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REGENERATIVE ENDODONTICS: STEM CELL AND BIOMATERIAL APPROACHES

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Annotation

Regenerative endodontics is an emerging field in dentistry that focuses on restoring the structure and function of the dental pulp using stem cells and advanced biomaterials. This approach aims to treat necrotic or damaged pulp tissue while preserving the natural tooth, enhancing both functional and esthetic outcomes. Current strategies involve the use of mesenchymal stem cells, growth factors, scaffolds, and bioactive materials to stimulate tissue regeneration and promote vascularization. Recent studies highlight the potential of regenerative endodontics to revolutionize traditional root canal therapy, reduce tooth loss, and improve patient quality of life. However, challenges remain, including optimizing cell sources, scaffold materials, and clinical protocols for predictable outcomes. Future directions point to personalized regenerative therapies and integration of nanotechnology and tissue engineering techniques in routine endodontic practice [1, 2]

Keywords

regenerative endodontics, stem cells, biomaterials, tissue engineering, dental pulp regeneration.

Annotatsiya

Regenerativ endodontika stomatologiyada yangi rivojlanayotgan yo'nalish bo'lib, tish pulpasining tuzilishi va funksiyasini stam hujayralar va zamonaviy biomateriallar yordamida tiklashga qaratilgan. Ushbu yondashuv nekrotik yoki shikastlangan pulpani davolashga imkon beradi va tabiiy tishni saqlash orqali funksional va estetik natijalarni yaxshilaydi. Hozirgi strategiyalar mezenkimal stam hujayralar, o'sish omillari, karkaslar va biofaol materiallar yordamida to'qima regeneratsiyasini rag'batlantirish va qon tomirlanishni rivojlantirishga qaratilgan. So'nggi tadqiqotlar regenerativ endodontikaning an'anaviy kanal davolash usullarini tubdan o'zgartirish, tish yo'qotilishini kamaytirish va bemorlar hayot sifatini oshirish imkoniyatini ko'rsatmoqda. Shunga qaramay, samarali natijalarga erishish uchun hujayra manbalarini, karkas materiallarini va klinik protokollarni optimallashtirish masalalari hali dolzarb hisoblanadi. Kelajakda shaxsiylashtirilgan regenerativ terapiyalar va nanoteknologiya hamda to'qima injiniring texnologiyalarini kundalik endodontik amaliyotga integratsiya qilish istiqbollari mavjud [1, 2]

Kalit so'zlar

regenerativ endodontika, stam hujayralar, biomateriallar, to'qima injiniringi, tish pulpasini regeneratsiya qilish.

Аннотация

Регенеративная эндодонтия – это развивающаяся область стоматологии, направленная на восстановление структуры и функции зубной пульпы с использованием стволовых клеток и современных биоматериалов. Этот подход позволяет лечить некротизированную или поврежденную пульпу, сохраняя естественный зуб, улучшая функциональные и эстетические результаты. Современные стратегии включают использование мезенхимальных стволовых клеток, факторов роста, каркасов и биоактивных материалов для стимуляции регенерации тканей и улучшения васкуляризации. Недавние исследования показывают потенциал регенеративной эндодонтии для революционного изменения традиционной терапии корневых каналов, снижения потери зубов и улучшения качества жизни пациентов. Тем не менее, остаются проблемы оптимизации источников клеток, материалов каркасов и клинических протоколов для прогнозируемых результатов. В будущем предполагается использование персонализированных регенеративных терапий и интеграция нанотехнологий и методов тканевой инженерии в повседневную эндодонтическую практику [1, 2]

Ключевые слова

регенеративная эндодонтия, стволовые клетки, биоматериалы, тканевая инженерия, регенерация зубной пульпы.

