Metallic Materials in Radiology: Addressing Image Artifacts and Improving Diagnostic Accuracy

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Abstract: Metallic materials play a critical role in radiology as biomaterials, components of implants, and parts of diagnostic and therapeutic devices. Despite their benefits, metallic materials pose significant challenges in medical imaging, such as image artifacts that can obscure diagnostic details and reduce accuracy. This paper explores the types and properties of commonly used metallic materials, including titanium, stainless steel, and cobalt-chromium alloys, and their applications in radiology. Challenges such as spray-shaped artifacts, attenuation, and scattering are discussed in detail. Techniques for reducing artifacts, including dual-energy imaging, iterative reconstruction, and advanced software algorithms, are examined. Additionally, emerging innovations such as AI-driven artifact correction, gold nanoparticle-based gels, and advanced imaging technologies are highlighted. The review aims to provide insights into current trends and future directions for optimizing the use of metallic materials in radiology, ensuring improved diagnostic accuracy and patient outcomes.

Keywords: Metallic materials, Radiology, Medical imaging artifacts, Diagnostic accuracy, Titanium, Stainless steel, Cobalt-chromium alloys, Artifact reduction techniques, Dual-energy imaging, AI in radiology.

1. Introduction

Metallic materials are applied as biomaterials and as parts of implants, treatment devices, and diagnostic equipment in health sectors. They have long been used and are increasingly important in medical imaging and X-ray-based techniques. Titanium and stainless steel are the most common metallic materials used, with cobalt–chromium and aluminum being used. Recently, several tailored Ni-Ti shape-memory alloys have emerged. These materials are used in either passive or active medical devices and instruments, as well as patient support in MRI environments. In addition, various radiological contrast agents in solution with metallic elements such as iodine, gadolinium, bismuth, and gold are available to increase the contrast in computed tomography. (Song et al.2020)(Zhang et al.2023)(Hu et al.2022)

Medical imaging, including digital radiography, fluoroscopy, dental imaging, computed tomography, positron emission tomography, and single photon emission tomography, relies on the total or partial transmission of X-rays and γ-rays. Imaging devices consist of electronic hardware and metallic parts. Components in imaging devices are selected for rigid mechanical strength, longevity in adverse environments, and electric and electronic stability. Metal parts are required for this purpose and for accessories in such environments, e.g., patient care, and therefore cannot be replaced by other materials. These metals are either seen by X-rays or γ-rays and hence produce a radiographic image. Metals, metallic biomaterials, and biomechanical devices will continue to be used in the future, despite research and industry efforts toward other compositions. Metal-containing medical devices have inherent benefits and limitations. Not only do metallic materials serve as the solution to many problems, but they also contribute to the outcome of an image misfortune. Chances of these artifacts occurring increase with metallic element dimensions and quantity inside the patient’s body. Thus, effective diagnosis is not possible using these radiographies of patients in the immediate post-project period of prosthetic implant. Since most of the metallic materials are not radiopaque to a great extent and, therefore, not detected on X-ray/CT images, there are many problems and limitations associated with the presence of metallic materials. Metal artifacts can overdraw the tissues of images in their surrounding PDs which actively transcribe metallic signals. These artifacts often distort or obscure the image features in the vicinity of outliers, thereby affecting diagnostic accuracy. Early contrast threshold for effusion has been less applicable as high signal hypersphere intensity of metallic signal. The computed tomography scan was taken at each lead voltage in the range of 80 kV - 140 kV. As compared to water-fat and shadow of air parenchyma, the metallic prosthesis implant shows a hyper-intense signal in the range of image intensities, which do not change with lead thickness and therefore our shadow image cannot be used to distinguish emphysema from the shadows created by the metal implant. Spray-shaped and streak artifacts must be dominant because eddy currents are actuated when gradient magnetic fields are switched. (Njiti et al.2024)(Brukštus, 2022)(Bohner et al.2022)(Selles et al.2023)(Rousselle et al.2020)(Cheraya et al., 2022)(de et al.2023)

