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Advances in Metallic Materials for Biomedical Applications: A Focus on Dental, Orthopedic, Nursing, and Pharmaceutical Innovations

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Abstract
Advances in metallic materials have significantly enhanced biomedical applications, particularly in the fields of dentistry, orthopedics, nursing, and pharmaceuticals. This paper explores the development, properties, and applications of metallic materials such as titanium alloys, stainless steel, and cobalt-chrome in healthcare. These materials offer high strength, corrosion resistance, and biocompatibility, making them essential in dental implants, orthopedic prosthetics, surgical instruments, and pharmaceutical containers. Recent innovations in surface modifications and additive manufacturing have further improved the functionality and longevity of biomedical devices. For example, titanium alloys with advanced coatings enhance osseointegration and reduce the risk of implant failure, while precision-designed prosthetics improve patient outcomes in dentistry and orthopedics. The role of metallic materials in nursing tools and pharmaceutical applications, such as sterile containers and drug delivery systems, is also highlighted. Despite their widespread use, challenges such as corrosion, biocompatibility, and cost remain areas of ongoing research. This paper concludes by discussing future trends in metallic materials for biomedical applications, including 3D-printed implants, custom designs based on clinical imaging, and the integration of nanotechnology to address emerging healthcare needs.
Keywords
Metallic materials, biomedical applications, titanium alloys, dental implants, orthopedic prosthetics, surgical instruments, pharmaceutical containers, biocompatibility, corrosion resistance, 3D printing, surface modification, nanotechnology, osseointegration, healthcare innovations.

1. Introduction to Metallic Materials in Biomedical Applications

The development of metallic materials has driven the enhancement of healthcare and medical technology, improving the quality of life and the survival of individuals in at-risk populations. Metals selected for medical applications include established metals of high fatigue and strength for orthopedic implants: Ti6Al4V and 316L stainless steel. In addition to this, the noble metals gold, silver, and nanoparticles have been investigated as antimicrobial agents, especially in dental and wound management applications. In cases of hip replacements, bone plates, and screws, the most widely used metals are Ti6Al4V, 316L stainless steel, and CP-titanium. Durable and corrosion-resistant materials have revolutionized medical procedures, extending life and improving health for a range of physical and mental health conditions since the first surgical wires were used in the eighteenth century. These so-called biomaterials are used in two main application areas: orthopedic implants and dental implants. Titanium and its alloys are often used for orthopedic implants that involve hip and knee replacements due to their high mechanical strength properties and corrosion resistance in the harsh environment present in the human body. Although widely used in surgical procedures across the world, there remain challenges and areas of research that need to be addressed in the quest for increased patient benefit. The next few sections will report recent research findings in the development of titanium-based materials for dental, orthopedic, nursing, and pharmaceutical applications. (Nabeel et al.2023)(Ali et al.2022)(Hasiak et al.2021)(Aufa et al., 2022)(Teo et al., 2021)(Ahmed et al.2023)

2. Dental Innovations

In dental medicine, different metallic materials coupled with innovative technologies are used based on procedures and prostheses that include dental implants and teeth. Besides the most common ligatures of the aforementioned metallic prosthesis, the preventive robotic supplement is quite innovative. On the other hand, today, the most modern instruments in dentistry are being researched with the application of nanoparticles in the dental field, as well as the modernization of pharmaceutical robotics and nursing improvement using dental, orthopedic, and orthodontic materials. Today's dental implants are made of alloys of titanium and niobium.

Insufficient dental health can have first, minor external effects, such as tooth stains, tartar formation, and additional complications requiring accurate brushing of the teeth and monthly specialist oral hygiene. Innovatively, in order to prevent oral complications in nursing, the prevention of certain intraoral disorders is essential. In this sense, dental implants are formed and placed entirely based on design details manufactured with a combination of zirconia, with fine manufacturing properties for dental treatment with robotic manufacturing implemented in innovative dentistry. Also, pure and noble metals may represent the modern materials that constitute parts of the high-quality alloy under dental robotic operations. Thus, titanium and cobalt-chromium prosthetic components in dental alloys are highly reliable. With the use of mixed zirconia crowns composed of lithium zirconate and other dental implant ornaments. (Ban, 2021)(Zhang et al.2022)(Zhang et al.2022)(Panchal et al., 2022)(Saha & Roy, 2022)(Cinquini et al.2023)