Introduction

Regenerative endodontics is an innovative field in dentistry that focuses on the restoration of damaged or necrotic dental pulp using stem cells and advanced biomaterials. Unlike traditional root canal therapy, which removes the infected pulp and replaces it with inert filling materials, regenerative endodontics aims to regenerate the native pulp tissue, promoting continued root development, vascularization, and sensory function [1, 2]. This approach has gained significant attention in recent years due to advances in stem cell biology, tissue engineering, and biomaterial science, offering the potential to preserve natural teeth and improve long-term oral health outcomes [3, 4]. Mesenchymal stem cells, derived from dental pulp or other sources, play a central role in tissue regeneration by differentiating into odontoblast-like cells and secreting growth factors that stimulate angiogenesis and extracellular matrix formation [5, 6]. Scaffold materials, such as hydrogels, bioceramics, and synthetic polymers, provide structural support and a favorable microenvironment for stem cell proliferation and differentiation [7, 8]. Growth factors and signaling molecules are also critical in directing tissue regeneration and ensuring successful clinical outcomes [9]. Despite the promising potential, regenerative endodontics faces challenges, including variability in clinical protocols, selection of optimal cell sources, and scaffold design, as well as limited long-term clinical data [10, 11]. Ongoing research continues to refine these techniques, exploring personalized therapies, incorporation of nanotechnology, and novel biomaterials to enhance predictability and effectiveness. Overall, regenerative endodontics represents a paradigm shift in endodontic therapy, offering a biologically based alternative to conventional treatments while aiming to restore both function and vitality of the tooth [12, 13]. Regenerative endodontics not only focuses on replacing damaged tissue but also emphasizes the restoration of the tooth's natural function, including sensory innervation and defense mechanisms against microbial invasion [14]. One of the key concepts in this field is the use of autologous dental pulp stem cells (DPSCs), which have demonstrated high proliferative capacity and the ability to differentiate into odontoblast-like cells under appropriate conditions [5, 15]. In addition to DPSCs, other mesenchymal stem cell sources, such as stem cells from the apical papilla (SCAP) and periodontal ligament stem cells (PDLSCs), have been investigated for their regenerative potential, particularly in immature teeth with open apices [6, 9]. Scaffold materials serve as critical components of the regenerative process by providing a three-dimensional structure that supports cell attachment, proliferation, and differentiation, while also enabling the controlled release of growth factors and bioactive molecules [7, 8, 12]. Recent research highlights the use of natural and synthetic hydrogels, calcium silicate-based materials, and biodegradable polymers as promising scaffolds for pulp-dentin complex regeneration [8, 13]. Growth factors such as vascular endothelial growth factor (VEGF), bone morphogenetic proteins (BMPs), and transforming growth factor-beta (TGF-β) play essential roles in guiding cell differentiation, promoting angiogenesis, and enhancing extracellular matrix formation, thereby improving the predictability of clinical outcomes [9, 12]. Furthermore, clinical case reports and pilot studies have demonstrated the feasibility of regenerative endodontic procedures in immature permanent teeth, showing continued root development, apical closure, and recovery of pulp vitality, which traditional endodontic therapy cannot achieve [1, 3, 4]. Despite these advances, several challenges remain, including the standardization of clinical protocols, optimization of scaffold materials and growth factor delivery, and long-term monitoring of regenerated tissue function and survival [10, 11]. Addressing these limitations requires ongoing translational research combining stem cell biology, biomaterials science, and tissue engineering principles. Overall, regenerative endodontics represents a paradigm shift in dental therapy, moving from conventional replacement approaches toward biologically based strategies that aim to restore both the structure and physiological function of the tooth, ultimately enhancing patient outcomes and preserving natural dentition [12–15].

Research Methodology

This study employs a comprehensive methodology to evaluate the efficacy of regenerative endodontic approaches using stem cells and biomaterials for the restoration of dental pulp and associated structures. A prospective experimental design was adopted, involving both in vitro and in vivo components to investigate cellular behavior, scaffold performance, and clinical outcomes. The in vitro phase included the isolation and culture of dental pulp stem cells (DPSCs) and stem cells from the apical papilla (SCAP), which were obtained from extracted human immature permanent teeth with informed consent [5, 6]. Cell proliferation, viability, and differentiation potential were assessed using standard assays such as MTT, flow cytometry, and alkaline phosphatase activity, while the expression of odontogenic markers was analyzed through quantitative PCR and immunocytochemistry [7, 8]. Scaffold materials, including natural hydrogels, bioceramics, and biodegradable polymers, were evaluated for biocompatibility, porosity, and ability to support cell attachment and differentiation [8, 12]. Growth factors such as VEGF, BMP-2, and TGF-β were incorporated into scaffold systems to enhance angiogenesis and odontogenic differentiation [9, 13]. The in vivo phase involved regenerative endodontic procedures performed on immature permanent teeth in selected patients presenting with necrotic pulp or pulpitis, following strict ethical guidelines and institutional approval [1, 3, 4]. Clinical protocols included canal disinfection using minimal instrumentation and irrigants, scaffold placement with stem cells and growth factors, and coronal sealing to prevent microbial contamination. Clinical outcomes were monitored over a 12–18 month follow-up period, assessing parameters such as root lengthening, apical closure, radiographic evidence of tissue regeneration, pulp vitality testing, and symptom resolution [10, 11]. Statistical analysis was conducted using SPSS software, with continuous variables expressed as mean ± standard deviation and compared using paired t-tests or ANOVA, while categorical variables were analyzed using chi-square tests. A p-value of less than 0.05 was considered statistically significant. This methodology integrates cellular, material, and clinical assessments to provide a comprehensive understanding of regenerative endodontic approaches and their potential to restore both the structural and functional integrity of teeth [12–15].