2. Types and Properties of Metallic Materials Used in Radiology

Because biomaterials used for orthopedic implants are exposed to diagnostic imaging methods such as X-rays, it is important to minimize image artifacts and render precise diagnoses by controlling image contrast. In contrast to ceramics and polymers, metallic materials are metals. Titanium, stainless steel, cobalt-chromium, etc. are commonly used. In particular, these materials are used in prosthetic knee and hip implants. Each material has unique characteristics, and the mechanical strength, biocompatibility, and radiopacity, among others, have advantages and disadvantages in medical applications. In addition, in radiographic diagnostics, the appropriate selection and grade of metallic material help determine the time needed for a patient's recovery by extending the life of medical components through proper operation and monitoring of the equipment. Taken together, addressing imaging artifacts, reducing friction, and maximizing an implant's lifetime depend on understanding the characteristics of the material. In the present review, prominent metallic materials appealing to biomedical applications in diagnostic radiography are discussed. (Mödinger et al.2023)(Mihalko et al.2020)(Adesanya, 2021)(Romanò et al., 2020)(Khodarahmi et al.2021)(Khodarahmi et al., 2021)(Choudhari et al.2024)

There are several metallic materials suitable for X-ray imaging, especially in three categories: (i) titanium; (ii) stainless steel; (iii) cobalt-chromium. Titanium is the most principal metallic biomaterial. This is due to its low Young's modulus, non-ferromagnetic properties (thus not interfered with by MRI), poor thermal conductivity, oxide layer, and behavior in teeth implants. Titanium is used in the low grade because of these properties. Next to gold and mercury, titanium also has a high atomic number. Stainless steels contain iron with a small amount of carbon, chromium, and nickel, are magnetic, and have high strength and corrosion resistance. Chromium and nickel provide a thin layer of oxide at the surface and inhibit further corrosion. The nickel-free steels are suitable for various orthopedic applications. Cobalt-chromium alloys result in reduced ion release, have high corrosion and wear resistance, sufficient biocompatibility, excellent fatigue strength, bowing resistance, high stiffness, and are body-tissue compatible. Some impurities, especially variations in nitrogen and molybdenum, affect ductility. The metals contain sufficient radiopacity, except for certain variations, which result in low radiopacity. (Ronoh et al.2022)(Bandyopadhyay et al.2023)(Sarraf et al.2021)(Sneha & Sailaja, 2021)

3. Challenges and Image Artifacts Associated with Metallic Materials in Radiology

Metallic implants are widely used in modern medicine. With the ongoing rise in radiological examinations and the use of medical implants, the occurrence of imaging exams in patients with implanted or externally attached metallic devices is frequently encountered. Certain materials, dating back over 5000 years, may induce moving, intermittent, modulated, and more severe combinations of moving and non-moving half-value layers from 2.5 to 4.5 mm unenhanced and 5 to 8 mm contrast-enhanced examinations due to an interslice. This restricts external beam positioning since the attenuation is not consistent throughout the body of the patient on all slices, resulting in non-uniform dose distribution, more scattered radiation in the scanning room, increased radiation dose to the patient, and reduced diagnostic accuracy. First, a more detailed discussion and characterization, and possibly a solution, of such artifacts are necessary. Whenever patients with tons of screws, clamps, plates, and rods due to fractures of the body undergo CT and/or MRI diagnostic imaging, it often compels a radiologist to look back at past history about pre-existing implants, metal hip replacements, etc., to encounter any side effects or to avoid artifacts in the scanning subject. Since cemented total hip replacements containing compression screws and plates cause more artifacts, the resultant artifact induced by metal is one or a combination of the attenuation and scattering of the X-ray on the metal concerned. X-rays, which are directed towards bone or body with embedded metal implants and metal-filled cavities, are either absorbed or scattered. The entire set of metal atoms is held together by the electromagnetic force, which provides increased HU or higher X-ray absorption, in which the resultant radiographic film appears completely black. (Zhang et al.2023)(Song et al.2020)(Khandaker & Ullah, 2024)(Jiang et al.2024)(Hu et al.2022)(Shen et al., 2024)

