The impact of metal implants on the dose and clinical outcome of radiotherapy (Review)

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Abstract. Radiotherapy (RT) is one of the most widely used and effective cancer treatments. With the increasing need for organ reconstruction and advancements in material technology, an increasing number of patients with cancer have metallic implants. These implants can affect RT dosage and clinical outcomes, warranting careful consideration by oncologists. The present review discussed the mechanisms by which different types of metallic implants impact various stages of the RT process, examined methods to mitigate these effects during treatment, and discussed the clinical implications of metallic implants on RT outcomes. In summary, when metallic implants are present within the RT field, oncologists should carefully assess their impact on the treatment.

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1. Introduction

Tumors remain an important threat to lives and health of individuals with the burden of cancer incidence and mortality rapidly increasing throughout the world. With advances in medical technology, oncologists are increasingly developing additional strategies for oncology treatments, such as neoadjuvant chemoradiotherapy (CRT), concurrent CRT (CCRT), immunotherapy and targeted therapy; however, radiotherapy (RT) continues to play a vital role in the response to the disease spectrum of most cancers (1).

Biomaterials are commonly defined as non-viable materials intended to interface with biological systems to evaluate, treat, augment or replace any tissue, organ, or function of the body (2). Metallic implants are types of biomaterials, commonly used for reconstructing certain important structures or alleviating symptoms. According to statistics, ~4% of patients undergoing RT have metal implants in their bodies, such as in the teeth, esophagus, breast, spine, hip and other areas (3) (Fig. 1). These metal implants are usually present around the tumor. For instance, self-expandable metal stents are often used to palliate malignant dysphagia, either alone or before definitive or preoperative CRT for esophageal cancer (4-6). In addition, metal implants are often present in patients with head and neck cancer (7). However, these metal implants have a non-negligible effect on the dose distribution and delineation of target volumes during RT.

Due to the dose perturbation, the local control of the tumor would be affected and cause excessive damage to the normal tissues and organs at risk surrounding the tumor, resulting in short- or long-term toxicity (8,9). In addition, metal implants tend to be markedly denser than tissue or bone (10); therefore, they produce more severe artifacts when computer irradiation is performed for treatment planning. Although several algorithms exist to reduce metal artifacts, they still impact the accuracy of RT (11,12). Therefore, the present study reviewed the effects of different types of metal implants on radiation dose and clinical outcomes. It also explored methods to minimize the impact of metal implants on RT.

2. The mechanism of metal implants affecting RT

The presence of metallics compromises computed tomography (CT) image quality by generating metal artifacts mainly through beam hardening, noise and scattering (13,14) and thus affecting the accuracy of target volumes. Beam hardening is due to the fact that metals with high atomic numbers absorb photons more strongly, which ultimately results in a higher average energy. Absorption of photons by metallic implants results in a significant reduction in the number of photons detected by the photon detector, which manifests as bright streaks and thin, dark, areas in the image, defined as noise. As the predominant type of interaction in CT, Compton scattered X-rays are the signals usually detected by detectors. This scattering changes the direction of the incident beam away from the center axis. This causes the metal to appear white, with dark streaks along the axis of maximum attenuation (15). Furthermore, metal implants also have an effect on the delivery and distribution of the dose during the course of RT. When photons or electrons pass through a metal implant, secondary electrons or scattering can cause dose perturbation, resulting in an overdose on the front surface of the metal and tissue and a lower dose on the rear surface (16). The metal prosthesis is commonly made from 'high-Z' elements, which are defined as material with an atomic number greater than that of cortical bone. The presence of high-Z material during the administration of an RT schedule can lead to local perturbations through interface effects (17) and distort dose distributions from therapeutic beams (18). The scattered radiation caused by high atomic number materials when introduced into the photon beam from megavoltage RT consists of both scattered photons and electrons. The backscatter is especially important to be aware of when the tumor is placed between the beams and metal implant, as it can cause the dose to reflect and then build up on the surface, resulting in an unplanned escalation in the dose, which can increase the side effects of RT (19). In the study of Dietlicher *et al* (20), the dose of backscattered radiation is related to the angle between the axial beam and the scattering material; however, not all metals can be detected with such a significant relationship, such as silver. Moreover, the sharp density interfaces of a metal prothesis with the surrounding tissues can degrade the homogeneity of the delivered target dose (21).

