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Short communications and technical notes

Technical report: 3D-printed patient-specific scalp shield for hair preservation in total skin electron beam therapy

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Introduction

Total skin electron beam therapy (TSEBT) is a highly effective treatment for mycosis fungoides, the most common primary cutaneous T-cell lymphoma, and is employed for widespread skin involvement [1,2]. Since treatment is generally palliative, low dose TSEBT has become the standard of care due to high efficacy, low toxicity, and capacity for repeated treatments [2,3]. As a referral center, Stanford treats approximately 20 patients per year. Treatment is delivered in 12 Gy fractionated courses using 6-dual field or rotational techniques. Alopecia is a common concern of patients, with understandable impact on quality of life. Temporary alopecia is expected after 12 Gy [1,4,5], and hair regrowth typically takes months. With cumulative doses >20–25 Gy, alopecia may be permanent [1,5]. The extent of follicle recovery, and the permanent alopecia risk with repeated low dose TSEBT courses, are poorly understood. Given the impact of alopecia on quality of life, and palliative intent of TSEBT, scalp shielding is offered for patients without scalp involvement, or if the patient prioritizes hair preservation despite disease involvement, especially if scalp disease is minimal, asymptomatic, and controlled on topical medications; shielding may be most relevant for patients proposed to undergo two consecutive low dose TSEBT courses (in which case shielding may be done for one or both courses depending on the degree of scalp involvement), or if the patient previously received TSEBT. Shielding is standardly done with a lead helmet. These lead helmets are typically large, heavy, generous in coverage, and cannot be modified. They can block the nape of the neck/forehead/preauricular regions, making treatment planning difficult if disease is near the hairline. Lead is also toxic to mold and handle.

This report describes a novel technique using custom three-dimensional (3D) printed scalp shielding, which yields a lighter and more conformal shielding option compared to lead. Two patients have been treated with this technique thus far; one patient underwent shielding for the entire course with promising results. Application of 3D-printing in radiation oncology has been expanding since its introduction several years ago given the promise of patient-specific conformality, ease of production, and

cost-effectiveness [6]; however, it has not been studied in scalp shielding for total skin treatments.

Patients and methods

Two patients, a 67-year-old male (patient A) and 76-year-old male (patient B), presented in clinic with widespread cutaneous progression of mycosis fungoides:

Patient A had undergone three prior courses of low dose TSEBT (total dose 36 Gy, most recent course 1.5 years prior), and now presented with diffuse patches and plaques. Given the aggressiveness of his disease, two consecutive courses of low dose TSEBT were recommended (24 Gy in 20 fractions; the two courses were separated by one week to allow for resolution of acute toxicities). He notably had thick lesions near the hairline and diffuse mildly itchy scalp concerning for subclinical scalp disease. Given the cumulative scalp dose from prior courses and the patient's desire to reduce risk of permanent alopecia, 3D-printed scalp shielding was offered to expose the thick lesions near the hairline while providing coverage for the remainder of the scalp during the second 12 Gy course. It was discussed that the intent of shielding for the second course would be to minimize the risk of permanent alopecia.

Patient B had undergone two consecutive courses of low dose TSEBT, separated by 8 weeks, six months prior to presentation. He had an excellent initial response but short interval recurrence. Given the aggressiveness of his disease, two consecutive courses of low dose TSEBT were recommended (with courses separated by one week). Exam was notable for disease at the nape of the neck and posterior hairline, without scalp involvement. Given the cumulative scalp dose from prior courses and the patient's desire to reduce the risk of permanent alopecia, 3D-printed scalp shielding was recommended for both 12 Gy courses that would leave the neck and posterior hair line exposed.

Topography for scalp shields was acquired with a handheld 3D camera (Intel RealSense D415) after wiring the hairline (accommodating for lesions near the hairline), which takes several minutes and can be done by a therapist or dosimetrist; the use of 3D cameras for body surface contouring was described previously [7].

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Although CT simulation (with hairline wired) could be used to define the required contours, TSEBT is typically performed with a clinical set-up, thus the handheld scan was more convenient. Using Meshmixer (www.meshmixer.com), the head surface structure was cropped around the wire marks then expanded 3 mm to define the inner surface of the helmet. The structure was duplicated then further expanded to 15 mm to define the outer surface. The overlap volume of the two structures was then saved. Alternatively, 3D slicer v4.10 [8], can be used to convert the data to dicom format for import into a treatment planning system. The helmet volumes were 3D-printed using an Ultimaker S5 3D printer (Ultimaker, Geldermalsen, Netherlands) with a 0.8 mm nozzle and polylactic acid (PLA), which took ~1–1.5 days to print, depending on the size of the shield.

