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Biomedical Engineering Approaches in Stem Cell Based Therapies: Current Advances and Future Perspectives

Piruz Shadbash[1]*

[1]*Department of Microbiology and Microbial Biotechnology, Faculty of Life Sciences and Biotechnology, Shahid Beheshti University, Tehran, Iran*

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***Corresponding author:** Piruz Shadbash, department of Microbiology and Microbial Biotechnology, Faculty of Life Sciences and Biotechnology, Shahid Beheshti University, Tehran, Iran

Abstract

Stem cell–based therapies have emerged as a transformative approach in regenerative medicine; however, their clinical translation remains limited by challenges related to cell survival, differentiation control, delivery efficiency, and safety. Biomedical engineering has played a pivotal role in overcoming these barriers through the development of biomaterials, tissue engineering strategies, bioreactors, microfluidic systems, and advanced imaging and geneengineering tools. This minireview highlights recent advances at the intersection of biomedical engineering and stem cell science, focusing on engineered microenvironments, scaffoldbased delivery systems, organonchip platforms, and emerging technologies such as 3D bioprinting and nanotechnology. Finally, future perspectives and translational challenges are discussed, emphasizing the role of interdisciplinary engineering solutions in advancing stem cellbased clinical therapies.

Keywords: Biomedical engineering, stem cells, tissue engineering, biomaterials, regenerative medicine, organonchip

Introduction

Stem cells, including embryonic stem cells (ESCs), induced pluripotent stem cells (iPSCs), and adult stem cells, possess unique capacities for selfrenewal and multilineage differentiation, making them promising candidates for regenerative medicine [1]. Despite encouraging preclinical and early clinical results, the therapeutic efficacy of stem cellbased interventions has been hampered by poor engraftment, uncontrolled differentiation, immune rejection, and tumorigenicity [2].

Biomedical engineering has emerged as a critical discipline to bridge the gap between basic stem cell research and clinical application [3]. By integrating principles from materials science, mechanical engineering, microfabrication, and systems biology, biomedical engineering enables precise control over the stem cell microenvironment, also known as the “stem cell niche” [4]. This interdisciplinary approach has led to innovative platforms that enhance stem cell viability, functionality, and therapeutic outcomes.

Engineering the Stem Cell Microenvironment

The fate of stem cells is highly influenced by biochemical, mechanical, and topographical cues [5]. Biomedical engineers have developed biomimetic scaffolds that replicate native extracellular matrix (ECM) properties, allowing precise regulation of stiffness, porosity, and ligand presentation [6].

Hydrogels based on natural (collagen, gelatin, alginate) and synthetic polymers (PEG, PLGA) have been widely used to modulate stem cell differentiation [7]. Studies demonstrate that matrix stiffness alone can direct mesenchymal stem cell (MSC) differentiation toward osteogenic, myogenic, or neurogenic lineages [8,9]. Such engineered microenvironments are essential for reproducible and safe stem cell therapies.

Tissue Engineering and ScaffoldBased Stem Cell Delivery

Tissue engineering strategies combine stem cells, scaffolds, and bioactive factors to regenerate damaged tissues. Advances in 3D scaffold fabrication, including electrospinning and additive manufacturing, have enabled the creation of highly organized constructs for bone, cartilage, cardiac, and neural tissue regeneration [10]. Scaffoldbased delivery systems improve stem cell retention at target sites and protect cells from hostile inflammatory environments. In cardiovascular and orthopedic applications, engineered scaffolds seeded with MSCs or iPSCderived cells have shown superior functional recovery compared to direct cell injection [11].

Microfluidics, OrganonChip, and Stem Cell Modeling

Microfluidic and organonchip technologies represent a major breakthrough in stem cell research and personalized medicine. These platforms allow precise control of fluid flow, oxygen gradients, and mechanical forces, closely mimicking in vivo conditions [12]. Stem cellderived organonchip systems have been successfully applied to model cardiac toxicity, neurodegenerative diseases, and liver metabolism. From a biomedical engineering perspective, these systems reduce reliance on animal models and accelerate drug discovery and translational research [13].

Emerging Technologies: 3D Bioprinting and Nanotechnology

3D bioprinting enables the spatial patterning of stem cells and biomaterials with high precision, facilitating the fabrication of complex tissuelike structures. Bioprinted constructs have shown promise in skin regeneration, vascularized tissues, and tumor modeling [14].

Nanotechnology further enhances stem cell therapies through nanoparticlemediated gene delivery, controlled release of growth factors, and realtime cell tracking using nanoprobes [15]. These approaches significantly improve the safety, efficacy, and monitoring of stem cellbased interventions.

Challenges and Future Perspectives

Despite rapid progress, several challenges remain, including largescale stem cell manufacturing, longterm safety, immune compatibility, and regulatory hurdles [16]. Future biomedical engineering research should focus on standardized platforms, smart biomaterials, and AIassisted design of stem cell systems. The convergence of biomedical engineering, stem cell biology, and digital health technologies is expected to accelerate the translation of stem cell therapies into routine clinical practice, offering novel solutions for currently incurable diseases.

Conclusion

Biomedical engineering has become indispensable in advancing stem cellbased therapies from bench to bedside. Through engineered microenvironments, advanced delivery systems, and innovative modeling platforms, engineering approaches address critical limitations of traditional stem cell therapies. Continued interdisciplinary collaboration will be essential to unlock the full therapeutic potential of stem cells in future medicine.

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