2.1. Titanium-Based Alloys in Dental Implants

Titanium (Ti) is one of the most popular metals used as raw materials for implants and is produced in various compositions: 99.7% primary, 99.5% secondary, commercial pure titanium, and α-β alloys are mainly used in medicine and dental surgery. Pure titanium α has a better capacity to combine with bone compared to cobalt and titanium-based alloys, which are not easily combined with bone. These materials have higher fracture strength, fatigue limit, and good resistance to corrosion and hypoallergenic properties, causing no irritation in the tissues. Nowadays, the use of titanium-based alloys loaded with possible foreign agents is limited to dental implants with a low metal mass. Furthermore, in implant surgeries, β-stabilizing elements are tantalum, zirconium, and molybdenum. Tantalum has a positive effect on the integration of screws with human cancellous bone, while zirconium reduces the adverse effects of vanadium. Some vessels can lose transparency when part of the microvascular tissue of the oral mucosa shrinks and inhibits bone growth. The femoral stem is loaded perpendicularly to the affected bone joint under axial load, while screws are implanted into the parasymphyseal jawbone and the masticatory joint in harmony with patients' occlusal forces. Until now, despite the various grades of titanium alloys traditionally offered, dental implants have been produced and used without considering the distribution of stress and strain on the jawbone lesion. Various implants have been designed according to the information found in the patient's computed tomography images and produced by electron beam melting utilizing Ti6Al4V powder. (El Khalloufi et al., 2021)(Baltatu et al.2021)(Depboylu et al.2022)(Marin & Lanzutti, 2023)(Gummadi & Alanka, 2023)

2.2. Advancements in Dental Prosthetics

The field of dentistry has seen significant advancements in restoring the functions and aesthetics of teeth affected by diseases and trauma. Prosthetic restorations—prostheses or a "bridge"—can replace one or several missing teeth. These help in redistributing arch distribution and enabling a balanced bite during chewing and speaking. Materials used in prostheses should be durable and compatible with oral tissue to provide long-term function and comfort. Mostly, non-precious alloys based on cobalt-chrome, nickel, and chromium show desirable corrosion resistance and biocompatibility. They are wear-resistant and polished to achieve excellent luster. Ceramics are also used as in-layer compatible materials in prostheses. Recent designs have been directed toward precision fit of the crown, long-term retention, and antimicrobial components. New research is focusing on bioactive and bioinert overdenture prosthetic materials.

In dentistry, the term "prosthetic" refers to restoration procedures such as fitting a prosthesis over a present structure in the body to straighten or return to normal function. Dental prosthetics refer to sciences such as the design, manufacture, and fitting of artificial replacements for natural teeth and tissues. Dental prostheses can be classified based on materials as follows: • Metallic (oxides). • Ceramics. Metallic prostheses replacements are generally made from metals like chrome-cobalt, in which the latter also contains a sensitivity rate and hence is very little used—the base of prostheses alloys like titanium and biocompatible alloys like nichrome. In the past, precision attachments were also made of gold. The tooth section or the crown part of a prosthetic replacement is made out of bioinert materials (e.g., ceramics). In dentistry, the research outcomes of prostheses are not often expressed in impact factors. Most of the research topics are related to dental implant improvements, including improved materials, antimicrobial properties, and applications. The advancements in metallic dental prosthetic materials will be more clinical rather than typical reviewing research. To improve the variety and interest for our readers, we have added innovations in prosthetic technology. Digital dentistry allows for the modulation of prosthetic teeth to enable patients to visualize how they will look when finished. Increasing comfort with modified prosthetics will allow a precise fit without the use of dental loupes or microscopes. New designs for prosthetic teeth have also been presented with reinforcing cross-sections in each tooth to reduce brittleness and minimize the risks of fracture, coupled with colorful ceramics to produce life-like aesthetic teeth. Overall, innovations and research in the near future should focus more on the development of overdenture prosthetic materials. Fundamental research in wear parameters of materials and a market survey to understand the true needs of researchers in dental prostheses reconstruction has been relatively more prevalent. The increasing focus has been much on dental implant properties and peri-implantitis, which is the leading cause of dental implant failure. Techniques on tooth prostheses, complete denture impression techniques, including high and low viscosity impression materials, have also been widely studied. Other areas where there is moderate research include the development of antimicrobial properties associated with dental prostheses. As a fingerprint for this type of research, glass ionomer cements have a long history of dental restorative materials, which have had moderate work done compared with metallic and ceramic materials. (Thienpont, 2023)(Hesse & Özcan, 2021)(Płusa et al.2023)(Ude et al.2021)