3. The effect of different kind of metal implants on dosage

Since the density of metallic implants differs significantly from that of human tissue, there is an effect on the dose transmitted to the surrounding tissue as the beam passes through the metal implants. Several studies have investigated the dose perturbation scenarios by means of phantom measurements, algorithmic simulations and other methods. Type of metal, shape of the implant and energy of the radiation have an effect on the dose distribution (5,8,19,22-29) (Table I). The measured distance is the distance from the film to the surface (ray incident surface or ray exit surface) of the metal implant, and the film is used to detect the dose of RT. As for the geometry of the implants, this is more prominent in the esophageal stent, such as the size of the stent mesh, the thickness of the line that constitutes the mesh. In other types of implants, it is mostly manifested as the thickness or length of the implant.

Stainless steel. Stainless steel is widely used in bone fixation, cardiovascular systems, catheters, surgical instruments and dental crowns (30). Furthermore, Bhushan *et al* (27) studied the effect of stainless-steel hip prosthesis on radiation using a customized prosthesis containing wrought austenitic stainless steel. It was observed that for 6 MV of photon irradiation, at a depth of 10 cm below the prosthesis, with field sizes of 5x5, 10x10 and 20x20, the dose attenuation was 8.3, 7.4 and 7.5% when the prosthesis was present compared with in its absence. In addition, when the energy was increased to 15 MV, the dose attenuations were 7.6, 7.1 and 5.0% for the same distances 5x5, 10x10 and 20x20, respectively, of the field sizes. Moreover, Mahuvava and Du Plessis (25) observed that when bilateral stainless steel hips were present, the attenuation of radiation by a prosthesis was 22.8, 20.4, 18.5 and 16.9% with photon irradiations at 6, 10, 15 and 20 MV, respectively. Furthermore, Liu *et al* (23) used human cadavers to simulate tumor resection for internal fixation surgery by placing stainless steel plates in the anterior and upper 1/3 of the human femur with a muscle strip of the same size and thickness for control purposes. It was observed that the absorbed dose at the incident surface increased by 21.65%. Conversely, the absorbed dose at the exit surface was attenuated by 8.42% compared with the control group, as measured with a pyroelectric dosimeter under 6 MV X-ray irradiation. Additionally, their experiments also used the treatment planning system (TPS). It was observed that the distance from the tissue to the metal surface was an important factor affecting dose absorption, and this effect was greatest at a distance of 0.5 cm from the metal surface, resulting in a 6.1% increase in dose upstream and a 2.2% dose attenuation downstream. In addition, He and Ni (26) used the Monte Carlo (MC) algorithm to simulate 6 MV X-ray irradiation and observed that the incident surface dose of stainless steel implants with thicknesses of 1, 2 and 4 cm increased by 23.8, 24.0 and 24.3%, respectively, compared with the dose without the implant; by contrast, the dose at the exit surface decreased by 23.0, 35.2 and 55.1%, respectively. This indicates that the thickness of the implant did not significantly affect the incident radiation dose; however, the dose attenuated more with increasing metal thickness at the exit surface.

Stainless steel is majorly used in stents. Chen *et al* (5) used a solid water phantom to simulate the tissue environment of the human esophagus and measured the surrounding irradiation dose using thermo-luminescent dosimeters. It was observed that the increase in dose to the Z-stent's (stainless steel) anterior surface was 3.5-7.8% when using single beams. Abu Dayyeh *et al* (19) used a solid water phantom irradiated with 6, 10 and 18 MV photons and observed that the dose enhancements of the stainless-steel stent Wallflex front upstream were 4.2, 5.2 and 6.7%, respectively, at three different photon energy irradiations. The aforementioned experiments revealed that the presence of stainless-steel implants could have a non-negligible effect on the accuracy of the RT dose; therefore, when stainless steel implants are present in the irradiation field, this dose perturbation should be considered when making RT plans.

Titanium and its alloys. Since the introduction of pure titanium for oral implants in the 1960s, it has been widely used as a material for surgical implants. Subsequently, Ti-3Al-2.5V and Ti-6Al-4V were gradually used as femoral and tibial

