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FULL PAPER

Dosimetric characteristics of brass mesh as bolus under megavoltage photon irradiation

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Objective: This article presents a set of dosimetric measurements describing the properties of brass mesh (Whiting and Davis, Attleboro Falls, MA) under megavoltage photon irradiation conditions, with particular relevance to its use in breast radiotherapy.
Methods: The effectiveness of brass mesh as a bolus material was investigated using 6-, 15- and 6-MV flattening filter-free photon beams. The effect on dose build-up at the entrance surface, build-down at the beam-exit surface, dose with surface entrance obliquity, beam profiles, penumbra and percentage depth doses were investigated.
Results: One layer of the brass mesh produces a build-up effect equivalent to 1.1 mm of water at 6 MV and 1.9 mm at 15 MV. The brass generates a backscattered component of dose, if the photon beam exits through it. Percentage depth-dose curves are largely unaffected by the mesh and are shown to be equivalent to plain-field data. Beam penumbra and profiles are unchanged by the brass except within the first millimetre (mm) of phantom, where a periodic pattern of dose enhancement is seen.
Conclusion: The data presented demonstrate that one layer of brass mesh provides a similar dose build-up effect equivalent to only a few millimetres of water. However, backscatter from the high atomic number (Z) mesh, at the beam exit, contributes appreciably to the overall dose surface enhancement. This dosimetric consequence cannot be neglected and indeed should be considered and accounted for, when determining the bolus effect of the brass mesh in the case of tangential breast irradiation.
Advance in knowledge: This article provides dosimetric data necessary for the introduction of brass mesh bolus into the clinical setting for external-beam breast radiotherapy.

INTRODUCTION

Megavoltage photons are a widely used treatment modality for external-beam radiotherapy for patients with breast cancer. They are used for their depth penetration properties; but, as a result of the dose build-up effect, they produce skin sparing. This is not always advantageous but can be negated with the use of tissue-equivalent bolus placed over the treatment area. This is especially relevant, for example, where patients have undergone a mastectomy and there is a very narrow thickness of tissue overlying the chest wall. In such cases, the addition of tissue-equivalent bolus can be beneficial in providing a more homogeneous dose distribution to the targeted volume. It is common to use commercially available tissue-substitute materials such as Superflab (Radiation Products Design Inc, Albertville). This is typically available in 0.5- or 1-cm-thick sheets. In this department, it is standard practice to CT scan patients for treatment localization purposes with the tissue-equivalent bolus in place and for this to be present during all subsequent treatment fractions. This has the advantage that any contour distortions created by the weight of the material are captured for subsequent dose calculation and applicable to the entire treatment course. However, it is apparent from the cross-sectional CT imaging that the bolus does not adhere fully to the patient contour and that there are indeed many air gaps, which will reduce the efficacy of the build-up material. This effect was noted by Anderson et al,[1] who indicated that air gaps between the bolus and patient skin may lead to deleterious dose "hotspots" or underdosage. It has previously been reported in the literature that high-density/high-Z materials may be of use as alternatives to tissue-equivalent bolus with both photon and electron treatments.[2–6] Recently, brass mesh material (Whiting and Davis, Attleboro Falls) has been shown to be useful in breast photon radiotherapy as an alternative to more traditional methods.[2,7] It consists of a regular mesh of interlocking brass discs. The brass discs cover in the region of 75% of the surface area, with a periodicity of approximately 3.3 mm. Brass, being a high Z material, generates a larger quantity of Compton scattered electrons than an equivalent thickness of tissue. Therefore, a build-up effect can be produced with a relatively thin layer of brass as compared with tissue-equivalent bolus. This has the benefit of generating very little attenuation of the incoming photon beam. As previously reported,[2,7] the brass mesh is able to conform well to the patient's skin with little or no air gaps, which is seen as a desirable bolus property.

This article aimed to present a set of comprehensive dosimetric measurements of the properties of the brass mesh bolus under megavoltage photon irradiation, with particular relevance to breast radiotherapy; in particular, the effect of brass bolus on dose build-up at the entrance surface, build-down at the beam-exit surface, surface obliquity, beam profiles and penumbra and percentage depth doses.