3. Orthopedic Applications

The development and application of metallic materials for the treatment of human bone fractures have grown exponentially over the past years, reaching a 10% share of the global implants materials market. Orthopedic implants have contributed significantly to biocompatible alloy research, with an emphasis on the need to create materials to compensate for human bone deficiency when the implant is to be removed. Materials that have undergone the most pertinent metal matrices are Nitinol, stainless steels, and cobalt-based systems. Basing bone implants on materials of metallic nature has grown widely because there are many advantages to using them in bone grafting; their factors are lightweight, lack of allergenic potential, high fracture strength, and compatibility with magnetic resonance imaging, especially with the possibility of osseointegration. A number of metallic materials are commonly used as friction plates in biologically active buffering layers when producing orthopedic devices. This is because biocompatible materials allow for osseointegration, vertically directing the stress to the bone, allowing changes in size and shape of the trauma fixation plates without being affected by the interfacial bond of the peri-implant.

Surgeons are continuously innovating the orthopedic sector by updating the innovations used in orthopedic trauma devices with modeling studies concerning their mechanics, coatings, and additive designs. Their experiences have shown that, given the growth of biocompatible materials in applications, a patent was taken from a double-thread implant to repair trochanteric hip fractures in order to improve their specific mechanical strength. Other innovations include coated lag screws containing shark skin and necrotized colonies using the anodizing and plasma spraying method. The transition between stainless steel and Ti6Al4V rods opens up a wide field of research concerns on biocompatible hip implant materials, such as causing excessive force in the placement area. Together, there is an interesting shift in many countries towards implant designs that exhibit a buffer layer, delaying the failure of biomedical materials, enhancing their properties, and increasing patient care. This growing market has led to many companies producing such innovations and a focus on the need for surgeons to work hand in hand with materials scientists. This is important so that high-quality innovations are presented to the orthopedic biomechanics market, and the new innovations can attract the right market. While metal materials are widely used for orthopedic and dental applications, the main challenge that researchers face is the ability to slow down corrosion within the human body while the product is exposed to body fluids for a period often reaching thousands of hours. Additionally, the pistons resulted in high wear rates from orthopedic materials such as Ti-based, Mg-based, and Zn-based materials. As the technologies of highly distributed titanium alloys and dense ceramics develop for continued innovation, thermite materials are still important, ultra-dense bonded ceramics. Prior to military introduction to the market, these developed materials must undergo animal testing, in vitro studies, and in vivo studies. (Lewandrowski et al.2023)(Donnelley et al.2021)(Vaishya et al., 2022)

3.1. Biocompatible Metallic Alloys for Orthopedic Implants

Generally, the metallic materials used to make orthopedic implants can be summarized into stainless steels and titanium alloys, due to their inherent strength, corrosion resistance, and biocompatibility. The most widely recognized stainless steels include 316L and 316LVM, where the corresponding titanium alloys include Ti-6Al-4V and Ti-6Al-7Nb. About 55% of the root mean square curve of tensile strength-extension rate scatter of bone–implant materials, respectively, are the best of 316LVM, where its Young's modulus is the lowest. Currently, 350,000 total hip replacements, 750,000 total knee replacements, and 673,000 fixations of hip fractures are carried out each year in the USA. The oxide layer increases the bond strength of stainless steels or titanium alloys with synthetic bioceramics. In clinical practice, mechanical interlock between an implant and autologous bone is improved by coating a bond layer comprising bioglass or bioceramic.

