Addressing the dose perturbation of metallic implant in spinal Stereotactic Body Radiotherapy (SBRT)

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Abstract. This study compares methods of addressing the dose perturbation occurred in planning and delivery stage of spinal adjuvant Stereotactic Body Radiotherapy (SBRT) caused by the presence of titanium implants. Dose prediction by TPS was conducted while the CT number of titanium was (a) default, calculated by AAA algorithm (“No Overridden”); (b) relative electron density, mass density matched, calculated by AAA algorithm (“AAA”); (c) relative electron density, mass density matched, calculated by AXB algorithm (“AXB”). In (i) phantom study, dose predictions were compared with measurement conducted with 2 mm, 6 mm and 10 mm thickness of titanium alloy Grade 5 (Ti6Al4V) using field sizes of 1 x 1 cm², 2 x 2 cm², and 4 x 4 cm². In (ii) planning study, retrospective dose predictions on patient plans were carried out to evaluate the impact on clinical outcome. The mean discrepancies (%) between measurement and “No Overridden”, “AAA”, “AXB” at tissue – titanium interface were respectively -16.86 (10.93), -14.05 (11.24), 0.71 (1.54) for 2 mm and 6 mm thickness of titanium; and -18.42 (11.20), -18.29 (11.04), -10.14 (0.01) for 10 mm thickness of titanium, respectively. The patient study results by “AXB” yielded a significant deficit in tumour volume coverage at prescribed dose compared to “AAA” and “No Overridden” by 5.23 % and 9.06 %, respectively. “No Overridden” and “AAA” can potentially generate acceptable prediction in specific scenarios where the depth of target remains approximately unchanged while the gantry rotates. The AXB algorithm is recommended to be used in routine practice involving titanium implants.

1. Introduction
Postoperative radiotherapy often has to take into account of metallic implant as a result of surgical procedure. The presence of metallic implant creates an inhomogeneous interface which can significantly affect the dose to tissues located adjacent to the implant. The electron fluence from tissue to metal interface establishes an enhanced dose to the tissues prior as a result of backscattering of electrons from the tissue-metal interface. On the other hand, the electron fluence from metal to tissue establishes a reduction of dose due to the attenuation by the metal implant. These two phenomena can potentially affect the planning phase and subsequently the treatment outcome if appropriate attention is not paid. Physical measurements have revealed substantial dose perturbation...
by the metallic implants compared to the corresponding plan derived from treatment planning system (TPS) [1, 2]. The insufficiently characterization of the computed tomography (CT) numbers assigned to the involved metallic material in planning phase was the consensus of the conclusions in various studies addressing this issue [3]. There are two common algorithms being used in Varian Eclipse version 13 (Varian Medical System, Inc., Palo Alto, CA, USA). Analytical Anisotropic Algorithm (AAA) addresses inhomogeneity correction by applying electron density data to dose kernels [4]. On the other hand, Auros XB (AXB) directly accounts for the heterogeneity by solving the Linear Boltzmann transport equation (LBTE) [5], hence requiring mass density and chemical composition of relevant volumes and sacrificing its calculation speed for accuracy compared to AAA.

The objective of this study is to investigate the impact of metallic implant on dose delivery in planning phase and treatment phase for spinal metastasis using SBRT. The specific objectives are: (i) to compare the metal (titanium) affected dose measured in phantom with simulation derived doses, which are derived by TPS default electron density and an overridden electron density and (ii) to compare the effects of user-defined electron density of metal plates (titanium) on previous SBRT patient plans in which TPS derived electron density was used.