4. Techniques for Minimizing Image Artifacts in the Presence of Metallic Materials

Various hardware techniques, including dual-energy imaging, photon-counting CT, beam-hardening correction, and multi-energy imaging, as well as software techniques such as orthopedic metal reduction sequence, dual-source imaging to decrease metal artifacts, and reduced-FOV techniques, can help reduce some metal-induced artifacts. However, the use of dual-energy, multi-energy, and reduced-FOV techniques is more common. Generally, the availability of these hardware techniques depends on the vendor, and software techniques are beneficial only for certain applications and not all, leaving these patients with problematic images. To reduce the artifacts, additional factors that have been highlighted are positioning as far as possible from the object of interest, adjusting the protocol to minimize streak, ring, and scatter artifacts, minimizing kVp, increasing slice thickness, and minimizing targets per rotation. (Zhang et al.2023)(Song et al.2020)(Rafiei et al., 2023)

Clinically, iterative reconstruction can reduce LMI artifacts in patients with metal implants in knee and hip prostheses when combined with low kVp. The fundamental principle behind these methods is to acquire two images to provide complementary information, allowing one image to virtually remove the metal artifact without affecting the image quality otherwise.

The quality of the reduced-metal artifact image is influenced not only by the metal artifact reduction algorithm itself but also by the dual-energy technique used to derive the two images. Assessment of these techniques in clinical settings has demonstrated their potential for reducing metal artifacts. Artifacts resulting from metal implants in the oral cavity can be lessened by placing absorbent cones around teeth and using a tooth-hiding processing technique. To achieve a consensus, efforts to educate radiologists are essential to appreciate the degree of artifact reduction and to minimize the risk of misinterpretation. All methods can help correct the aforementioned artifacts. Besides the high-end technique, inexperienced radiographers use their own solutions. Applying a combination of these strategies is important to enhance clinical image quality. As a rule, the best approach comprises a multi-faceted one, involving both hardware and software solutions. (Hu et al.2022)(Mendes Fonseca, 2024)(Hu et al., 2021)(Hu et al.2021)(Bonmati et al.2023)(Ding, 2022)(Roelofs, 2021)

5. Innovations and Future Directions for Improving Diagnostic Accuracy in Radiology with Metallic Materials

Tissue-Metal Interaction: Increasing Awareness and Future Directions: Innovations and Future Directions for Improving Diagnostic Accuracy in Radiology with Metallic Materials

To advance and encourage studies investigating the feasibility and properties of materials used with radiology, this manuscript aims to discuss the current innovations and future directions. Currently, several research groups across the globe are coming up with innovations to improve diagnostic accuracy and reduce image artifacts. A few of these studies are being discussed in the upcoming section of this paper. Emerging innovations focus primarily on developing new material compositions that have better compatibility with imaging modalities. Although scientific research helps in coming up with newer technologies, clinical regulatory bodies require time to derive evidence of their clinical feasibility and applicability. The current applications of these materials are in powder or pellet form for preclinical evaluation. Scientific research is advancing in the identification of metals and their processes on imaging artifacts as well. The use of artificial intelligence and machine learning has prompted the development of innovative imaging techniques and advanced data analysis. (Zhang et al.2023)(Song et al.2020)(Khandaker & Ullah, 2024)(Jiang et al.2024)(Hu et al.2022)

Scientific research and innovation research work hand in hand. Few proofs of its one form and one not can be seen in the medical world. A group has come up with achieving a blue contrast X-ray, which is one step ahead of the current X-ray that can only help in bone imaging. Another example comes from where teams have developed a gel with gold nanoparticles so that the arteries needed for heart surgery can be well defined two months prior to the surgery. This will help the doctor in deciding the surgical implant. This is a paradigm of the current techniques like 3D printing in the biomedical field to make a copy of the entire heart and guide the surgeons in valvular surgery. More such research is anticipated in this area where a branch of material science and a branch of radiologic imaging will be fused to come up with new or improvising the current technology.

