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Stem cell-based cancer therapy: A precision oncology paradigm

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ABSTRACT

Stem cell-based approaches have emerged as a promising direction in cancer therapy by combining targeted treatment strategies with regenerative potential. Conventional cancer treatments, including chemotherapy, radiation, and surgery, often lack specificity and may result in significant toxicity, treatment resistance, and disease recurrence. In contrast, stem cells offer unique advantages such as self-renewal, differentiation capacity, and tumor-targeting ability, enabling both direct therapeutic applications and support for tissue repair and immune recovery. This review provides a comprehensive overview of stem cell biology and its relevance to cancer therapy, including key applications such as hematopoietic stem cell transplantation and mesenchymal stem cell-mediated drug delivery. It also examines the dual role of stem cells in cancer, highlighting both their therapeutic potential and associated risks, including tumor promotion and immune-related complications. Furthermore, the review discusses recent advances in engineered stem cell systems for gene and drug delivery in oncology. A key focus of this article is the integration of artificial intelligence and machine learning in optimizing stem cell-based therapies. These computational approaches enable improved cell characterization, treatment personalization, and prediction of therapeutic outcomes using multi-dimensional biological and clinical data. The convergence of stem cell biology with data-driven technologies is accelerating the development of more precise and effective cancer treatments. Despite ongoing challenges related to safety, ethical considerations, and regulatory constraints, stem cell-based therapies represent a rapidly evolving field with significant clinical potential. Continued interdisciplinary research integrating biotechnology and computational methods is expected to play a critical role in advancing personalized and durable cancer treatment strategies.

KEYWORDS

Stem Cell Biology, Cancer Therapy, AI/ML Models, Precision Oncology

HOW TO CITE THIS ARTICLE

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Cancer remains one of the leading causes of mortality worldwide (Chu *et al*., 2024), despite significant advances in its diagnosis and treatment. It is characterized by the uncontrolled growth and division of abnormal cells, leading to the formation of tumors. These malignant cells can spread from their original site to other parts of the body through a process known as metastasis, which significantly complicates treatment and reduces survival rates. Conventional therapeutic approaches, including surgery, chemotherapy, and radiation therapy, primarily aim to eliminate cancer cells.

However, these methods often lack specificity and may damage healthy tissues, resulting in adverse effects such as fatigue, organ toxicity, immune suppression, and an overall decline in quality of life. Moreover, many cancers develop resistance to treatment or recur after remission, emphasizing the need for more targeted and sustainable therapeutic strategies. In recent decades, there has been growing interest in biological approaches that not only target cancer cells but also promote tissue repair and recovery.

Among these, stem cell-based therapy has emerged as a promising area of research. Stem cells are undifferentiated cells with the unique ability to self-renew and differentiate into multiple specialized cell types. Unlike fully differentiated cells with fixed functions, stem cells possess developmental flexibility, allowing them to contribute to tissue regeneration and repair. This distinctive capability has positioned them as valuable tools in regenerative medicine and cancer therapy. Stem cells play a multifaceted role in cancer treatment. One of the most established applications is hematopoietic stem cell transplantation (HSCT), commonly referred to as bone marrow transplantation, which is widely used in the treatment of hematological malignancies such as leukemia and lymphoma (Chu *et al*., 2024).

In this procedure, damaged or diseased bone marrow is replaced with healthy stem cells capable of restoring normal blood and immune system function. While this approach has significantly improved patient outcomes, it is associated with risks such as infection, graft-versus-host disease, and high treatment costs. Additionally, other stem cell types, particularly mesenchymal stem cells (MSCs), have demonstrated the ability to migrate toward tumor sites, modulate immune responses, and serve as carriers for targeted drug delivery (Silva *et al*., 2025). Furthermore, increasing attention is being directed toward cancer stem cells, a subpopulation of tumor cells believed to contribute to tumor initiation, progression, and resistance to therapy.

This review article, titled 'Stem cell-based cancer therapy: A precision oncology paradigm" aims to provide a clear and structured overview of the field for readers without a formal background in biology. It discusses the fundamental properties of stem cells, their role in cancer development and treatment, and the associated advantages and challenges. In addition, the review highlights the growing role of data science and computational techniques, including artificial intelligence and machine learning, in optimizing stem cell-based therapies and enabling personalized treatment strategies. By integrating biological insights with accessible explanations, this article seeks to present stem cell therapy as both a scientifically significant and clinically relevant advancement in modern oncology (fig 1).