METHODS AND MATERIALS

Measurements

Measurements in this study were undertaken using an Elekta linear accelerator with a Agility™ multi-leaf collimator (MLC; Elekta AB, Sweden). This was operated at 6 and 15 MV in flattened beam mode and at 6 MV in flattening filter free (FFF) with quality indices ($TPR_{20/10}$) of 0.684, 0.757 and 0.677, respectively, determined by direct open-field measurement in water. Diagrams illustrating the measurement setups described in the following sections are shown in Figure 1.

Attenuation

The attenuation coefficient of the brass bolus was determined using a Farmer® type chamber (PTW, Freiburg, Germany) in WT1 solid water (Scanplas, St Bartholomew's) coupled to a PTW Unidos electrometer operating at a bias voltage of −250 V. A source-to-surface distance (SSD) of 90 cm was used, and measurements were made at 10 cm depth using $10 \times 10\ cm^2$ open fields (Figure 1a). The attenuation was determined by comparison of the ionization charge collected for 200 MU with one or two sheets of brass mesh on top of the phantom as compared with none.

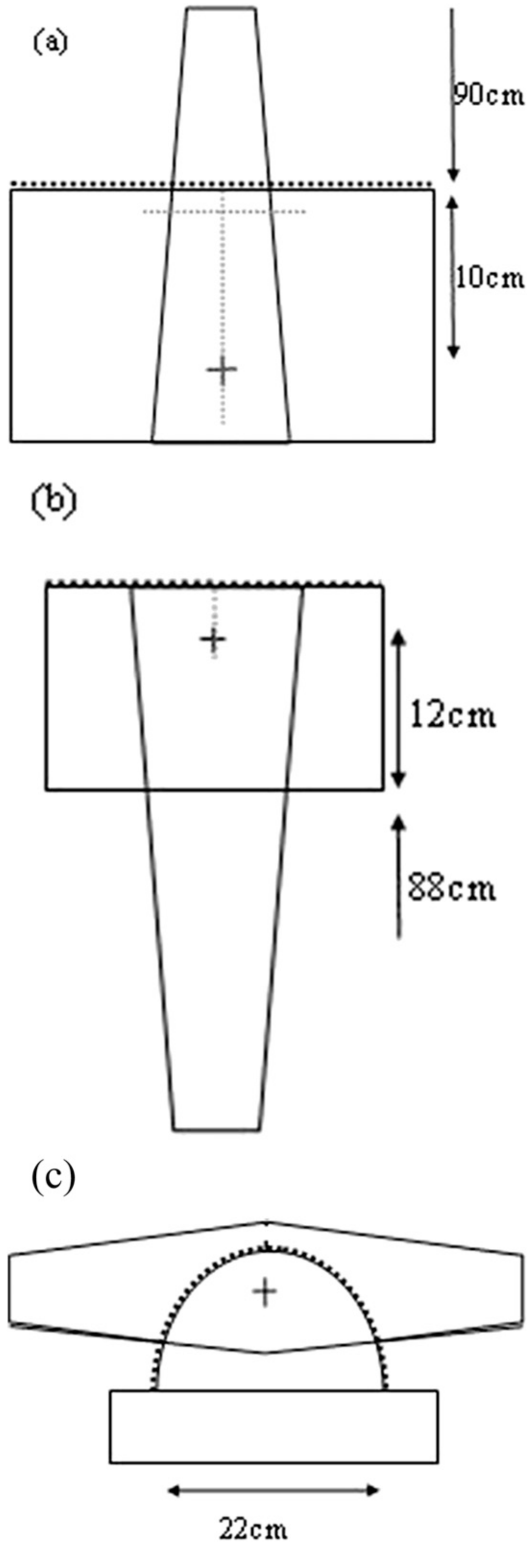
Surface dose and build-up

Build-up curves were measured in WT1 solid water (Scanplas, St Bartholomew's) with a Advanced Markus chamber, type 34045 (PTW), coupled to a PTW Unidos electrometer operating at a bias voltage of −300 V. A SSD of 90 cm was used, and measurements were made from the surface to a depth of 5 cm (Figure 1a). Data were collected for 10 × 10- and $20 \times 20\text{-}cm^2$ open fields, and both one and two layers of brass mesh bolus. All readings were corrected for chamber over-response using published methods[8,9] and normalized to a depth of D_{max}.