2. Material and methods

2.1. Film measurement versus dose calculated by TPS

Gafchromic film EBT3 (Ashland Inc., Covington, KY, USA) was used in this experiment. Titanium alloy Grade 5 (Ti6Al4V) was investigated in this study because of its popularity as a material to fabricate medical implants nowadays [6]. Titanium plates and film pieces were positioned in Solid Water phantom (Gammex-RMI, Middleton, WI, USA) with total thickness of 20 cm. The metallic plates were placed at depth of 5.6 cm while film pieces were respectively placed at depths of 1.5 cm, 4 cm, 5 cm, 5.2 cm, 5.4 cm, 5.6 cm, 5.6 + x cm, 5.8 + x cm, 6.0 + x cm, 6.5 + x cm, and 7.0 + x cm with $x \in \{0.2, 0.6, 1.0\}$ (cm) is the thickness of the titanium insert. Radiation beam was delivered by Novalis Tx linac (Varian Medical System, Inc., Palo Alto, CA) using the 6 MV beam energy at SSD of 100 cm. Each irradiation delivered 600 MU to field sizes of $1 \times 1 \text{ cm}^2$, $2 \times 2 \text{ cm}^2$, and $4 \times 4 \text{ cm}^2$, respectively. The images were analyzed using ImageJ software [7]. Only information from red channel was utilized since this channel is the most sensitive at dose range below 8 Gy [8]. PDD curves were derived while the normalization was referred to dose at depth of maximum dose (1.5 cm).

The same setup with phantom as in film measurement as described in the previous section was reproduced in simulation procedure. Brilliance Big Bore simulator (Philips Health Care, Cleveland, OH) was utilized in 120 kVp setting with metal artifact reduction for orthopedic implants (O-MAR) algorithm [9] applied to derive images with slice thickness of 2 mm. The acquired data was transferred to the TPS: Varian Eclipse version 13 (Varian Medical System, Inc., Palo Alto, CA, USA). Dose calculation was conducted while the CT number of the titanium plates was (a) automatically assigned by the TPS; (b) manually assigned to match both the electron density and the mass density of titanium (RED = 3.735, $\rho = 4.51 \text{ g/cm}^3$ according to CIRS Inc. [10]). Since AXB algorithm requires an extension of the current CT calibration curve to calculate plans involving titanium implant, plans of scenario (a) were calculated by AAA algorithm whereas plans of scenario (b) were respectively calculated by AAA and AXB algorithm. Depth dose line profiles were generated in each plan to be compared to the PDD curves from film measurement.

2.2. Retrospective study of SBRT patients with titanium implants

Two patient cases with posterior instrumentation (PI) were selected to evaluate the clinical significance of titanium implants. The first patient had planning target volume (PTV) at T7 vertebrae while the second patient had PTV at T2 vertebrae.

The PTVs were prescribed 24 Gy in two fractions using RapidArc. The dose was planned to deliver using two arcs in two full rotations. Optimization was carried out to ensure the PTV received the prescribed dose and to put a dose constraint of 15 Gy on the spinal cord. Dose calculation was
conducted following the two scenarios described in the above section. The generated dose volume histograms (DVHs) and dose distributions were evaluated and compared to each other.

3. Result and discussion

3.1. Phantom study: comparison between film measurement with dose calculation from TPS

3.1.1. Default CT number assigned to titanium plates. Figure 1(a), (b) and (c) illustrate the results of comparison between measurement and calculation by AAA and AXB at field size of 1 x 1 cm² with 2 mm, 6 mm, and 10 mm thickness of titanium, respectively. Results from other field sizes within their respective titanium thickness followed the same trend.

In every setup, a general trend was observed in the calculated PDD by TPS derived by automatically assigned CT number to titanium (average of 2400 HU, which corresponds to mass density of 2.5269 g/cm³ and RED of 2.2006). The PDD at 2 mm and 4 mm anterior to the entrance interface was sufficiently matched to the measurement, although overestimation at the latter position appeared when there was air gap in the setup. A significant underestimation at the entrance interface was observed followed by a drastic overestimation at the exit interface. Table 1 shows the mean differences of PDD values at positions that are adjacent to the two interfaces. The accuracy of photon fluence and electron fluence modeling starting from the first interface is insufficient, since the derived electron density corresponding to the automatically assigned CT number was truncated at the value of cortical bone. Consequently, discrepancies that could subsequently induce clinical significances would occur if there was no action to address the issue.

Figure 1. Illustration of phantom study in field size of with titanium thickness of 1 x 1 cm²: (a) 2 mm, (b) 6 mm, (c) 10 mm.

