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The Future of Zinc Implant: Its Revolutionary Effects in Modern Advancements – A Short Overview

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ABSTRACT

Conventional non-biodegradable medical implants made of stainless steel, cobalt and titanium alloys used as fixation devices in various orthopaedic applications in human body need to go for secondary surgical removal, as it leaves the effect of patient trauma and medical device-associated infections, creating a challenging complication. Current research has shown an optimistic pathway by developing next-generation temporary orthopaedic implants holding the hand of Zn-based biodegradable alloys and its composites as an alternative to customary implants that could eliminate the scope of revision surgeries and ease the biocompatibility issues. The fundamental benefit of using Zn-alloys, including Zn-Mg, Zn-Mn, Zn-Ca and Zn-Al, instead of pure zinc metal as biomedical implants in terms of its mechanical properties, considering its strength, hardness, tensile and corrosion properties along with its composition and microstructure, has been discussed here. Usage of zinc as a metal in the implant has an additional utility to overcome its deficiency in human body. Surface coating with bioactive material, hydroxyapatite on the zinc medical implant becomes fruitful, enabling better interaction with biological tissues and enhancing its osteogenic potential, making it suitable for placing in the body. This article methodically discusses the overview about the utility of biodegradable bone implants in fracture healing and its effects on the reduction of implant-associated infections. The future direction regarding the problems of using zinc implants and further betterment in its orthopaedic application reducing the risk of side effects has also been reviewed here. Overall, the purpose of using zinc biomedical implants is considered to offer greater cost-effectiveness compared to traditional metallic implants such as titanium or stainless steel.

Keywords: *Alloying; Biocompatibility; Corrosion Resistance; Orthopaedic Surgeries; Zinc Implant*

Introduction

Bone fractures present a significant global health challenge, with an increasing prevalence due to factors like an ageing population, trauma from traffic accidents, sports injuries and metabolic diseases. The most commonly fractured bones are those of the lower leg, including the patella, tibia, fibula and ankle, which can lead to momentous long-term burdens for patients due to their frequent occurrence (Shuai *et al*., 2019; Wu *et al*., 2021). The process of fracture healing is intricate and involves the restoration of both the biological and biomechanical integrity of the bone, including the repair and regeneration of bone tissue. Successful healing is heavily dependent on the mechanical stability provided during the recovery phase, which is typically achieved through internal fixation surgical methodology by the use of screws, plates and pins, placing them strategically to hold the fractured bone fragments in place, providing the necessary support for the bone to heal by minimising movement that could disrupt the healing process (Foster *et al*., 2021).

In recent years, the field of biomedical engineering has witnessed significant advancements aimed at enhancing the efficacy, high strength and safety of medical implants. Metallic materials and their alloys are widely favoured as implant materials due to their considerable strength, adequate ductility, formability, reasonable corrosion, wear resistance and hardness, which becomes extremely difficult to achieve with other conventional materials. Millions of patients worldwide rely on these implants to restore physiological functions and enhance their quality of life significantly. Fracture fixation implants are commonly used in orthopaedic surgery to stabilise bone fractures and facilitate proper healing. These implants are designed to provide mechanical support to the bone during the healing process, allowing patients to recover by minimising the risk of malunion or nonunion of fractured bones. These implants predominantly consist of non-biodegradable metals like stainless steel, cobalt (Co) and titanium (Ti) alloys, serving both permanent and temporary implant needs (Al-Shalawi *et al.*, 2023). However, employing non-biodegradable materials in medical applications can lead to future complications and the risk of chronic inflammation or infection, often necessitating revision surgery to remove or replace the implants once they have fulfilled their purpose.

In response to these confinements, the exploration of biodegradable metals, particularly zinc, is revolutionising the way medical implants are conceived and used. Recent research on biodegradable metals offers the potential to eliminate the need for secondary surgeries, significantly enhancing patient compliance and reducing medical expenses (Paiva *et al.*, 2022). Unlike traditional permanent implants, the medical field has shown significant interest in biodegradable metals such as magnesium, iron and zinc alloys because of their exceptional mechanical properties that are comparable to traditional permanent implants made of stainless steel or titanium in addition to their ability to degrade naturally. These metals are strong enough to support bone healing or provide structural stability in cardiovascular devices during the necessary healing period.

Among the materials explored for implant applications, zinc, a material long known for its essential biological functions in the human body, has garnered significant attention in the medical field as a promising candidate for its use as biodegradable implants due to its unique combination of bio-compatibility and corrosion resistance (Paiva *et al.*, 2022). This material, when used in the body, does not provoke an adverse immune response or cause toxicity and also integrates well with biological tissues. Zinc exhibits a favourable combination of corrosion resistance and biodegradability, making it an ideal candidate for temporary implants.

In orthopaedic surgeries, zinc-based implants have materialised as a propitious alternative, particularly for the repair and reconstruction of injured or damaged bones. Owing to their eccentric combination of mechanical properties, biocompatibility and biodegradability, zinc materials are establishing to be highly promising for a wide range of biomedical applications. By harnessing zinc's natural properties, involving its ability to promote tissue integration and minimise inflammatory responses, this mini-review article drives towards substantial advancements in the field of implantology, with the ultimate goal of developing safer, more efficient medical devices. Furthermore, this review article seeks to address key challenges in implant technology, such as ensuring long-term stability and improving material properties, through the exploration of innovative approaches. By expanding the understanding of the potential of zinc implants, the advancement of medical technology is promoted, leading to improved patient outcomes across a variety of surgical treatments.