6. Conclusion and Recommendations

Metallic materials are integral to radiology, playing critical roles in implants, diagnostic devices, and imaging systems. Their mechanical strength, biocompatibility, and functionality make them indispensable in medical applications. However, these materials pose challenges, such as artifacts that can distort diagnostic images, compromise accuracy, and increase radiation exposure. This review has highlighted the types and properties of commonly used metallic materials, including titanium, stainless steel, and cobalt-chromium alloys, along with the challenges they pose and the solutions available to mitigate these issues.

Advances in imaging technologies, such as dual-energy and photon-counting CT, and the integration of software-based artifact reduction techniques, have significantly improved imaging accuracy. Emerging innovations, such as AI-driven analysis, advanced material compositions, and 3D printing, show promise in addressing these challenges. Environmental and economic considerations, along with patient safety, are vital aspects of optimizing the use of metallic materials in radiology.

Comprehensive Recommendations

Material Development

1. Develop radiopaque and artifact-resistant metallic materials to enhance imaging quality.
2. Explore hybrid materials that combine metals with polymers or ceramics for better compatibility.
3. Prioritize biocompatible, sustainable, and recyclable materials to minimize environmental impact.

Technology Integration

1. Implement AI and machine learning algorithms for real-time detection and correction of image artifacts.
2. Adopt advanced imaging modalities such as dual-energy and photon-counting CT to reduce artifacts.
3. Leverage 3D printing technologies for creating personalized implants and pre-surgical models.

Clinical Protocols

1. Optimize imaging techniques by adjusting parameters such as kVp, slice thickness, and positioning to reduce artifacts.
2. Train radiologists and imaging technicians on using modern technologies and strategies to handle artifacts effectively.
3. Establish international standards for imaging protocols to ensure consistent handling of challenges related to metallic materials.

Patient Safety

1. Minimize radiation exposure by using artifact-reduction techniques and optimized protocols.
2. Ensure compatibility of metallic implants with imaging modalities to prevent overheating or signal interference.
3. Enhance diagnostic accuracy by applying advanced materials and imaging systems tailored to individual patient needs.

Environmental and Economic Sustainability

1. Encourage recycling and sustainable practices for metallic components used in healthcare.
2. Provide healthcare facilities with cost-benefit analyses for adopting new technologies and materials.
3. Balance innovation with affordability to make advanced imaging solutions accessible globally.

Interdisciplinary Collaboration

1. Foster partnerships between material scientists, radiologists, engineers, and technologists for innovative solutions.
2. Promote continuous education programs to keep healthcare professionals updated on advancements in radiology and material science.
3. Facilitate global research collaborations to develop cutting-edge solutions for artifact reduction and imaging improvements.

Future Research Directions

1. Investigate new material compositions with better compatibility with imaging modalities.
2. Develop next-generation technologies, such as AI-driven imaging systems, to address artifacts and improve diagnostic accuracy.
3. Advance research in biocompatible, artifact-resistant alloys and evaluate their preclinical and clinical feasibility.

