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Design, Validation and Implementation of a Novel 3D-Printed Chest Wall Bolus

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ABSTRACT

Purpose :
To develop a novel composite mesh bolus (CMB) as an alternative to hand-molded bolus in chest wall radiotherapy. The CMB is a 3D-printed flexible mesh with silicone layers. Its design allows surface conformity, skin adhesion, a reproducible bolus effect and compatibility with surface gated optical tracking systems.

Methods :
The CMB consists of a 3D-printed chainmail made of a biocompatible resin with silicone-filled compartments. To assess water-equivalent thickness of the CMB, EBT4 film dosimetry was performed using VMAT and direct fields delivered on a solid-water phantom. To test the CMB under clinical conditions, the body contour of four chest wall patients was extracted and 3D-printed to fit on top of a Lungman phantom with inserts for film dosimetry. Each phantom was scanned with CMB and SuperStuff successively to evaluate surface conformity. Clinical treatment plans were transferred onto the scanned phantoms and delivered on a linear accelerator. Films placed in the inserts were used to measure dose under each bolus for the clinical plans. CMB visibility on CRAD and VisionRT was assessed for a range of skin tones.

Results :
Film measurements in solid water showed that the CMB is comparable to a 4 mm water-equivalent bolus. Plan film measurements under CMB and SuperStuff agreed within 2% and were within 5% of the calculated dose. On the phantom CT scans, the CMB fit was visually comparable to the SuperStuff. The CMB was visible on CRAD and VisionRT for all tested conditions.

Conclusion :
The CMB provides an adequate skin bolus effect under clinical beam arrangements and presents good conformity to skin surface. It requires no prior preparation, is biocompatible, and can be washed and reused, making it a cost- and resource-efficient alternative. Since its implementation, it has been used clinically for over 200 fractions.

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INTRODUCTION

Post-mastectomy radiation therapy (PMRT) plays a crucial role in reducing the risk of breast cancer recurrence. In some cases, bolus material must be applied on the patient to ensure the delivery of an adequate radiation dose to the skin. Creating a chest wall bolus can be challenging because it has to cover a large area, be able to conform to an irregular surface and be flexible to allow for slight variations in patient positioning.

Several types of bolus material exist for PMRT[1], each with its own advantages and disadvantages. Pink Superstuff and patient specific 3-D printed bolus are widely used for chest wall irradiation. They both present major limitations that either affect efficiency, by affecting bolus preparation time, or dose deposition, by creating air gaps.

This work presents a novel 3D-printed bolus called composite mesh bolus (CMB) for PMRT treatments. The flexible 3D-printed chainmail design with silicone layers allows surface conformity, skin adhesion, a reproducible bolus effect, ease of use, and compatibility with surface gated optical tracking systems. A pre-clinical phantom study was conducted to evaluate the performance of CMB on clinically relevant chest wall anatomies.

METHODS AND MATERIALS

The CMB consists of a 3D-printed chainmail made of biocompatible Tough 1500 resin using a stereolithography (SLA) printer (Form 3B, Formlabs, Somerville, USA). Each chainmail unit's top and bottom sides incorporate a well which is filled with silicone. The volume rendering and technical design of the chainmail are shown in Figure 1. The silicone on each side is dyed with Silc Pig pigments (Smooth-On Inc.) in a light and dark skin tone color.

To assess efficacy and water-equivalent thickness of the CMB, EBT4 film dosimetry (Ashland, USA) was performed using direct and VMAT fields delivered on a solid-water phantom. To test the CMB under clinical conditions, the body contour of three chest wall patients was extracted from Eclipse. The 3D models were modified to fit on top of a Lungman phantom (Kyoto Kagaku, Japan) with inserts for film dosimetry and 3D-printed at 100% density with a Ultimaker S5 printer in polylactic acid (PLA), as shown on Figure 2. Each phantom was CT-scanned with CMB and SuperStuff successively to evaluate bolus conformity.