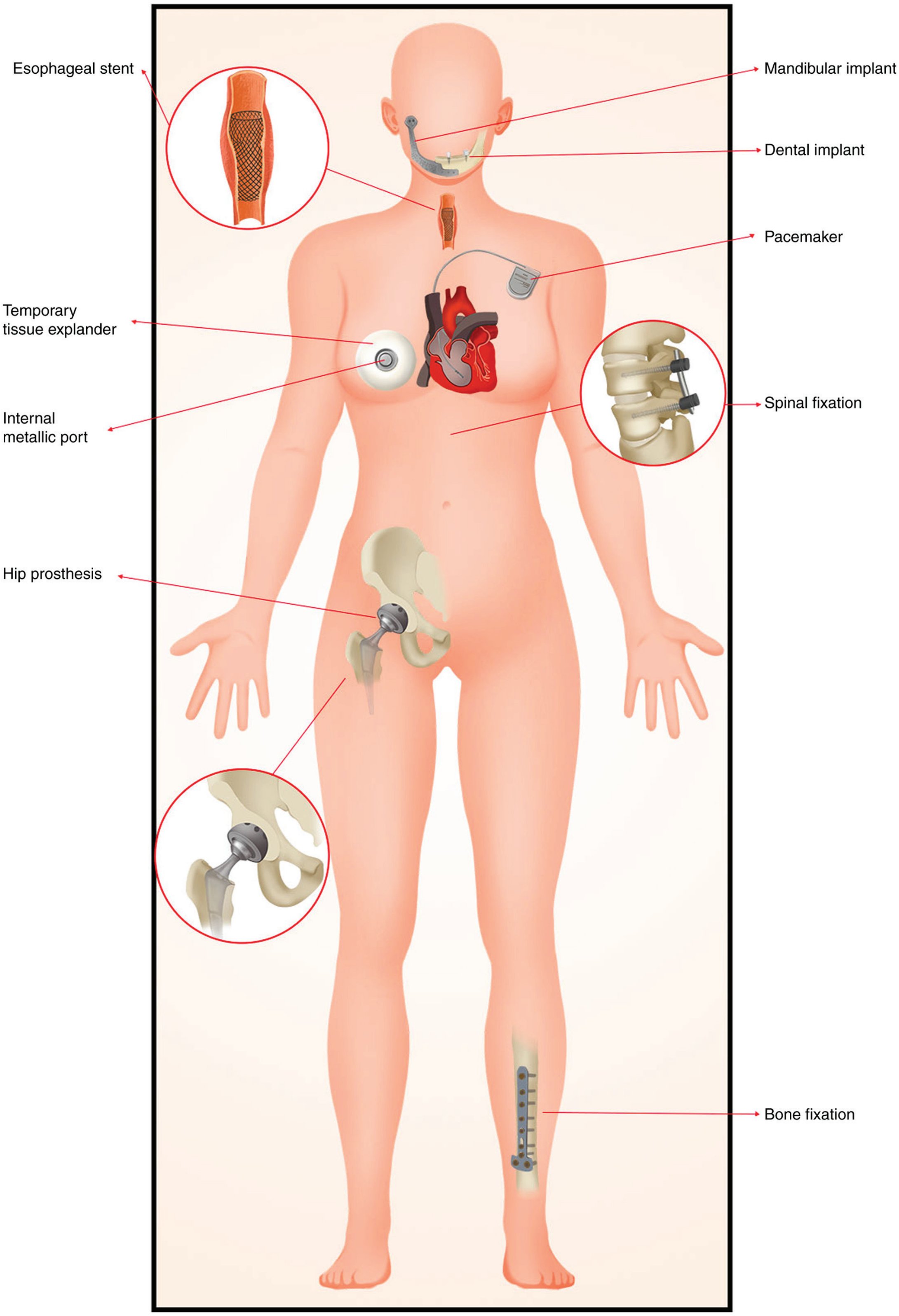

Figure 1. Metal implants in the bodies.

replacement materials. Ti_6Al_4V is an important titanium alloy widely used as a material in surgical implants (31).

External irradiation is a common treatment modality for prostate cancer. With an aging population, several patients treated for prostate or pelvic tumors undergo partial or total hip replacement because of osteoarthritis and hip dysfunction (27). Titanium is often used for hip implants because of its excellent biomedical properties, however it inevitably may affect dose delivery (32).

Ade and du Plessis (29) investigated the perturbation effect of a unilateral titanium prosthesis on the dose distribution of 6 MV and 15 MV photon beams. Using a built-in titanium hip

Table I. Effect of metal implants on radiotherapy dose under different conditions.

