% with conventional insulin pump therapy [47].

Emerging devices for neurodegenerative diseases, such as deep brain stimulation (DBS) systems with programmable drug reservoirs, offer dual benefit by combining neuromodulation with localised delivery of neuroprotective agents. A multicenter trial (n = 950) reported a 35% delay in Parkinson's disease progression in patients using these hybrid systems [48].

3. Data-Driven Personalisation and AI-Enhanced Feedback Systems

An increasing amount of research is centred on the integration of DDCPs with AI and real-time data analysis. Devices integrated with biosensors and AI algorithms, such as smart cardiac patches, can detect arrhythmias and autonomously adjust medication dosage via subcutaneous micro-pumps [49]. These feedback loops have been shown to reduce hospital readmissions for atrial fibrillation by 21% in a cohort study of 3,400 patients [50].

Moreover, in diabetes management, AI-enabled insulin calculators embedded in smart pens reduced human calculation errors by 87%, improving time-in-range metrics by 28% and minimising long-term complications [51]. The integration of such devices with electronic health records (EHRs) further enhances physician oversight and facilitates real-time therapeutic adjustments [52].

4. Regulatory Pathways and Classification Dilemmas

Despite technical progress, the literature documents persistent regulatory inconsistencies. For instance, while the U.S. FDA classifies most DDCPs as combination products under 21 CFR Part 3, the European Union often requires separate market authorisation for drug and device components [53]. This misalignment prolongs approval timelines by an average of 12–18 months, increasing development costs by up to 40% [54]. The lack of harmonised post-market surveillance requirements further complicates global deployment.

Several scholars call for the creation of international DDCP regulatory frameworks, particularly for AI-enabled products, which often lack predefined validation protocols for software-as-a-medical-device (SaMD) functions [55].

5. Economic Impact and Health Technology Assessment

Economic evaluations suggest that DDCPs may offer long-term cost advantages despite higher upfront prices. A cost-utility analysis in the UK health system estimated that smart inhalers produced an incremental cost-effectiveness ratio (ICER) of £4,800/QALY—well below the NICE threshold of £20,000 [56]. Similarly, digital chemotherapy pumps reduced hospitalisation days by 2.6 on average, saving approximately $6,100 per patient annually [57].

Yet, access remains unequal. In low- and middle-income countries (LMICs), 82% of reviewed studies reported limited adoption due to infrastructure gaps, weak reimbursement policies, and lack of clinician training [58]. These disparities underscore the need for scalable, low-cost DDCP models adapted to LMIC contexts.

6. Ethical Considerations and Equity in Implementation

Concerns about data security, informed consent, and algorithmic bias are prominent in recent literature. For example, a 2023 review reported that 70% of AI-enabled DDCPs do not offer patients transparency on how their health data are used or stored [59]. Additionally, models trained on non-representative datasets risk exacerbating health disparities, particularly for marginalised populations with different physiological baselines or limited digital literacy.

7. Innovation Trajectories and Research Gaps

The field is rapidly evolving, with next-gen DDCPs incorporating nanotechnology, smart polymers, and bioelectronic interfaces. For example, 3D-printed drug-device systems capable of controlled-release profiles customised to individual pharmacogenomic profiles are in preclinical development [60]. However, major research gaps include the lack of long-term clinical data, underrepresentation of pediatric and geriatric populations, and limited studies on device usability in real-world environments.

The synthesis of current evidence demonstrates that Drug-Device Combination Products (DDCPs) are not only technologically feasible but also clinically impactful in advancing individualised care. Their integration with AI, smart sensors, and cloud-based analytics creates a robust ecosystem for adaptive, patient-specific therapy. However, systemic challenges—particularly in regulatory standardisation, ethical safeguards, and equitable deployment—must be addressed. A coordinated, multi-stakeholder effort is required to ensure these innovations translate into inclusive, globally scalable solutions that fulfil the promise of precision medicine.

DISCUSSION

The integration of Drug-Device Combination Products (DDCPs) into precision medicine represents a significant shift toward more personalised therapeutic strategies. This qualitative review has highlighted that the combination of advanced drug delivery technologies with patient-specific therapeutic approaches enhances treatment efficacy, improves patient compliance, and offers adaptive solutions for chronic and complex diseases. By analysing data from 67 peer-reviewed articles, this study confirms that DDCPs have emerged as a cornerstone in the evolution of individualised care, demonstrating both promise and challenges.

The role of smart technologies in DDCPs, such as smart insulin pens, digital inhalers, and implantable drug delivery systems, has been consistently emphasised in the literature. These devices are particularly transformative in chronic disease management, where the precision of medication administration is crucial. For instance, smart insulin pens equipped with Bluetooth connectivity have demonstrated a 26% increase in patient adherence, while also improving glycemic control by 31% in Type 1 and Type 2 diabetic populations [61]. Such advancements illustrate how DDCPs provide real-time data monitoring, enabling dynamic adjustments to therapy based on the physiological needs of patients [62]. Similarly, in asthma management, digital inhalers have been shown to reduce the frequency of emergency inhaler use by 34%, contributing to overall better disease control [63].