Exit dose and build-down

Build-down and exit-dose measurements were made using the Advanced Markus chamber in WT1 in "reverse" chamber geometry.[10] A SSD of 88 cm was used throughout, with the chamber effective point of measurement positioned at 100 cm (Figure 1b). The thickness of material beyond the chamber was varied to generate data to plot build-down curves. Build-down curves with none, one and two layers of brass mesh bolus placed on the exit surface were recorded.

Figure 1. Experimental measurement geometries for (a) beam attenuation, dose build-up and beam profile measurements with the photon beam normally incident through the bolus, (b) exit-dose measurements with mesh bolus covering the back surface of the phantom and (c) measurements of dose around a curved surface with obliquely incident fields. The brass bolus is represented by the dark dashed line. Measurement planes are indicated by grey dashed lines.



Percentage depth dose

Percentage depth-dose (PDD) measurements were made in a PTW watertank using the Advanced Markus chamber as above. A 2 mm sheet of WT1 was located with the underside touching the water surface, and 100 cm SSD was set to the front face. The WT1 was suspended to allow the brass mesh to be placed on top above the water. Percentage depth-dose curves were measured from an equivalent water depth of 25 cm to1 cm (including WT1) for the three beam energies: open, one and two layers of brass bolus.

Profiles and penumbra

Beam profiles were measured in the watertank at 1-, 2-, 5- and 10-cm water-equivalent depths in the cross-plane direction using a PTW p-type photon diode (type 60016) operating with zero bias voltage. A SSD of 90 cm to the top of the 2 mm WT1 block was used throughout (Figure 1a). The WT1 was used to suspend the brass bolus as for the PDD measurements above.

Beam profiles in the cross-plane direction at depths closer to the surface than 2 mm were made using EBT2 film (ISP, New Jersey) in WT1. Films were placed at the phantom surface 0.5-, 1- and 2-mm deep in turn and exposed for 800 MU. Calibration films were acquired by delivering between 500 and 1000 MU in 100-MU increments using a $10 \times 10\,\text{cm}^2$ field, with three separate films used for each irradiation level. The calibration and measurement films were subsequently scanned at 72dpi using an Epson 10000XL flatbed scanner with transparency adaptor, and saved as 48-bit TIF (tagged image format) images. For each calibration film, a 15-pixel-diameter circular area ($=0.22\,\text{cm}^2$) was sampled at the centre of the irradiated area. Calibration curves for each colour channel (red, green and blue) were generated using the average values from the three films for each "dose" level. The "dose" for each field size was then determined by minimizing the difference between the "dose" calculated using each of the three calibration curves, using an implementation of the multichannel approach described by Micke et al[11]

Dose around a curved surface

Surface dose measurements were made with a EBT2 film tightly shrouding a cylindrical phantom (Figure 1c). An opposed tangential beam geometry was employed to mimic commonly used tangential breast irradiation treatments. One half of the Delta4 phantom (ScandiDos, Uppsala, Sweden) was positioned on top of a 5 cm-thick WT1 block and isocentrically irradiated with a pair of 10×20 cm (width $\times$ length) fields at gantry 90 and 270°. The diameter of the Delta 4 phantom is 22 cm. The beam isocentre was located at the phantom midline, 3 cm from the anterior surface. A strip of film was attached to the surface of the phantom around the circumference. The films were irradiated with 400 MU from each beam and either no bolus, 5 mm of Superflab or one sheet of brass bolus at 6 and 15 MV. The resulting films were scanned and results processed as above.

