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Nanomedicine-Based Drug Delivery and Rehabilitation Framework for Pancreatic Cancer: A Conceptual Research Prototype

Sidra Sabir[1], AHM Mahmudur Rahman[2,*], KM Mahfuzur Rahman[3], Abdul Haseeb Bhutta[4]

[1] Centre for Physiotherapy Studies, Department of Physiotherapy, Faculty of Health Sciences, Universiti Teknologi MARA Selangor Branch, 42300 Puncak Alam, Selangor, Malaysia
[2] Department of Pure and Applied Chemistry, Faculty of Sciences, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
[3] Department of Mechanical and Production Engineering, Ahsanullah University of Science and Technology, Dhaka 1208, Bangladesh
[4] Department of Physical Therapy, Ibadat International University Islamabad, Islamabad, Pakistan

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ABSTRACT

Pancreatic cancer remains one of the most fatal malignancies, with poor prognosis and limited therapeutic options. This study proposes an innovative approach that integrates nanomedicine with a multidisciplinary framework to address the critical challenges of treatment and recovery. By leveraging the expertise of pharmacists, mechanical engineers and physiotherapists, this study outlines a precision-based nanomedicine delivery system combined with personalized rehabilitation protocols. This comprehensive framework aims to enhances drug encapsulation, optimize release kinetics, improve tumour targeting and support post-treatment recovery. Detailed methodologies, anticipated results and a roadmap for clinical implementation are presented, offering a transformative approach to pancreatic cancer care.

1. Introduction

Pancreatic cancer is a difficult challenge in oncology, with a five-year survival rate of less than 10% [1]. This dismal prognosis is attributed to late diagnosis, rapid disease progression and limited efficacy of existing therapies, such as chemotherapy, surgery and radiation [2]. These conventional treatments are often accompanied by severe systemic toxicities and high therapeutic resistance rates, necessitating the exploration of novel strategies. Nanomedicine is a cutting-edge field that leverages nanotechnology for medical applications and offers a beacon of hope. The unique physicochemical properties of nanoparticles, including their size, surface functionality and drug-loading capacity, enable precise tumour targeting while reducing off-target effects. Recent studies have demonstrated the potential of nanomedicine in improving therapeutic outcomes for various cancers; however, its application in pancreatic cancer therapy remains underexplored [3]. A comparative analysis revealed the limitations of current nanomedicine approaches, such as suboptimal drug encapsulation efficiency and poor release kinetics. These challenges underline the

* *Corresponding author.*
E-mail address: ahm.rahman@strath.ac.uk

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need for a more comprehensive framework that integrates advanced nanomedicine with patient-centred rehabilitation strategies. While different traditional approaches focus solely on tumour eradication, there is a strong need for a holistic model that addresses both treatment efficacy and patient recovery [3].

This research aims to design a smart nanomedicine delivery system that combines multidisciplinary expertise. Pharmacists will focus on optimizing drug formulations, mechanical engineers will develop precision delivery devices and physiotherapists will create individualized rehabilitation protocols to revolutionize pancreatic cancer therapy by enhancing treatment outcomes and improving patients' quality of life.

2. Methodology

The methodological framework of this study integrates three essential components: development of nanomedicine formulations, design of a microfluidic delivery device and creation of rehabilitation protocols:

i. The first phase involves the synthesis of nanoparticles using a bottom-up approach to ensure high drug-loading capacity and targeted delivery. These nanoparticles are fabricated using biocompatible materials like PLGA (poly (lactic-co-glycolic acid)) and lipids to encapsulate chemotherapeutic agents. The synthesis process is meticulously optimized to produce nanoparticles with an average size of 100-150 nm, encapsulation efficiency of 70-80% and a biphasic release profile to maintain drug availability over extended periods. Surface modifications, including ligand functionalization enhance tumour-specific targeting and minimize off-target effects.
ii. In the second phase, a microfluidic-based delivery device is engineered to precisely administer the nanoparticles. This device is developed using biocompatible materials such as PDMS (polydimethylsiloxane) and incorporates computational fluid dynamics simulations to optimize drug release. Prototyping and iterative testing ensure the device's ability to deliver nanoparticles consistently at controlled flow rates. By mimicking clinical scenarios, the device can be fine-tuned to achieve high targeting efficiency and scalability for broader clinical applications.
iii. The third phase focuses on the design of rehabilitation protocols to support patients during and after treatment. These protocols address the physical, nutritional and psychological needs of patients undergoing pancreatic cancer therapy. A combination of targeted physical therapy, nutritional interventions and psychosocial support is tailored to individual patient profiles, with an emphasis on reducing treatment-related fatigue and enhancing overall well-being. Outcome measures such as the Functional Assessment of Cancer Therapy (FACT) scale and Visual Analogue Scale (VAS) to assess pain are used to evaluate the effectiveness of these interventions.

The incorporation of multidisciplinary expertise is pivotal in advancing innovative healthcare solutions, with pharmacists, mechanical engineers and physiotherapists collaboratively contributing their specialized knowledge to improve patient care and therapeutic outcomes [5]. The roles of Multidisciplinary experts are as follows:

i. Pharmacists: Design and optimize nanomedicine formulations, focusing on stability, pharmacokinetics and therapeutic efficacy.
ii. Mechanical Engineers: Develop and refine the microfluidic delivery device to ensure precision, scalability and ease of clinical use.
iii. Physiotherapists: Create personalized rehabilitation protocols, addressing pain, fatigue, physical activity level, muscle strength, functional recovery, mental well-being and long-term health outcomes.

3. Results

The proposed smart nanomedicine delivery system for pancreatic cancer therapy addresses the key challenges in drug delivery, targeting and post-treatment rehabilitation. The expected outcomes from this prototype system will be based on the successful formulation of nanoparticles, their efficient release profiles, the performance of the microfluidic delivery device and the anticipated impact of rehabilitation protocols on patients.

3.1 Nanoparticle Characteristics

The nanoparticles will be specifically designed to optimize drug encapsulation, stability and targeting efficacy. It is anticipated that the nanoparticles will exhibit the specific characteristics listed in the Table 1.

Table 1
Anticipated nanoparticle characteristics

Parameter	Expected Value
Particle Size	100-150 nm
Drug Load Capacity	10-30%
Zeta Potential	-25 mV
Surface Charge	Negative
Release Kinetics	Biphasic, sustained release
Drug Encapsulation Efficiency	50-70%

The nanoparticle design will ensure maximum stability and biocompatibility, which are critical for safe clinical applications. A sustained release profile will be established to ensure continuous drug delivery over an extended period, potentially improving therapeutic outcomes by maintaining consistent drug levels in the tumour microenvironment [4].

3.2 In Vitro Drug Release Profile

The in vitro drug release of the nanoparticles follows a typical biphasic release pattern. Initially, a small burst release is expected, followed by a sustained, slower release of the drug over a 24-48 hours period [5]. This pattern ensures that the most drug is available to target tumour cells in the early and late stages of therapy. The released kinetics will be tested under controlled conditions using pancreatic cancer cell lines, to refine the release parameters for optimal therapeutic effectiveness [6].

3.3 Microfluidic Device Performance

The microfluidic delivery device will be engineered to offer precise control over drug release, ensuring that nanoparticles are delivered to the tumour site in a controlled and efficient manner. The device will be tested at different flow rates to ensure that it mimics clinical conditions, with the goal of achieving predictable and consistent drug release. The device's performance will be evaluated by measuring the release rates of nanoparticles at varying flow rates, ensuring that the device is both effective and scalable for clinical use [7].

3.4 Feasibility of the Rehabilitation Protocol

The rehabilitation component of the system will be crucial for patient's post-treatment recovery. Based on existing data, it is expected that tailored physiotherapy protocols will improve patient strength and physical activity level, reduce pain and enhance treatment outcomes. Moreover, these protocols will focus on reducing cancer-related fatigue and improving physical function, helping patients recover from the physical toll of cancer therapy and enhancing their overall quality of life.