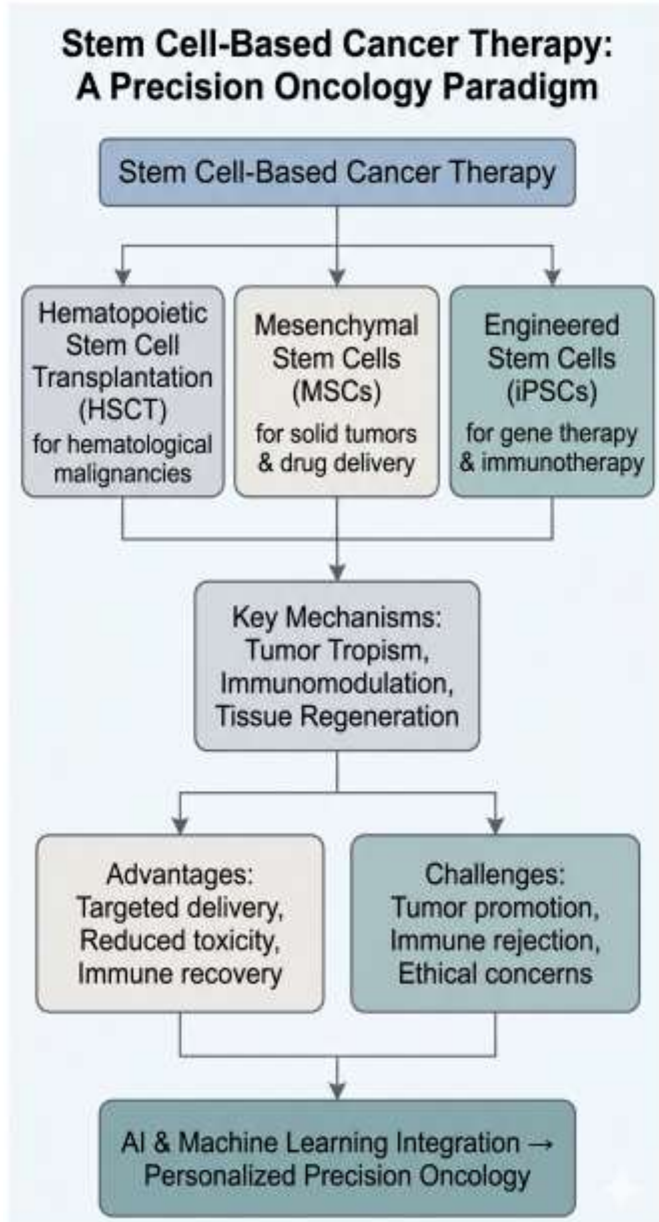

Fig1. Stem Cell - Based Cancer Therapy: A Precision Oncology Paradism

Fig 1 schematic overview of stem cell-based cancer therapy strategies. The diagram illustrates three major therapeutic approaches: hematopoietic stem cell transplantation (HSCT) for hematological malignancies, mesenchymal stem cells (MSCs) for solid tumors and targeted drug delivery, and engineered stem cells (iPSCs) for gene and immunotherapy. Key mechanisms include tumor tropism, immunomodulation, and tissue regeneration. Advantages and challenges are summarized, with artificial intelligence integration enabling personalized precision oncology.

Types and Properties of Stem Cells

Stem cells represent a unique class of cells distinguished by their ability to both self-renew and differentiate into specialized cell types. These properties make them fundamental to biological development, tissue maintenance, and regenerative medicine (Patel *et al*., 2019). Broadly, stem cells are categorized into three major types: embryonic stem cells, adult (somatic) stem cells, and induced pluripotent stem cells, each differing in origin, differentiation capacity, and therapeutic potential.
A defining characteristic of stem cells is self-renewal, the process by which they divide to produce at least one daughter cell that retains stem cell identity. This ensures the long-term maintenance of the stem cell pool within tissues. Another essential property is differentiation, which refers to the ability of stem cells to develop into specialized cell types such as neurons, blood cells, muscle cells, or bone cells.