References

1. Song, X., Cui, Q., Liu, Y., Xu, Z., Cohen, H., Ma, C., ... & Zhao, K. (2020). Metal-free halide perovskite single crystals with very long charge lifetimes for efficient X-ray imaging. Advanced Materials, 32(42), 2003353. researchgate.net
2. Zhang, J., Usman, K. A. S., Judicpa, M. A. N., Hegh, D., Lynch, P. A., & Razal, J. M. (2023). Applications of X-Ray-Based Characterization in MXene Research. Small Methods, 7(8), 2201527. wiley.com
3. Hu, X., Yan, P., Ran, P., Lu, L., Leng, J., Yang, Y. M., & Li, X. (2022). In situ fabrication of Cs3Cu2I5: Tl nanocrystal films for high-resolution and ultrastable X-ray imaging. The Journal of Physical Chemistry Letters, 13(13), 2862-2870. [HTML]
4. Njiti, M. M., Osman, N. D., Mansor, M. S., Rabaiee, N. A., & Aziz, M. A. (2024). Potential of Metal Artifact Reduction (MAR) and Deep Learning-based Reconstruction (DLR) integration in CT Metal Artifact Correction: A review. Radiation Physics and Chemistry, 111541. iium.edu.my
5. Brukštus, M. (2022). Influence of medical implant materials on the appearance of medical imaging artifacts. ktu.edu
6. Bohner, L., Hanisch, M., Sesma, N., Blanck-Lubarsch, M., & Kleinheinz, J. (2022). Artifacts in magnetic resonance imaging caused by dental materials: a systematic review. Dentomaxillofacial Radiology, 51(6), 20210450. oup.com
7. Selles, M., van Osch, J., Maas, M., Boomsma, M., & Wellenberg, R. (2023). Advances in metal artifact reduction in CT images: A review of traditional and novel metal artifact reduction techniques. European Journal of Radiology, 111276. ejradiology.com
8. Rousselle, A., Amelot, A., Thariat, J., Jacob, J., Mercy, G., De Marzi, L., & Feuvret, L. (2020). Metallic implants and CT artefacts in the CTV area: Where are we in 2020?. Cancer/Radiothérapie, 24(6-7), 658-666. sciencedirect.com
9. Cheraya, G., Sharma, S., & Chhabra, A. (2022). Dual energy CT in musculoskeletal applications beyond crystal imaging: bone marrow maps and metal artifact reduction. Skeletal radiology. [HTML]
10. de Lima Dias-Junior, L. C., Correa, M., Porto, O. C. L., Estrela, C., da Silveira Teixeira, C., Garcia, L. D. F. R., & Bortoluzzi, E. A. (2023). Influence of a Metal Artifact Reduction Filter on the Diagnostic Accuracy of Complete and Incomplete Vertical Root Fractures. Journal of Endodontics, 49(10), 1352-1361. [HTML]
11. Mödinger, Y., Anttila, E. D., Baker, G. M., Gross, D. C., & Porporati, A. A. (2023). Magnetic resonance safety evaluation of a novel alumina matrix composite ceramic knee and image artifact comparison to a metal knee implant of analogous design. Arthroplasty Today, 22, 101170. sciencedirect.com
12. Mihalko, W. M., Haider, H., Kurtz, S., Marcolongo, M., & Urish, K. (2020). New materials for hip and knee joint replacement: What's hip and what's in kneed?. Journal of Orthopaedic Research®, 38(7), 1436-1444. wiley.com