RESULTS AND DISCUSSION

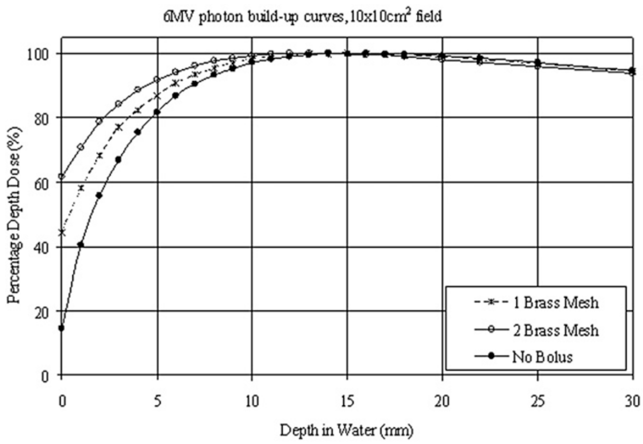
Attenuation

One layer of the brass mesh bolus gave an attenuation factor of 0.993, 0.995 and 0.993 for the 6-MV, 15 MV and 6 FFF beams, respectively. Two layers of the brass mesh bolus material gave attenuation factors of 0.987, 0.989 and 0.986, respectively. All measured factors are subject to an experimental measurement uncertainty of ± 0.003. It can therefore be seen that the two 6 MV beams are attenuated by 0.7% for each layer of brass bolus used and the 15 MV beam by 0.5%. These values are small and can be easily incorporated in patient treatment monitor unit calculations to account for the attenuating properties of the brass mesh. There is essentially no difference between the attenuation factors for the flattened and unflattened beams, which is expected, as the two have very similar measured quality indices.

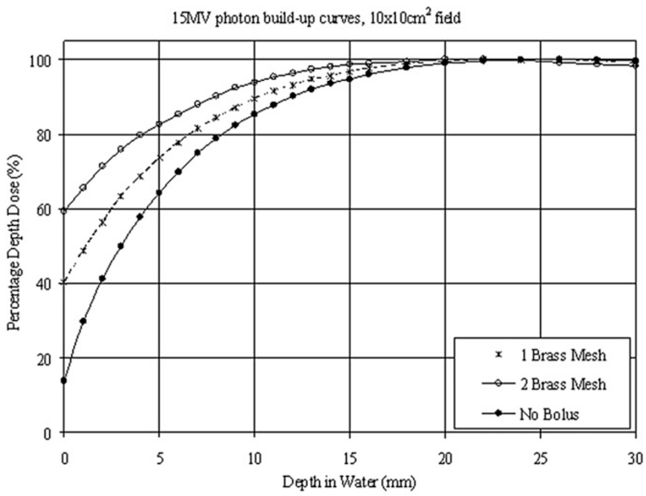
Surface dose and build-up

The measured build-up curves for 6- and 15-MV photons with a $10 \times 10\,\text{cm}^2$, 90 cm SSD, are shown in Figure 2. The brass mesh material has the effect of increasing surface dose as compared with open-field irradiation as expected owing to the photon interactions taking place within the material. The data for 6 MV FFF and the $20 \times 20\,\text{cm}^2$ field size measurements are not shown, as they demonstrate similar behaviour to the 6 MV $10 \times 10\,\text{cm}^2$ build-up

Figure 2. Build-up curves for $10 \times 10\,\text{cm}^2$ fields, 90 cm source-to-surface data, with no bolus, one layer of brass mesh and two layers of brass mesh bolus. Figure 2a depicts data determined with a 6 MV flattened photon beam and Figure 2b with 15 MV photons.



(a)



(b)

curves. For the 6 MV and 6 FFF beams, one layer of brass mesh has a similar effect on surface dose as 1.1 mm of water-equivalent material. This depth value was determined by shifting the build-up curve until it overlaid the one measured for the open field. A shift of 1.1 mm in the depth direction created a match. This effect increases to 1.9 mm water equivalence determined in the same manner when 15 MV photons are used. Similarly, two layers of brass mesh have the water-equivalent effect of 2.5 mm for the 6 MV beams and 4.2 mm for the 15 MV beams. The actual shape of the build-up curves for the brass mesh and non-bolus fields are extremely similar and therefore can be considered as depth translated versions of each other. We interpret the similarity in shape of the build-up curves as evidence that the brass material is simply providing photon scatter and having negligible effect on the photon spectrum owing to its modest thickness.