The extent of this differentiation capacity is described as potency, indicating the range of cell types a stem cell can generate. Embryonic stem cells (ESCs) are derived from the inner cell mass of early-stage embryos, typically at the blastocyst stage. These cells are pluripotent (Chu *et al*., 2024), meaning they have the capacity to differentiate into nearly all cell types of the adult body, excluding extra-embryonic tissues such as the placenta. Due to their extensive differentiation potential, ESCs serve as powerful tools for studying early developmental processes and generating specialized cells in vitro. However, their application is associated with ethical concerns related to embryo use, as well as technical challenges in controlling differentiation and preventing uncontrolled proliferation. Adult or somatic stem cells are present in various tissues of the mature body, including bone marrow, skin, brain, and gastrointestinal tract. These cells are generally multipotent or unipotent, indicating a more restricted differentiation capacity compared to embryonic stem cells. For instance, hematopoietic stem cells give rise to diverse blood and immune cells, whereas mesenchymal stem cells can differentiate into bone, cartilage, and adipose tissue. Adult stem cells play a crucial role in tissue homeostasis by replacing damaged or aging cells within their respective organs.

Induced pluripotent stem cells (iPSCs) are generated by reprogramming differentiated adult cells, such as skin fibroblasts or blood cells, into a pluripotent state. Similar to embryonic stem cells, iPSCs possess the ability to differentiate into a wide range of cell types. A significant advantage of iPSCs is their potential for patient-specific applications (Kim *et al*., 2020), as they can be derived from an individual′s own cells, thereby reducing the risk of immune rejection. However, challenges remain, including ensuring genetic stability during reprogramming and minimizing the risk of abnormal cell growth. In summary, stem cells can be classified into embryonic, adult, and induced pluripotent types, each with distinct biological characteristics and clinical relevance. Despite these differences, all stem cells share the fundamental abilities of self-renewal and differentiation, which underpin their importance in both basic research and the development of innovative therapeutic strategies, including cancer treatment.

Overview of Conventional Cancer Therapies

Cancer treatment has traditionally relied on three primary modalities: surgery, chemotherapy, and radiation therapy (Silva *et al*., 2025). These approaches are used individually or in combination, depending on the type, stage, and location of the malignancy. Their primary objective is to eliminate cancer cells and reduce the likelihood of disease recurrence. However, despite their widespread use, each modality is associated with significant limitations, including damage to healthy tissues, adverse side effects, and the potential development of treatment resistance. Surgery is one of the most established and direct methods of cancer treatment. It involves the physical removal of the tumor, often along with surrounding tissues or lymph nodes to limit the spread of malignant cells. Surgical intervention is most effective in cases where the tumor is localized and has not metastasized to distant organs. In early-stage cancers, such as certain breast, colorectal, and skin cancers, surgery can be curative. Nevertheless, complete removal of all cancerous cells is not always achievable, and residual microscopic disease may lead to recurrence. Additionally, surgical procedures carry inherent risks, including infection, bleeding, and extended recovery periods, and may not be feasible for tumors located in critical or inaccessible regions.

Chemotherapy involves the use of cytotoxic drugs that circulate through the bloodstream to target rapidly dividing cells (Choudhury *et al*., 2025). These agents typically act by damaging DNA or disrupting cellular processes essential for cell division. Chemotherapy is particularly useful in treating metastatic cancers or those with a high risk of systemic spread. It may be administered prior to surgery (neoadjuvant therapy) to reduce tumor size, after surgery (adjuvant therapy) to eliminate residual disease, or as a primary treatment modality. However, chemotherapy lacks specificity, affecting not only cancer cells but also healthy rapidly dividing cells, such as those in the bone marrow, gastrointestinal tract, and hair follicles. This results in common side effects, including fatigue, nausea, hair loss, anemia, and increased susceptibility to infections. Furthermore, the emergence of drug resistance in cancer cells remains a major challenge, often leading to reduced therapeutic effectiveness over time.

