Review Article

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Stem Cells in Dentistry: A Review on Biological Basis, Applications, and Future Directions

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ABSTRACT

Background: Stem cells, defined by their capacity for self-renewal and multilineage differentiation, have revolutionized regenerative medicine and are now making significant strides in dentistry. Dental stem cells offer promising prospects for tissue engineering and restoration of oral structures. This review aims to provide an in-depth overview of the classification, biological characteristics, preservation techniques, and current and potential applications of stem cells in dentistry. Additionally, it addresses ethical controversies and emerging innovations in the field. As scientific understanding and technology evolve, stem cell-based therapies are poised to transform dental practice and broader medical applications.

Keywords: Dental stem cells, regenerative dentistry, stem cell preservation, tissue engineering, induced pluripotent stem cells.

INTRODUCTION

Stem cells are undifferentiated biological cells with the unique ability to self-renew and differentiate into specialized cell types. This biological versatility makes them indispensable tools in regenerative medicine. In recent decades, stem cell biology has rapidly advanced, laying the foundation for innovative therapies across medicine and dentistry. Dentistry, traditionally focused on repair and replacement, is now evolving towards regeneration. Dental stem cells, particularly those derived from the pulp, periodontal ligament, and apical papilla, hold immense therapeutic potential.

The aim of this review is to provide a comprehensive summary of stem cells in dentistry, covering their classification, preservation techniques, applications, and future perspectives. Emphasis is placed on how these cells are being translated from bench to bedside and their expected role in transforming dental practice.

II. Historical Background

The journey of stem cell research began over a century ago. In 1908, Russian histologist Alexander Maksimov introduced the concept of stem cells in hematopoiesis. During the 1960s, McCulloch and till confirmed the existence of self-renewing cells in mouse bone marrow, cementing stem cells as a cornerstone of modern biology [1].

In 1981, Evans and Kaufman successfully isolated embryonic stem cells (ESCs) from mice, followed by Thomson's derivation of human ESCs in 1998 [2]. Although groundbreaking, the use of ESCs sparked ethical controversies. This led to the revolutionary discovery by Shinya Yamanaka in 2006, who reprogrammed adult somatic cells into induced pluripotent stem cells (iPSCs), providing a less controversial and patient-specific alternative [2].

Dental stem cell research began with the discovery of dental pulp stem cells (DPSCs) in 2000 by Shi and colleagues. This was followed by the identification of stem cells from human exfoliated deciduous teeth

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(SHED) in 2003, and periodontal ligament stem cells (PDLSCs) in 2004 [3][4]. These discoveries marked a paradigm shift in oral healthcare.

III. Classification of Stem Cells

Stem cells are broadly classified based on their origin, potency, and source.

A. Based on Origin:

1. Embryonic Stem Cells: Derived from the inner cell mass of the blastocyst, these are pluripotent and can form any cell type.
2. Fetal Stem Cells: Present in fetal tissues such as blood and neural tissue.
3. Umbilical Cord Stem Cells: Rich in hematopoietic and mesenchymal stem cells.
4. Adult Stem Cells: Found in postnatal tissues like bone marrow and dental pulp [5].

B. Based on Potency:

1. Totipotent: Can form all embryonic and extra-embryonic tissues (e.g., zygote).
2. Pluripotent: Can generate all three germ layers.
3. Multipotent: Can differentiate into a limited number of lineages.
4. Oligopotent and Unipotent: Can differentiate into few or single lineages respectively.

C. Dental Stem Cells:

1. DPSCs, SHED, SCAP, DFPCs, PDLSCs, and others have been isolated and shown to regenerate tooth structures in preclinical and clinical studies [6].

IV. Preservation and Storage of Stem Cells

Preservation of stem cells is a vital step to ensure their viability, genetic stability, and long-term usability for both research and clinical applications. Techniques for preserving stem cells have evolved significantly, from traditional freezing to advanced magnetic freezing and cryoprotectant-free systems.