The surface dose for the open $10 \times 10\,cm^2$ 6 MV beam was measured to be 14% of the dose at d_{max}. We found that one layer of brass bolus enhanced this to 44% and two layers to 62% of the dose maximum value. This is quite different to the results of Manger[12] measured with a parallel-plate chamber, who found a surface dose enhancement of 62% of maximum with one layer of brass mesh, although it was not stated what SSD or field size were used for the measurements. It is also not stated whether a correction was made for chamber overresponse in the build-up region; so, direct comparison of the results is difficult. Gong[13] found the 6 MV surface dose to be 15% lower with one layer of mesh than that with the 0.5 cm of tissue-equivalent bolus. Our results indicate a 37% reduction in surface dose. The measurements made by Irwin[14] indicated that four layers of brass mesh would be required to equate to the bolus effect of 0.5 cm of Superflab, and Gong[13] suggested three layers. Our measurements of build-up with one and two layers of mesh would point towards a similar number of brass mesh sheets. This many, three or four, would be clinically quite demanding to implement owing to the weight on the patient and the shearing movement of the layers making them difficult to position during a treatment fraction. Recently published data[2] experimentally determined with thermoluminescent dosimeters (TLDs) gave an open-field dose of 50% of d_{max} at 1 mm depth for 6 MV open-field irradiation. This was enhanced to 70% with the use of the brass mesh bolus. Our measurements gave 40% and 58%, respectively, at a depth of 1 mm. Although our measurements were recorded at 90 cm SSD and the published data were at 100 cm SSD, the increase in dose at 1 mm using one layer of brass mesh was similar at approximately 20%. Our open-field dose at 1 mm depth is quite different to the published data,[2] although this would be highly dependent on the treatment machine delivery platform head geometry. Our measurements were made using an Elekta Synergy linear accelerator with Agility MLC. It is not stated which machine was used for the comparison data, although it may be inferred from the article to be a Varian linear accelerator. Our 15 MV measured doses at a depth of 1 mm for $10 \times 10\,cm^2$ fields were 30% and 49% for the open and one layer of brass mesh. These are in broad agreement with published[2] data, notwithstanding the technical differences noted above.

