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REVIEW

Progress of biodegradable metals

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Abstract

Biodegradable metals (BMs) are metals and alloys 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. In the present review article, three classes of BMs have been systematically reviewed, including Mg-based, Fe-based and Zn-based BMs. Among the three BM systems, Mg-based BMs, which now have several systems reported the successful of clinical trial results, are considered the vanguards and main force. Fe-based BMs, with pure iron and Fe–Mn based alloys as the most promising, are still on the animal test stage. Zn-based BMs, supposed to have the degradation rate between the fast Mg-based BMs and the slow Fe-based BMs, are a rising star with only several reports and need much further research. The future research and development direction for the BMs are proposed, based on the clinical requirements on controllable degradation rate, prolonged mechanical stability and excellent biocompatibility, by optimization of alloy composition design, regulation on microstructure and mechanical properties, and following surface modification.

Keywords: Biodegradable metals; Magnesium; Iron; Zinc; Biocompatibility

1. Introduction

With the development of society and the improvement of living standards, the expectation for a better quality of life has been increasing. Researchers have to develop new materials and technologies in order to provide implants with higher clinical performance. In practical clinic applications, some specific clinical problems (such as bone fracture and vessel blockages) need only temporary support for tissue healing process. This temporary support can only be provided by an implant made of degradable biomaterials which allow the implant to progressively degrade after fulfilling its function. The concept of biodegradation has been known in medical applications for a long time, such as the use of biodegradable polymer sutures. However, implants that degrade, especially those made of metals and alloys, can be considered as a novel concept which actually breaks the established paradigm of “metallic biomaterials must be corrosion-resistant”[1].

The definition of biodegradable metals (BMs) had been 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 BMs should be essential metallic elements that can be metabolized by the human body, and demonstrate appropriate degradation rates and modes in the human body [2].

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Till now, the newly-developed BMs include three main body systems: Mg-based BMs [3–9] (pure Mg, Mg–Ca alloys, Mg–Zn alloys, Mg–Sr alloys, Mg–RE alloys, Mg-based bulk metallic glasses (BMGs), etc.), Fe-based BMs [10–13] (pure Fe, Fe–Mn alloys, Fe–W alloys etc.), Zn-based BMs [14–17] (pure Zn, Zn–Mg alloys and Zn-based bulk metallic glasses) and other BMs (Ca-based [18–21] and Sr-based BMGs [22–24], etc.). Fig. 1 shows the research status of the three main body BM systems: Mg-based BMs [4,7,9,25–42], Fe-based BMs [12,13,43–49], and Zn-based BMs [15–17,50–52]. It is quite clear that among these BMs, Mg-based BMs [3–9] are the research's vanguard and main force with hundreds of publications on the *in vitro* cytoxicity, animal testing and clinical trails, Fe-based BMs [10–13] are reported in tens of publications on alloy design and several animal testing as potential vascular stent, Zn-based BMs [14–17] are referred with less than ten publications but seems to be a rising star in the family of biodegradable metals.

2. Mg-based BMs

Mg based BMs are attractive for biodegradable implants because of their good mechanical properties and biocompatibilities. Promising Mg alloying systems including Mg–Ca, Mg–Sr, Mg–Zn, Mg–Si, Mg–Sn, Mg–Mn, Mg–RE and Mg–Ag have been developed [3–9]. The microstructures, mechanical properties, degradation behavior, ion release, in vitro and in vivo animal biocompatibility studies and clinical trials have been widely explored in order to evaluate their feasibility for biomedical purposes.

2.1. Mechanical properties

Fig. 2 shows the tensile properties of magnesium alloys, including pure Mg [30], Mg–Zn–Mn [53], Mg–Ca [4], Mg–Sr [7], Mg–Si [30], Mg–Zr [30], AZ91D [54], AZ31 [54], LAE442 [54], WE43 [54].

It is quite clear that magnesium alloys have a large range of ultimate tensile strength (UTS) and elongation to failure (EL), from 86.8 to 300 MPa and from 3% to 30%, respectively. Alloying and processing history have great effect on the mechanical properties of magnesium alloys. Adding Sn, Si, Zr and Zn can improve both the UTS and EL [30], while Ca, Sr and Mn will deteriorate their ductility to some extent [4,7,30]. Processing deformation (including hot rolling, hot extruding, and ECAP) also contribute to the strength and elongation of magnesium alloys [4,7,32].

2.2. Corrosion behavior

Although the reported inspiring results indicated that Mg-based BMs may be possible alternatives for permanent biomaterials. However, Mg-based BMs have rapid degradation rates in body fluids. The rapid degradation rate would result in the loss of mechanical integrity in a short period which can limit its application as an implant material. To control the biodegradation rate of Mg-base BMs, selection on alloying elements, microstructural adjustment and surface modification methods have been applied.

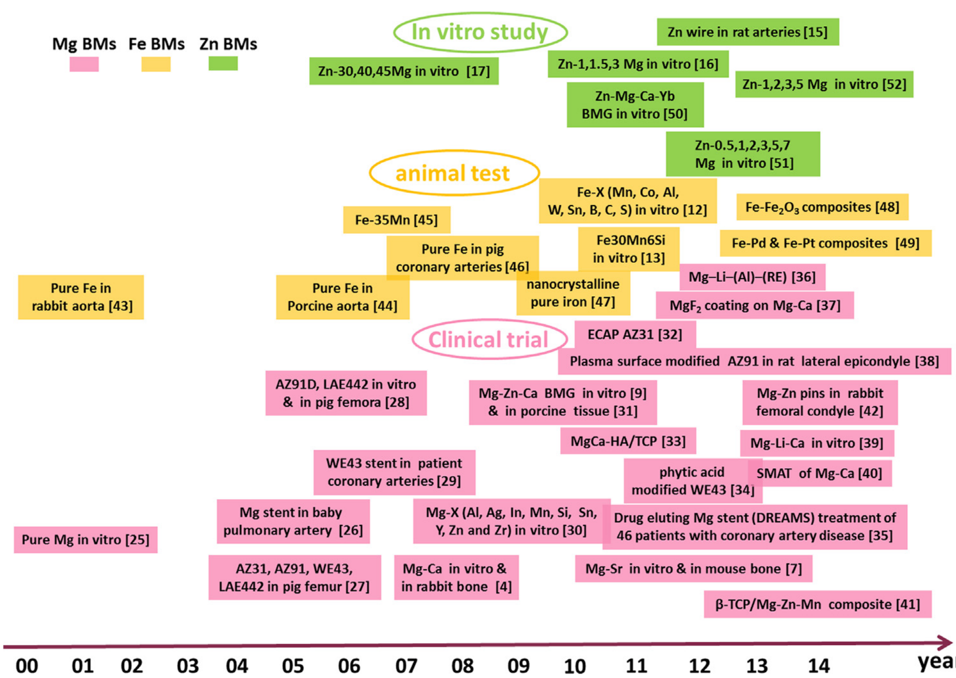

Fig. 1. Research status of the three BM systems: Mg-based BMs [4,7,9,25–42], Fe-based BMs [12,13,43–49], and Zn-based BMs [15–17,50–52].