First author, year	Material	Method	Location	Energy	Radiation source	Technology of radiation	Increase the dose in incident surface	Reduce the dose in exit surface	PTV Dose (Gy)	(Refs.)
Tsuji *et al,* 2003	Stainless steel	Phantom	Tracheal	10 MV	X-ray	Single beams	9%	8%	6	(22)
		Phantom	Lower limb arteries	10 MV	X-ray	Single beams	3%	3%		
		Phantom	Coronary artery	10 MV	X-ray	Single beams	-	2%		
Liu *et al*, 2010		Monte Carlo	Femur	6 MV	X-ray	Single beams	21.6%	8.42%	-	(23)
Chen *et al*, 2011		Phantom	Esophageal	6 MV	Photon beams	Single beams	3.5-7.8%	negligible	0.05	(5)
		Monte Carlo	Esophageal	6 MV	Photon beams	Single beams	6.2%	<1.0%		
		Monte Carlo	Esophageal	6 MV	Photon beams	Dual beams	3.0%	3.0%		
Lin *et al*, 2013		Monte Carlo	Dental	6 MV	X-ray	Volumetric modulated arc therapy	0.8%	10%	-	(24)
Mahuvava and Du Plessis, 2018		Monte Carlo	Unilateral hip	6 MV	Photon beams	Six fields	-	10.3%	75	(25)
				10 MV	Photon beams	Six fields	-	6.9%		
				15 MV	Photon beams	Six fields	-	3.5%		
				20 MV	Photon beams	Six fields	-	2.1%		
He and Ni, 2018		Monte Carlo	Water	6 MV	X-ray	Single beams	24%	16.2~55.1%	-	(26)
Bhushan *et al*, 2020		Phantom	Unilateral hip	6 MV	Photon beams	Single beams	-	7.5-8.3%	-	(27)
				15 MV	Photon beams	Single beams	-	5.0-7.6%		
Ozen *et al*, 2005	Titanium	Phantom	Lower jaw	Co-60	Gamma ray	Single beams	17-21%	-	2	(28)
				6 MV	X-ray	Single beams	17-18%	-		
				24 MV	X-ray	Single beams	15-16%	-		
Liu *et al*, 2010		Monte Carlo	Femur	6 MV	X-ray	Single beams	15.46%	5.26%	-	(23)
Ade and du Plessis, 2017		Phantom	Hip	6 MV	Photon beams	Single AP beams	21-23%	18-21%	-	(29)
				15 MV	Photon beams	Single AP beams	25-30%	15-18%		
Mahuvava and and Du Plessis, 2018		Monte Carlo	Unilateral hip	6 MV	Photon beams	Six fields	-	6.2%	75	(25)
				10 MV	Photon beams	Six fields	-	4.2%		
				15 MV	Photon beams	Six fields	-	2.4%		

Table I. Continued.

First author, year	Material	Method	Location	Energy	Radiation source	Technology of radiation	Increase the dose in incident surface	Reduce the dose in exit surface	PTV Dose (Gy)	(Refs.)
				20 MV	Photon beams	Six fields	-	1.0%		
He and Ni, 2018		Monte Carlo	Water	6 MV	X-ray	Single beams	20%	11.5~35%	-	(26)
Akyol *et al*, 2019		Monte Carlo	Dental	6 MV	Photon beams	Single beams	11.2%	15.5%	-	(8)
Dayyeh *et al*, 2012	Nitinol	Phantom	Esophageal	6 MV	Photon beams	Perpendicular beam	4.2%	0	0.3	(19)
				10 MV	Photon beams	Perpendicular beam	5.2%	1.0%		
				18 MV	Photon beams	Perpendicular beam	6.7%	1.3%		
Akyo *et al*, 2019	Ti-6Al-4V	Monte Carlo	Dental	6 MV	Photon beams	Single beams	10.7%	15.4%	-	(8)
Akyol *et al*, 2019	Al2O3	Monte Carlo	Dental	6 MV	Photon beams	Single beams	3.3%	7.0%	-	(8)

prosthesis, it was observed that the proximal dose enhancement of the prosthesis ranged as 21-23%, and the distal dose reduction of the prosthesis was 18-21% with 6 MV photon beam irradiation. However, when the radiation energy was increased to 25 MV, the proximal dose enhancement and distal dose attenuation were 25-30 and 15-18%, respectively. It could be inferred from their experiments that the field size does not significantly affect the dose, and that the most significant dose change is within 1.0 cm from the implant surface. Additionally, Akyol *et al* (8) used the pencil beam convolution (PBC) algorithm of the TPS and MC simulation techniques for their study. They simulated a linear accelerator to produce a 6-MV photon beam and observed an 11.2% increase in dose anterior to the titanium dental implant and a 15.5% decrease in dose posteriorly.