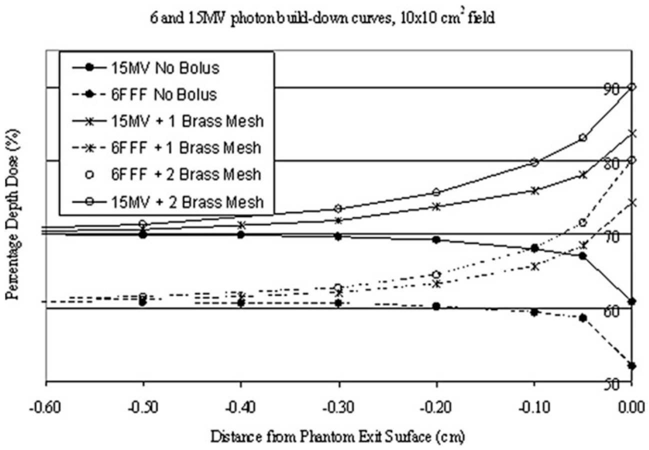
Exit dose and build-down

Figure 3 shows the change in measured dose within the last centimetre of phantom material, as the photon beam exits for the 15 MV and 6 FFF $10 \times 10\,cm^2$ beams. There is a build-down effect at the exit surface owing to a lack of backscatter material, when no bolus is used as the beam leaves the phantom. The depth-dose value expected at the exit surface of the phantom, assuming full scatter, would be 58.0% and 67.0%, respectively, for 6 FFF and 15 MV incident photon beams. The lack of backscatter reduces this to a measured value of 52.1% and 60.9%. With one layer of brass bolus covering the back surface of the phantom, the exit dose was enhanced to 74.4% and 83.7%, respectively. This increased to 80.1% and 90.0% of d_{max} for 6 FFF and 15 MV, with two layers of brass mesh covering the exit surface. Measurements made using the 6 MV flattened beam were equivalent to those determined using 6 FFF and are not shown. The high Z material is generating a significant proportion of backscatter, which is contributing to a large change in measured dose near the exit surface of the phantom. The dose increase with the brass material is much greater than that seen with full backscatter in water. The influence of the backscatter from the brass can be seen to be still of the order of a few percentage points increase in depth dose at 5 mm from the exit surface of the phantom. The effect of backscatter from this particular high-Z mesh material has not previously been measured and discussed in the literature, although the physical effect is well understood. Published data on the use of the brass mesh as a bolus have not addressed the importance of backscatter into the surface layers of tissue, as a result of beam exit through the material when used in tangential irradiation geometry, *i.e.* breast treatments. The measurements presented here show that the effect of the mesh is clearly not insignificant.

Percentage depth dose

The 90 cm SSD 6 MV percentage depth-dose curves, normalized to a depth of d_{max}, indicate no changes from the open field >0.3% from a depth of d_{max} to 25 cm depth, when either one or two layers of brass bolus are added to the phantom surface. Percentage depth-dose differences of <0.5% with one or two layers of brass mesh bolus are also observed for 15 MV and 6 MV FFF beams, respectively. The data are

Figure 3. 6 MV flattening filter-free and 15 MV flattened-beam build-down curves at the exit surface of the phantom for $10 \times 10\,cm^2$-fields, 90 cm source-to-surface data. Data shown are for no bolus, one layer of brass mesh and two layers of brass mesh bolus at the phantom exit surface.



not graphically presented here owing to the marginal differences between measurements. The results presented are in good agreement with those of previously published data,[2,15] where changes in PDD of <0.7% were reported when one layer of brass mesh bolus was used with 6- or 15-MV photons. The high-density mesh is having little effect on of the spectrum of the irradiating photon beam, as demonstrated by the negligible change in measured depth-dose characteristics.

Profiles and penumbra

No changes in beam profile shape measured in the watertank were observed for any energy at measured depths from 1 cm to 5 cm depth. The measured beam penumbras with and without the brass bolus were also indistinguishable at these depths at all photon energies examined (data not shown). One might have expected a small increase in the width of the field penumbra owing to the increased scattering from the brass, but this was not demonstrated. It should be noted, however, that if a tissue-equivalent bolus were used in the form of 0.5 or 1 cm of Superflab, then the field penumbra would invariably be greater at all depths within the patient to that created by the brass mesh. The beam profiles measured at depths closer than 0.5 cm to the phantom surface using films were all also essentially similar, with and without brass mesh, except for those determined at the entrance surface and up to 1-mm deep in the phantom. Figure 4 demonstrates the measured beam profile at the phantom surface with one layer of brass mesh with a 6 MV beam. A repeating pattern of enhanced dose under each brass disc can be seen with peak-to-trough dose differences of the order of 12% at its maximum. This peak-to-trough dose variation effect is reduced to the order of 3% at 0.5 mm depth and is not seen at 1 mm for 6 MV irradiation in the inset figure. Profiles of the 6 MV FFF beam show identical behaviour to that of those of the 6 MV flattened beam. There is a similarly varying periodic dose variation pattern seen on the 15 MV film profiles at the phantom surface with a peak-to-trough dose difference of 17% reducing to 3% at 1 mm depth and is not seen at all at a depth of 2 mm.

Figure 4. 6 MV cross plane, 10 × 10 cm^2, profile measured with EBT2 film at the phantom surface using one layer of brass mesh bolus. Inset profile is at a depth of 1 mm in WT1 under the same irradiation conditions. CAX, central axis.