Clinically acceptable plans were created in Eclipse on the scanned anthropomorphic phantom using a virtual bolus. These plans were delivered on a linear accelerator with CMB and Superstuff in place successively. Films placed in the inserts were used to measure dose under each bolus for the clinical plans. CMB visibility on CRAD and VisionRT was assessed for a range of skin tones.

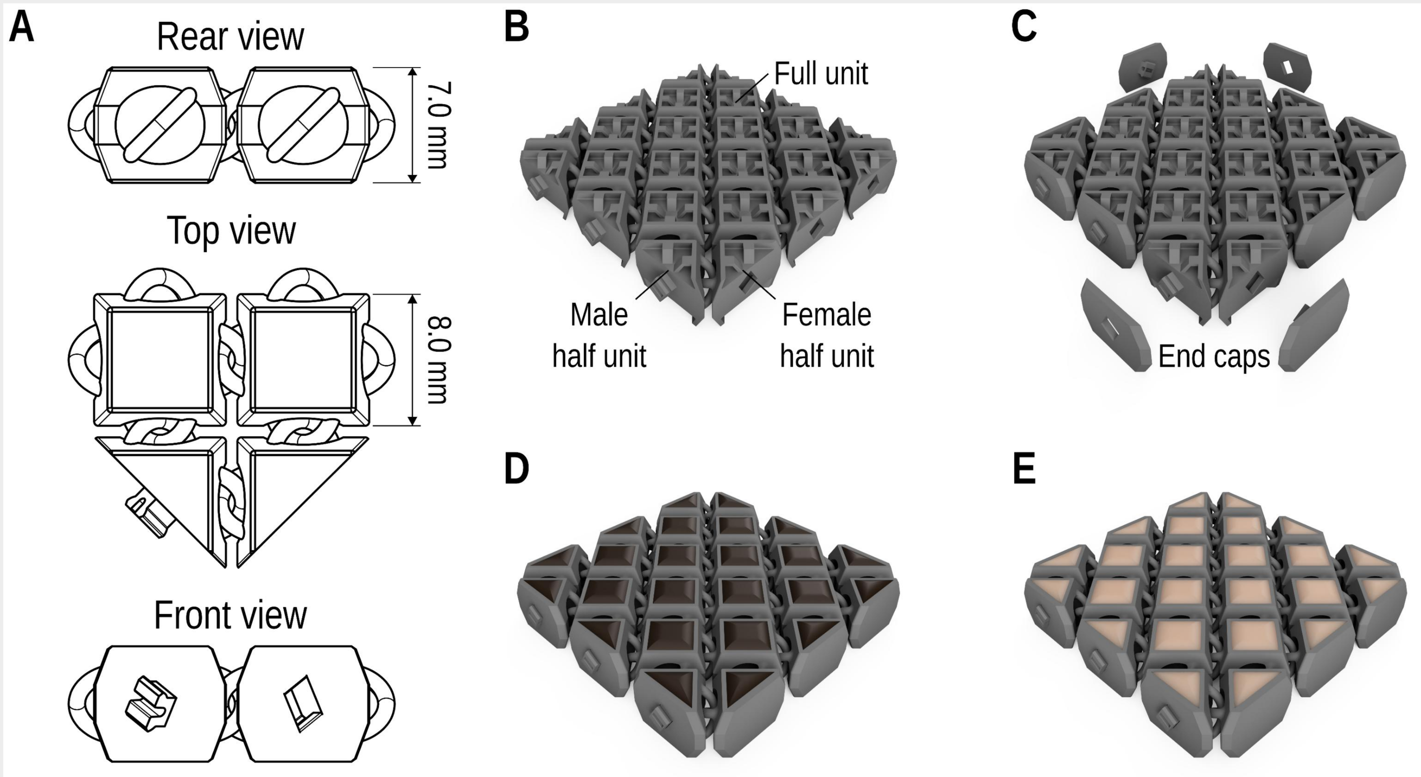

Fig 1: Design of the CMB. (A) Simplified technical schematic of the mesh units in the chainmail. (B) Rendered volume of a chainmail patch composed of 12 full units and 6 male and 6 female half-units at the periphery. (C) Magnified view showing the end caps, connectors, and wells with integrated anchors. Rendered volumes of two patches with (D) dark-toned and (E) light-toned silicone pads.