Furthermore, He and Ni (26) used an MC algorithm to simulate 6-MV X-ray irradiation and compared the effect of different thicknesses of stainless-steel plates with that of titanium metal implants on the radiation dose. It was observed that titanium implants increased the upstream dose by 19.8, 20.3 and 20.6% at the thicknesses of 1, 2 and 4 cm, respectively, while decreasing the downstream dose by 18.4, 23.6 and 35.0%, respectively. Additionally, it was observed that the effect of titanium implants on radiation dose was less than that of stainless-steel implants. Similarly, experiments by Liu *et al* (23) on human cadavers revealed that the effect of stainless-steel plates on the radiation dose distribution was more pronounced than that of titanium plates under the same conditions.

Titanium and its alloys are also often used in oral implants, which may have an impact on the radiation dose to patients with nasopharyngeal tumors. Lin *et al* (24) observed that titanium used as a dental implant in head-and-neck volumetric modulated arc therapy (VMAT) had clinically significant effects on the dose. They used the MC and TPS methods and observed that at a distance of 2 mm from the implant surface, the upstream dose increased by 0.8%; by contrast, the downstream dose was attenuated by 10%. In addition, Ozen *et al* (28) implanted titanium dental implants of different diameters and lengths into the human mandible and irradiated them with 6 MV X, 25 MV X and Co-60 gamma rays. At the proximity to the titanium, the different sizes of titanium implants increased the dose of Co-60 gamma rays by 17-21%, and the same dose was increased by 17%. However, for 6 MV and 25 MV X-ray irradiation, the dose increased by 17-18% and 15-16%, respectively. Therefore, it could be inferred that the dose increase of 25 MV energy X-rays was slightly lower than that of other energy rays. Nevertheless, there was no significant difference in the dose effect due to the difference in implant size.

Nitinol, a titanium alloy, is widely used to fabricate several types of stents, such as esophageal and tracheal stents. Abu Dayyeh *et al* (19) used a solid water phantom irradiated with 6, 10 and 18 MV photons. The nitinol stent and wall stent were used; the anterior surface dose was increased by 4.1, 7.1 and 3.2%, respectively; and the other nitinol stent ultraflex was irradiated with the anterior surface dose enhancements of 4.7, 6.1 and 3.7%, respectively. The stainless-steel stent was also used in the aforementioned study, and the effect of the different stent materials on the radiation dose was similar. The main determinant of the dose effect in metallic stents was not the stent material, but the mesh density of the stent. From extensive studies, it was observed that the widely used implants made of nitinol could reduce the effect on RT dose more than the stainless-steel stents; however, caution should be exercised when choosing metal implants because the shape of the stent itself can also affect radiation dose.

Other metals. In addition to the commonly used stainless steel, titanium and its alloys, several other metals such as gold, ZrO2, and Al_2O_3 are used as materials for artificial implants. These metallic materials are more widely used in the field of dental implants. As reported by Akyol *et al* (8) the calculated dose increment by MC simulation in front of a dental implant was 15.5 and 3.3% for ZrO2 and Al_2O_3, respectively. The dose decrease behind the dental implant for ZrO2 and Al_2O_3 was 22.2 and 7.0%, respectively. The authors also calculated the change in dose after implantation of metal implants such as titanium. The aforementioned study thus revealed that the density of the implants has an effect on the dose increase in the front of the material, with the higher density increasing the dose to the front surface.

A temporary tissue expander (TTE) is commonly used in patients who require post-mastectomy RT to maintain breast shape and create space between the chest wall and skin. TTE contains an internal metallic port (IMP) used as the injection port for saline injection, which is usually composed of high-density rare-earth magnets, and inevitably perturbs the RT dose (33-35). Using a film dosimetry phantom experiment, Shankar *et al* (36) observed that the dose attenuation measured at a depth of 22 mm was 22% when irradiated with a single photon beam of 6 MV light. When the energy was raised to 15 MV, the dose attenuation at the same depth was 16%. Furthermore, Gee *et al* (37) performed *in vitro* water phantom measurements, measuring the dose distribution at 0.5, 50.0 and 100.0 mm downstream from the IMP, and revealed that the angle of the rays to the IMP had a different effect on the dose, with a 28% metric attenuation when the rays were parallel to one another and a 16% dose attenuation when they were perpendicular to one another. Various degrees of dose reduction were observed downstream in IMP studies (38,39); however, some researchers consider that such dose reduction falls into the saline of TTE and does not significantly affect the surrounding tissues (40).

