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Clinical viability of explicit metal bolus simulation during dose calculation with acuros XB™

Abstract

To assess the dose to both target tissues and organs at risk, accurate surface dose estimation is a key factor of many radiation treatment plans. Traditional water-equivalent bolus materials, such as Superflab™ (Radiation Products Design, Inc. (RPDinc) in Albertville, Minnesota), have limitations in conforming to complex patient topography, while metal mesh bolus, such as brass, offers better conformity but presents challenges in dose calculation. This study aimed to assess the viability of using virtual metal bolus in treatment planning systems (TPS) to accurately simulate the dosimetric effects of brass mesh bolus. Dose measurements were performed using EBT gafchromic film (Ashland) beneath 1.5mm brass mesh and 5mm superflab for both en face and 60-degree incident 6MV photon beams. In the TPS, brass mesh bolus was simulated using 1mm of aluminum (Al), stainless steel, or titanium (Ti), and 2.5mm of water. Additionally, irradiations of an Alderson RANDO anthropomorphic phantom with breast attachment were performed to assess dose at six surface locations. Results showed that for en face beams, the dose measured beneath brass mesh deviated from TPS estimates by 1.15% for 1mm virtual Al bolus, compared to 9.37% for 2.5mm virtual water bolus. For 60-degree incidence, the deviations were 0.30% and 16% for Al and water, respectively. For RANDO phantom irradiations, EBT film measurements showed an average surface dose increase of 58% with brass bolus compared to no bolus. The TPS estimated a 101% increase for 1mm virtual Al bolus. This was closer to the measured value than the 143% increase estimated for 2-3mm virtual water bolus. The study concludes that virtual 1mm Al bolus in the TPS may provide a more accurate representation of brass mesh bolus effects on surface dose compared to commonly used 2 to 3mm water-equivalent alternatives. This method offers improved accuracy in surface dose estimation without significantly affecting deep dose calculations. However, challenges remain in simulating submillimeter bolus on complex patient topographies and accurately computing surface dose.

Keywords: Bolus, AcurosXB™, Dose Algorithm, Surface Dose

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Introduction

Radiation therapy aims to maximize the dose delivered to a lesion while minimizing the dose to surrounding healthy tissue. If a lesion does not involve the skin, generally skin is avoided as a healthy tissue. At times, the tumor tissue can be quite near, or even directly involve, the skin of the patient. In particular, radiation treatment of the breast may require increased surface dose. However, care must be taken to manage skin reactions, ranging from erythema to necrosis.[1]

Often treatment of superficial lesions may use a surface bolus material to increase the radiation dose to the patient's skin surface and immediately adjacent underlying tissues. The most commonly used bolus agent used is a water-equivalent rubber known as Superflab. This material has favorable dosimetric properties, but is limited by its ability to conform to large variations in patient topography. When surface conformity is lost, the bolusing effect is reduced, resulting in decreased skin dose. Metal mesh bolus, such as brass, has a higher atomic number than water, which makes it more effective at scattering and attenuating the radiation beam; metal mesh bolus can be thinner while achieving similar dose build-up. The chainmail construction and thinner profile of brass mesh allow for higher conformity to the patient's skin.[2] However, accurate calculation of dose under a metal bolus is challenging.[3]

When imaged using computed tomography, brass bolus may create a streaking artifact and may result in significant inaccuracies in subsequent dose computation. Thus, it is standard practice for simulation imaging to be done without bolus and then have bolus added within the TPS. Current standard practice for dose computation beyond metal-mesh bolus involves substituting a virtual 2 to 3 mm water-equivalent thickness bolus in the treatment planning software (TPS) per 1.5mm sheet of brass mesh bolus planned for use during treatment. While this method predicts dose beneath brass bolus well at depths of several centimeters, dose immediately beyond the brass bolus may not be accurately represented. This is because the stopping power ratios of water and metal are different, potentially leading to significant differences in photon and electron spectra in the dose build-up region. The clinical significance of these discrepancies, which may affect intended benefits and potential toxicities is still not settled.[4]

