Chapter 12
Exploring the Role of Metal Ions in Modern Medicine From Antimicrobial Coatings to Diagnostic Imaging and Targeted Therapies

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ABSTRACT

Metal ions are vital in modern medicine, contributing to antimicrobial coatings, diagnostic imaging, and therapeutic treatments. This review explores their diverse roles, emphasizing biological interactions and clinical importance. Transition metals like gold, silver, copper, and zinc possess antimicrobial properties, while iron and gadolinium enhance imaging techniques, notably MRI. Platinum-based drugs like cisplatin are crucial in cancer chemotherapy, showcasing the therapeutic value of metal ions. The review discusses metal ion interactions with biological systems, focusing on roles as enzymatic cofactors, redox agents, and signaling molecules. Challenges such as toxicity, resistance, and environmental impact are also addressed. Advances in nanotechnology, biomaterials, and personalized medicine are driving the

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development of safer, more effective metal ion-based therapies. It highlights the importance of continued research to unlock the potential of metal ions in healthcare, paving the way for future innovations in antimicrobial, imaging, and targeted therapeutic applications.

1. INTRODUCTION

Metal ions have long been integral to the development of medical treatments, providing solutions for a wide array of diseases and conditions. Their unique chemical properties, such as their ability to accept and donate electrons, make them indispensable in biological systems and therapeutic applications. Whether serving as components of enzymes, cofactors in biological reactions, or elements that interact directly with cellular structures, metal ions are pivotal to the maintenance of life. From iron's role in oxygen transport via hemoglobin to calcium's involvement in bone mineralization, metal ions are embedded in the fundamental processes of human physiology. Given the increasing challenges posed by infectious diseases, cancer, and chronic conditions, leveraging metal ions for medical innovation has become more urgent. By examining the ways in which metal ions can be used to target microbial pathogens, assist in diagnostic imaging, and serve as therapeutics, this review seeks to underscore the significance of these ions in contemporary healthcare solutions. Metal ions are no longer viewed solely as ancillary components but as active agents in the design of cutting-edge medical technologies.

The use of metals in medicine can be traced back to ancient civilizations. Egyptians utilized copper to sterilize wounds and drinking water, while the Romans used silver for similar purposes, owing to its well-documented antimicrobial properties (Figure 1) (Burdusel et al., 2018). The use of mercury in early treatments for syphilis, though eventually deemed toxic, highlights how metal-based remedies have been pivotal even in historical contexts. Gold salts were famously employed in the early 20th century for the treatment of rheumatoid arthritis, leading to modern developments in gold nanoparticle applications (Daraee et al., 2014). The use of platinum in cancer therapy, beginning with the introduction of cisplatin in the 1970s, marked a significant advancement in metallopharmaceuticals, with these treatments revolutionizing cancer care due to their effectiveness in halting the progression of tumors (Khoury et al., 2020). The historical context illustrates that the therapeutic potential of metal ions has long been recognized, even if the mechanisms of action were poorly understood at the time. With modern advancements in chemistry, materials science, and biotechnology, we now have a greater understanding of the interaction between metal ions and biological systems, offering opportunities for enhanced therapeutic precision and reduced side effects.

Understanding how metal ions interact with biological systems is fundamental to their successful application in medicine. Metal ions such as zinc, copper, iron, and magnesium are essential for numerous physiological processes, including enzymatic reactions, electron transport chains, and DNA synthesis (Khursheed et al., 2022). These ions act as cofactors for enzymes, playing key roles in metabolic pathways that are crucial for cellular function. For example, zinc ions are vital in DNA replication and transcription processes, while copper ions facilitate redox reactions in respiration and antioxidant defense. The bioavailability, transport, and detoxification mechanisms of these ions in the body are finely regulated, involving specialized proteins such as transferrin (for iron transport) and metallothioneins (for metal ion detoxification and storage) (Rahman, 2023). A delicate balance in metal ion homeostasis is critical; imbalances can lead to conditions like anemia (iron deficiency), Wilson's disease (copper accumulation), or neurodegenerative diseases such as Alzheimer's, which may involve abnormal metal