3.1.2. Manually assigned CT number for titanium – AAA algorithm. With 2 mm thickness of titanium, PDDs at depths prior to the first interface were predicted accurately followed by a slightly better agreement with measurement at the entrance surface compared to default CT number (Figure 1(a)). Subsequently, an increase in the overestimation of PDD was observed at the exit interface followed by a better, yet still overestimated, prediction at 4 mm posterior to it. The method of scaling electron
density to water material used by AAA seem to ‘‘stretch out’’ the electron fluence posteriorly, incorrectly predicting a part of dose in first interface to be delivered to deeper positions. The magnitude of mentioned phenomenon was increased with thickness of titanium. With 6 mm thickness of titanium (Figure 1(b)), a miscalculation of imparted energy occurred at 2 mm prior to the first interface due to an anterior stretch of the electron fluence, which consequently lower the imparted energy predicted to posterior depths. Still, significant overestimation at second interface was observed. With 10 mm thickness of titanium, the adverse effect on fluence modeling was so drastic that no significant peak was observed at the entrance interface (Figure 1(c)). Besides, the slope of dose fall off changed at 0.9 cm posterior to the exit interface, indicating that the spread out was prolonged until that position.

3.1.3. Manually assigned CT number for titanium – AXB algorithm. The overall results of AXB algorithm are markedly better than AAA algorithm (Table 1). The dose at the two interfaces, where AAA failed to predict accurately, deviated from measurement by $−3.77 \pm 0.45 \%$ and $2.17 \pm 0.25 \%$ at first and second heterogeneous surface, respectively. The results were expected since in addition to mass density, AXB requires detailed cross sections of specific material [5], resulting in better fluence modeling than AAA. However, the accuracy of the algorithm also varied with thickness of titanium. While prediction at the first interface with 2 mm and 6 mm thickness of titanium yielded good results, calculated dose at this depth with 10 mm thickness of titanium did not sufficiently match the measurement. The excess thickness of titanium could have significantly deformed the fluence model as in the AAA algorithm. In addition, the 10 mm thickness of titanium in this study was formed from sheets of 2 mm thickness, which could induce inter-sheet air gap. Hence, the over-responding behavior of AXB towards air gap could drastically change the dose calculation. Regardless of titanium thickness, AXB calculations resulted in higher dose at second interface and lower dose at 2 mm and 4 mm depth posterior to it compared to measurement. These deviations were within 3\%, whose significance in clinical situation is investigated in the following patient study.

3.2. Patient study: The impact of titanium implants on treatment plans for SBRT

Figure 2(a) and (b) show the DVHs of two patient plans with default CT number to the implants (“No overridden”), assigned CT number to the implants calculated by AAA (“AAA”) and AXB (“AXB”) algorithm, respectively.

3.2.1. Using AXB algorithm to address the titanium implants in patient study. In the first patient case, the 100\% (24 Gy) isodose line of “AXB” was predicted to cover less volume than that of “AAA” and “No overridden” by an amount of 6.56 \% and 11.16 \%, respectively. Furthermore, there was a sharp fall off from 80\% (20 Gy) to 100\% (24 Gy) in “AXB” DVH compared to the respective “AAA” and “No Overridden” DVH. This is because at level of T7 vertebrae, the depth of target is the smallest when the beam entered from posterior of patient. Hence, posterior beams of the arc had more weight in dose delivery. These highly contributing beams had to traverse through the titanium implants before reaching the target, which AXB algorithm showed to predict smaller and more accurately dose compared to AAA algorithm.

In the second patient case, the discrepancies of the 100\% isodose lines of “AXB”–“AAA” and “AXB”–“No Overridden” yielded values of 4.90\% and 6.95\%, respectively. Sharp fall-off in the PTV doses was also observed, although the slope was shallower. This marked discrepancy observed between two cases is was due to the difference of patient thickness in two cases. In second case where the arc revolved around the superior mediastinum, the thickness of medium that each beam had to traverse was relatively similar to each other. Consequently, the weight of posterior beams was decreased while that of anterior beams, which delivered excess dose at tissue – phantom entrance surface, were increased.

As in dose to the PTV, the prediction of dose to spinal cord using AXB algorithm yielded a more conservative result compared to using AAA algorithm. In addition, the deviation of “AXB” DVH from
“AAA” and “No overridden” DVH in patient 1 is larger than in patient 2. These phenomena can also be explained as in dose to the PTV, although their magnitude is smaller as a result of optimization process and due to the smaller volume of this organ at risk.