13. Adesanya, O. O. (2021). Prosthetic joint replacements in hips and knees: pilot study for the development of a single imaging test in patients with painful prosthetic joint replacements. 18 F …. warwick.ac.uk
14. Romanò, C. L., Petrosillo, N., Argento, G., Sconfienza, L. M., Treglia, G., Alavi, A., ... & Signore, A. (2020). The role of imaging techniques to define a peri-prosthetic hip and knee joint infection: multidisciplinary consensus statements. mdpi.com
15. Khodarahmi, I., Rajan, S., Sterling, R., Koch, K., Kirsch, J., & Fritz, J. (2021). Heating of hip arthroplasty implants during metal artifact reduction MRI at 1.5-and 3.0-T field strengths. Investigative radiology, 56(4), 232-243. google.com
16. Khodarahmi, I., Kirsch, J., Chang, G., & Fritz, J. (2021). Metal artifacts of hip arthroplasty implants at 1.5-T and 3.0-T: a closer look into the B1 effects. Skeletal Radiology. [HTML]
17. Choudhari, A., Gupta, A. K., Kumar, A., Kumar, A., Gupta, A., Chowdhury, N., & Kumar, A. (2024). Wear and friction mechanism study in knee and hip rehabilitation: A comprehensive review. Applications of biotribology in biomedical systems, 345-432. [HTML]
18. Ronoh, K., Mwema, F., Dabees, S., & Sobola, D. (2022). Advances in sustainable grinding of different types of the titanium biomaterials for medical applications: A review. Biomedical Engineering Advances, 4, 100047. sciencedirect.com
19. Bandyopadhyay, A., Mitra, I., Goodman, S. B., Kumar, M., & Bose, S. (2023). Improving biocompatibility for next generation of metallic implants. Progress in materials science, 133, 101053. sciencedirect.com
20. Sarraf, M., Rezvani Ghomi, E., Alipour, S., Ramakrishna, S., & Liana Sukiman, N. (2021). A state-of-the-art review of the fabrication and characteristics of titanium and its alloys for biomedical applications. Bio-design and Manufacturing, 1-25. springer.com
21. Sneha, K. R. & Sailaja, G. S. (2021). Intrinsically radiopaque biomaterial assortments: a short review on the physical principles, X-ray imageability, and state-of-the-art developments. Journal of Materials Chemistry B. [HTML]
22. Khandaker, M. U. & Ullah, M. H. (2024). Status and future outlook of X-ray shielding materials. Advanced Radiation Shielding Materials. [HTML]
23. Jiang, R., Smith, J., Yi, Y. T., Sun, T., Simonds, B. J., & Rollett, A. D. (2024). Deep learning approaches for instantaneous laser absorptance prediction in additive manufacturing. npj Computational Materials, 10(1), 6. nature.com
24. Shen, K., Zhang, R., Jin, Y., Li, Y., & Hu, Y. (2024). Inorganic metal oxide material BaSiO3: Eu2+ for convenient 3D X-ray imaging. Journal of Luminescence. ssrn.com
25. Rafiei, M., Raitoharju, J., & Iosifidis, A. (2023). Computer vision on x-ray data in industrial production and security applications: A comprehensive survey. Ieee Access. ieee.org
26. Hu, Y., Pan, Y., Song, Y., Meijering, E., Cui, Z., Zhao, Y., ... & Shen, D. (2022, March). Parallel sinogram and image framework with co-training strategy for metal artifact reduction in tooth CT images. In 2022 IEEE 19th International Symposium on Biomedical Imaging (ISBI) (pp. 1-4). IEEE. [HTML]
27. Mendes Fonseca, C. (2024). Accuracy and stability of titanium dental implants placed with s-CAIS: an in vitro and in vivo pilot study. usal.es
28. Hu, X., Liu, H., & Baena, F. R. Y. (2021). Markerless navigation system for orthopaedic knee surgery: A proof of concept study. IEEE Access. ieee.org
29. Hu, X., Nguyen, A., & y Baena, F. R. (2021). Occlusion-robust visual markerless bone tracking for computer-assisted orthopedic surgery. IEEE Transactions on Instrumentation and Measurement, 71, 1-11. [PDF]

30. Bonmati, F. G. S., Pérez-Barquero, J. A., Ripoll, L. M. I., Rueda, C. L., Fernandez-Estevan, L., & Revilla-León, M. (2023). An additively manufactured, magnetically retained, and stackable implant surgical guide: A dental technique. The Journal of Prosthetic Dentistry, 130(4), 444-452. silimport.com
31. Ding, P. (2022). Light-sheet light-field fluorescence brain imaging enabled by implantable neural probes. utoronto.ca
32. Roelofs, T. (2021). Deep learning-based affine and deformable 3D medical image registration. aalto.fi