Literature Review

Zn Vs Other Biodegradable Metals for Implant Technology

When comparing Zn to other biodegradable metals like Mg, Fe for implant technology, it's crucial to consider several critical factors, such as biocompatibility, degradation rate, mechanical properties and biological response of the body. Zinc is considered biocompatible, elucidating that upon its implantation into the body, it does not trigger any significant immune response or cause detrimental reactions (Li *et al*., 2024). Principally, it refers to the ability of a material to interact with the body without causing adverse effects, such as inflammation, toxicity or rejection, making it a scatheless preference for medical implants. Zinc's biocompatibility can be attributed to its natural presence in the body, reduced toxicity, healing-promoting effects, gradual degradation and minimal inflammatory response, converting it to an exemplary material for curative implants that communicate safely with living tissue (Roesner *et al*., 2023).

Magnesium is also a lightweight metal with marvellous biocompatibility, shaping it a challenging material for biodegradable implants. Magnesium alloys are especially favoured in bone implants because of their close resemblance of mechanical properties to those of natural bone (Tsakiris, Tardei & Clicinschi, 2021). In spite of having some explicit qualities, magnesium metal has a comparatively faster corrosion rate in the human body. Upon degradation, it reacts with water and body fluids, producing hydrogen gas. The general reaction is:

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$$

During accumulation of hydrogen gas in the surrounding tissue, gas pockets formation appear, giving rise to swelling and discomfort at the implant site potentially leading to gas embolism (Tsakiris, Tardei & Clicinschi, 2021). It disrupts the normal flow of blood, resulting in ischaemia or tissue death. The production of hydrogen gas can persuade an inflammatory reaction, as the body tries to remove or encapsulate the gas bubbles, delaying the healing process or even causing potentially local tissue damage, swelling and pain. In addition to this, the expeditious corrosion of magnesium could lead to the implant losing its structural integrity before the bone or tissue gets enough time to get fully healed, as the implant degrades at a much faster rate, leading to premature degradation (Chakraborty Banerjee *et al*., 2019).

Iron is another option as a biocompatible material, investigated for its utilisation as a biomedical implant, distinctly in the form of iron-based alloys. Familiarity with iron due to its strong mechanical properties is beneficial for load-bearing applications. The rate of corrosion of iron is typically slower than magnesium, resulting the formation of iron oxide and other by-products which can be accumulated around the implant. Slow corrosion, although it creates a lesser problem in terms of gas formation, can lead to long-term complications. The reasonably slow release of corrosion products like iron oxide into the surrounding tissue can cause an inflammatory response. In the long run, these corrosion products might lead to the formation of fibrous tissue around the implant, interfering with the healing process, or cause a foreign body reaction. This lowers the efficiency of the implant appreciably, which may require removal or replacement. Due to slower rate of corrosion of iron, the implant may persist in the body for an extended period. While this could be beneficial in some cases, it may also prevent the body from naturally replacing the implant with native tissue. This could lead to long-term issues like chronic inflammation, infection or even the implant's failure to integrate properly with surrounding tissue. Additionally, the implant may not degrade in particular time for complete healing of the body which may not allow the bone or tissue around it to bear the normal stresses, resulting in stress shielding (Liverani *et al*., 2021). The surrounding tissue becomes weaker with time as the implant takes on too much of the mechanical load.

Zinc exhibits a moderate corrosion rate that is generally slower and more controlled than Mg but faster than iron. This intermediate rate can be advantageous in implant applications, as it allows for gradual degradation, avoiding rapid gas formation like magnesium or long-term persistence in the body like iron. A moderate corrosion rate ensures more predictable degradation timeline of zinc-based implants, which aligns better with the body's natural healing processes (Liu *et al*., 2025). Moreover, zinc exhibits more favourable corrosion behaviour in a physiological environment. Unlike Fe, upon corrosion zinc forms zinc oxide, which is biocompatible and non-toxic to the body. Zinc degrades into products that can be easily handled and metabolised by the body (Kabir *et al*., 2021). Zn offers a favourable balance of mechanical properties, including sufficient strength and ductility, which can be customised through alloying. In contrast, Mg is less mechanically stable due to its rapid corrosion, which may be a limitation in load-bearing implants. Its low modulus of elasticity fails to match the mechanical properties of bone well, leading to stress shielding (Liverani *et al.*, 2021). Iron, while stronger than magnesium, is prone to forming rust when exposed to moisture, leading to the weakening of its structure over time, diminishing necessary stimulation for bone growth. Iron has a high modulus of elasticity, meaning it is rigid and resists deformation under stress. Although this stiffness can be advantageous in some situations for structural integrity, it can be problematic when used in the human body. Especially biomedical implants, while inserted into bone or soft tissue, they are usually at risk of bacterial colonisation, which can lead to infections. Natural antibacterial properties of zinc metal diminish this risk, making it an appropriate option for orthopaedic purposes. Zinc ions possess intrinsic antibacterial properties, offering a significant advantage in reducing the risk of infection at the implant site (Sirelkhatim *et al.*, 2015). Zinc ions inhibit the growth of a wide range of bacteria by disrupting bacterial cell walls, interfering with the enzymatic activity and promoting oxidative stress within the bacteria. This distinction in the properties of Zn from Mg and Fe, those lacking such antibacterial properties, makes it an optimistic member because it presents a well-rounded profile, striking a balance between all of these factors. Its antibacterial properties, along with its biocompatibility, moderate mechanical strength and predictable degradation rate, make it an ideal choice for biodegradable implant applications.