TSEBT was delivered via the Stanford “6-dual-field” technique, which utilizes 6 body positions and 2 gantry angles to provide a homogeneous total skin dose distribution [9,10]. TSEBT was delivered with a high dose rate 9 MeV electron beam passed through two PMMA spoilers, total thickness of 1.4 cm, and roughly 600 cm of air, which degrade the beam to 4.6 MeV at the skin surface. This set-up reduces depth of penetration while increasing skin dose compared to using a 4 MeV beam. The composite percent depth dose (PDD) curve as measured with film in a solid water phantom is shown in Fig. 1 (referenced from a prior review [1]). Notably, the 80% PDD is at 7 mm depth. The ideal thickness of shielding is a balance between adequate attenuation while minimizing the mass of material used (to optimize patient comfort and cost-effectiveness). For near complete attenuation, water-equivalent thickness of 23 mm would be required, consistent with the 2 MeV/cm energy loss of electron beams in water and practical range of a 4.6 MeV beam. A water-equivalent thickness of 20 mm would attenuate 87%, and thus would transmit ~1.5 Gy in a 12 Gy course. The difference in attenuation was thus determined to be clinically negligible (as temporary alopecia may occur with doses as low as 2–3 Gy in a single fraction [4], but higher for a fractionated course), thus thinner shielding was elected. PLA has a density greater than water (1.22 g/cc), thus printed scalp shields were slightly thinner than the water-equivalent thickness. Density of the PLA printed plastics vary by up to 10% (which translates to 1–2 mm water equivalent thickness in these cases), and was verified by comparing volume (planned volume or volume determined by

submerging in water) and weight of the printed helmet. Thickness of helmets was controlled by defining the 3D expansion at the patient surface contour and setting the printer to print at 100% infill. Even without additives, the PLA helmet is hard/rigid at room temperature (as room temperature is well below its glass transition), with flex of <1 mm for any reasonable loading. Thus, for added patient comfort at the time of fitting, 3 mm of Superflab was taped underneath the shield (without effecting fit accuracy). Dose attenuation was initially evaluated using nanoDot optically stimulated luminescence dosimeters (OSLDs, accuracy $\pm 5\%$) and a RANDO head phantom (The Phantom Laboratory, Salem, NY) (Fig. 2A). Dose was measured with the shield ± 3 mm of Superflab at three angles (PA, RPO, LPO). Transmission was defined as the ratio of dose measured on the scalp with shielding versus without shielding. Measured dose attenuation was reflective of the PDD curve: 28% transmission under the shield alone (16.5 mm water-equivalent thickness for patient A), and 9% transmission under the shield + Superflab (19.5 mm water-equivalent thickness for patient A). Thus, an added benefit of the 3 mm Superflab (1.02 g/cm³) was additional dose attenuation for a total shielding of ~19–21 mm water-equivalent thickness, which would reduce PLA printing time by 20% to achieve similar attenuation. The final scalp shields with Superflab weighed approximately 1.7 kg (3.7 lb).

Results

Shield set-up and treatment delivery were uncomplicated. Tape was used to stabilize the shield on the patient’s head (Fig. 2B) with little movement between the standing treatment positions; notably, tape stabilization was most critical for patient A as he had a receding hairline, and thus the shield was positioned more posteriorly on his head. Dose attenuation was verified with nanoDot OSLDs measured over two consecutive treatment days (to ensure dose reflects contributions from all six body treatment positions); four OSLDs were placed under the shield at the vertex, posterior scalp, and bilateral temporoparietal regions (Table 1). Measured transmitted dose was ~10%, as would be expected, except for the left lateral nanoDot for patient A: As the 3D camera outlines the topography of the patient’s head including the hair, there was a small gap between the shield and the left temporal area for patient A, who had afro-textured hair, thus resulting in higher transmission focally. At 2 months post-TSEBT, patient B, who underwent scalp shielding during both 12 Gy courses, had not experienced alopecia; in fact, he had undergone two haircuts in the interim. Patient A, who only underwent scalp shielding for the second 12 Gy course (to reduce risk of permanent alopecia), experienced total alopecia at 3 months post-TSEBT. Further follow-up is necessary to determine the duration of alopecia for patient A. Both patients demonstrated clinical complete response of their disease, including lesions near the hairline.