Dose calculation algorithms which solve Boltzmann transport equations, either stochastically (Monte Carlo) or deterministically (Acuros XB™, Varian) could theoretically improve accuracy by directly simulating dose deposition through a virtual metal material. These methods have been shown to provide a more accurate representation of the dose distribution in general, and to improve the accuracy of material interface dose estimates such as skin.[5] Commercial algorithms, such as Acuros XB™, provide a limited selection of materials for virtual assignment. Brass, the material most associated with metal bolus, is currently not available for selection (Acuros XB™ v15.6), further complicating dose calculation. However, other metals, such as Al, stainless steel, and Ti are available, and may be a sufficient surrogate. Despite the use of metal as the virtual representative of bolus, the exact composition of this metal mesh was not tested in this study. The brass mesh is not a uniform material; the mesh is a chain link. The solid component of the mesh has a variable topography and the mesh has holes between its components. If a single material were to be used to simulate brass mesh it likely would not be brass at a thickness equal to the maximum thickness of the brass mesh.

As it is near the resolution limit of commercially available treatment planning systems, accurate virtual representation of a 1 mm thick materials is also challenging generally. Imaging and calculation resolutions ideally would be submillimeter to provide high fidelity, 1 mm thick, contours atop complex geometries. Small inaccuracies in virtual thickness may result in significant dosimetric discrepancies due to the high density of the bolus material. However, direct imaging by computed tomography with brass bolus in place during simulation causes significant streaking artifact. This makes contouring of the bolus difficult and requires contouring, and density correction, of any artifacts. Additionally, the thinner physical thickness of the metal bolus makes accurate delineation reliant on the resolution of the simulation scan. Due to these challenges, virtual creation of the metal bolus at a preset thickness within the TPS, rather than direct imaging, is more reproducible and less time consuming. Nevertheless, either method has the potential to lead to increases in uncertainty while using metal bolus within the TPS compared to the use of virtual water surrogate which would be affected by submillimeter thicknesses inaccuracy less.

Confirmation of surface doses via measurement is challenging due to complex radiation interactions within the patient's skin and the surrounding tissue. Electrons liberated by the incident photon fluence in this build-up region have not yet reached a steady state. As a result, dose distributions change rapidly; inaccuracies of a millimeter can result in measurement differences of several percent. Measurements of dose in the build-up region have been seen to disagree with computed doses for oblique fields on the order of 4%, even at 2mm depth.[6] Yet skin dose of concern as defined by the Nuclear Regulatory Commission is 0.07mm deep and is increasingly difficult to reliably approximate. Typically, assessment of dose at this depth in a patient is assessed by reasonable approximation utilizing *in-vivo* surface dosimeters such as thermoluminescent dosimeters, optically stimulated dosimeters, radiochromic film, metal oxide-semiconductor field-effect transistors, or diodes.

This study evaluates the feasibility of utilizing a commercial dose calculation algorithm (Acuros XB™ v15.6, Varian) to directly calculate radiation transport through a virtual metal bolus.

Methods

Treatment plans were created in the Eclipse treatment planning system (v15.6, Varian) simulating various bolus setups. A 5cm solid water phantom with a 1mm virtual bolus was created. A 25x25cm 6MV photon beam was placed at 100 cm source to detector distance in the enface (AP) position. The treatment machine utilized was a Varian TrueBeam STx. 200 MU were prescribed. A second plan was created for evaluation of oblique delivery with an identical beam at 60 degrees incidence. The 1mm bolus was assigned a material of either Al, stainless steel, or Ti, and dose was evaluated in the TPS immediately below the bolus. Plans were also generated for both enface and oblique incidence using the current vendor-recommended standard 2.5mm (simulated using the 2mm and 3mm simulations and averaging the result) bolus assigned the material of water. Again, dose was evaluated immediately below the bolus. To ensure adverse deep dose effects were not observed, all plans within the TPS were additionally evaluated for dose at 10cm depth; it was ensured that vendor recommendation agreed with potential alternatives at relevant treatment depths.

