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Clinical Implementation of a Patient-Specific 3D-Printed HDR Brachytherapy Applicator Workflow for Cutaneous Malignancies: A Single Institution Experience

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ABSTRACT

Purpose: To develop and clinically implement a reproducible workflow for the design, fabrication, and validation of patient-specific 3D-printed HDR brachytherapy applicators for cutaneous malignancies.
Methods: Patients requiring HDR brachytherapy for cutaneous targets underwent CT simulation using a conventional skin flap applicator constructed from commercially available materials (Varian, Palo Alto, CA). A separate CT dataset was used to design a patient-specific 3D-printed applicator using Eclipse (Varian, Palo Alto, CA) and 3D Brachy (Adaptiiv, Halifax, NS). Applicators were fabricated using a Form 3B printer (Formlabs, Somerville, MA) with BioMed Clear resin. Post-production quality assurance included evaluation of CT Hounsfield Unit (HU) consistency relative to water, spatial fidelity of applicator dimensions and source channels, and afterloader compatibility. Following fabrication, patients underwent an additional CT simulation with the 3D-printed applicator in place to confirm fit and generate the clinical treatment plan. Time required for CT simulation, and applicator design and production was recorded for both workflows. Material and labor costs were tracked to estimate relative financial impact.
Results: All 3D-printed applicators demonstrated acceptable HU values, geometric accuracy, and afterloader compatibility for clinical use. Although the 3D-printed workflow required an additional CT simulation, total CT simulation time was reduced compared to the traditional skin flap workflow due to improved initial fit and reduced on-table modifications. Treatment setup time was also reduced with 3D-printed applicators. The average cost of applicator production was lower for the 3D-printed workflow compared to traditional skin flap construction.
Conclusion: A clinically viable workflow for patient-specific 3D-printed HDR brachytherapy applicators was successfully implemented. Early experience demonstrates reductions in CT simulation time, treatment setup time, and applicator production cost. Ongoing work will evaluate dosimetric differences and clinical outcomes as additional patients are treated.

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INTRODUCTION

- Keratinocyte carcinoma (KC) is the most common form of cancer worldwide, affecting >3 million people per year within the United States alone [1].
- Treatment of KC includes surgical options, such as Mohs surgery, systemic or topical drug therapies, external beam radiation therapy, and brachytherapy.
- Traditional treatment methods such as surgery can leave patients deformed, while traditional applicators can be deficient in terms of conforming to the shape and obliquity of the treated area, especially in the face.
- The American Brachytherapy Society (ABS) and the American Association of Medical Physicists (AAPM) have provided guidelines on brachytherapy treatment of KC, involving conical applicators (such as Leipzig) flaps, and molds [2-3].
- Although specific consensus guidelines addressing additive manufacturing of brachytherapy applicators are limited, prior publications have demonstrated feasibility and promising dosimetric outcomes [4].
- The work presented here, shows a reproducible workflow for 3D printing applicators for cutaneous malignancies and reports on the financial and time savings for our clinic compared to traditional skin flaps in the early stages of use.

METHODS AND MATERIALS

The methods of this work are provided below as step-by-step directions, with Figure 1 provided as a visual guide.

1. Patients were simulated with and without wire markers, denoting the area to be treated.
2. The images were imported to the TPS, Eclipse (Varian, Palo Alto, CA), where the body contour was edited using a lung window to accurately represent the skin surface facilitate applicator design. In this step the size/shape of the applicator was determined.
3. The CT dataset and contours were then exported to 3D Brachy software (Adaptiiv, Halifax, NS). Within 3D Brachy, all aspects of the applicator were determined including the number of channels, orientation, spacing, distance to surface, radius of curvature, etc. Additionally, within 3D Brachy, text was added to the print (patient name, channel labeling, etc.).
4. After applicator design, the design was reimported back to the TPS for a pre-plan to ensure the design provided adequate target coverage and OAR sparing.
5. Once the applicator design was confirmed, a .stl file of the print was exported for 3D printing, in our case 3D printing was done using Form 3B printer (Formlabs, Somerville, MA) with Biomed clear resin. Following fabrication, each applicator underwent patient-specific QA including visual inspection, dimensional verification, applicator CT number assessment, and catheter pathway evaluation.
6. Finally, a second CT simulation was done with the applicator in place to ensure fit and provide accurate channel digitization for treatment planning as normal.

RESULTS

- Preliminary results from 5 patients show financial benefit, with reduced per-patient costs associated with producing applicators (Table 1).
- This workflow has shown a reduction in the time spent in setting the patient up during initial CT simulation, 8.0 ± 6.7 min (3D printing workflow) versus 29.5 ± 11.3 min (traditional flap workflow).
- Time spent setting the patient up for treatment was also reduced, 3.0 ± 1.2 min (3D printing workflow) versus 9.0 ± 3.2 min (traditional flap workflow).

Table 1. Comparison of the financial cost of producing 3D printed applicators (in-house printing) versus the cost of purchasing a skin flap from a commercial vendor. Time spent setting up the patient for initial simulation and for a single treatment are presented as mean ± standard deviation.