4. Target delineation

Accurate delineation of the target area and organs at risk is crucial for ensuring the efficacy of RT and controlling the occurrence of toxic reactions. Incorrect delineation may lead to under-dosage of the treatment and over-dosage in the target area and organs at risk. A previous study revealed that a dose deficit of 1% volume of the target that is >20% of the prescription dose may lead to serious loss of tumor control probability with intensity-modulated RT (IMRT) (41). Due to the current target delineation in RT being primarily based on CT images, the presence of metal implants in CT images may negatively impact the image quality and accuracy of the target delineation. Metal implants mainly exhibit white and dark stripes along the maximum attenuation axis on CT images, which are caused by a combination of beam hardening and scattering (15). In addition, photon starvation caused by strong attenuation can lead to statistical errors, which manifest as thin dark and bright stripes around metal implants in CT images (42). The presence of artifacts on CT images is challenging for delineating target areas and organs at risk, especially when there is a lack of prior knowledge about the type of implant (shape, size, metal or alloy composition, and effective atomic number of metals), resulting in increased uncertainty in the delineation of target areas and organs at risk (42,43).

5. Methods to reduce the influence of metal implants during RT

Metal implants can generate metal artifacts which can increase the error of structure visualization and reduce the accuracy of radiation oncologists' delineating targets and that of radiation dose calculation, which can result in damage to the adjacent normal tissues and reduced control rate of the tumor. There are various methods to reduce metal artifacts. Dose calculation algorithms can override the adverse impact of metal implants on RT.

Methods to reduce metal artifacts. Various strategies to minimize metal artifacts and improve image quality techniques have been investigated and developed over the years. Dual energy CT is a common method to reduce metal artifacts. It was reported to reduce beam hardening artifacts between 95 and 150 kilo electron volt levels (44,45). Additionally, the use of iterative metal artifact reduction algorithms can reduce metal artifacts and improve dose calculation accuracy, which enables the precise irradiation of tumors (42,46). These techniques are based on projection data and the image-based metal segmentation method that was used as a start (47). There are also commercially available techniques to minimize metal artifacts such as iterative metal artifact reduction (IMAR; Siemens Healthineers) (48), O-MAR (Philips Medical Systems, Inc.) (49), single-energy metal artifact reduction (SEMAR; Toshiba Medical Systems; Canon Medical Systems) (50), and smart metal artifact reduction (Smart MAR (General Electric Healthcare) (51,52). The technique based on projection data and image-based metal segmentation method was used recently, and VM imaging with projection-based material decomposition algorithm can not only reduce metal artifacts effectively, but also simultaneously prevent object blurring at the metal artifact position and image distortion of the metal implants (53,54). Ceccarelli *et al* (55) considered that combining information from virtual monoenergetic reconstructions and MAR software images could be the best way to solve the issue of metal artifacts on CT images. Those tools were helpful in reducing metal artifacts; however, improved methods need to be further explored. First of all, most of the current research is carried out on the phantom, and it is necessary to verify the effectiveness of its application in the human body, so as to provide a reliable basis for clinical application. In addition, numerous reconstruction algorithms are time-consuming and need to be further optimized to improve the reconstruction efficiency. Finally, the algorithm based on deep learning to reduce metal artifacts has gradually attracted attention. Compared with non-machine learning algorithms, it has advantages in reducing signal-to-noise ratio. In the future, combining big data, deep learning and digital twin technology with increasingly enhanced computer algorithms may improve methods that reduce metal artifacts.

The methods of dose calculation algorithms. Using the aforementioned techniques, oncologists can obtain a relatively precise processed CT image, making target delineation more accurate. However, it is only through an accurate and fast dose distribution calculation that oncologists can be more confident in RT delivery and avoid unnecessary harm to patients in advance. The algorithm for simulating photon dosage focuses on modeling the deposition pattern of X-rays generated by a linear accelerator in the patient. The common dose calculation algorithms included PBC, analytical anisotropic algorithm (AAA), collapsed cone convolution (CCC) and MC. PBC is the simplest and fastest kernel-based dose computation method. Kernel-based algorithms make use of kernels and ray tracing to model the dose deposition resulting from interactions at a given point. The kernel represents the spread of energy resulting from an interaction at a given point or line, and the ray tracing algorithm represents the energy that passes through the tissue from the energy source. AAA is a convolution-based algorithm which was released in 2005 and implemented in the Eclipse (Varian Medical Systems, Inc.) Integrated TPS (56). CCC algorithm uses one or more-point kernels rather than a line kernel which could accurately model beam hardening as the beam traverses the medium for multiple point kernels. MC is a method of finding numerical solutions to a problem by random simulation which may be used to compute dose distributions by simulating the interactions of a large number of particles (including photons, electrons and protons), as they travel through a medium. It is both the most accurate and computationally intensive method of dose calculations on account of large number of simulated interactions at an atomic level (57).