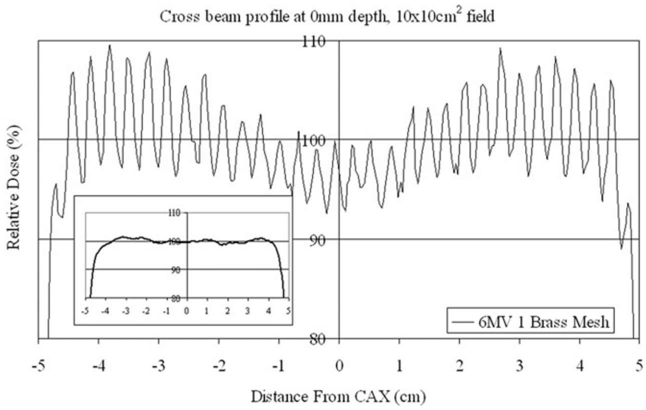
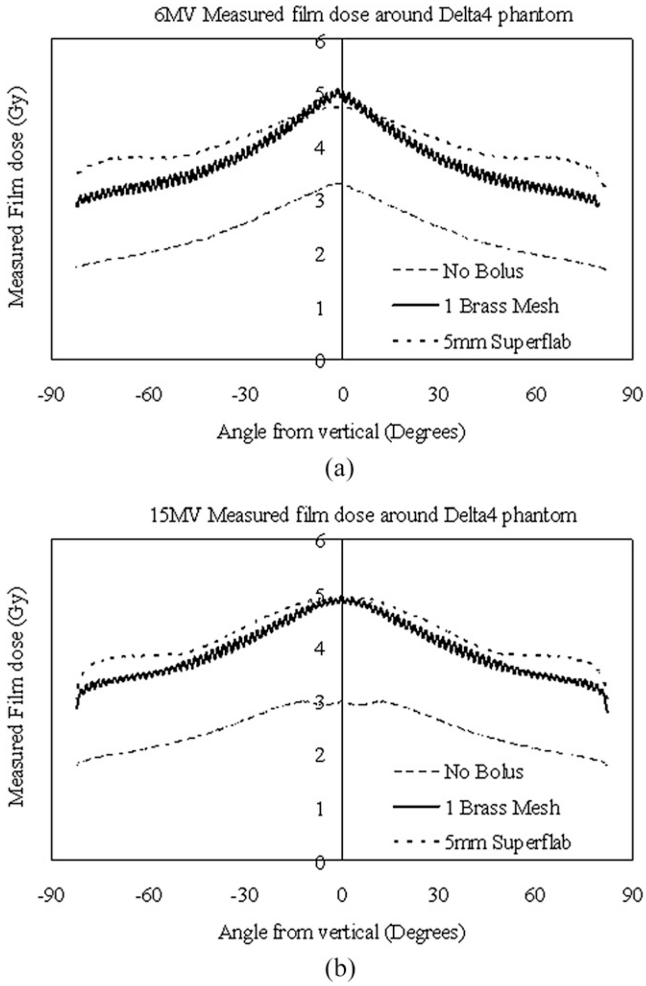


Figure 5. Dose profiles around cylindrical phantom surface with no bolus, 5 mm Superflab or one sheet of brass mesh. Figure 5a uses 6-MV photons and Figure 5b 15-V photons. 0° on the *x*-axis represents the anterior surface of the phantom with ±90° the posterior edges of the two tangential fields.