Importance of Zinc in the Human Body

Zinc is an indispensable trace mineral that plays a vital role in many of the human body's biological processes. It is found to be present in all organs, tissues, fluids and body secretions (Weyh *et al*., 2022). However, its concentration varies remarkably across different parts of the body. Zinc is particularly present in significant abundance in skeletal muscles and bones, as it plays a crucial role in protein synthesis, enzyme activation and bone mineralisation. It helps in bone growth, tissue repair and largely in maintaining muscle integrity, promoting recovery after exercise or injury. A small amount of the body's total zinc is present in the skin as well. Zinc is involved in wound healing and immune function of the skin, protecting against infections and supporting tissue regeneration (Mutlu *et al*., 2022). The liver stores a small percentage of the body's total zinc and is involved in digestion and zinc metabolism. It plays a key role in detoxification, hormone synthesis, and storage of essential nutrients and produces proteins such as albumin. In the brain also, zinc is involved in several important functions, such as neurotransmitter regulation, neuroplasticity and synaptic transmission. It has significant role in memory formation, learning and cognitive function. It is also crucial for the enzymes in the brain that manage oxidative stress and safeguard neurones from damage (Li *et al*., 2022). The remaining percentage of zinc in the body is distributed across various other tissues and fluids, including blood plasma, cerebrospinal fluid, saliva, etc., and in semen, breast milk, urine and sweat as a part of body secretions. Zinc plays a crucial role in various physiological processes.

Functions

1 Impact of Zinc in Immune Function

Zinc is an essential mineral for the actual functioning of the immune system, playing a role of the utmost importance in both innate and adaptive immunity (Weyh *et al.*, 2022). Innate immunity provides a rapid, non-specific response to a broad spectrum of pathogens, including bacteria, viruses, fungi and parasites, while adaptive immunity is highly specific to the pathogen as it encounters by recognising unique molecules known as antigens on the surface of pathogens. It assists in the development, differentiation and activation of key immune cells, most impressively T-cells and B-cells, which are central to the body's ability to defend against pathogens such as viruses, bacteria and other harmful invaders (Maywald & Rink, 2022).

Zinc plays a pivotal role in the development and differentiation of T-cells, which are typically a subset of white blood cells that is essential in the immune system. T-cells are responsible for directly attacking infected cells, simultaneously coordinating the overall immune response. Zinc is necessary for the activation of T-cells upon encountering pathogens. When the immune system detects an infection, T-cells are activated to either attack infected cells directly via cytotoxic T-cells or regulate other immune cells to orchestrate an effective immune response through helper T-cells. A zinc deficiency results in lowering number of T-cells and hinders T-cell response, which becomes difficult for the body to effectively mount an immune response. Individuals with zinc deficiency are more susceptible to infections due to a compromised T-cell-mediated immunity. Zinc is equivalently important for the development and function of B-cells, which are necessary for adaptive immunity. B-cells are fundamentally responsible for producing antibodies, also known as immunoglobulin, which are proteins that recognise and bind to specific pathogens, neutralising them and signalling for their destruction by other immune cells. Inadequate zinc levels in the body can result in a reduced ability to produce antibodies, leaving the body more susceptible to infections and disturbing the formation of immune memory (Haase & Rink, 2009).

2. Zinc as a Co-Factor in Enzyme

Zinc serves as a predominant cofactor for many enzymes may be more than 300 (Sangeetha *et al*., 2022), which is a non-protein substance required for the proper functioning of these enzymes. Zinc is essential for enabling critical biochemical reactions in the body. Insufficient amount of zinc results in making the enzymes incapable of functioning efficiently, leading to disruptions in various biological processes. Zinc dependent enzymes, DNA Polymerases are responsible for DNA replication, a crucial process where a cell duplicates its DNA before division. Zinc acts as a cofactor in DNA polymerase to facilitate the addition of nucleotides and ensure the smooth progression of DNA replication (Costa, Sarmento-Ribeiro & Gonçalves, 2023). Zinc is also involved in the activity of DNA ligases, enzymes that are essential for DNA repair. Another enzyme where zinc plays an essential role is RNA polymerase, which is responsible for transcribing DNA into RNA. This is a crucial step in the process of protein synthesis. Zinc ensures the correct function of RNA polymerase, facilitating the process of transcription.

3. Bone Health: The Importance of Zinc in Mineralization

Zinc contributes an essential character for the bone formation, remodelling, and mineralisation and in the activity of osteoblasts (O'Connor *et al*., 2020). It also influences calcium metabolism by maintaining bone density and strength by supporting collagen synthesis, which is a primary component of bone matrix. It also escalates mineral deposition, mainly calcium and phosphorus into the bone matrix, which are crucial for the hardening and strengthening of bones. Zinc helps in maintaining balanced bone turnover that involves both bone resorption by breaking down old bone and bone formation through the building of new bones. Requisite zinc levels are essential for preventing conditions like osteoporosis and promoting overall skeletal health, preventing fractures.

4. Wound Healing and Tissue Repair

Zinc accelerates wound healing by promoting collagen synthesis at the proliferative phase of wound healing, when new tissue is formed. It is responsible for modulating inflammation, preventing excessive or chronic inflammation, which could impair healing. An imbalance in the inflammatory response can lead to prolonged healing times or poor wound closure. Zinc has a direct impact on cell proliferation and differentiation, which makes the formation of new tissue and the closure of the wound difficult. Zinc provides significant antioxidant protection involving prominent cellular activity, including cell turnover, immune cell function, and collagen synthesis, all of which generate reactive oxygen species (ROS) or free radicals. Excessive ROS can cause oxidative stress, which can damage cells and impair the healing process (Mutlu *et al*., 2022). It is mention-worthy that, in spite of frequent recommendations of zinc supplements for individuals with chronic wounds or impaired healing processes, one should be careful in terms of avoiding excess zinc intake. Overall, zinc plays a major role in all stages of the wound healing process, ensuring efficient tissue repair and regeneration.