Radiation therapy utilizes high-energy radiation to induce DNA damage in cancer cells, thereby inhibiting their ability to grow and divide. It can be delivered externally through targeted beams (external-beam radiation) or internally via radioactive materials placed near or within the tumor (brachytherapy). Radiation therapy is commonly employed for localized tumors and for palliative purposes, such as alleviating pain or controlling bleeding. While it offers greater spatial precision compared to chemotherapy, surrounding healthy tissues may still be affected, leading to side effects such as skin irritation, fatigue, and organ-specific complications. Similar to chemotherapy, certain tumors exhibit radiation resistance, often due to enhanced DNA repairs mechanisms or hypoxic conditions within the tumor microenvironment, which reduce the effectiveness of radiation. In summary, surgery, chemotherapy, and radiation therapy constitute the foundational approaches in cancer management, each offering distinct advantages. Surgery enables the direct removal of tumors, chemotherapy provides systemic treatment, and radiation therapy delivers localized control. However, their limitations particularly non-specific toxicity, side effects, and the development of resistance highlight the need for more targeted and effective treatment strategies.

These challenges have driven the development of advanced approaches, including targeted therapies, immunotherapy, and stem cell-based interventions, which aim to improve treatment precision and long-term outcomes.

Role of Stem Cells in Cancer Therapy

Stem cells are increasingly recognized not only as subjects of investigation in cancer biology but also as active agents in cancer therapy (Chu *et al*., 2024). One of their most significant properties is their ability to migrate toward tumor sites, a phenomenon known as tumor tropism. Various stem cell types, particularly mesenchymal stem cells (MSCs) and certain neural or embryonic-like stem cells, can respond to signals released by tumors, including inflammatory cytokines, growth factors, and chemokines. This directed migration enables stem cells to function as natural delivery systems, transporting therapeutic agents directly into the tumor microenvironment, where conventional drugs may have limited penetration. As a result, stem cell-based approaches have the potential to enhance drug concentration at the tumor site while minimizing systemic toxicity. In addition to their targeting capability, stem cells contribute to cancer therapy through both direct therapeutic effects and supportive roles in tissue repair and recovery. In their direct role, stem cells can be genetically engineered to produce anticancer agents such as cytotoxic proteins, suicide genes, or immune-stimulating cytokines.

For instance, MSCs have been utilized to deliver oncolytic viruses or tumor-suppressing genes, which are released within the tumor microenvironment to induce localized cancer cell death (Silva *et al*., 2025). In experimental studies, such strategies have demonstrated the potential to inhibit tumor growth, reduce metastasis, and enhance the effectiveness of conventional therapies such as chemotherapy and radiation. However, these benefits must be carefully balanced against the possibility that certain stem cell populations may, under specific conditions, promote tumor progression or provide protective niches for cancer cells. Stem cells also play a critical supportive role in cancer treatment, particularly in facilitating recovery following intensive therapies.

Hematopoietic stem cell transplantation (HSCT) is a well-established treatment for hematological malignancies such as leukemia and lymphoma (Chu *et al*., 2024). In this procedure, high-dose chemotherapy or radiation is used to eliminate cancerous cells, but it also damages the patient's bone marrow. The subsequent infusion of healthy hematopoietic stem cells enables the regeneration of the blood and immune systems, restoring essential cellular components such as red blood cells, platelets, and immune cells. This approach not only improves patient survival but also permits the use of more aggressive treatment regimens. Similarly, MSCs and other stromal stem cells have been investigated for their ability to reduce inflammation, protect organ function, and accelerate tissue repair following therapy-induced damage, thereby improving treatment tolerance and patient outcomes.

Furthermore, stem cells are being explored for their capacity to modulate the tumor microenvironment and enhance antitumor immune responses. Certain stem cell types can influence immune cells, including T lymphocytes, natural killer cells, and macrophages, potentially shifting the tumor environment from immunosuppressive to immunologically active. When combined with immunotherapeutic approaches such as immune checkpoint inhibitors or CAR-T cell therapy, stem cell-based strategies may help overcome resistance and improve the durability of treatment responses. In summary, stem cells serve multiple roles in cancer therapy, ranging from targeted delivery of therapeutic agents to systemic support of tissue regeneration and immune function. Their versatility and ability to integrate with existing treatment modalities position them as a promising component in the advancement of modern oncology.

Applications of Stem Cells in Cancer Therapy

Stem cells are being explored through multiple therapeutic strategies to enhance cancer treatment, ranging from immune system reconstitution to targeted drug delivery. Among these, hematopoietic stem cell transplantation (HSCT) represents the most established and clinically advanced application, while other approaches focus on mesenchymal stem cells (MSCs) and engineered stem cell systems for drug and gene therapy in solid tumors.

