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Biocompatibility, Corrosion Behavior, And Ion Release Characteristics Of Mg–Zn Alloys For Biodegradable Urological Stents

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Abstract

The development of biodegradable metallic materials has become a major focus in modern biomedical engineering due to their ability to provide temporary mechanical support while eliminating the need for secondary surgical removal. Magnesium-based alloys have emerged as promising candidates for biodegradable implants owing to their favorable mechanical properties, biodegradability, and biological compatibility. The present study evaluates the corrosion behavior, ion release characteristics, and potential biocompatibility of Mg–Zn alloys intended for application as biodegradable urological stents. Particular attention is given to Mg–4Zn alloys under simulated physiological and acidic conditions. In vitro investigations demonstrated that the concentrations of released Mg^{2+} and Zn^{2+} ions remained within biologically acceptable ranges throughout the experimental period. Furthermore, Mg–4Zn alloys maintained structural integrity for up to 30 days even under conditions of elevated acidity, which simulates pathological urinary environments. These findings suggest that magnesium-zinc alloys possess suitable degradation kinetics and biological safety for temporary urinary tract implants. The study contributes to the growing body of evidence supporting the clinical potential of biodegradable magnesium-based devices in urological applications.

Keywords: Magnesium Alloys, Biodegradable Stents, Urology, Biocompatibility, Corrosion, Magnesium Ions, Zinc Ions, Biomaterials

Introduction

The increasing prevalence of urinary tract disorders requiring temporary stenting has stimulated the search for innovative biomaterials capable of providing adequate mechanical support while minimizing long-term complications. Conventional urological stents are commonly manufactured from polymeric materials or permanent metallic alloys. Although these devices effectively restore urinary flow, they frequently require secondary procedures for removal, increasing patient discomfort, healthcare costs, and the risk of complications.

Biodegradable materials have emerged as an attractive alternative because they gradually degrade after fulfilling their clinical function. Among various biodegradable metals, magnesium and its alloys have received considerable attention due to their favorable combination of mechanical strength, low density, and biological relevance. Magnesium is an essential element involved in numerous physiological processes, including enzyme activation, nucleic acid synthesis, and bone metabolism.

Despite these advantages, the rapid degradation of pure magnesium in physiological environments remains a significant challenge. Excessive corrosion may lead to premature loss of mechanical integrity and uncontrolled hydrogen evolution. Alloying magnesium with zinc represents an effective strategy for improving corrosion resistance while maintaining biocompatibility. Zinc is also an essential trace element involved in cellular proliferation, immune regulation, and tissue repair.

The present study investigates Mg–Zn alloys with varying zinc concentrations and focuses on the corrosion behavior and ion release characteristics of Mg–4Zn alloys under simulated urinary conditions. The findings provide important insights into the suitability of these materials for biodegradable urological stents.

Literature Review

Biodegradable Metals in Urology

Biodegradable implants have revolutionized several fields of medicine, including orthopedics, cardiovascular surgery, and tissue engineering. In urology, biodegradable stents offer the possibility of eliminating retrieval procedures while maintaining adequate urinary drainage during healing.

Several classes of biodegradable materials have been investigated, including polymers, ceramics, and metals. While biodegradable polymers have shown promise, they often suffer from inadequate mechanical strength and unpredictable

degradation behavior. Metallic biomaterials provide superior mechanical performance and therefore have become increasingly attractive for load-bearing and lumen-supporting applications.

Magnesium as a Biomaterial

Magnesium possesses mechanical properties that closely resemble those of natural tissues. Its elastic modulus is substantially lower than that of stainless steel and titanium, reducing stress shielding effects. Furthermore, magnesium naturally participates in human metabolism and can be safely excreted or incorporated into physiological processes.

Previous studies have demonstrated that magnesium degradation products are generally well tolerated by biological systems. However, excessive corrosion may lead to local alkalization and hydrogen accumulation, necessitating optimization of alloy composition.

Role of Zinc in Magnesium Alloys

Zinc is one of the most commonly used alloying elements in biodegradable magnesium systems. Its addition improves mechanical strength through solid solution strengthening and grain refinement mechanisms. Moreover, zinc contributes to enhanced corrosion resistance by modifying microstructural characteristics.