However, the integration of AI and real-time feedback systems into DDCPs presents both an opportunity and a challenge. The ability of devices to adjust drug delivery based on data from biosensors or AI algorithms holds considerable potential. In the case of cardiovascular diseases, AI-enabled smart patches can autonomously detect arrhythmias and adjust medication doses accordingly, reducing hospital readmissions by 21% [64]. However, widespread adoption of such systems is hindered by regulatory hurdles, including the lack of standardised guidelines for AI in medical devices and discrepancies in regulatory frameworks across regions [65], [66]. These barriers slow the approval process and may limit

the ability of patients to benefit from these innovations promptly.

One of the most significant findings from this review is the regulatory and economic challenges surrounding the development and deployment of DDCPs. As DDCPs are hybrid products that combine pharmaceuticals with medical devices, they often face complex approval pathways. Regulatory bodies, such as the FDA and EMA, have differing requirements for the classification, testing, and approval of these products [67], [68]. In addition, the high upfront development costs, extended timelines for regulatory clearance, and uncertain reimbursement policies are major obstacles to their commercialisation. The studies reviewed indicated that the costs associated with DDCPs could increase by as much as 40% due to the need for dual-component testing and certification [69], [70]. Furthermore, the economic viability of DDCPs is questionable in low- and middle-income countries (LMICs), where healthcare infrastructure and patient access are often limited [71], [72]. These challenges underscore the need for more efficient regulatory processes and innovative solutions for financing and reimbursement.

Ethical concerns also emerge prominently in the literature, particularly around data privacy, informed consent, and equity in access to these advanced therapeutic technologies. With the integration of digital health platforms, DDCPs generate large volumes of patient-specific data, raising concerns about the security of this information and its potential misuse [73], [74]. Furthermore, studies have shown that algorithmic bias in AI-powered DDCPs could exacerbate health disparities, particularly in underserved or underrepresented populations [75], [76]. These ethical considerations highlight the need for robust frameworks to ensure that DDCPs are deployed in ways that are equitable and just, particularly in settings where technological infrastructure is limited.

The findings also point to the growing importance of collaborative innovation in advancing DDCPs. The development of next-generation DDCPs requires a multidisciplinary approach that includes collaboration between pharmaceutical companies, medical device manufacturers, regulatory bodies, and healthcare providers. Researchers have emphasised the need for open data sharing and collaboration between stakeholders to accelerate the development of more effective and accessible DDCPs [77], [78]. This includes the incorporation of patient feedback into the design and testing of these products to ensure that they meet the real-world needs of diverse patient populations [79], [80].

In conclusion, while DDCPs have the potential to revolutionise personalised medicine, their widespread implementation faces significant hurdles. The technological advances in drug-device integration, alongside AI-driven feedback systems, are clearly beneficial in improving therapeutic outcomes. However, challenges related to regulatory approvals, economic accessibility, and ethical concerns need to be addressed to maximise their impact. Future research should focus on harmonising regulatory frameworks, exploring cost-effective solutions for low-income settings, and ensuring patient-centred care in the development and deployment of these products. By addressing these gaps, the field of precision medicine can move closer to realising the full potential of DDCPs in personalised care.

In future studies, it is essential to focus on long-term clinical trials that evaluate the safety, efficacy, and cost-effectiveness of DDCPs in diverse populations. Additionally, research into AI and machine learning algorithms for drug-device synergy could further improve the precision of these products. Collaborations between regulatory authorities and industry stakeholders will be critical in developing globally accepted guidelines for the approval and use of DDCPs. Addressing these issues will ensure that personalised medicine is accessible, affordable, and ethically sound, ultimately benefiting patients across the globe.

CONCLUSION

The integration of Drug-Device Combination Products (DDCPs) into the framework of precision medicine has significantly advanced individualised therapy by offering synergistic benefits in terms of treatment effectiveness, patient adherence, and real-time therapeutic adaptability. Through a comprehensive analysis of 67 peer-reviewed sources, this review confirms that DDCPs—ranging from smart insulin pens to AI-powered implantable systems—demonstrate substantial potential to improve clinical outcomes in managing chronic and complex conditions.

The technological sophistication of these products facilitates dynamic dosing, remote monitoring, and improved disease control. For example, digital inhalers and AI-integrated smart patches have shown measurable reductions in emergency events and hospital readmissions, reinforcing the clinical value of digital-augmented therapeutics. Despite these innovations, critical barriers such as fragmented regulatory standards, economic constraints, and data privacy risks continue to limit their scalability and accessibility, particularly in low- and middle-income countries.

This review also underscores the ethical urgency to address algorithmic biases and unequal access, ensuring these technologies do not inadvertently widen health disparities. Moreover, the development of DDCPs demands robust, cross-sectoral collaboration, including transparent regulatory frameworks, inclusive product design, and sustainable financing models. Strengthening these areas is vital to bridging the gap between technological advancement and equitable healthcare delivery.

Future investigations should expand on these findings by evaluating DDCPs through longitudinal clinical validation, focusing on real-world effectiveness, cost-efficiency, and AI integration safety. Establishing harmonised global regulatory pathways and fostering inclusive innovation ecosystems will

be essential in actualising the full promise of DDCPs in precision medicine.

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