5 Sources of Zinc for Optimal Health

Zinc is a vitally important trace mineral that takes part in an extensive role in several key biological processes, such as supporting the immune system, facilitating protein synthesis, promoting wound healing and availing DNA synthesis. As zinc cannot be stored in the body system, its intake must be in a regular fashion from various dietary sources. These sources can be classified into two main groups: animal-based foods and plant-based foods.

1. Animal-Based Sources of Zinc

Animal-based foods are considered the most bioavailable sources of zinc. Compared to plant-based sources, animal-based ones are more easily absorbed by the body. In animal-based products, zinc is bound to proteins and is generally better absorbed due to reduced levels of compounds like phytates that inhibit absorption. The richest sources of zinc are available in shellfish, chiefly oysters and other seafood like crab and lobster are also considered to be wonderful sources. Among red meats, beef and lamb, particularly from their lean cuts, are excellent sources of zinc along with pork, chicken, and most importantly, organ meats like liver, which also provide substantial amounts of zinc. Dairy products like cheese, especially cheddar, are a perfect source of zinc. Milk, yoghurt and eggs are also considered to be the animal-based sources of zinc in moderate amounts (Sangeetha *et al*., 2022).

2. Plant-Based Sources of Zinc

Most legumes, involving chickpeas, lentils, kidney-beans and soy products, are excellent sources of zinc. Different kinds of nuts and seeds particularly pumpkin seeds, sesame seeds, cashews, almonds, peanuts, and hemp seeds have very good contribution to the daily intake of zinc as plant-based sources (Ayaz *et al*., 2024). Certain vegetables like spinach, mushrooms, asparagus and broccoli provide some zinc, making it a good addition to a balanced diet. Quinoa, brown rice, whole wheat, oats and fortified cereals contain good amounts of zinc. But it is mention-worthy that, like legumes, phytate in grains can reduce adsorption of zinc in human body (Sangeetha *et al*., 2022). Maintaining a varied diet and employing strategies to improve zinc absorption can help ensure optimal zinc levels in the body.

3. Systematic Symptoms of Zinc Deficiency and Excess in Human Body

Zinc has appeared as a dominant trace element owing to its remarkable characteristics in carrying out an assorted set of physiological processes in human body. Problems arising out of deficiency and excess amounts of zinc intake can give rise to various significant symptomatic impacts in bodily systems.

Inadequate dietary intake, poor absorption arising from illness or mal-absorption disorders can show broad effects causing zinc deficiency. Deficiency of zinc results in immune system dysfunction, leading to increased susceptibility to infections and delayed wound healing. It affects growth and development issues, causing stunted growth in infants and children along with their delayed sexual maturation. It causes skin problems involving dermatitis, particularly acrodermatitis enteropathica, acne and hair loss complications. The effects of cognitive dysfunction and delayed mental development are also the outcomes of zinc deficiency. Anorexia-like symptoms showing impairment in the senses of taste and smell together with the problem of infertility also materialise due to a lack of zinc intake (Prasad, 1985).

Consumption of higher concentration of zinc supplements or prolonged exposure to its high level, i.e., more than 40 mg/day for adults, can cause severe toxicity showing a wide range of symptoms in the body (Hussain *et al*., 2022). It results in gastrointestinal distress, including nausea, vomiting, abdominal cramps and diarrhoea along with loss of appetite. Excessive zinc intake can cause immune system dysfunction, disrupting the balance of copper in the body, leaving one more disposed to infections. Chronic zinc toxicity can interfere with the absorption of copper, leading to copper deficiency, resulting in symptoms such as anaemia. Zinc excess in the body can show neurological disorders, with cognitive impairments having issues such as difficulty in concentrating and memory problems. Kidney and liver damage and elevated cholesterol levels are also the effects arising out of excessive zinc consumption. There also develops a metallic taste in the mouth diminishing the sense of taste and smell (Prasad, 1985). It is of the foremost importance to balance zinc intake to avoid toxicity while it ensures vital benefit for optimal health.

Potentiality of Zinc in Bio-Application

For human health, zinc, as an essential trace element, plays a decisive role in numerous biological processes. Its key role in the involvement of crucial enzymatic reactions, cellular signalling, and gene expression makes it indispensable for maintaining cellular function and overall health (Stiles, Ferrao & Mehta, 2024). Beyond these fundamental physiological functions, the distinctive properties of zinc have led to its growing importance in biomedical applications. In the biomedical industry, zinc holds considerable promise, with a broad range of potential applications. Its use in drug delivery system has been increasingly explored, where it enhances its efficacy in the targeted release of medications to specific areas of the body, developing therapeutic effectiveness and diminishing side effects. Besides its role in drug delivery, zinc is also being investigated for its utilisation in medical imaging, where its unique properties can aid in the detection and monitoring of diseases through advanced imaging techniques (Firth *et al*., 2022). Moreover, zinc's bactericidal properties make it an ideal candidate for developing antimicrobial coatings. These coatings can be applied to medical devices, such as catheters or surgical instruments, to reduce the risk of infections and enhance patients' safety. Zinc's ability to combat bacterial growth is also being harnessed by the development of coatings on implants, which are used in orthopaedic and dental procedures. Zinc-based materials are particularly attractive in implant technology because they can promote cell growth, reduce inflammation, support the healing process and, most importantly, provide an antimicrobial effect. Zinc oxide coatings are well known for their antifungal and antibacterial properties, making them useful for coating biomedical devices and reducing the risk of becoming infected. All in all, zinc's versatility and distinct biological properties make it a highly valuable element in advancing multiple aspects of biomedical technology, boosting treatment effectiveness, and enhancing the safety and performance of medical devices and implants.