During the past three decades, extensive research activities have been carried out concerning the modification of the bulk or surface of bone–implant systems. For instance, porous metallic with pre-coating of bioceramic enhancement, bioactive coating, and fibrous structure with colloidal deposition of different biomaterials. The long-term success of implanted devices in the human body is typically influenced by the proper interactions among neighboring tissues of implants, which depend on the overall sub-properties of constituent materials. Alloying and surface treatment might not only protect bioimplant materials from additional corrosion, but they can also be used as a drug-eluting surface to minimize the risks of bioinfection. The growing degree of efforts is dedicated to improving the mechanical or cellular performance of the implants by designing new alloy compositions. Their performances from in vitro and in vivo findings, as well as in clinical aspects, have been validated. The requirements to apply these materials in clinics are also extensive, but this requires ensuring the biological safety and biocompatibility of these materials. (Oladapo et al.2021)(Bairagi & Mandal, 2022)(Gautam et al.2022)(Guo et al.2022)(Davis et al.2022)

3.2. Surface Modifications for Enhanced Osseointegration

Although biomechanical load sharing in vitro and in vivo is essential for a successful osseointegration process, the bone healing mechanisms are significantly affected by the surface characteristics. Therefore, the philosophy and technology of modern orthopedic implants are focused on topographical and chemical surface modifications that provide the driving force for favorable cellular and interfacial reactions. The intriguing role of roughened surfaces was postulated more than 20 years ago regarding load-bearing implants. If originally load sharing is limited to early healing, the modifications facilitate load sharing up to final osteotomy repair and, in some cases, beyond.

Currently, numerous top-down and bottom-up strategies to modify the surface characteristics are available. They can be classified into coatings and non-coating methods such as acid-alkali treatment, chemical etching, electric discharge texturing, and gelatin dialdehyde. According to rigorous standards and substantiation methodology, several studies have shown a positive correlation between specific surface modifications and superior clinical outcomes. Titanium dental implants with a sand-blasted and acid-etched yield a higher success rate than smooth implants. Additionally, some important studies in the field have been conducted on the patient-specific nature of the surface demand, because surface requirements in the elderly, diabetics, and osteoporotic patients should differ from those of healthy young adults. This is an exception to the rule, and the most challenging part of developing modern implants is the proper combination of superior mechanical strength, enabling faster fracture healing and bone neoformation with biological, anti-inflammatory, and drug-eluting capacity. This balance can be tailored by using cutting-edge innovation. Modern additive systems can be used to create a bioactive iron oxide, hydroxyapatite, and sulfonated graphene oxide coating onto treated biometals. These new-generation implants can be used to influence the behavior of several immune system pathways, such as the release of specific cytokines or P-glycoproteins, CXCL2, and VEGF. In addition, such a surface should have a dual biological effect, as revealed by a significant decrease in oxidative stress markers and an increase in vWF factor. The additive systems offer several advantages, including maximum elimination of adhesion and flakes and homogeneous adherence, which can significantly increase the probability of use in clinical practice. (Thakur et al.2022)(Zhu et al., 2021)(Kligman et al.2021)(Stich et al.2022)(Chhetri and Bougherara2021)(Chan et al.2021)(Usman et al.2021)

In conclusion, surface characteristics seem to be significantly important for orthopedic success. Even though well-established and validated criteria are lacking, novel surface strategies will impact the mechanobiology of the peri-implant environment in various ways. Modern additive systems are the optimal choice to obtain a surface that combines mechanical strength and biological capacity. They go far beyond conventional coating techniques and may potentially be the new bone-bedside implants.

4. Nursing Tools and Devices

The practice of nursing incorporates the use of a wide array of instruments that contribute to us tending to the ill in a safe, effective, hygienic, and compassionate manner. Durable and reliable instruments are essential in the daily operation of a clinic or hospital. Stainless steel surgical instruments have many desirable functional characteristics that can easily be applied. One significant value of some of these properties is the safety of one-handed use or disposability; these instruments are often designed with a focus to be easy to handle, with some including distinctly colored arms or buttons to avoid the risk of cross-contamination from surface contact. Along the shaft of the medical-grade hypodermic needle, angle indents occurring at every 45 degrees help encourage cap removal in the orientation that reduces the risk of harm to the user. Surgical eyeglasses and face masks are designed to prevent moisture droplets from patients' coughs or liquids from splashing into workers' eyes and faces; they are not safety goggles that are resistant to high-speed projectiles. The inadequacy of personal protective equipment prompted coordinated efforts and funding behind the rapid development of effective vaccines and therapies, with mixed success in their outcomes.