Absolute dose was measured using EBT gafchromic film beneath both 1.5mm brass mesh and 5mm superflab for both enface and 60-degree incident beams. These films rested on 5 cm of solid water backscatter material. Measurement results were compared to results calculated by the TPS.

For assessment of realistic clinical scenarios, a simulated breast treatment plan utilizing 6MV open tangent beams was created for delivery on the Alderson RANDO anthropomorphic phantom™ with breast attachment. Virtual boluses of 1mm Al, 2mm water, and 3mm water were created, and dose was evaluated below the bolus at six clinically relevant locations. The virtual bolus was then removed, and dose recomputed. A relative bolusing effect was then calculated as a ratio of the bolused dose to the unbolused dose. The phantom was then placed on the treatment machine and set up in the planned position via cone-beam CT. EBT film and 1.5mm brass bolus were placed following cone-beam CT. Film measurement locations, which corresponded to the locations selected in the treatment planning system, can be seen in Figure 1. Effort was made to minimize wrinkles and overlaps in the bolus. The bolus was then removed, and dose remeasured, and a ratio of bolused to unbolused dose computed and compared to the ratio obtained from the TPS.

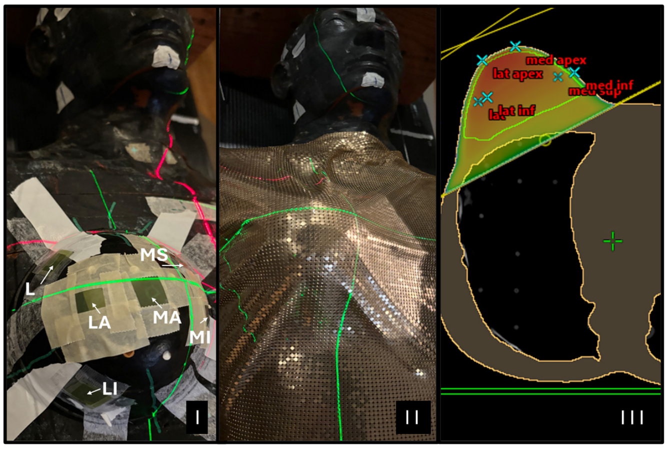

Figure 1 RANDO Phantom setup for film measurement and simulation in TPS.

I. RANDO phantom with film placed at anatomical locations (L=Lateral, MS=Medial superior, LA =Lateral apex, MA=Medial apex, LI=Lateral inferior, MI=Medial inferior). II. RANDO phantom with brass bolus in place as would be clinically implemented. III. Measurement reference points on RANDO phantom in TPS associated with locations measured using film

Finally, the effect of virtual bolus selection on deep dose was evaluated using the RANDO-based treatment plan. A point was selected to approximate deep dose within the breast. This point was 5cm from both the lateral and medial aspects of the breast phantom surface, and 4cm from the breast apex as seen in Figure 2. Dose to this point was computed for the same treatment plan with a virtual bolus of 1mm Al, 2mm water, or 3mm water. MUs were held constant to ensure equivalence.

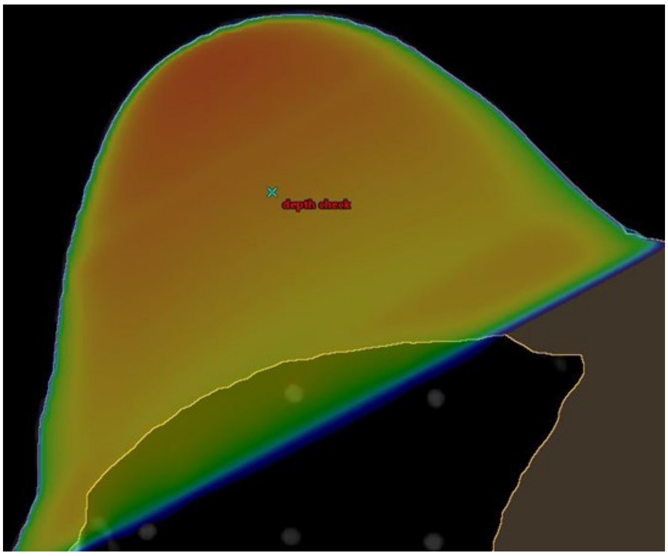

Figure 2 Alderson RANDO Phantom deep dose reference point location within TPS.