Hematopoietic stem cell transplantation (HSCT) is widely employed in the treatment of hematological malignancies, including leukemia, lymphoma (Chu *et al*., 2024), and multiple myeloma. In this procedure, patients undergo high-dose chemotherapy or radiation therapy to eliminate cancerous bone marrow cells; however, this process also severely damages normal blood-forming tissues. To restore hematopoietic function, stem cells are infused intravenously, either from the patient's own cells (autologous transplantation) or from a compatible donor (allogeneic transplantation). These stem cells migrate to the bone marrow and regenerate the blood and immune systems, producing essential components such as red blood cells, platelets, and immune cells.

In allogeneic transplantation, an additional therapeutic benefit known as the graft-versus-tumor effect may occur, wherein donor immune cells recognize and eliminate residual cancer cells. Despite its clinical success, HSCT is associated with significant risks, including infections, organ toxicity, and graft-versus-host disease, particularly in allogeneic settings. In addition to HSCT, mesenchymal stem cells (MSCs) are being extensively investigated for their role in the treatment of solid tumors. MSCs can be isolated from various tissues, including bone marrow, adipose tissue, and umbilical cord, and possess the ability to migrate toward sites of inflammation and tumor growth, a property known as tumor tropism. In this context, MSCs serve both supportive and therapeutic delivery functions (Martinez *et al*., 2018). They have been studied for their capacity to repair tissue damage induced by chemotherapy or radiation, such as oral mucositis and pulmonary injury, while also modulating local immune responses. When genetically engineered, MSCs can act as carriers for anticancer agents, including chemotherapeutic drugs, oncolytic viruses, and pro-apoptotic genes, delivering them directly to the tumor microenvironment. This targeted approach aims to increase therapeutic efficacy while reducing systemic toxicity. Beyond these applications, stem cells are also being developed as platforms for drug delivery and gene therapy. In such strategies, stem cells function as "living carriers" that can be modified to express tumor-targeting proteins, cytokines, or enzymes capable of activating prodrugs at the tumor site.

For example, MSCs and neural stem cells have been engineered to produce immunomodulatory molecules such as interleukins and interferons, thereby enhancing antitumor immune responses. Additionally, the incorporation of suicide gene systems allows for controlled activation of cytotoxic pathways within tumor tissues. Experimental studies have demonstrated that these approaches can inhibit tumor growth and reduce metastasis more effectively than conventional therapies alone. Furthermore, induced pluripotent stem cells (iPSCs) are being explored as a source for generating patient-specific immune cells, including T lymphocytes and natural killer cells, thereby integrating stem cell technology with advanced immunotherapeutic strategies (Kim *et al*., 2020). In summary, stem cell-based applications in cancer therapy can be broadly categorized into three domains: hematopoietic stem cell transplantation for hematological cancers, mesenchymal stem cell-based approaches for tissue repair and targeted delivery in solid tumors, and engineered stem cell systems for drug and gene therapy. Collectively, these strategies highlight the versatility of stem cells as both therapeutic agents and supportive tools in modern oncology.

Advantages and Challenges of Stem Cell-Based Cancer Therapy

Stem cell-based cancer therapy represents a promising approach (Chu *et al*., 2024), that integrates tumor-targeting capabilities with the potential for tissue regeneration. However, these advantages are accompanied by significant scientific, clinical, and ethical challenges that must be carefully considered. One of the primary advantages of stem cell-based therapies is their capacity for targeted delivery. Certain stem cell types, including mesenchymal stem cells (MSCs) and neural stem cells, exhibit a natural ability to migrate toward tumor sites and regions of inflammation, a phenomenon referred to as tumor tropism. By engineering these cells to carry anticancer agents such as chemotherapeutic drugs, oncolytic viruses, or immunomodulatory molecules, it becomes possible to deliver therapy directly to the tumor microenvironment. This targeted approach has the potential to enhance therapeutic efficacy while minimizing systemic toxicity, in contrast to conventional chemotherapy, which affects both malignant and healthy tissues.