Zinc in Medicine: Applications and Therapeutic Roles

Zinc has numerous applications in medicine due to its essential role in various physiological processes.

1. Treatment of Diarrhoea

Zinc is comprehensively recognised for its effectiveness in the treatment of diarrhoea, particularly in children. Diarrhoea is one of the dominant causes of mortality in children under five years of age, especially in developing countries. The World Health Organisation (WHO) and UNICEF recommend zinc supplementation, typically 10-20 mg per day for 10-14 days at a particular dosage, as part of the treatment for acute diarrhoea in children (Ali *et al*., 2024).

2. Treatment of Wilson's Disease

Zinc is used in the treatment of Wilson's disease, a rare genetic disorder characterised by excessive copper accumulation in the liver and other tissues, including the brain and kidneys in the body (Avan *et al*., 2022). Zinc helps in lowering the copper level in the body by blocking copper absorption in the intestines and promoting its excretion through the gastrointestinal tract. It is considered a safe and effective long-term treatment, especially for maintenance therapy after initial treatment with chelating agents.

3. Dental Application

Zinc oxide-eugenol is widely used in dentistry for temporary fillings and as a base for dental cements (Peutzfeldt & Asmussen, 1999). Its soothing properties and ability to form a tight seal in cavities make it effective in protecting the underlying dental pulp and also reduce sensitivity, preventing further decay. In addition to this, zinc in dental alloys enhances their resistance to corrosion and wear, ensuring longer-lasting dental restoration that is less likely to degrade or cause adverse reactions in the mouth.

4. Topical Treatment

Zinc in topical treatments is significantly used for its anti-inflammatory, antimicrobial and wound-healing properties. Zinc oxide is one of the most common forms of zinc used in topical applications. It is a common ingredient in creams and ointments which treat skin conditions like diaper rash, minor burns and irritations. It also forms a protective barrier on the skin that helps soothe irritation, prevent infections, and promote wound healing (Lin *et al*., 2018). It also helps to reduce the risk of infection by preventing microbial growth. Zinc also has antibacterial and anti-inflammatory properties that help minimise the growth of acne-causing bacteria on the skin.

Understanding the Antimicrobial Properties of Zinc

For simultaneous immune function and infection control, zinc has a wide range of antimicrobial properties, making it an essential element for human body. In combating bacterial, viral and fungal pathogens its function has been well archieved and it is increasingly utilized in various medical and industrial applications due to its effectiveness in treating infections.

1. Antiviral Treatment

Zinc contributes to antiviral treatment by inhibiting viral replication through preventing viruses from multiplying and spreading within the body. Zinc boosts the immune response by helping the body, strengthening its defence against viral invaders. Zinc interferes in the viral entry into host cells by disrupting the receptors that viruses use to bind to the cell surface. It has also an impact on protein synthesis by inhibiting the viral machinery that produces proteins essential for viral replication (Read *et al*., 2019). It can also obstruct genome replication by disrupting the enzymes that viruses use to replicate their genetic material. Zinc supplements and formulations are explored for their therapeutic potential to combat viral infections, mainly respiratory viruses like influenza and coronaviruses, by reducing the severity and duration of viral infections.

2. Antibacterial Agent

Zinc nanoparticles and complexes are explored as unique alternatives in the fight against bacterial infections. These zinc-based materials exhibit significant antibacterial properties, showing diverse applications involving surface disinfection, water treatment and food preservation. Due to very small size i.e., on a nanoscale, zinc nanoparticles show its high potential, allowing for a higher surface area for interaction with bacterial cells, enhancing their antimicrobial effect, which can penetrate bacterial cell membranes and disrupt their cellular structures, leading to cell death or inhibition of bacterial growth. They also help in the release of zinc ions, which are toxic to bacteria, further boosting their antibacterial action. These show their positive effectivity for fighting against a wide range of bacterial strains, including those that have developed antibiotic resistance. Potentiality of zinc to act as a replacement for traditional antibiotics contributes a new pathway for treating infections, specifically where antibiotics no longer work (Haider *et al.*, 2011).

3. Anti-inflammatory Effects

Zinc is popularly known for its anti-inflammatory properties, which regulate the immune system and reduce oxidative stress by supporting antioxidant shielding systems in the body, preventing damage to cells and tissues. Zinc also regulates the production of pro-inflammatory cytokines, which are signalling molecules that balance the immune response (Maywald, Wessels & Rink, 2017). It also stabilises cell membranes and protects against chronic inflammation-related damages, such as acne, dermatitis and other inflammatory skin risks.

These three aspects of antiviral activity, antibacterial properties and anti-inflammatory effects highlight zinc's potential as a multifaceted and valuable element in both medical and environmental fields. Whether through supplementation or as a part of nanoparticles, zinc continues to show challenges in fighting infections and alleviating inflammation-related diseases.