Results

Dose measured in simple geometry beneath 5mm of superflab showed agreement within 2.44%, and 0.340% when compared to the TPS for enface and 60-degree incidence exposures, respectively. Dose physically measured beneath brass mesh for enface beams deviated from dose estimated in the TPS by 1.15%, 27.4%, 12.4%, and 9.37% for deliveries with simulated boluses of 1mm of Al, steel, and Ti, and 2.5mm water, respectively. For 60-degree incidence beams, physically measured dose beneath brass mesh bolus deviated from the TPS by 0.30%, 14%, 4.8%, and 16% for 1mm of Al, steel, and Ti, and 2.5mm water, respectively.

When measured at 10 cm depth within a virtual phantom en face beams within the TPS for 1 mm of Al, steel, and Ti bolus agent agreed within 0.07%, 1.47%, and 0.42% when compared to the vendor recommended 2.5 mm of virtual water bolus.

Irradiations of RANDO phantom with breast attachment as measured with EBT film at 6 locations demonstrated bolus-related dose increases of 50%, 50%, 59%, 74%, 52%, and 64% for medial apex, lateral inferior, lateral apex, medial inferior, lateral, and medial superior locations, respectively, utilizing the 1.5mm brass bolus compared to no bolus. The average increase measured was 58±9%. The use of a virtual 1mm Al bolus introduced surface-dose increases of 66%, 139%, 98%, 30%, and 96% for the same positions, with an average increase of 101±48%. Water boluses of 2 and 3mm introduced average increases of 139±38 and 147±38%, respectively. Measured and calculated results for each location and virtual bolus configuration can be found in Table 1.

Virtual boluses of 1mm Al, 2mm water, and 3mm water all produced similar deep dose values in the RANDO phantom plan at the point evaluated, with 1mm Al agreeing with the average of 2mm and 3mm water within 0.044%.

Table 1 Change in surface dose due to bolusing material at six anatomical locations on Alderson RANDO phantom

	Bolus Material	Lateral	Lateral Apex	Lateral Inferior	Medial Apex	Medial Inferior	Medial Superior	Average
TPS Calculation	1 mm Al	96%	98%	139%	66%	30%	178%	101%
	2 mm Water	102%	129%	161%	82%	166%	194%	139%
	3 mm Water	110%	130%	169%	98%	170%	206%	147%
Measurement	EBT Film	52%	59%	50%	50%	74%	64%	58%

Discussion

For simple solid water geometries calculated with the Acuros XB™ algorithm, a virtual bolus of 1mm Al produced excellent surface dose results compared to physical measurement with 1.5mm brass mesh bolus for both enface and oblique beams (1.15 and 0.30%, respectively). Notably, agreement was significantly better in the surface region for Al compared to virtual 2 or 3 mm water bolus, which is the current vendor recommendation. Other evaluated material surrogates such as 1mm stainless steel and Ti also showed increased difference compared to measurement compared to Al, though 1mm Ti did also offer improved results compared to water. Dose computed at 10cm depth for an enface 6MV beam was not affected significantly by choice of virtual bolus material, with 1mm of Al, stainless steel, or Ti all agreeing to within 1.5% of a 2.5mm virtual water bolus. Al in particular showed less than 0.1% difference compared to virtual water bolus, indicating that it allows deep dose to remain similar to the vendor-recommended 2.5mm virtual water bolus, while offering improved surface dose calculation accuracy.