In addition to targeted delivery, stem cells contribute to tissue regeneration and immune recovery. For example, hematopoietic stem cell transplantation (HSCT) enables the restoration of blood and immune system function following high-dose chemotherapy. Similarly, MSCs have demonstrated the ability to repair tissue damage induced by chemotherapy or radiation, such as oral mucositis and pulmonary injury, while also modulating immune responses to improve patient outcomes. Despite these advantages, stem cell-based cancer therapy is associated with several challenges and risks. A major concern is the potential for tumor promotion or secondary tumor formation. In certain contexts, stem cells particularly MSCs may contribute to tumor progression, metastasis, or therapeutic resistance (Silva *et al*., 2025) by altering the tumor microenvironment or providing protective niches for cancer cells. Additionally, pluripotent stem cells, including embryonic stem cells and induced pluripotent stem cells (iPSCs), carry the risk of forming teratomas (Kim *et al*., 2020) or other abnormal growths if not adequately controlled prior to transplantation. Another significant limitation is immune rejection, particularly in allogeneic therapies, where donor-derived cells may be recognized as foreign by the recipient's immune system. Although immunosuppressive treatments can reduce this risk, they may increase susceptibility to infections and other complications. Beyond biological and clinical considerations, ethical and regulatory challenges also play a critical role.

The use of embryonic stem cells raises ethical concerns due to the involvement of early-stage human embryos, leading to ongoing debates regarding acceptable research practices. Although iPSCs circumvent some of these issues, they introduce new considerations related to genetic manipulation, informed consent, and long-term safety monitoring. Furthermore, stem cell therapies are often complex and costly to produce under stringent good manufacturing practice (GMP) conditions, limiting accessibility and raising questions regarding scalability and cost-effectiveness. In addition, the long-term safety and efficacy of many stem cell-based interventions remain uncertain, as clinical data are often derived from limited patient populations and heterogeneous treatment protocols.

In summary, stem cell-based cancer therapy offers significant advantages, including targeted drug delivery, regenerative potential, and immune system restoration. However, these benefits must be balanced against substantial risks such as tumor promotion, immune rejection, ethical concerns, and technical as well as regulatory challenges. A cautious and evidence-based approach is therefore essential to fully realize the potential of these therapies while ensuring patient safety and responsible scientific advancement.

Role of Artificial Intelligence and Machine Learning in Stem Cell-Based Cancer Therapy

Artificial intelligence (AI) and machine learning (ML) are increasingly contributing to the advancement of stem cell-based cancer therapy (Gupta *et al*., 2025). By enabling the analysis of large and complex datasets, these technologies enhance the design, delivery, and monitoring of stem cell interventions. In parallel, ML models support the prediction of patient-specific treatment responses, thereby promoting a more personalized and data-driven approach to oncology. One of the key contributions of AI lies in optimizing stem cell production and behavior. In laboratory settings, stem cells must be carefully guided to differentiate into specific cell types while maintaining their therapeutic functionality. AI-driven image analysis and pattern recognition techniques allow automated classification of stem cells from microscopy data, real-time tracking of cell growth, and early detection of abnormalities such as contamination or unintended differentiation (Smith *et al*., 2022).

Furthermore, machine learning models can integrate diverse biological data including culture conditions, gene expression profiles, and protein markers to identify optimal protocols for cell expansion, differentiation, and quality control. Such approaches have improved the reproducibility and safety of stem cell products used in cancer-related research and clinical trials. Beyond laboratory optimization, AI plays a critical role in designing and personalizing stem cell-based treatment strategies (Zhang *et al*., 2023). Many emerging therapies combine stem cells with gene editing or immunotherapeutic approaches, requiring careful consideration of patient-specific variables such as tumor genetics, immune status, and prior treatment history.

Machine learning algorithms can integrate heterogeneous datasets including genomic, imaging, and clinical information to identify patients most likely to benefit from specific therapeutic interventions. In the context of hematopoietic stem cell transplantation, predictive models have been developed to estimate outcomes such as relapse risk and graft-versus-host disease, enabling clinicians to tailor conditioning regimens and supportive care strategies. Machine learning also contributes significantly to predicting cancer treatment response more broadly. Resistance to conventional therapies remains a major challenge in oncology, and ML models trained on large-scale datasets, such as those from The Cancer Genome Atlas (TCGA) (Liu *et al*., 2020), can identify relationships between molecular profiles and drug sensitivity. For example, support vector machine and neural network-based models have demonstrated the ability to predict patient-specific responses (Zhang *et al*., 2023) to chemotherapeutic agents with high accuracy. These predictive frameworks are increasingly being extended to stem cell-based therapies, including forecasting immune system recovery following transplantation and evaluating the effectiveness of stem cell-mediated drug delivery systems. Fig 2 workflow illustrating the integration of artificial intelligence and machine learning in stem cell-based cancer therapy. Patient-derived multi-omic, imaging, and clinical data serve as inputs for AI/ ML models, which optimize cell characterization, predict therapeutic responses, and personalize treatment protocols.