In the case of metallic tools, their often smooth surface finish is of great advantage in the cleaning and sterilization process. Materials that are used within the medical field must be traceable and fully labeled in addition to being regularly tested and within the legal framework set up by different authorities. Establishing efficient sterilization and hygiene protocols is necessary to prevent the spread of contamination from one tool to the next. In the case of metallic devices, adequate and renewed training on sterilization procedures is also important to prevent the transfer of bacteria from a contaminated fuel canister to the patient, thus rendering even the best dental handpieces mainly useless. More complex integrated devices where reusable components can be more difficult to reach with a brush may benefit from the ease of sterilization and cleaning of some polymers. Likewise, these companies constantly innovate with new design traits to assist in the prophylactic fight against hospital-acquired complications, as have companies in providing the robotic sewing of suture threads and employing spun fiber in making transfusion filters, whose fiber density prohibits cross-contaminating blood groups. A reusable metallic tool must be resistant to the sterilization mechanism and, in the case of harsh, alkaline, and oxidative chemicals, the design must be such that the chemicals do not overly build up in nooks and crannies and are readily rinsed away. In other ways, easy rinsing of the washing or lubricant degradation products will increase the reliability of the final reusable metallic tool. For those tools using a fixative bonding, care must be taken to ensure not only a proper bond and heat-affected zone, but also to ensure that the joined zones have an equivalent strength and hardness to the parent material or that any variable properties are known and designed for in the loads and stresses encountered by the tool. (Musamih et al.2021)(Uddin et al.2021)(Omar et al.2022)(Leal et al.2021)(Herman et al.2021)(Ma et al.2022)(Casino et al.2021)

4.1. Metallic Materials in Surgical Instruments

Introduction Reducing patient trauma during minimally invasive procedures requires the highest amount of precision in surgical procedures and the proper design of surgical devices. In the hands of a trained surgeon, metallic materials such as steel and aluminum offer the qualities needed to produce such precise instruments via stamping or forming, wire EDM, or abrasive waterjets and other manufacturing methods. Whether meant for single or reusable use, any surgical device must withstand the forces required to perform its duties without deforming and will be exposed to a number of biofluids, making sterilization necessary to eliminate or reduce any surviving microbes. Common metallic materials used to manufacture such surgical devices should be high-strength, corrosion-resistant, biocompatible, and easily sterilizable. One recent driver of surgical device design for minimally invasive surgery has been the push toward single-use devices for safety purposes, which often use a lesser grade of wear-resistant steel while still considering cost. Another trend includes the use of integrated technologies with devices to measure, monitor, and control burr formation, sharpness, or suturing accuracy.

Materials must balance the need for sharp tips and edges with the inherent weaker areas where fractures may be likely to occur.

Several different surgical instruments are commonly used in endoscopic or arthroscopic surgery, with each category of device using varying degrees of sharp tips and edges, linkage of metallic and polymer components, and straight or pre-bent working envelopes. Orthopedic and dental fixation devices, such as plates, screws, pins, and wires, must be made of a metallic material that provides the needed holding force and stability for bone healing. The advantage of using a metallic material rather than other materials lies in the number of characteristics of relative importance for surgical device populations, including function, characteristics, and performance, as well as material properties or advancements affecting design. The longevity of these devices can be influenced by the strength of the bone and therefore the working load, making fatigue studies for these populations essential as well. Revisions can occur for weight-bearing implants such as hips and knees, so for these patients, corrosion mechanisms that are not well understood can eventually create bone fractures and/or effects of toxicity as recent international regulations have been passed. (Choi et al., 2023)(Szczęsny et al.2022)(Barber et al.2021)(Mazurek-Popczyk et al.2022)(Bandyopadhyay et al.2023)

Conclusion In summary, materials such as steel and aluminum are indispensable in a surgical setting, where precision and permanence are required. The tensile, bending, and torsional strengths of a material play a significant role in its functionality, in addition to corrosion resistance and the ability to be sterilized. A surgical instrument is a collective term with many subcategories, each of which requires different designs for its ideal function. The locking screw and other parallel wire fixation devices are designed to surpass interfragmentary strain in comparison to modern bone plates and work towards solving these common orthopedic problems.