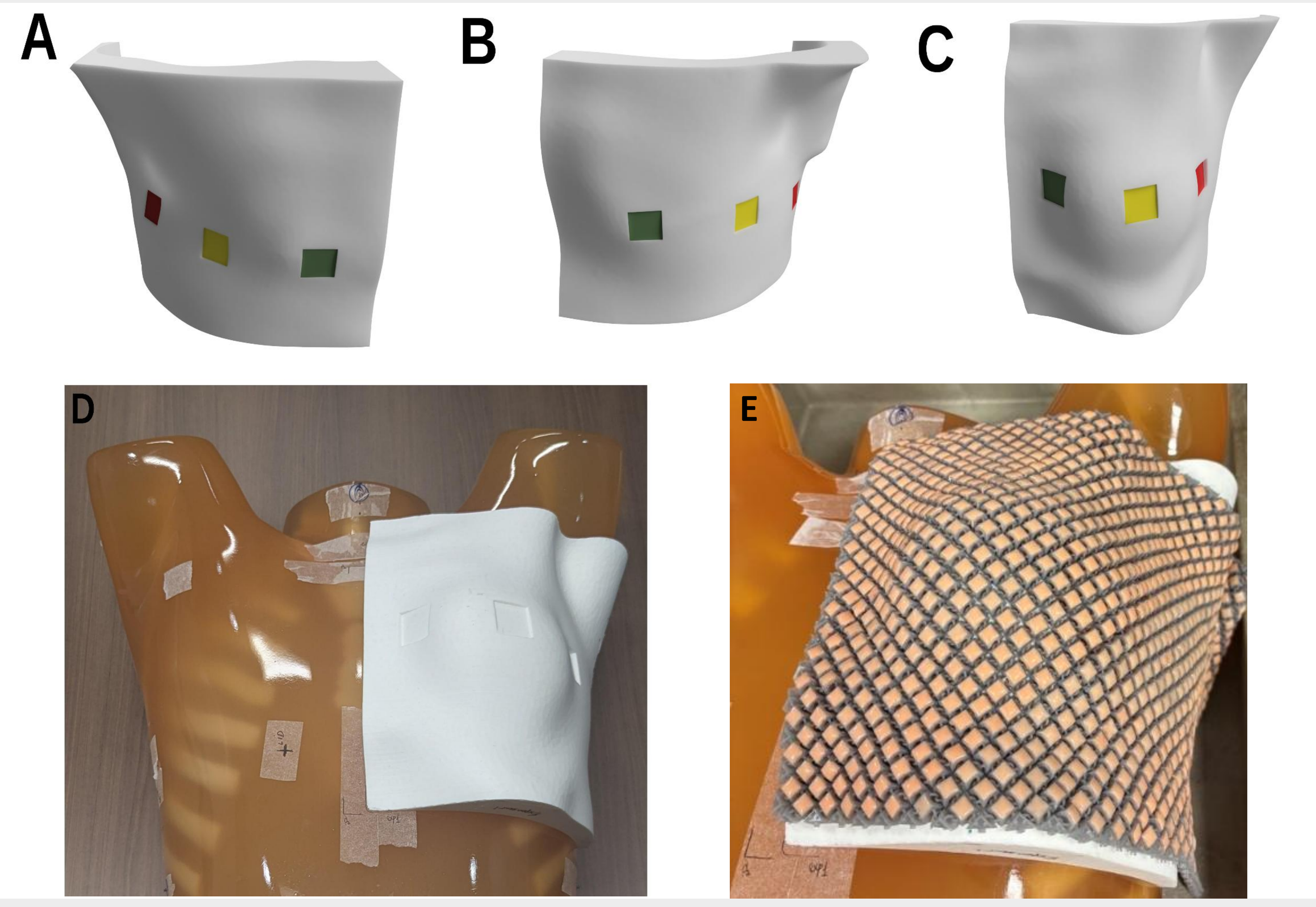

Fig. 2: (A to C) 3D-printed body contours extracted from chest wall patients. Film inserts are highlighted in color. (D) 3D-printed body contour fitted over a Lungman phantom for dosimetric validation with (E) CMB placed over it.