Discussion

Three-dimensional printing in radiation oncology is still in its infancy with potential applications undiscovered. The most common uses include creation of quality assurance phantoms and custom bolus [6], with rare reports of custom shielding [11–13]. This report describes a novel technique for patient-specific scalp-shielding in TSEBT using 3D-printing which provided similar hair-preservation as would be expected for lead shielding, with the added benefit of customized shielding at the hairline. Given how indispensable TSEBT is in the treatment of mycosis fungoides, and given the inconvenience of the standard lead helmet, novel techniques for customized non-lead shielding are much needed. Two other reports have evaluated novel techniques for scalp-

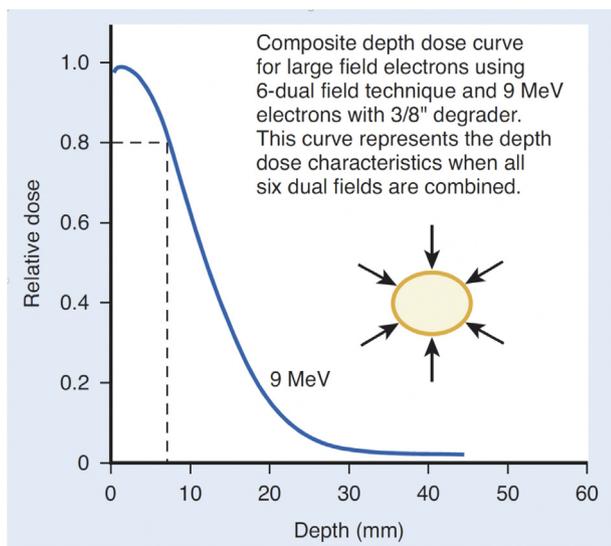


Fig. 1. Composite percent depth dose curve of TSEBT (6-dual field) with 9 MeV electron beam and 1 cm Lucite (PMMA) degrader. Reprinted from Ref. [1] with permission from John Wiley and Sons.



Fig. 2. (A) 3D-printed scalp shield for patient A, placed on a RANDO head phantom. Helmet shape was defined by the 3D scan of patient, and Rando phantom head is shown only for illustration. The outlined shape is deliberately nonuniform as it fits precisely to his hairline and hair topography, a function of the handheld camera. (B) Tape was used to stabilize the scalp shield on the patient.

Table 1

In vivo dosimetry with nanoDot OSLDs on-treat.

Location of nanoDot on scalp	Transmitted dose, as % of prescribed dose	
	Patient A	Patient B
Vertex	3.6%	4.0%
Posterior	7.0%	12.0%
Right lateral	13.0%	11.0%
Left lateral	31.0%	13.0%

Transmission was defined as the ratio of dose measured on the scalp with shielding versus without shielding.

shielding to minimize use of lead [14,15]. Patel et al reported on a non-lead technique using a thermoplastic mask and Superflab; notably the entire device weighed approximately 4 lb, and there was unintended dose compromise near the temples requiring additional boosts [15]. Williams et al also reported on a novel technique using a motorcycle half-helmet with 1 mm lead, which weighed almost 5 lb [14]. Unlike these techniques, with 3D-printing it becomes possible to accommodate complex geometries to allow for highly conformal shielding particularly around the hairline; this high level of conformality avoids under-dosing of lesions near the helmet rim which would necessitate additional radiotherapy boosts, or deferring the helmet altogether. An added benefit of 3D-printing is that different stock materials can be used for printing. While this report utilized PLA (producing full scalp shields weighing under 4 lb), other plastics/materials may be considered for attenuation, although high Z materials ($Z > 50$) are ideally avoided to minimize Bremsstrahlung production. Transitioning to a higher density Copper or bronze-loaded plastic may be advantageous to allow for production of thinner helmets and faster printing.

One limitation of the 3D camera is that it outlines the patient's head topography including the hair, which can overestimate the helmet size needed, in particular for patients with larger hair volume or Afro-textured hair (like patient A). In Fig. 2A, the outlined shield shape is deliberately nonuniform as it fits precisely to the hairline and hair topography of patient A. However, the higher dose to the left temporal area was partly reflective of the poorer fit along this area due to overestimation by his hair topography. For patients with large hair volume, an improved future workflow would be to scan the head while the patient wears a swim cap; additionally, a diagnostic CT scan may also be fused with the 3D camera information to reduce uncertainty.

In conclusion, this report describes effective scalp hair preservation in a patient undergoing repeated courses of TSEBT with a 3D-printed scalp shield. Longer follow-up is needed to determine

duration of alopecia in patient A, who underwent shielding only during the second course. This technique provides a simple, fast, highly conformal, and nontoxic method for scalp preservation that should be considered as 3D-printing becomes more widespread in radiation oncology.

Data sharing statement

Research data are stored in an institutional repository and will be shared upon request to the corresponding author.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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