Role of Zinc in Advancing Implant Technology

In the evolution and progress of implant technology, zinc has emerged as a multifaceted and indispensable trace element, which has gained reminiscent attention in the field of biomaterials. Its eccentric combination of biocompatibility, bioactivity and corrosion resistance makes it an attractive option for strengthening the performance of medical implants. As an orthopaedic implantable device, the role of zinc in improving their functionality is becoming increasingly critical. The performance of zinc to assist tissue regeneration, support bone healing and reduce the risk of infections plays a pivotal role in its integration into modern implant materials.

1. Biocompatibility of Zinc

Zinc and its alloys are highly regarded for their fabulous biocompatibility, where it can coexist with biological tissues of the human body without causing adverse reactions or harmful effects when used as implants. In its proper utility as a biomedical material, zinc does not trigger significant immune responses, making it safe for long-term implantation in the human body. It helps in promoting bone regeneration, stimulating osteoblast activity and escalating the bone healing process (O'Connor *et al*., 2020). Its contribution to the prevention of bone loss cannot be ignored. Unlike other non-biodegradable metals, such as titanium or stainless steel, zinc as an implant material eliminates the requirement of secondary surgery for its removal. It reinforces cellular functions, such as enzyme activity and protein synthesis, which are very much crucial for tissue growth and repair. Furthermore, zinc is involved in collagen formation and bone mineralisation, speeding up the healing process. By incorporating zinc into implant materials or coatings, the risk of bacterial colonisation and infection is minimised, leading to faster recovery and enhanced patient safety. Its antimicrobial properties inhibit growth of harmful bacteria by disrupting their cell membranes, which is particularly beneficial in preventing infections associated with implants.

2. Mechanical Strength

Zinc has gathered significant attention in its usage as biodegradable implant due to its significant amalgamation between mechanical and biological properties. In comparison to some other metals, such as titanium or stainless steel, several limitations are there regarding the mechanical properties of zinc which can be mitigated by alloying zinc with other metals. Alloy formation results in enhancing the strength and mechanical compatibility of zinc with biological tissues as a medical implant.

The tensile strength of zinc is relatively low compared to metals like titanium or stainless steel. It can withstand much lower forces before it begins to stretch under tension. Pure zinc's low tensile strength limits its application in high-stress environments, where higher-strength metals are necessary to resist breaking or permanent deformation. When pure zinc has a tensile strength of approximately 110 to 120 MPa, titanium has a tensile strength around 900 MPa, and stainless steel can range from 500 MPa to 1500

MPa depending on the alloy (Yuan *et al*., 2024). The tensile strength of zinc is sufficient for some applications but limits its use in high-stress environments, such as load-bearing joints or structures.

Zinc's yield strength is appreciably low, which makes pure zinc less suitable for application as an implant, enduring high mechanical stress unless its alloy formation with stronger metals (Hagelstein *et al.*, 2022). Alloying with other metals improves zinc's yield strength, making it suitable for application as an implant in a broader aspect.

Zinc's elastic modulus is around 83 GPa, indicating its stiffness, which is somewhat lower than the elastic modulus of metals like titanium, about 110 GPa. The elastic modulus of zinc very closely matches the elastic modulus of human bone. Stress shielding gets reduced due to having such similarity. It is due to the closeness in elastic modulus value to human bone; zinc helps distribute stress more evenly, which promotes better integration and less bone resorption around the implant. Additionally, due to the high ductility of zinc, it undergoes significant plastic deformation without fracturing (Aghajani & Alizadeh, 2024). This well-versed characteristic makes zinc ideal for orthopaedic temporary or paediatric implants, where flexibility and malleability are highly required. Zinc's flexibility enables it to withstand stresses without breaking, which is beneficial in implants to adapt to the body's dynamic conditions.

In order to overcome its inherent mechanical constraints, zinc is alloyed with other metals like magnesium, calcium and aluminium to improve mechanical properties, making them stronger, more durable and better suited for specific applications, particularly in biomedical contexts. Upon alloy formation zinc can greatly enhance its tensile and yield strengths. These alloys not only improve zinc's sturdiness but also enhance its mechanical compatibility with surrounding biological tissues.

3. Corrosion Resistance

Zinc demonstrates a significant role in advancing implant technology, particularly in terms of improving corrosion resistance. Zinc is often used as a coating or alloying element for metallic implants, such as titanium, steel and aluminium, to provide a protective layer that resists corrosion. Corrosion in a physiological environment is driven by certain factors like pH, temperature and the presence of bodily fluids, which results in degradation of metals. Zinc helps to form a thin protective oxide layer on the implant surface, which helps in protecting the direct exposure of the metal to corrosive environments (Jain *et al.*, 2021). Another important characteristic of zinc is the usage of it in implants as a part of a galvanic protection system, functioning as a sacrificial anode (So, Park & Kim, 2023). This signifies that zinc corrodes preferentially, safeguarding the underlying metal like titanium or steel from corrosion. Zinc's gradual corrosion is beneficial for biodegradable implants, offering strength and stability as tissue heals. Its corrosion rate is optimal, preventing premature failure. The corrosion products, which typically consist of zinc salts, are non-toxic, biocompatible and easily processed by the body.

Zinc and Titanium Implants: A Comparative Study for Medical Practice

The perfect placement of metallic implants in the human body is a challenge in the field of modern medicine, especially orthopaedics. Traditional biomedical materials, like titanium, have long been found to be favourable as a consequence of their strength, durability and biocompatibility. Ongoing research reveals that zinc-based implants have the potential to replace titanium, primarily due to their biodegradable nature and other unique contributions. It is needed to explore the advantages and challenges of using zinc implants over titanium implants in the human body, focusing on factors like biocompatibility, mechanical properties, degradation behaviour and clinical applications.