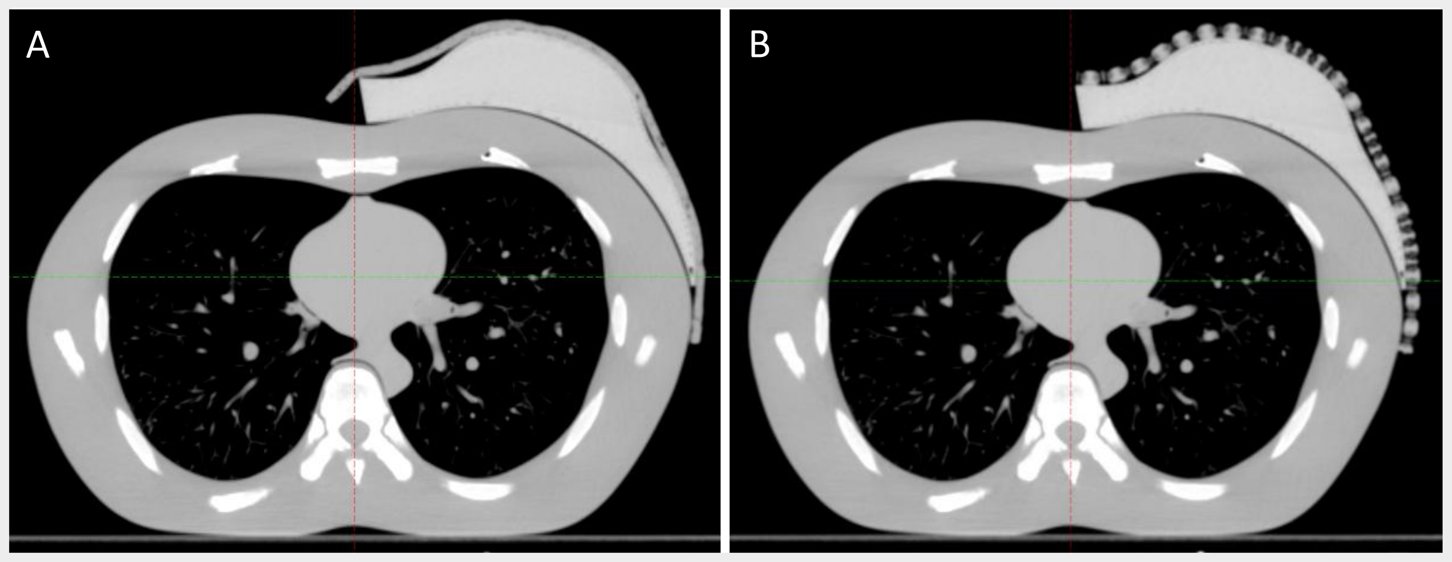

Fig. 3: CT scan of a 3D-printed body contour fitted over a Lungman phantom with Superstuff (A) and CMB (B) placed over it to evaluate bolus conformity over curved surfaces.