4. Discussion

The integration of nanomedicine with tailored rehabilitation protocols represents a ground-breaking approach to the treatment of pancreatic cancer, a disease that continues to pose significant challenges due to its aggressive nature, poor prognosis and limited therapeutic options [8]. Traditional treatments, including chemotherapy, surgery and radiation, often have severe side effects and are limitedly effective, particularly in advanced stages of the disease. These treatments are associated with significant systemic toxicities and often fail to provide long-term relief, making the need for innovative solutions more urgent [7]. Nanomedicine has emerged as a promising field in oncology because of its unique ability to enhance drug delivery, improve bioavailability and reduce off-target effects. The distinct physicochemical properties of nanoparticles (such as their size, surface functionality and drug-loading capacity) allow them to navigate biological barriers and precisely target tumour cells. The potential of nanomedicine in improving therapeutic outcomes has been demonstrated in various cancers, but its application in pancreatic cancer remains underexplored [9]. One of the primary challenges in pancreatic cancer treatment is the dense tumour stroma, which limits the penetration of therapeutic agents. As a result, many current nanomedicine strategies fail to effectively deliver drugs to tumour sites. Some previous studies have demonstrated that nanoparticles can overcome some of these barriers by enhancing drug solubility and enabling targeted drug delivery, thus reducing the toxic effects on healthy tissue. However, despite these advances, pancreatic tumours remain particularly difficult to target and many nanoparticle formulations still struggle with low drug encapsulation efficiency and suboptimal release kinetics. In this context, the approach proposed in this study aims to address these challenges by designing a nanoparticle formulation that offers high drug encapsulation efficiency, a biphasic release profile and targeted tumour delivery. The characteristics of nanoparticles, including particle size, surface charge and encapsulation efficiency, are carefully optimized to ensure that the drug is delivered effectively to the tumour site, thereby enhancing therapeutic outcomes [9]. By adopting a surface modification strategy, such as ligand functionalization, these nanoparticles can specifically target pancreatic cancer cells, improving the precision of drug delivery. This approach has shown promise in other types of cancer, as evidenced by a few studies, in which folate-targeted nanoparticles demonstrated better drug delivery to tumours. Similarly, a few studies highlighted the success of biphasic release

profiles in nanoparticles, ensuring sustained drug availability over extended periods and ultimately improving therapeutic outcomes. These strategies form the core of our approach to overcome the limitations of conventional cancer treatments [8].

In addition to the innovative nanomedicine component, the rehabilitation protocols integrated into this study constitute an essential part of the proposed treatment framework. Chemotherapy and radiation therapies are known to induce significant physical and psychological side effects, including pain, fatigue, muscle wasting and emotional distress [10]. These adverse effects often reduce patients' quality of life and hinder their ability to adhere to treatment regimens. Rehabilitation strategies, such as physical therapy, nutritional support and psychosocial interventions, are crucial for improving the overall well-being of patients. Previous studies also have demonstrated that tailored rehabilitation programs can significantly reduce pain and fatigue and enhance physical strength among patients with cancer. By addressing these needs, the rehabilitation component of this study aims to improve patient outcomes and support recovery during and after treatment. To sum up, incorporating multidisciplinary expertise into the development of this system will be crucial to its success. Pharmacists, mechanical engineers and physiotherapists will each contribute specialized knowledge to ensure that both nanomedicine formulations and rehabilitation protocols are optimized for clinical use. Pharmacists will focus on developing and optimizing the drug formulations to ensure their stability, pharmacokinetics and overall therapeutic efficacy [8]. Mechanical engineers will design and refine the microfluidic delivery device, ensuring that it can administer the nanoparticles with precision and efficiency. Physiotherapists will create individualized rehabilitation protocols to mitigate the side effects of treatment and enhance patients' overall recovery. However, despite the potential of this integrated approach, several challenges remain. The complexity of developing stable and effective nanomedicine formulations and the need for scalable production processes are significant challenges [11]. Additionally, regulatory approvals for both drug formulations and microfluidic delivery device will require substantial investment in clinical trials and rigorous testing [12]. Ensuring the scalability of the system, while maintaining cost-effectiveness and clinical feasibility, will be another critical challenge. Addressing these challenges requires continued research, collaboration and development in both the nanomedicine and rehabilitation fields [8]. Ultimately, the integration of nanomedicine and personalized rehabilitation represents a holistic approach to the treatment of pancreatic cancer. By combining precise drug delivery with tailored recovery strategies, this framework aims to improve treatment outcomes, reduce side effects and enhance patients' quality of life [13]. The multidisciplinary collaboration at the heart of this study will offer a comprehensive solution to the multifaceted challenges of pancreatic cancer therapy, providing a strong foundation for future clinical applications and research.

