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Biodegradable metals

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ABSTRACT

After decades of developing strategies to minimize the corrosion of metallic biomaterials, there is now an increasing interest to use corrodible metals in a number of medical device applications. The term "biodegradable metal" (BM) has been used worldwide to describe these new kinds of degradable metallic biomaterials for medical applications and there were many new findings reported over the last decade. In this paper, the definition of BM and its classification are given for the first time, along with the summary of the degradation mechanisms of BMs and its environmental influencing factors, which includes the degeneration of mechanical integrity and the metabolism of the degradation products. The recently-developed representative Mg-based BMs (pure Mg, Mg–Ca alloy, Mg–Zn alloy, etc.), Fe-based BMs (pure Fe, Fe–Mn-based alloys, etc.) and other BMs (pure W, pure Zn and its alloys, Ca-based and Sr-based bulk metallic glasses, etc.) were comprehensively reviewed with emphases on their microstructures, mechanical properties and degradation behaviors, *in vitro* and *in vivo* performances, pre-clinical and clinical trials. Moreover, current approaches to control their biodegradation rates to match the healing rates of the host tissues with various surface modification techniques and novel structural designs are summarized. Finally, this paper comprehensively discusses the directions of future development and the challenges of transitioning BMs from raw materials to semi-products to final medical devices. All in all, BM belongs to "bioactive" biomaterials and its future research and development direction should lean towards "third-generation biomedical materials" with "multifunctional capabilities" in a controllable manner to benefit the local tissue reconstruction.

Contents

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1. Introduction

1.1. Definition and classification of biodegradable metals

The traditional paradigm of metallic biomaterials requires metals with improved corrosion resistance in the body. A new class of biodegradable materials – so called "biodegradable metals" (BMs) – has been breaking this paradigm recently, emerging as an alternative for biomedical implants.

The definition of BMs can be given as follows: BMs are metals expected to corrode gradually *in vivo*, with an appropriate host response elicited by released corrosion products, then dissolve completely upon fulfilling the mission to assist with tissue healing with no implant residues. Therefore, the major component of BM should be essential metallic elements that can be metabolized by the human body, and demonstrate appropriate degradation rates and modes in the human body.

From the point of view of the materials science, BM can be classified as follows:

1. "Pure metals" (BM-PM)

This category includes the metals mainly composed of one metallic element, with impurity levels lower than the commercial tolerance limits. The corrosion rates of biodegradable metals in this category are mainly driven by the included trace of impurities.

2. "Biodegradable alloys" (BM-BA)

This category encompasses biodegradable metals with various microstructures and one or more alloying elements. Given the concerns for bio-safety of the corrosion products, the alloying elements and their quantities should be controlled without causing adverse pathophysiological and toxicological effects. BM-BA also encompasses biodegradable metallic glasses and biodegradable single crystal metals, which exhibit glassy or single crystal states, respectively, and intend to readily corrode in the human body.

3. "Biodegradable metal matrix composites" (BM-MC)

This category requires that all components within the composites are biodegradable with the major component being