Several investigations have shown that increasing zinc content can effectively reduce corrosion rates while maintaining favorable biological properties. Mg–Zn alloys have therefore become leading candidates for biomedical applications requiring controlled biodegradation.

Corrosion Behavior in Urinary Environments

The urinary tract presents a particularly challenging environment for biodegradable implants due to fluctuations in pH, ionic composition, and infection status. Pathological conditions may result in acidic urine, accelerating degradation processes.

Studies have reported that alloy composition significantly influences corrosion kinetics in urinary simulants. The ability of Mg–Zn alloys to retain structural integrity under acidic conditions is particularly important for clinical success.

Methodology

Materials Preparation

Magnesium-zinc alloys containing varying zinc concentrations were prepared using conventional metallurgical techniques. Experimental groups included pure magnesium, Mg–0.5Zn, Mg–1Zn, and Mg–4Zn alloys.

Corrosion Testing

Samples were immersed in simulated physiological media designed to reproduce urinary tract conditions. Additional experiments were conducted under acidic environments to simulate pathological urinary pH values.

Mass loss measurements, surface morphology analyses, and structural evaluations were performed over a 30-day period.

Ion Release Analysis

Concentrations of magnesium and zinc ions released during degradation were quantified using standard analytical techniques. Measurements were performed at predetermined intervals throughout the immersion period.

Biocompatibility Assessment

Biocompatibility was assessed indirectly through evaluation of released ion concentrations and comparison with established biological safety thresholds reported in the literature.

Discussion

The results demonstrated that Mg–Zn alloys exhibit degradation characteristics suitable for temporary biomedical applications. The release of Mg^{2+} and Zn^{2+} ions remained within biologically acceptable limits throughout the experimental period.

Magnesium ions are naturally present in extracellular fluids and play important physiological roles. Moderate increases in local magnesium concentrations may even promote tissue regeneration and cellular activity. Similarly, zinc ions participate in numerous enzymatic processes and contribute to tissue repair mechanisms.

The observed ion concentrations suggest that degradation products generated by Mg–Zn alloys are unlikely to induce toxic effects. This finding represents a critical requirement for clinical translation.

A particularly significant observation was the ability of Mg–4Zn alloys to maintain structural integrity for 30 days under acidic conditions. Acidic environments generally accelerate magnesium corrosion; therefore, preservation of implant stability under such conditions indicates enhanced corrosion resistance.

For urological stents, maintaining mechanical functionality during the healing period is essential. Premature degradation may result in loss of urinary drainage and treatment failure. The results indicate that Mg–4Zn alloys provide a favorable balance between biodegradability and mechanical persistence.

The improved performance of Mg–4Zn alloys may be attributed to microstructural modifications induced by zinc addition. Zinc-containing phases likely contribute to the formation of more protective corrosion layers, reducing degradation rates.

These findings align with previous studies demonstrating enhanced corrosion resistance in magnesium-zinc systems. However, the present work specifically highlights their suitability for urinary tract applications characterized by variable pH conditions.

Clinical implications are substantial. A biodegradable stent capable of maintaining functionality for approximately one month while gradually degrading thereafter could eliminate the need for device retrieval procedures. Such an approach would reduce patient burden and healthcare costs while minimizing procedure-related complications.

Conclusion

The present study demonstrates that magnesium-zinc alloys possess promising characteristics for biodegradable urological stent applications. In vitro investigations revealed that released Mg^{2+} and Zn^{2+} concentrations remained within biologically acceptable limits, indicating favorable biocompatibility.

Furthermore, Mg–4Zn alloys maintained structural integrity for up to 30 days under acidic conditions, suggesting sufficient corrosion resistance for temporary urinary tract support. The combination of controlled degradation, acceptable ion release, and prolonged structural stability supports the potential use of Mg–4Zn alloys as biodegradable stent materials.

Future studies should include comprehensive in vivo evaluations to further investigate tissue responses, degradation kinetics, and long-term clinical performance.

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