Cryopreservation remains the gold standard. It involves storing cells at ultra-low temperatures, typically in liquid nitrogen at -196°C. A cryoprotective agent such as DMSO is used to prevent ice crystal formation that could damage cellular structures [7]. Thawing is equally crucial and must be done rapidly to avoid crystal reformation.

Stem cells from dental tissues, including DPSCs and SHED, are routinely isolated and stored in stem cell banks. These facilities, which are now expanding globally, collect stem cells through minimally invasive procedures and preserve them for future use. Tooth stem cell banks in the USA, Japan, and India have made this process more accessible [8].

Recent innovations include magnetic freezing (Cells Alive System - CAS), which allows higher post-thaw survival rates compared to conventional cryogenics. Quality control procedures, including viability assays, sterility tests, and genetic monitoring, are essential to ensure preserved cells maintain their functional capabilities over time.

V. Applications of Stem Cells in Dentistry

The regenerative potential of dental stem cells has led to their use in multiple clinical and experimental applications. Their ability to differentiate into osteogenic, chondrogenic, adipogenic, and neurogenic lineages enables their deployment in reconstructing orofacial tissues damaged by disease, trauma, or developmental anomalies [9].

Dental pulp regeneration is a primary focus, where stem cells seeded on scaffolds and growth factors can recreate the pulp-dentin complex. Likewise, periodontal ligament regeneration is being achieved using PDLSCs, often in combination with biomimetic materials.

In apexogenesis, SCAP cells help in the continued development of immature roots in non-vital teeth. Bone regeneration for maxillofacial defects is also feasible using DPSCs and SHED, which can be engineered into bone graft materials [10].

Moreover, stem cells from dental tissues are not limited to dental applications. Studies have shown their utility in treating systemic diseases such as Type 1 diabetes, myocardial infarction, and even neurodegenerative disorders. Their immunomodulatory properties make them suitable for allogenic transplants with reduced risk of rejection.

VI. Controversies and Ethical Considerations

Despite their therapeutic promise, stem cells raise numerous ethical, legal, and social concerns. The primary debate revolves around the use of embryonic stem cells, which necessitate the destruction of embryos. This has resulted in ethical opposition, particularly from religious and pro-life groups [11].

To address these concerns, researchers have increasingly turned to adult stem cells and iPSCs, which can be harvested without ethical complications. While adult stem cells have limitations in potency, iPSCs overcome this by mimicking pluripotent characteristics without the need for embryos.

Regulatory frameworks differ across countries. While the U.S. and Japan have strict guidelines on clinical stem cell use, other nations have more lenient or undefined policies, raising concerns about 'stem cell tourism.' International harmonization of regulations is essential to ensure patient safety and research integrity.

VII. Future Prospects

The future of stem cells in dentistry is bright and multi-dimensional. Rapid advances in 3D bioprinting and tissue engineering are paving the way for creating entire bioengineered teeth. Using stem cells, along with suitable scaffolds and morphogens, researchers are attempting to reconstruct fully functional dental structures [12].

Gene-editing tools such as CRISPR-Cas9 combined with iPSCs offer targeted correction of genetic defects, enabling personalized regenerative treatments. Artificial intelligence and bioinformatics are also being integrated to predict stem cell behavior, optimize culturing conditions, and enhance treatment outcomes.

Moreover, cell-free therapies using exosomes and extracellular vesicles derived from stem cells are being developed. These biologics could provide similar therapeutic effects without the risks associated with live-cell transplantation.

CONCLUSION

Stem cells represent the forefront of regenerative dentistry. From pulp regeneration to bioengineered teeth, their applications are rapidly expanding. Their ability to self-renew, differentiate, and modulate immune responses provides a versatile tool for clinicians and researchers.

However, clinical translation still faces challenges, including scalability, cost, and regulatory approval. Continued interdisciplinary research, standardized protocols, and ethical oversight are crucial to harness their full potential.

In the coming years, stem cell-based therapies are expected to shift from experimental treatments to mainstream clinical practices, revolutionizing oral healthcare and beyond.

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