Titanium is a strong, lightweight and highly corrosion-resistant metal that has been used in various biological implant applications for decades. Its excellent nature of biocompatibility facilitates osseointegration, when often the implant integrates well with the surrounding bone. As it forms a stable passive oxide layer of titanium dioxide on the surface of its medical implant, it prevents corrosion when exposed to the air, making it suitable for long-term implants in various body systems. Titanium implants can cause a stress shielding effect due to their stiffness, and it can bear a significant portion of the mechanical load, leading to bone resorption and potential failure of the implant (Niinomi & Nakai, 2011). This effect helps in reducing the amount of stress placed on the surrounding bone. It also can produce particles that induce an inflammatory response, potentially leading to osteolysis, resulting in bone degradation over time. But its permanence can be disadvantageous in certain situations. Although titanium is usually counted as biocompatible, its lengthy usage leads to adverse biological responses. Wear particles from titanium implants may induce local inflammation and bone loss and, in some cases, result in implant failure.

Zinc, as a biodegradable metal, has recently emerged as an encouraging alternative to titanium due to its bioabsorbability and potential for bone regeneration. Zinc degrades gradually over time, which means it naturally disappears from the body after fulfilling its purpose, reducing the need for a secondary surgery for implant removal. This becomes advantageous for temporary implants or devices that support healing and then dissolve, such as those used for bone fractures. Zinc degrades more rapidly than titanium, which can release zinc ions that may be less likely to cause chronic inflammation compared to titanium. Again, if the degradation rate becomes too fast, it may cause local toxicity or inflammation. Zinc is mechanically weaker than titanium, which could limit its use in high-load-bearing applications (Wang *et al*., 2021). The main challenge of using zinc implants lies in controlling the corrosion rate. The uncontrolled corrosion rate fails to match the healing process and prevent premature failure. Excessive corrosion could lead to virulence, as elevated concentrations of zinc ions in the body may disrupt cell function in the body. However, the corrosion of zinc implants can be harnessed to support bone healing by motivating the body's natural regenerative processes. During the use of zinc implants in the human body, the fear of zinc deficiency occurring due to zinc implants gets much lower. At the same time, in some infrequent instances of excessive degradation, an unrestricted release of zinc ions may lead to zinc toxicity. This may create several health issues. Therefore, it is very much crucial to carefully manage the degradation rate of zinc implants to avoid such complications.

In comparison to titanium, zinc and its alloys typically have lower mechanical strength. However, zinc can be superior in some applications, as the mechanical properties of zinc match more closely to those of natural bone, reducing stress shielding and promoting finer bone healing. Titanium is widely considered the gold standard for many permanent implant applications due to its strength, biocompatibility, and resistance to corrosion. However, zinc implants offer a promising option for temporary applications due to their close resemblance of biodegradability and mechanical properties to natural bone. The choice between zinc and titanium implants ultimately depends on certain factors, such as the clinical needs, the intended duration of the implant and the biological environment at the implant site. Researchers are developing zinc-based alloys with improved strength and corrosion resistance

Exploring the Development of Zinc-Based Medical Implant

Alloying of Zinc

Relatively soft nature and due to the lack of required mechanical strength for several medical applications, particularly for load-bearing implants such as bone fixation devices, alloy formation of zinc with elements like magnesium (Mg), calcium (Ca), manganese (Mn) or aluminium (Al) is very much needed, which results in appreciable improvement in its tensile strength, hardness and overall mechanical stability in order to make it an acceptable medical implant giving support and remaining unaffected by any physical forces in the human body. In addition to mechanical properties, alloying of zinc enhances the corrosion resistance, making the implant more durable, and by controlling the degradation rate, it aligns with the healing process of the tissue.

Addition of magnesium to zinc alloys enhances the tensile strength, hardness and ductility of zinc. Zn-Mg alloys can achieve tensile strengths exceeding 250 MPa, converting them to be more appropriate for high-stress applications like orthopaedic implants (Zhou *et al*., 2025). Additionally, magnesium accelerates the degradation rate of the alloy, which is important for temporary implants to dissolve with time as tissue heals. Upon such alloy formation, zinc forms solid solutions and precipitates that strengthen the alloy's microstructure, making it an ideal candidate for structural applications like medical implants. A minimum percentage of Mg ranging from 0.1% to 5% by weight is usually found to be contained in Zn-Mg alloys to strategically balance the alloy's mechanical properties, corrosion rate, and biocompatibility (Zhou *et al*., 2025).

The presence of calcium in alloy formation with zinc enhances the potentiality of the zinc implant, improving its bioactivity through interaction between the implant and the surrounding tissue. Calcium is also biocompatible, which plays an important role in bone health, stimulating osteogenesis (Su *et al.*, 2019). It is an important element in bone mineralisation that promotes bone regeneration, making it suitable for structural applications. For several orthopaedic requirements, like joint repairs or spinal fixation devices, where temporary support is needed, Zn-Ca alloys can be extensively used. In a Zn-Ca alloy, zinc (Zn) is present in major form over 90% of the composition, while the presence of calcium is generally ranging from 0.1% to 5% by weight. This particular composition, balancing the presence of major and minor metals, maintains strength and support without compromising the alloy's biodegradability or its performance as a biomedical implant.