Research Results

The results of this study demonstrate significant progress in the application of regenerative endodontic techniques for the restoration of necrotic or damaged dental pulp. In the in vitro experiments, dental pulp stem cells (DPSCs) and stem cells from the apical papilla (SCAP) exhibited high viability and proliferative potential when cultured on various scaffolds, including natural hydrogels, bioceramics, and biodegradable polymers [5, 7, 8]. Cells seeded on bioactive scaffolds showed enhanced expression of odontogenic markers such as dentin sialophosphoprotein (DSPP) and dentin matrix protein 1 (DMP1), indicating successful differentiation toward odontoblast-like phenotypes [8, 12]. Incorporation of growth factors, including VEGF and BMP-2, further increased angiogenic activity and extracellular matrix deposition, promoting an environment conducive to pulp regeneration [9, 13].

In the in vivo phase, regenerative endodontic procedures performed on immature permanent teeth resulted in notable clinical improvements. Radiographic analysis over a 12–18 month follow-up period revealed continued root development, apical closure, and increased dentin wall thickness in a majority of treated teeth [1, 3, 4]. Pulp vitality tests indicated the return of sensory function in approximately 68% of cases, while patient-reported outcomes showed significant reductions in pain and inflammation [10, 11]. Teeth treated with stem cell-seeded scaffolds combined with growth factors demonstrated superior regenerative outcomes compared to scaffold-only or conventional treatments, highlighting the synergistic effect of cellular and biomaterial interventions [12–15].

Statistical analysis confirmed that the observed improvements in root length, apical closure, and pulp vitality were significant ($p<0.05$) across all experimental groups. Moreover, no major adverse events or post-treatment complications were reported, underscoring the safety and feasibility of regenerative endodontic therapies in clinical practice [5, 6, 10]. Subgroup analysis suggested that younger patients and teeth with open apices showed more pronounced regenerative responses, indicating that patient selection and anatomical factors play a critical role in clinical outcomes [4, 9]. Overall, the results provide compelling evidence that the combination of stem cells, biomaterial scaffolds, and growth factors can successfully regenerate pulp-dentin complexes, offering a biologically based alternative to conventional root canal therapy while preserving natural tooth structure and function [1–15].

Conclusion:

Regenerative endodontics represents a transformative approach in modern dentistry, shifting the paradigm from conventional root canal therapy toward biologically based strategies aimed at restoring both the structure and function of the dental pulp. This study, supported by extensive in vitro and in vivo evidence, demonstrates that the combination of stem cells, biomaterial scaffolds, and growth factors can successfully promote pulp-dentin complex regeneration, resulting in continued root development, apical closure, and restoration of sensory function [1–3, 5–9]. The findings indicate that patient-specific factors, such as age, tooth development stage, and anatomical characteristics, significantly influence treatment outcomes, emphasizing the importance of individualized therapeutic planning [4, 10]. Furthermore, the integration of advanced scaffolds and bioactive molecules enhances cell proliferation, differentiation, and vascularization, thereby improving the predictability and effectiveness of regenerative procedures [7–9, 12, 13]. Clinical outcomes observed in this study, including pain reduction, radiographic evidence of tissue regeneration, and functional pulp recovery, highlight the potential of regenerative endodontics to preserve natural dentition, reduce tooth loss, and improve long-term oral health [1, 3, 10–12]. Despite the promising results, challenges such as standardization of clinical protocols, optimization of scaffold materials, and long-term monitoring remain, indicating the need for continued research and technological innovation [10–15]. Overall, regenerative endodontics offers a patient-centered, biologically driven alternative to traditional therapies, with the potential to significantly enhance clinical outcomes, maintain tooth vitality, and improve quality of life for patients with necrotic or damaged pulp tissue. Future directions in the field are likely to involve personalized regenerative protocols, integration of nanotechnology, and the development of novel biomaterials to further advance the efficacy and reliability of these therapies [12–15].

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