This data-driven approach facilitates precision oncology and aims to improve patient outcomes. In clinical practice, AI-driven systems are beginning to support decision-making and trial design. Advanced computational platforms can recommend personalized treatment strategies by integrating real-time clinical data, imaging results, and historical patient outcomes. Such tools are particularly valuable for identifying patients who may benefit from stem cell-based approaches, especially in cases of treatment resistance or high toxicity risk. Additionally, AI-assisted clinical trial design enables improved patient stratification, optimization of dosing strategies, and simulation of virtual cohorts, thereby enhancing the efficiency and safety of early-stage trials.

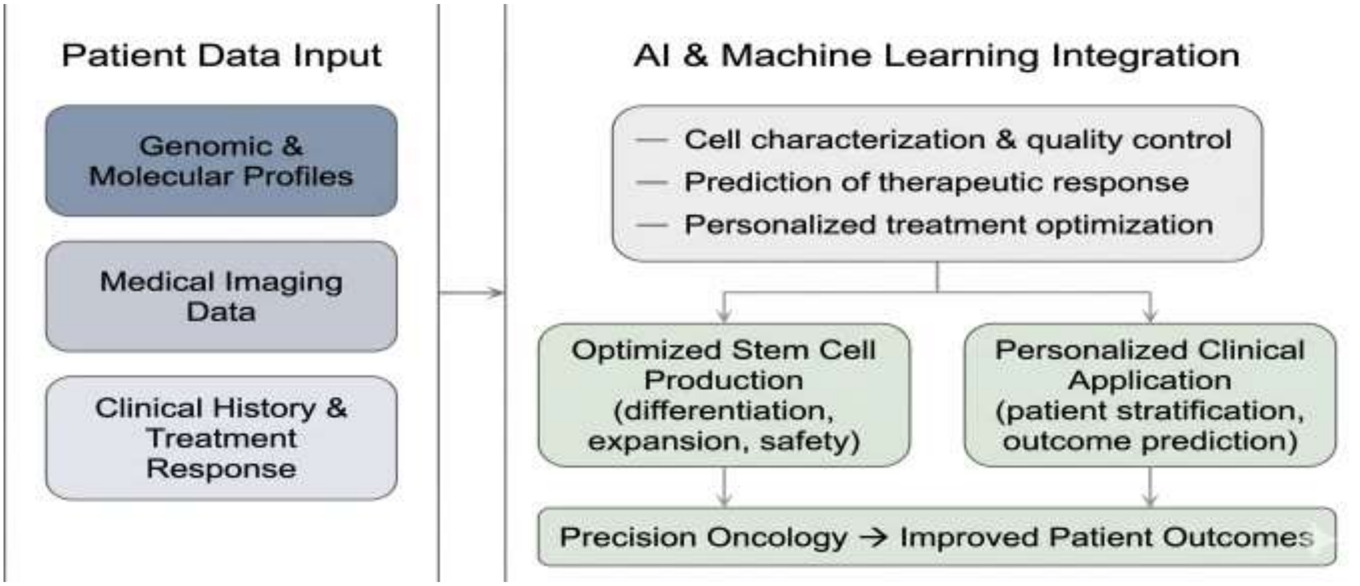

Fig 2. Patient Data Input, AI & Machine Learning Integration

In summary, artificial intelligence and machine learning are playing a transformative role in stem cell-based cancer therapy by improving cell manufacturing processes, enabling personalized treatment strategies, and enhancing the prediction of therapeutic outcomes. The integration of computational tools with stem cell biology is accelerating the transition toward more precise, efficient, and patient-centered cancer care.