5. Future Research and Clinical Implementation

Although the proposed nanomedicine delivery system offers a promising approach for the treatment of pancreatic cancer, several avenues for future research remain [14]. A key area for future investigation is the optimization of nanoparticles formulations to enhance their stability, drug-loading capacity and targeting efficiency. While the initial design of nanoparticles in this study aims to address some of the existing limitations, further exploration into different types of nanoparticle materials, surface modifications and drug combinations will be essential to enhance the system’s overall performance. For example, new materials such as lipid-polymer hybrid nanoparticles or advanced mesoporous silica nanoparticles could offer greater drug-loading capacity and more stable formulations, which could improve therapeutic outcomes [8]. Moreover, the development of novel techniques for the large-scale production of nanoparticles will be critical for the clinical translation

of this approach. The manufacturing process must be scalable, reproducible and cost-effective, which requires overcoming significant technical challenges. Additionally, the formulation should be adaptable to a wide range of chemotherapeutic agents, allowing for its application across different types of cancers, not just pancreatic cancer.

In terms of clinical implementation, the integration of nanomedicine systems into current treatment regimens will require rigorous clinical trials to assess the safety, efficacy and overall impact on patient outcomes. These trials should not only evaluate the therapeutic efficacy of the nanoparticles but also measure the effectiveness of rehabilitation protocols in improving quality of life and reducing treatment-related side effects. Given the complexity of the proposed system, clinical trials must be conducted in phases, starting with preclinical models and advancing to human trials as data on safety and efficacy become available [5]. Furthermore, the clinical implementation of this system will require close collaboration with regulatory agencies to ensure that both the nanoparticles and microfluidic delivery device meet the required safety and efficacy standards. These regulatory hurdles are often one of the most significant barriers to the clinical translation of innovative therapies and navigating them requires careful planning and strategic partnerships with regulatory bodies [9].

Another key consideration for future research is exploring the personalized medicine approaches. By using advanced diagnostic techniques, such as molecular profiling and liquid biopsy, we can identify specific biomarkers that predict the response of individual patients to nanomedicine treatments. This will allow for the development of truly personalized treatment plans that optimize the therapeutic outcomes of the nanomedicine system. Additionally, research into patient-specific factors, such as genetic predispositions or comorbid conditions, could further refine rehabilitation protocols to ensure they are tailored to each patient's unique needs [15]. Ultimately, the goal of this research is not only to improve the therapeutic outcomes for patients with pancreatic cancer and to provide a model that can be extended to other types of cancers. The interdisciplinary nature of this approach, which combines nanomedicine with personalized rehabilitation, provides a novel framework that could transform cancer care, offering more effective, less toxic treatments and improving patients' quality of life.

6. Conclusion

This study proposes a ground-breaking, interdisciplinary approach to the treatment of pancreatic cancer, integrating cutting-edge nanomedicine technology with evidence-based rehabilitation strategies. The development of a smart nanomedicine delivery system offers a new path for improving the effectiveness of cancer treatment while supporting patient recovery and quality of life. This integrated approach, combining the expertise of pharmacists, mechanical engineers and physiotherapists, provides a comprehensive solution to the complex challenges of pancreatic cancer care. The proposed system provides a strong foundation for future research and clinical translation, potentially transforming the treatment landscape of this aggressive cancer.

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