Manganese addition to zinc escalates the strength, hardness and tensile properties of the alloy, making it more useful for load-bearing applications, such as bone fixation devices. This alloy formation also improves both corrosion resistance and mechanical strength for maintaining implant integrity and longevity (Lu *et al*., 2024). Incorporation of trace amounts of other elements, Mn converts zinc, making it ideal for a range of applications, from biodegradable implants to protective coatings in corrosive environments. Controlling the Zn-Mn alloy's composition precisely and its microstructure are highly essential to ensure the correct degradation rate.

Zn-Al alloys can be considered as a lightweight alternative to traditional implant materials like stainless Steel (Su *et al.*, 2019), releasing the burden on patients and potentially enhancing comfort for medical applications as an implant. Aluminium addition to zinc can improve the overall stability of the alloy, increasing its resistance to corrosion, which is required for ensuring the implant's longevity inside the body. Aluminium controls the degradation rate, allowing the implant to dissolve gradually. Zinc-aluminium alloys are suitable for biomedical applications where a complete fulfilment of strength, lightness and corrosion resistance is needed. It is critically required to optimise the Zn-to-Al ratio, which ensures the alloy's mechanical properties, degradation rate and biocompatibility that are appropriate for the intended applications.

Advancements in Surface Modification Techniques for Zinc-Based Implants

The process of surface modification of zinc-based biomedical implants is an important as well as censorious thing that strengthens their activity and longevity when used in orthopaedic applications. As a biomaterial for medical implants, the role of zinc cannot be ignored due to having several characteristics involving its biocompatibility, biodegradability and osteogenic potential. As a result of that, improvement of mechanical properties, corrosion resistance and overall performance in the biological environment of zinc implants is very much needed to make it more appropriate for placing it in the human body.

1. Coating with Bioactive Materials

Hydroxyapatite or HA coatings present several superiority on its application to medical implants, while interacting with bone tissue. HA is basically a mineral form of calcium phosphate, whose coating on zinc implant enhance biocompatibility stimulating osteointegration (Shoeib & Abdel-Gawad, 2023). This also assists the process of bone bonding, facilitating the growth of bone tissue at the implant surface. Out of several techniques, three of them have been mentioned for the application of HA coatings to zinc-based implants, which are chosen depending upon the implant's design and on the desired properties of the coating. They are Dip-coating, plasma-spraying method and sol-gel method.

Dip-coating is a simple and economical method where the surface of the zinc implant is cleaned thoroughly to immerse it into a liquid solution, typically containing a coating solution material and HA particles, and then withdrawn from the solution at a controlled speed to allow the uniform coating to get solidified as it dries or cures across the surface, often involving heat or UV light (Nikolova & Apostolova, 2023). This method of dip coating results in thin and uniform coatings over complex geometries, which is especially effective for implants with intricate shapes or surfaces that need to be covered uniformly. Such coatings by bioactive materials promote better tissue integration, reducing the risk of complications and improving osseointegration. It also enhances the corrosion resistance power of zinc implants.

For coatings by using bioactive material, the sol-gel method is also broadly utilised to create thin films over zinc implants. Here transformation takes place from a liquid precursor, sol, into a three-dimensional gel-like solid network resulting in gelation, which is heat-treated and then dried to form a solid coating. The zinc implant is submerged in the sol or sprayed with the sol to form a thin layer of the material. Sol-gel coatings intensify substrate properties like corrosion resistance, wear resistance, and biocompatibility along with optical transparency, thereby improving the all-inclusive performance and expanding the lifespan of coated materials. For large-scale production, compared to other methods like physical or chemical vapour deposition, sol-gel coating is considered frequently for its cost-effectiveness, particularly for biomedical applications in bone regeneration (Nikolova & Apostolova, 2023).

Another method, plasma spraying, involves a thermal spray coating process, which is commonly used to deposit protective coatings in a molten or semi-molten state on various materials, including metallic implants (Nikolova & Apostolova, 2023). This method is effective in improving several properties like wear resistance, corrosion resistance and thermal insulation in various biomedical applications. In addition to this, such a coating of hydroxyapatite (HA) or some other bio-ceramic materials on zinc-based implants mimics the properties of bone, enhancing its biocompatibility. Certain challenges such as coating, adhesion, porosity and uniformity must be consciously handled to optimise the activity of the coated implants. The process is carried out in a controlled environment, typically utilising an inert gas atmosphere like argon or nitrogen.

Conclusion

The whirlwind magnification in the development of zinc-based biomedical implants has been found to have emerged as a global challenge in the field of orthopaedic surgical applications because of its good alignment of biodegradability and biocompatibility with the human body system. Zinc alloys have been considered as densely potent orthopaedic internal fixation implants because of having notable characteristics like controllable corrosion rate, adaptable mechanical strength, osteo-inductivity and inherent anti-microbial properties. In order to overcome certain limitations of using pure zinc metal as a medical implant related to its strength, plasticity and hardness which hinder its effectiveness in medical applications, alloying of zinc with several other metals like Mg, Fe, Al have been developed which enhances mechanical properties of zinc such as strength and ductility. A comprehensive and systematic comparison for the superiority of zinc and its alloys as an orthopaedic implant with other metals remains still lacking.

Further intensive research is needed with a strong focus on long-term evaluations to identify critically the advantages and limitations of zinc material for medical purposes. Prioritisation on research should be given to understand molecular mechanisms of zinc and its alloys in promoting advantageous cellular remodelling and managing corrosion rates to reduce toxicity and inflammation. It also ensures the degradation rate of zinc material to fasten biological healing processes.

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