Dose around a curved surface

The measured dose around the surface of a cylindrical phantom using no bolus, 0.5 cm of Superflab and one sheet of brass mesh bolus with 6- or 15-MV tangential irradiation are shown in Figure 5. The surface dose at the posterior edges of the beams is enhanced by the Superflab and brass mesh, as compared with no bolus, where the beam is essentially normally incident on the phantom surface. This is simply a manifestation of the dose build-up and backscattering effects created by the two different bolus materials. It should also be noted that the surface dose increases towards the apex of the phantom, as the beam entrance and exit angles become more oblique under all irradiation geometries. This is most pronounced for the non-bolused beam geometry, where the ratio of dose at the apex of the phantom is a factor of 1.9 higher than that at the posterior beam edges for irradiation with 6 MV. This factor has a value of 1.65 for the brass mesh and 1.35 for 5 mm tissue-equivalent bolus, respectively. The dose at the phantom surface is clearly non-uniform around the circumference, but using 5 mm of tissue-equivalent material, compared with brass mesh or no bolus, reduces this variation. The surface dose using one layer of brass is more homogeneous than no bolus but <5 mm of tissue-equivalent material. The brass mesh is clearly enhancing the surface dose from that seen with no bolus but not by as great an extent as 5 mm of Superflab. The apex of the phantom is an exception to this, where the mesh is causing a slight surface dose increase over the 5 mm conventional tissue-equivalent material. This is a result of a combination of both the scattering build-up effect on beam entry and backscatter dose enhancement on beam exit with the brass mesh. A similar effect is seen for the 15 MV photon beam irradiation with maximum-to-minimum dose ratios of 1.55, 1.50 and 1.30 for the non-bolus, brass and Superflab scenarios, respectively. It can also be seen that the Superflab and brass surface dose profiles are fairly similar to each other within 45° of the vertical, both in terms of shape and absolute dose. The effect of backscatter from the brass mesh and Superflab bolus materials also contributes to the flattening out of the dose variation around the phantom surface. Furthermore, the repeat mesh pattern of the brass bolus material is apparent on the film profiles. The dose profiles for both the brass mesh and 0.5 cm of Superflab are similar, especially with 15 MV photons. The areas of the phantom presenting normal to the beam central axis show the greatest difference in surface dose. The areas of oblique incidence and narrowest separation are dosed to a similar level. The combined dosimetric effect of build-up and backscatter from the mesh is a complex one on the phantom superficial layers, and the exact equivalence to tissue-equivalent bolus is variable across the surface. This makes determining the overall effect of the mesh non-trivial, even on a geometrically relatively simple hemispherical cylinder. Real-life patient outlines are never as regular and, as such, the surface dose due to the changing curvature in three dimensions would be difficult to establish.

CONCLUSION

The main aim of this experimental investigation was to examine the dosimetric properties of brass mesh as an alternate bolus material to tissue-equivalent substitutes, with particular reference to its use in tangential photon breast irradiation. From the data presented, it can be concluded that one layer of brass mesh is equivalent to only 1–2 mm of water with regard to the build-up dose created by the initial photon-scattering interactions at the phantom entrance surface with 6 MV, 6 FFF and 15 MV photons. It has been reported in the literature[13,14] that three or four layers of the brass mesh would be required to generate the same surface dose as 0.5 cm of tissue-equivalent bolus material under 6 MV irradiation. This result is consistent with the measurements presented here. There is, however, a significant backscatter component of dose created by the high Z brass mesh as a megavoltage photon beam exits through the material, as is the case for tangential breast irradiation, when compared with the dose build-down effect with no bolus being present. The use of tissue-equivalent bolus prevents the surface build-down effect owing to the lack of backscatter as a photon beam exits the patient but does not create an enhancement. This dosimetric consequence of backscatter cannot be neglected and indeed should be considered and accounted for, when determining the bolus effect of the brass mesh in the case of tangential breast irradiation. The ability of treatment-planning system algorithms to replicate and model this combination of build-up and backscatter on patient surface dose accurately when the radiation beam both enters and exits through a high Z material has not been considered in this work. It was found that the brass mesh bolus creates little beam attenuation (<1%) and has negligible effect on percentage depth-dose curves beyond d_{max}, which is consistent with the findings of other authors. Beam profile penumbras also remained unaltered with the use of brass mesh, in comparison with open fields. Hence, standard linear accelerator commissioning data measured for independent monitor unit check calculation purposes remains valid for use with the brass mesh. It should be concluded that brass has some interesting and desirable dosimetric properties owing to its high Z composition. Indeed, the ability to conform closely to a curved patient contour is seen as particularly advantageous compared with standard commercially available tissue-equivalent sheets. Brass mesh has been successfully introduced into clinical practice in several institutions[2,7] as an alternative to tissue-equivalent bolus, although usually for a percentage of treatment fractions. However, the effect of the mesh on surface and superficial dose when used in conjunction with tangential irradiation geometries is complicated and requires careful consideration before clinical use.

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