5. Pharmaceutical Innovations

Metallic materials have been widely employed in the pharmaceutical field. They have supported development in both the sciences and the industries specializing in drug design, control of food matrices, and manufacture of primary packaging materials. The use of metals has a significant impact on patient care and on nurse practice. From the beginning, metals and alloys have been used in the complex requirements of the design and manufacturing of pharmaceutical containers, ensuring drug stability, effectiveness, safety, and proper drug release.

Metallic container technologies are divided into different types that depend greatly on the scientific requirements of the functions of dosing, bioavailability, and final clinical efficacy of the drug: parenterals, named prefilled syringes and cartridges for automatic injectors; otic-pharyngeal formulations; nasal, dermal, ocular-local, and rectal drugs, in which droplets or fine powders are the basis of administration technologies, as well as assuring thermal and environmental protective functions; special heavy-metal pharmaceutical packaging aimed at containing and releasing the drug in diagnosis or therapeutics by means of containers adaptable to the machines used in radiodiagnosis and radioimmunotherapy. Special attention must be given to the impact of pharmaceutical technology innovations in mass production instruments, which require, in addition to dimensional guarantees, resistance and compatibility with the drugs that will fill the containers, blow-fill-seal fractional package, and aerosol doses.

Special notice is given for the physical and chemical, cosmetic, toxicological medicinal interactions with the environment that a container of drug molecules outside the area of the official international quality standards in relation to the possibility of off-label use can activate. Research trends are focused on the interaction of some metallic materials before and after the deposit over time, to verify the in vitro formation of biocompatible or injectable bioadhesives in the brain, as well as with new drugs for the treatment of stroke diseases such as ischemia maltreatment and neural or nephritic stones. New standards for drug container materials to be used in transplantation, with human milk banks and with plasma viruses have been designed. The technological and product issues, as well as within the main biopharmaceutical materials such as dendrimers, liposomes, nanospheres, vespa oviducts, and lipoproteins, are part of a formidable new and important therapeutic trend of nano-cures. The main therapy-targeted designs that have been developed recently by the search of pharmaceutical science aiming for the products containing drugs for lungs using inhalers, oral, bone, genital, intrauterine, breast, and brain therapies, and for the topical and ocular drug therapies are reported. As can be deduced, the use of metals and alloys has received a great deal of interest in research concerning the product of wear and the administration of parenteral and otic-pharyngeal drugs. Lungs account for 22% and 25% of the totals, and to this aim, a number of patents have been published on the improvements in the retained drug in the lungs. (Raabe, 2023)(Bandyopadhyay et al.2022)(Tan & Ramakrishna, 2021)(Heidarzadeh et al.2021)

5.1. Metallic Containers for Drug Storage and Delivery

Drug storage and preventive release are performed by employing suitable containers. Among the variety of different materials used for pharmaceutical packaging, including polymers and glass, metals have their importance because they provide an inert surface to maintain purity and strength for breakage resistance. These features are of significant importance, especially in drug storage and for the final dose production techniques. In long-term storage or for the storage of injections, infusions, and so forth, the integrity must not be compromised. Although metals are used for the storage of formulations from injections or infusions to tablets, capsules, and vials, they are more commonly used for the delivery of drugs where they are used to make capsules and vials to be sent to the different parts of the body.

Metals encompass pure metals such as aluminum, titanium, tungsten, zinc, steel, stainless steel, and aluminum alloys depending on the anticipated compatibility of the drug with metals in formulations. Another area of current interest relates to the removal of effervescent tablets for asthma treatment and designs where the container is to be entrapped in an article. Many of the metallic formulations are coated with various materials to minimize interfacial interaction, especially with non-compatible substances. On an extended note, metallic formulations with newer apparatus and delivery systems are available for drug administration. While these innovative techniques are in place, they are also subjected to limitations on compatibility, recyclability, and incineration, so focus is given to relevant areas concerning container delivery systems based on their original metallic forms. Regulatory standards for these containers are under development. (Arun et al., 2023)(Chakraborty et al.2022)(Nazari et al.2022)(Bandyopadhyay et al.2023)(Zhou et al.2021)