Future Perspectives of Stem Cell-Based Cancer Therapy

The future of stem cell-based cancer therapy is closely aligned with the broader transition toward personalized medicine **(**Choudhury *et al*., 2025**)**, in which treatments are tailored to an individual's genetic profile, tumor characteristics, and immune status. Rather than relying on uniform treatment strategies, emerging approaches aim to utilize patient-derived stem cells, such as induced pluripotent stem cells (iPSCs), to generate customized immune cells, tissue-repair systems, and targeted drug-delivery platforms. Such strategies have the potential to enhance therapeutic efficacy, minimize toxicity, and reduce the risk of immune rejection. A key driver of this transformation is the integration of artificial intelligence (AI) and machine learning (ML) (Chandrasekar *et al*., 2025) into biomedical research and clinical practice. AI-based platforms can analyze complex datasets derived from genomics, medical imaging, and electronic health records to identify patients most likely to benefit from specific stem cell-based interventions. Machine learning models can further assist in optimizing treatment protocols, monitoring therapeutic responses in real time, and accelerating drug and cell-therapy development through predictive simulations. In the future, advanced computational concepts such as "digital twins," which model a patient's tumor and immune system in silico, may enable highly precise selection and timing of stem cell-based therapies, advancing the field toward truly data-driven precision oncology. In parallel, gene editing technologies, particularly CRISPR-Cas9 (Choudhury *et al*., 2025) are expected to significantly enhance the effectiveness of stem cell-based therapies. These tools enable precise genetic modifications, allowing researchers to correct disease-associated mutations, enhance antitumor activity, and reduce immunogenicity. For instance, hematopoietic stem cells or iPSC-derived immune cells can be engineered to express improved chimeric antigen receptors (CARs) or to resist immunosuppressive signals within the tumor microenvironment. Similarly, mesenchymal stem cells can be modified to express anticancer cytokines or suicide genes, thereby increasing their therapeutic efficacy and safety as targeted delivery systems. As concerns regarding off-target effects and long-term safety are progressively addressed, gene-edited stem cell products are likely to become integral components of future cancer therapies.

Future research efforts will focus on improving the safety, control, and scalability of stem cell-based interventions. This includes enhancing the stability of engineered cells, understanding their interactions within the tumor microenvironment, and developing cost-effective manufacturing processes that comply with stringent regulatory standards. Long-term clinical studies will be essential to evaluate treatment durability, potential adverse effects, and the risk of secondary malignancies. Overall, the convergence of personalized medicine, artificial intelligence, and gene editing technologies is expected to transform stem cell-based cancer therapy into a more precise, adaptable, and effective approach, offering new possibilities for long-term cancer management and potential cure.

Conclusion

Stem cells represent a promising and rapidly evolving frontier in cancer therapy, bridging regenerative biology with modern oncology. This review has highlighted their dual role in cancer treatment, functioning both as direct therapeutic agents and as supportive tools that facilitate tissue repair and immune reconstitution. Hematopoietic stem cell transplantation remains a well-established approach for hematological malignancies, enabling high-dose therapy and long-term remission in selected patients. At the same time, mesenchymal and other stem cell types are being actively investigated for their tumor-targeting properties, immunomodulatory functions, and potential to deliver therapeutic agents directly to solid tumors, offering a more targeted alternative to conventional treatment strategies. Despite these advances, stem cell-based cancer therapy is associated with several important challenges. Risks such as tumor promotion, uncontrolled differentiation, and immune rejection require careful evaluation and management. Ethical considerations, particularly those related to embryonic stem cells and genetic modification, continue to shape research and clinical practice. In addition, the complexity of manufacturing, high costs, and stringent regulatory requirements limit the widespread adoption of stem cell-based interventions. However, emerging technologies are beginning to address these limitations.

The integration of artificial intelligence and machine learning enables improved patient stratification, treatment optimization, and outcome prediction, while advances in gene editing technologies, such as CRISPR-Cas9, offer new opportunities for developing safer and more effective engineered stem cell therapies. In conclusion, stem cell-based approaches provide a biologically grounded and versatile platform for advancing cancer treatment. Their successful integration into routine clinical practice will depend on continued research, standardization of protocols, and collaboration across multiple disciplines. With ongoing progress in personalized medicine, computational methods, and genetic engineering, stem cell-based therapies are expected to play an increasingly important role in shaping a more precise, durable, and patient-centered future for oncology.

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