Chapter 5
Application of Responsive Intelligent Biomaterials in Regenerative Medicine

Wenqiang Xie
https://orcid.org/0000-0002-3888-8733
Southern Medical University, China

Yuan Su
Southern Medical University, China

Ruiqi Zhang
Southern Medical University, China

Sijia Li
Foshan University, China

Jia Ni
Southern Medical University, China

Longquan Shao
Southern Medical University, China

ABSTRACT

Responsive intelligent biomaterials, characterized by their ability to sense and respond to external or internal stimuli, have emerged as promising candidates in regenerative medicine (RM). RM aims to replace or regenerate damaged human cells, tissues, or organs to restore normal function. However, their mechanisms of action are not fully understood, especially at the molecular level. Studies on long-term stability, in vivo degradation, and tissue impact are lacking. Translation from research to clinical application faces challenges due to physiological and genetic differences between animal models and humans, and inadequate clinical data. This chapter summarizes the current applications of responsive intelligent biomaterials in RM, encompassing bone regeneration, cartilage regeneration, skin regeneration, nerve regeneration, and myocardial regeneration. This chapter aims to help overcome these hurdles and successfully apply responsive intelligent biomaterials in regenerative medicine.

1.INTRODUCTION

Trauma, tumors, and infectious diseases can lead to damage in various tissues, including bone, cartilage, skin, nerves, and myocardium (Li et al., 2022; Tariq et al., 2022; Kharaziha et al., 2021; Qi et al., 2021; Poongodi et al., 2021), significantly impacting the quality of human life. Restoring the morphological structure and function of these organs has become one of the major challenges faced by modern medicine.

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Traditionally, reconstructive approaches such as surgical intervention or organ transplantation have been employed to repair damaged tissues; however, these methods are associated with high medical costs and limitations such as secondary injuries, chronic infections, and a shortage of donor organs, resulting in unpredictable treatment outcomes (Zhou et al., 2022; Schraffordt Koops & Hoekstra, 1994). In recent years, the steady development and optimization of biomaterials have shown promising prospects for regenerative medicine (RM) in addressing issues of tissue damage and functional impairment (Gao et al., 2015). RM encompasses cell therapy and tissue engineering, aiming to replace or regenerate human cells, tissues, or organs to restore or establish normal function (Mason & Dunnill, 2008). The utilization of biomaterials that closely mimic the hierarchical structure of natural tissues is a critical component in achieving regeneration, with responsive intelligent biomaterials being regarded as the most promising materials in the field of regenerative medicine (Narkar et al., 2022).

Responsive intelligent biomaterials encompass active, responsive, and autonomous biomaterials (Montoya et al., 2021). Active biomaterials are designed to provide a planned unidirectional effect on biological processes or the surrounding environment, without reacting to external changes (Santin & Phillips, 2012). In contrast, autonomous biomaterials not only deliver targeted and precise therapies upon appropriate stimulation but also possess the ability to actively sense, respond to, and adapt to specific signals, interacting with their environment (Montoya et al., 2021). Currently, autonomous smart biomaterials are still quite rare. In comparison, Responsive intelligent biomaterials have been extensively developed and researched due to their capability to initiate or execute specific biological functions by sensing external or internal stimuli (Morris et al., 2016). These smart materials can dynamically alter their properties in response to various stimuli such as electrical, magnetic, optical, reactive oxygen species (ROS), and pH, thereby optimizing cellular behavior and tissue regeneration processes. This adaptability opens up possibilities for more effective and personalized treatment strategies. However, these advancements have not been comprehensively reviewed.

This article summarizes the current applications of responsive intelligent biomaterials in regenerative medicine, including bone regeneration, cartilage regeneration,skin regeneration, nerve regeneration, and myocardial regeneration. It particularly emphasizes their significant roles in tissue engineering, drug delivery, and personalized medicine, while also looking ahead to future development directions.

2. APPLICATION

2.1 Bone Regeneration

The skeletal system not only provides mechanical support for the body but also plays a crucial role in hematopoiesis, the development of the immune system, mineral storage, and glucose metabolism, among other complex physiological functions (Emmanuelle et al., 2021). Clinically, various diseases such as tumors, severe infections, osteoporosis, osteonecrosis, and some congenital malformations can cause large bone defects (Wei et al., 2022). Bone regeneration typically involves three phases: inflammation, repair, and remodeling. Currently, there are numerous strategies to promote the process of bone regeneration, including the “gold standard” of autologous bone grafting, allografting, and the use of growth factors, bone-conductive scaffolds, and distraction osteogenesis (Figure 1) (Wei et al., 2022; Godoy-Gallardo et al., 2020; Chen & Lv, 2018; Amini et al., 2012). However, these methods often fall short of achieving ideal treatment outcomes due to factors such as high costs, the need for a second