![Figure 2. Dose-Volume histogram of (a) patient 1; (b) patient 2.](image)

**Figure 2.** Dose-Volume histogram of (a) patient 1; (b) patient 2.

3.2.2. Using AAA algorithm to address the titanium implants in patient study. Assigning CT number that represents the physical characteristics of titanium to the implants while using the same algorithm for calculation only generated sustainable discrepancy on target coverage at doses not less than 24 Gy (up to 7% in patient 1 and up to 9% in patient 2). This observation is in consensus with the phantom study results where the deviation between “AAA” and “No Overridden” is bigger with the smaller thickness of titanium. The dose to spinal cord predicted by “AAA” and “No Overridden” showed no significance in both cases. The small volume and relative position of this organ made the effect of CT number overridden with AAA algorithm to be modest.

3.2.3. The choice of correction method based on clinical scenario. The clinical significance of AAA in addressing titanium implant was previously investigated by various studies. When using PI technique at thoracic vertebrae (volumes of interest are relatively far from titanium implants), “No Overridden” was reported [11] to generate dose distribution that is clinically identical to “AAA”. Furthermore, [8] also concluded that in these particular cases, “AAA” and “No Overridden” generated dose distributions that sustainably matched the measurements in VMAT plans. However, their assessment was based on a dose line profile in anterior-posterior direction through the center of vertebral body and gamma passing rate between “AAA” plans and QA measurement in homogeneous phantom, which did not necessarily provide adequate information regarding clinical significance.

**Table 1.** Mean differences of PDD values between measurement and calculation by “no overridden”, “AAA”, “AXB” from 4 mm anteriorly of entrance interface to 4 mm posteriorly of exit interface.

| Position (mm) | X – 4 | X – 2 | X | Y | Y + 2 | Y + 4 |
|--------------|-------|-------|---|---|------|------|
| No overridden | 0.83  | -0.18 | -17.38 | 11.02 | 7.09 | 4.61 |
| AAA          | 1.31  | 1.44  | -15.47 | 11.17 | 4.85 | 1.43 |
| AXB          | 1.42  | -1.49 | -3.77  | 2.17  | -1.36 | -2.69 |
| SD           | 0.38  | 0.38  | 0.45  | 0.25 | 0.30 | 0.30 |

X: depth of the entrance interface; Y: depth of the exit interface.
Unit of all value is (%).
Standard deviation is identical for values in the same column.
On the other hand, reports in other clinical scenarios exhibited that “AAA” was not encouraged to be used other than mentioned situations. [12] investigated the dose perturbation at the proximity of titanium implant (sub-centimeter distance) and found discrepancy that went beyond clinical acceptance between “AAA” and measurements. Moreover, [2] studied on different implant techniques and found that in anterior instrumental implant (AIAC or AIABc), where the titanium is closer to the target and organ at risk compared to PI, dose calculation by AAA did not accurately match the measurements. By comparing to MC model, AXB algorithm was showed to be a better choice to addressing the dose perturbation in the vicinity of the titanium implant in these scenarios [13].

4. Conclusion
Dose calculation using TPS while the physical characteristics (mass density and relative electron density) of titanium was not correctly described yields significant underestimation to the phenomenon prior to the entrance interface and overestimation to the phenomenon beyond the exit interface. When the titanium implants were properly defined in TPS, only modest improvement has been observed with AAA algorithm. Whereas by using AXB algorithm, the resultant difference between measurement and calculation is tremendously reduced. However, the effectiveness of AXB algorithm reduces with increasing in titanium thickness.

In patient studies using RapidArc plans, since posterior beams have more weighting than other beams, the effect occurred beyond the exit titanium – tissue interface has more contribution to the dose calculation. Hence, dose calculation using correction methods shows conservative prediction compared to when no correction was applied. As expected from phantom study, there is significant discrepancy between DVHs derived by AXB algorithm and by AAA algorithm. “No correction” and “AAA” practice can only derive acceptable prediction in particular clinical scenarios where the depth of target remains approximately unchanged while the gantry rotates. Hence, using AXB algorithm to take into account the titanium implant in treatment is recommended.

5. Reference
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