The increase in surface dose caused by the addition in the TPS of a virtual 1mm Al bolus also agreed more closely with measurement on the anthropomorphic RANDO phantom for 6MV tangential fields delivered with the 1.5mm brass bolus in place when compared to virtual water alternatives. The addition of a virtual 1mm Al showed a 101%±48 increase in surface dose on average, compared to calculation without bolus. The addition of 2 or 3mm of virtual water bolus in the TPS caused average increases of 139±38 and 147±38%, respectively. Measurement with EBT film beneath a 1.5mm brass bolus in this clinically-relevant geometry showed an average increase of 58±9%. All evaluated virtual boluses seemed to overestimate the bolusing effect compared to measurement on average, but the virtual 1mm of Al provided the closest result on average to measurement. Not only was the average increase in dose closest to measurement for the virtual 1mm Al bolus, but each individual location evaluated also showed better agreement compared to 2 or 3mm virtual water bolus. Notably, the measured bolusing effects of this study agree with data observed in the literature as measured using thermoluminescent dosimeters.[7]

There is a notable discrepancy between the measured bolusing effects on the Alderson RANDO phantom and computed bolusing effects in the TPS. Although 1mm of virtual Al provided the most accurate relative increase in dose due to bolus when compared to measurement of all tested configurations, the calculated bolusing effect was still nearly double that measured. Furthermore, in absolute terms, measured doses beneath brass bolus best agreed with those calculated beneath 5mm of water. Surface contour definition accuracy is dependent on finite CT scan resolution which can lead to surface image voxels that are representative of a point in space that is physically partially tissue and partially air. In addition, dose grid resolution is limited to 1mm. If this CT resolution and dose grid resolution are offset, the uncertainty could be further increased. For deep dose calculation this is well within reason, but for precise surface dose estimation this prevents dose on a virtual point of the body contour from being equivalent to a true surface point dose at less than 1mm depth. For these reasons it may be prudent to refrain from using virtual bolus that relies on accuracy of 1mm or less until further validation leads to a consensus on this application. Additionally, measurement of surface dose is challenging. Most dosimeters have an inherent thickness, precluding the ability to measure true surface dose. EBT film's active layer is 28 microns thick and is behind a 125 micron base. The 139 micron midpoint of the active layer is not true surface dose, but is a clinically useful gauge of potential skin effects as the shallow-dose equivalent representing exposure of the skin is defined at 70 microns depth, not 0 microns. (10cfr 20.1003).

Dose calculated at a deep-dose point within the RANDO phantom showed no significant difference between virtual boluses of 1mm Al, 2mm water, or 3mm water. All three options agreed within 0.1%. The change in virtual simulation method does not appear to undesirably perturb deep doses while significantly changing the surface dose estimation.

Conclusion

Simple and clinical irradiation scenarios demonstrated the viability of explicit metal bolus simulation when computing dose with an algorithm capable of taking material-specific properties into account, such as Acuros XB™. Of the materials available for virtual simulation, 1mm of Al was found to agree most closely with measurement beneath Radiation Product Design Incorporated 1.5mm Brass Mesh Bolus™ for both simple and clinical setups.

Though, these results show promise, clinical implementation presents challenges. Virtual simulation of a thin bolus at submillimeter resolution on complex patient topography is difficult and can lead to potential inaccuracies in the thickness generated due to the limit of the spatial resolution of clinical CT scans. CT slice thickness and voxel size must be significantly smaller than the planned bolus thickness, or thickness errors of greater than 10% may occur. While these errors may not significantly affect calculated dose for a virtual water bolus, a virtual bolus of a high atomic number material such as metal must be meticulously delineated. In addition, evaluation of dose near the patient surface may necessitate a smaller dose grid than what is typically used clinically.

Despite these potential technical constraints, the results of this work suggest simulation of metal bolus directly may lead to more accurate surface dose estimation when compared to use of a virtual water equivalent. More work is necessary to validate these results with other commercial treatment planning systems capable of calculation of dose to medium. In addition, clinics should take care to further validate these results for their specific brass bolus, due to potential variations in manufacturing.

Acknowledgments

None.

Conflicts of interest

The authors declare no competing interests.

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