PBC is only suitable for homogeneous media; its accuracy in non-homogeneous media is poor, and therefore, there are limitations to using it to simulate dosage in the presence of metal implants. A CCC algorithm was used in several TPSs because of its accuracy in homogeneous tissues. In a study by Panettieri *et al* (58), for the modeled 6-MV photon beams, both the PBC algorithm and the AAA tended to underestimate the absorbed dose in the build-up region compared with the MC results. Paulu and Alaei (59) studied the results of three common dose calculation algorithms in the presence of a hip prosthesis. The aforementioned study found that near the surface of the prosthesis for all energies, a Pinnacle collapse cone convolution algorithm created a 5-22% higher measured dose than calculated, and for the Eclipse Acuros XB and the Eclipse AAA the overestimation of dose was 2-23% and 6-25%, respectively. MC methods are regarded as the 'gold standard' for patient dose calculations and are widely used in clinical practice. Ade and Plessis (60) revealed that the MC algorithm used in Monaco was significantly more accurate than the CCC algorithm used in XiO. As Parenica *et al* (61) reported, the CCC algorithm in Pinnacle demonstrated a significant 9.2% error in calculating the dose and for the MC algorithm in the Monaco TPS the error was 3.6%. Therefore, to the best of our knowledge, the MC algorithm can be used to calculate the dose for the tumor and its surroundings more accurately in the presence of metal implants. Additionally, it can be used as a second check to ensure the accuracy of the RT plan. However, the MC algorithm has some drawbacks, such as the long time period required for computation and the statistical noise when the number of simulated particles is insufficient. Further optimization of the simulation algorithm is needed. For example, in heterogeneous medium, especially at the junction of different density materials, the accuracy of the measurement simulation algorithm needs to be improved. To improve application of these algorithms to clinical practice, it is necessary to further optimize the computational complexity and reduce the computational time.

6. The dosimetric effect analysis of metal implants in different RT modalities

Currently, RT techniques commonly used in clinical practice include single-field techniques, three-dimensional conformal RT (3D-CRT), IMRT and VMAT. The dosimetric effects when applying different RT techniques need to be considered when treating patients with metallic implants.

Given the accelerating aging population and the rise in hip replacement surgeries, the incidence of patients with cancer and metallic hip implants (MHI) undergoing pelvic RT has increased over the past few decades. Su *et al* (62) compared RT plans for patients with prostate cancer and bilateral MHI using IMRT vs. 3D-CRT. Their findings indicated that IMRT provided improved protection for the bladder and rectum across all treatment stages, particularly in high-dose regions. Both RT strategies, 3D-CRT and IMRT, provided adequate target coverage, and the dose-volume histograms (DVHs) for the prostheses were similar. However, IMRT had a drawback of dose inhomogeneity within the Planning Target Volume. Van Der Est *et al* (63) proposed methods to further optimize IMRT, which effectively reduced the radiation dose to the bladder and rectum during pelvic irradiation, offering enhanced protection for patients with either unilateral or bilateral MHI.

VMAT is a technique that utilizes inverse planning without restricting beam angles. Singh *et al* (64) developed IMRT and VMAT plans for patients with MHI using various optimization methods. Their results revealed that, regardless of the optimization method, VMAT consistently outperformed IMRT, offering greater volumetric coverage, fewer hotspots, and less heterogeneity. Koutsouvelis *et al* (65) demonstrated that standard 2-co-planar arc 360˚ VMAT treatment, when applying artifact reduction algorithms, could mitigate errors induced by prostheses during pelvic RT in patients with bilateral MHI. The dose errors due to the MHI were between 0.3 and 0.5%. This technique enabled effective treatment without avoiding the prostheses, particularly when the distance between the prosthesis and the target was >0.5 cm. Another study also revealed that VMAT not only resulted in lower rates of acute and chronic genitourinary and gastrointestinal adverse effects but also offered an improved therapeutic option overall (66). Soda *et al* (67) directly compared the performances of 3D-CRT, IMRT and VMAT in treating patients with prostate cancer and bilateral MHI. Their findings revealed that VMAT delivered improved DVH and required shorter treatment times compared with the other two methods. Additionally, VMAT significantly improved dose distribution in the presence of MHI compared with 3D-CRT, highlighting its advantage in managing the complexities introduced by metal prostheses during RT.