6. Future Trends and Challenges in Metallic Materials for Biomedical Applications

The future of metallic materials for biomedical applications is currently full of cutting-edge developments in the fields of medical 3D printing, metallomics, stainless steel surface antibacterial effects, dental welding, and the relationship between dental restorations and obstructive sleep apnea. Furthermore, new developments in the use of antibacterial metallic surfaces are expected. It is envisioned that custom implants based on clinical imaging data of patients will completely change the orthopedics scenario. Currently, the new technologies and their near future developments are expected to change the metallic materials in biomedical applications scenarios. Involvement of various experts from different fields like medicine, chemistry, biology, material science, and mechanical engineering are expected to overcome the drawbacks and challenges of metal development for biomedical applications.

New regulatory laws are of concern in transition and developing countries, as they could hinder the use of current patients. It is also needed to discuss social aspects, such as the production of metals and their raw materials for medical purposes. Metallic biomaterials could revolutionize the future in various fields in healthcare, as it is possible to 3D print them, which would enable customization. Ophthalmology, wound healing, and cardiology could be the new landscapes for metallic materials in the near future when healthcare and technology co-developments are connected. In the near future, new market trends are expected with the emergence of new healthcare facilities with technologies that could be available only to a few in the population due to high prices in high-resource countries, and are also entering lower socioeconomic classes in low-resource countries. This would make metallic materials strong emerging products in the future of healthcare with the technologies. The new healthcare facilities are supposed to have technologically advanced treatment for specific patients based on the various biomedical data collected from patients. Hence, continuous development in metallic biomaterials research is expected as the healthcare facilities are changing with the advancements in technology.

Conclusion

The advancements in metallic materials have revolutionized biomedical applications, enhancing healthcare outcomes across dentistry, orthopedics, nursing, and pharmaceuticals. Materials such as titanium alloys, stainless steel, and cobalt-chrome have demonstrated exceptional properties, including high strength, corrosion resistance, and biocompatibility, making them indispensable in medical devices, implants, and tools. Innovations in surface modifications and additive manufacturing have further improved the performance and longevity of these materials, particularly in critical applications like dental and orthopedic implants. Despite their success, challenges such as implant corrosion, biocompatibility concerns, and cost barriers persist and require ongoing research and development.

The integration of emerging technologies such as 3D printing, nanotechnology, and custom-designed implants based on clinical imaging has the potential to address these challenges. These advancements not only improve the functionality and safety of medical devices but also pave the way for personalized medicine, where patient-specific solutions become the norm. As healthcare systems evolve, the demand for innovative metallic materials will grow, necessitating interdisciplinary collaboration and continuous innovation to meet future healthcare needs.

Recommendations

1. **Enhance Research on Corrosion Resistance and Biocompatibility**
   - Develop advanced coatings and surface treatments to mitigate corrosion and improve compatibility with human tissues.
   - Explore alternative metallic alloys and hybrid materials with improved mechanical and biological properties.
2. **Invest in Additive Manufacturing**
   - Expand the use of 3D printing technologies for creating custom implants and prosthetics tailored to individual patient needs.
   - Focus on improving the precision and cost-efficiency of 3D-printed metallic materials.
3. **Promote Interdisciplinary Collaboration**
   - Encourage collaboration between material scientists, engineers, and healthcare professionals to design innovative solutions for biomedical applications.
   - Support partnerships between academic institutions and industry to accelerate technology transfer.
4. **Integrate Nanotechnology in Medical Devices**
   - Utilize nanomaterials and nanocoatings to enhance the antimicrobial properties and osseointegration of implants.
   - Develop nanostructured surfaces for improved drug delivery systems and pharmaceutical applications.
5. **Develop Sustainable and Cost-Effective Solutions**
   - Focus on sustainable manufacturing processes and recycling of metallic materials to reduce environmental impact.

- Prioritize cost-effective designs to ensure accessibility in resource-limited healthcare settings.

6. **Strengthen Regulatory Frameworks**
    - Update and standardize guidelines for the testing and approval of new metallic materials to ensure safety and efficacy.
    - Encourage global collaboration to streamline regulatory pathways for innovative medical devices.

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