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Review

Assessing the corrosion of biodegradable magnesium implants: A critical review of current methodologies and their limitations

N.T. Kirkland [a,b], N. Birbilis [b], M.P. Staiger [a,*]

[a] Department of Mechanical Engineering, University of Canterbury, Private bag 4800, Christchurch 8020, New Zealand
[b] Department of Materials Engineering, Monash University, Clayton, 3800 Victoria, Australia

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ABSTRACT

Magnesium (Mg) and its alloys have been intensively studied as biodegradable implant materials, where their mechanical properties make them attractive candidates for orthopaedic applications. There are several commonly used in vitro tests, from simple mass loss experiments to more complex electrochemical methods, which provide information on the biocorrosion rates and mechanisms. The various methods each have their own unique benefits and limitations. Inappropriate test setup or interpretation of in vitro results creates the potential for flawed justification of subsequent in vivo experiments. It is therefore crucial to fully understand the correct usages of each experiment and the factors that need to be considered before drawing conclusions. This paper aims to elucidate the main benefits and limitations for each of the major in vitro methodologies that are used in examining the biodegradation behaviour of Mg and its alloys.

1. Introduction

Magnesium (Mg) and its alloys have been investigated since as early as 1878 for their potential use as a biomaterial [1]. They can offer a number of benefits as implant materials, especially with their unique ability to act as load-bearing implants that may safely degrade in vivo [2]. Although the majority of practical applications so far have focused on stents [3,4], the biodegradation/mechanical properties of Mg alloys is an especially attractive combination for orthopaedic applications, where long-term permanent fixtures typically have mismatched mechanical properties with bone and may suffer a number of issues induced from wear and undesirable corrosion [5]. Although their potential for biological applications is clear, the development of a clinically relevant biomedical magnesium implant would require thorough in vivo testing, initially using animal models and eventually humans. However, several factors significantly hinder the effective use of in vivo tests, including time and cost, but most notably the potential harm and discomfort such studies can cause to the experimental subjects. Thus, it is vital to use appropriate in vitro tests to pre-screen Mg alloys to determine their suitability for subsequent in vivo studies.

In vitro tests for Mg are classified into two broad categories, concerned with either: (i) biocorrosion resistance (or biodegradation behaviour) or (ii) toxicity/interaction with biological organisms. Clearly, the latter in many cases is related to the former since rapid degradation can lead to toxicity and other negative biological reactions. Toxicity is almost always assessed in the presence of living cells, while corrosion testing does not have this requirement. Corrosion of magnesium alloys is a complex process, requiring a combination of different techniques for complete characterization [6]. The various test methods available to measure corrosion are grouped into two categories: (i) unpolarized and (ii) polarized. The difference between these methods relates to the presence of a driving force (i.e. electrochemical polarization) which is applied or measured during the test. In this particular work, degradation behaviour is the predominant concern. It should be noted that the terms "biocorrosion" or "biodegradation" used in this work refer to any corrosion that takes place in a simulated body environment.

It should be considered that, at present, a strong correlation between in vitro and in vivo corrosion results has yet to be established in any reported work. However, this does not detract from the need or the relevance of the present work, as it will only be possible to potentially establish a useful correlation in any sense if the in vitro experiments are carried out and analysed appropriately. In addition, most of the studies that have performed in vitro tests alongside in vivo have suffered from an unphysiological or uncontrolled pH during testing [7–9], an inappropriate amount of test solution to surface area [10], or only reported qualitative results [11–13]. Thus, a lack of correlation at this point in time does not preclude the development of such a relationship at a later stage.

Correct interpretation of corrosion-related data is dependent on the experimental setup parameters that must be understood and

* Corresponding author. Tel.: +64 3 364 2987; fax: +64 3 364 2078.
E-mail address: mark.staiger@canterbury.ac.nz (M.P. Staiger).

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