Furthermore, Rana *et al* (68) conducted a dosimetric study comparing uniform scanning proton therapy (USPT) and VMAT for patients with prostate cancer and MHI. Their findings indicated that USPT provided superior dose uniformity and improved protection for the rectum and bladder. These results suggested that uniform scanning proton therapy offers potential dosimetric advantages in treating prostate cancer involving MHI.

Metal implants are also common in the oral cavity. Shimamoto *et al* (69) compared dose differences when using single-field RT, 3D-CRT and IMRT in the presence of dental metal implants (DMI). The aforementioned study employed various types of DMIs and revealed that single-field RT resulted in a scatter dose increase of 3.7-19.3% due to the DMI, while 3D-CRT and IMRT demonstrated increases of 1.4-6.9 and 1.4-4.3%, respectively. The results indicated that both 3D-CRT and IMRT were superior to single-field RT in mitigating the increase in scatter dose caused by DMI. Additionally, there was no significant difference in scatter doses between 3D-CRT and IMRT for metals other than gold.

Based on these findings, oncologists should consider the type of metallic implant and the specific circumstances of their treatment center when selecting the appropriate RT technique for patients with metallic implants in the treatment area, aiming to minimize the impact of metallic implants on RT dosing.

7. The effects of metal implants on clinical outcomes of RT

Although different metal implants have different effects on RT dose, the methods of reduce metal artifacts and dose calculation algorithms can decrease the impact to minimum, which result to a favorable clinical outcome.

The self-expanding metallic stents (FCSEMS) have been widely used in patients with esophageal cancer and is often combined with RT. Post-stenting external beam RT effectively prolongs duration of dysphagia relief and improves overall survival in inoperable esophageal cancer (70). A meta-analysis involving eight randomized controlled trials enrolling 732 patients were included with three distinct comparisons: Stents combination therapy (RT or chemotherapy or both) vs. stents alone, stents alone vs. brachytherapy alone, and stents + brachytherapy vs. brachytherapy alone. This revealed that combination therapy significantly improves the overall survival as well as demonstrated improvements in the quality-of-life scores (71). Another study revealed that palliation of dysphagia or fistulas with FCSEMS in patients with incurable esophageal cancer before or after RT was not associated with an increased risk of life-threatening complications (72). The latest research revealed that RT treatment in patients with an esophageal stent increases the frequency of minor, however not life-threatening adverse events (73). Stents have also been used in contact with biliary obstruction caused by tumors such as pancreatic cancer. Hayakawa *et al* (74) retrospectively analyzed the impact on the safety of receiving CCRT after stent implantation in 30 cases (seven patients had SEMS while 23 had plastic stents). It was observed that patients with biliary stents had a higher CCRT completion rate, and CCRT after stenting was not associated with significant toxicity or side effects. Furthermore, SEMS may benefit patients more than plastic stents by keeping the bile duct more normal for an extended duration and reducing stent obstruction.

Similar clinical results also appear in pelvic RT with metal hip prostheses. Fischer and Hoskin (75) reported that no significant differences were observed in genitourinary and gastrointestinal toxicity incidence between patients with bilateral hip prostheses and a control group (75). A multi-institutional retrospective study demonstrated that their hip prostheses were not affecting the prognosis of patients with prostate cancer (76). TTE with an IMP was commonly used for breast reconstructions and was inserted subcutaneously at the time of mastectomy. Most patients who undergo mastectomy require postoperative RT. A study revealed that patients with TTE completed RT and did not experience any unacceptable adverse effects during RT. No manifestations of infection, tissue necrosis, or hematoma were observed during the RT (36).

8. Conclusion

RT is an essential modality in cancer treatment. With an aging population and advancements in surgical techniques, an increasing number of patients undergoing RT have metallic implants. These implants impact various aspects of RT, including target delineation, dose calculation and dose delivery, which in turn affect dosimetric outcomes, control rates and side effects. To address the influence of metallic implants and improve the efficacy of RT, researchers have made efforts in reducing metal artifacts, optimizing algorithms, and enhancing RT techniques. However, when metallic implants are present within the radiation field, oncologists must carefully choose appropriate dose calculation methods and RT strategies based on the type of implant to improve control of the tumor and minimize complications.

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Availability of data and materials

The data generated in the present study may be requested from the corresponding author.

Authors' contributions

YL and HX drafted the manuscript. YL, HX and WT reviewed and collected data for the study. XD conceived the study and contributed in the review and edit of the manuscript. All authors read and approved the final manuscript. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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