	3D Printing	Traditional Skin Flap
Cost (USD)	\$250 (20-200 ml), \$400 (201-400 ml), \$800 (401-800 ml)	>\$4,900 (per 20x29x1 cm^3)
Average cost per patient (USD)	\$362.50	\$408.33
Time spent setting up patient for simulation (minutes)	8.0 ± 6.7	29.5 ± 11.3
Time spent setting up patient for treatment (minutes)	3.0 ± 1.2	9.0 ± 3.2

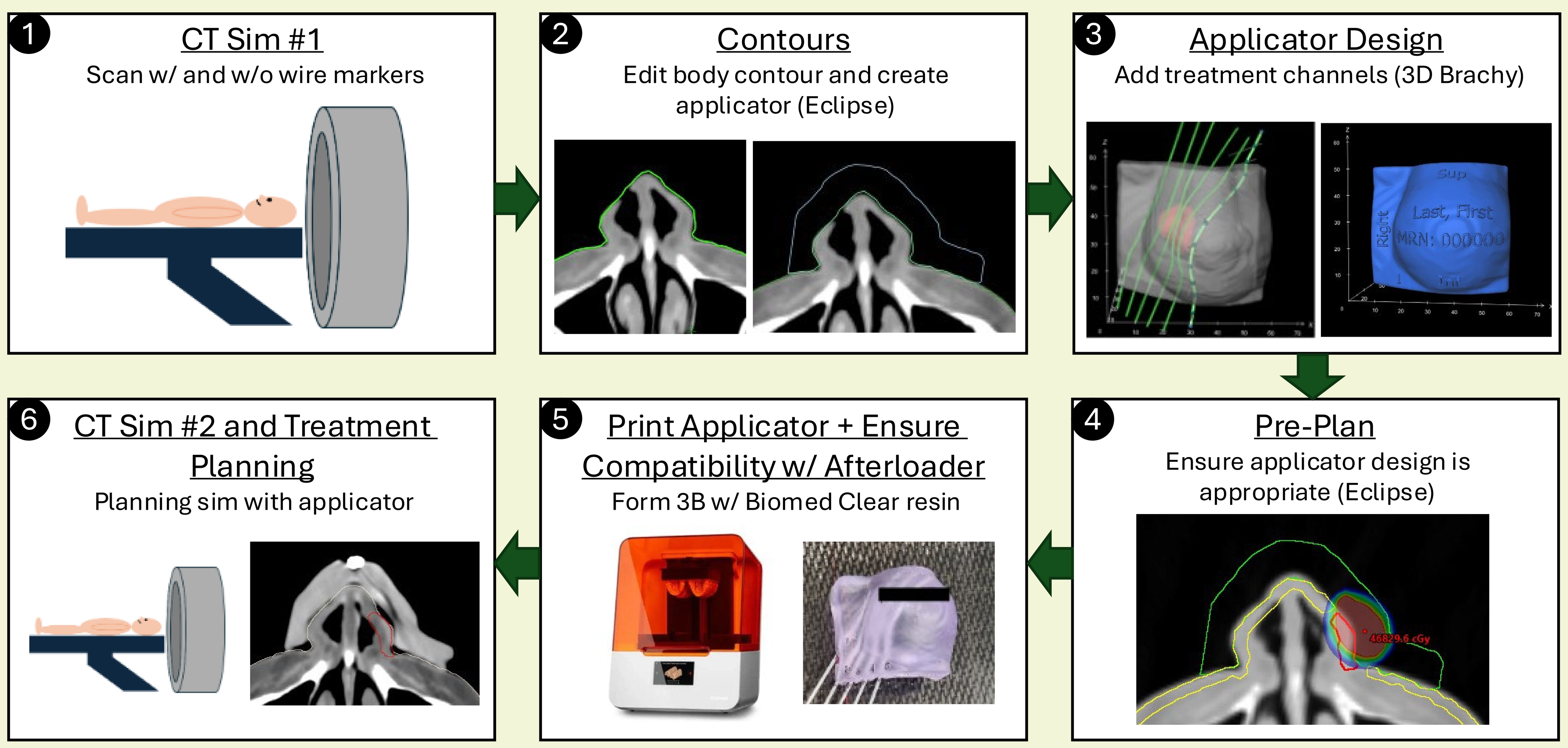

Figure 1. Workflow diagram showing key steps in the applicator production process including 1) initial simulation, 2) body and applicator contouring in Eclipse, 3) applicator design within 3D Brachy, 4) pre-planning, 5) applicator fabrication and testing, and finally 6) simulation and treatment planning.

DISCUSSION

- A reproducible workflow was developed for the design, fabrication, and clinical implementation of patient-specific 3D-printed HDR brachytherapy applicators for cutaneous malignancies.
- Compared with traditional skin flap applicators, 3D-printed applicators can provide improved geometric conformity to irregular treatment surfaces while reducing simulation and treatment setup time.
- Although the financial analysis presented here is institution-specific, we anticipate similar workflow efficiencies may be realized at other centers implementing patient-specific HDR applicators.
- The primary advantages of 3D printing include improved applicator reproducibility, patient-specific channel placement, and potential reduction in clinical resource utilization.
- Traditional skin flap applicators remain advantageous for cases requiring rapid fabrication or when advanced imaging and design resources are unavailable.
- Implementation of patient-specific applicators requires rigorous quality assurance including dimensional verification, source channel evaluation, CT number assessment, and end-to-end treatment validation prior to clinical use.
- These workflow improvements may be particularly valuable in high-volume clinical environments where HDR procedures compete for CT simulation and treatment room resources
- Additional patients are being enrolled under IRB approval to evaluate dosimetric outcomes including target coverage and skin sparing – early results show improved dosimetry.

CONCLUSIONS

- A complete end-to-end workflow for patient-specific 3D-printed HDR brachytherapy applicators was successfully implemented in a clinical environment (Figure 1).
- Compared to traditional skin flap applicators, the 3D-printed workflow reduced total CT simulation time despite requiring an additional verification scan, attributable to improved applicator fit and elimination of iterative on-table modifications at the time of simulation.
- Similarly, treatment setup time was reduced due to reproducible applicator positioning and elimination of iterative adjustments.
- The average cost of applicator production was lower for 3D-printed applicators compared to traditional skin flap construction.
- Initial clinical experience demonstrates the feasibility and safety of patient-specific applicators while ongoing data collection will evaluate dosimetry and compare against traditional skin applicators.

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