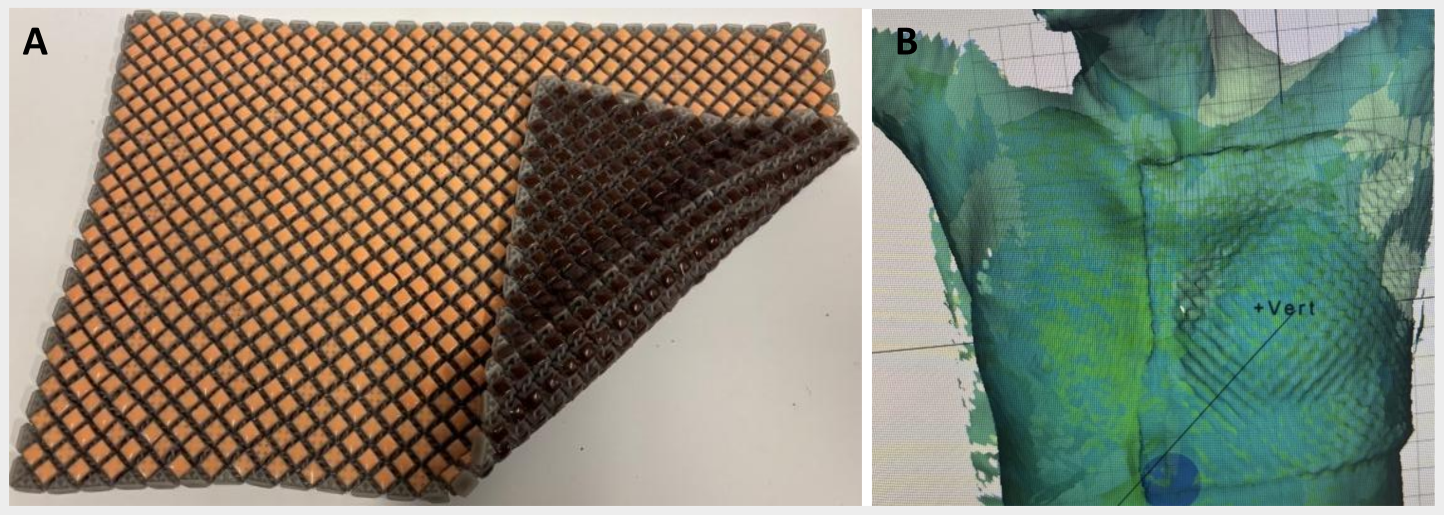

Fig. 4: (A) CMB with dual-colored silicone for optical tracking of a wide range of skin tone. (B) Screen capture of the CRAD system for a chest wall patient with CMB in place, showing good tracking over the whole treatment area.

RESULTS AND DISCUSSION

Film measurements in solid water showed that the CMB is equivalent to a 4 mm water-equivalent bolus. In clinical practice, a 5 mm of water-equivalent material is frequently used. Eclipse plans performed using a 4 mm virtual bolus showed no significant difference in skin dose compared to current clinical practice. Plan film measurements under CMB and 4 mm of SuperStuff agreed within 2% of each other, and were within 5% of the calculated Eclipse dose, showing that CMB is adequate for VMAT beam arrangements

The silicone component of the CMB allows good skin adherence while the chainmail structure conforms well to curved surfaces. On the phantom scans, the fit of the CMB is visually comparable to that of the Superstuff bolus, as shown in Figure 3.

Some optical tracking systems can have difficulty with skin tracking when bolus is used. For example, because of a limited dynamic range, CRAD cannot properly track the pink Superstuff bolus over dark-skinned patients. As shown in Figure 4, the dual coloring of the silicone component of the CMB successfully allows simultaneous tracking of skin and bolus over a wide range of skin colors, simplifying and improving treatment for all patients.

Durability of the CMB under standard use has been tested since its clinical implementation. No damage to the chainmail assembly or the silicone has been observed on any of the CMB sheets produced over their combined use of over 200 treatment fractions.

CONCLUSIONS

The CMB provides an adequate skin bolus effect under clinical beam arrangements and presents good conformity to skin surface. It requires no prior preparation, is biocompatible, and can be washed and reused, making it a cost- and resource-efficient alternative. Since its implementation, it has been used clinically for over 200 fractions with no damage to any of its components. The unique chainmail design of the CMB offers opportunities for additional clinical applications. Its feasibility as a plesiotherapy applicator has already been demonstrated[2], highlighting its broader potential in radiation therapy.

REFERENCES

1. Li, Fengyan et al. / Techno Cancer Res Treat 24 (2025): 15330338251344521.
2. J. Bernier et al. / Brachytherapy 25 (2026) 478–485