TECHNICAL NOTE

Impact of Flattening Filter-Free Beams on Lower-Neck Skin Dose in Head and Neck Cancer: Mechanisms and Mitigation

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Abstract

Purpose: Acute radiation dermatitis (ARD) of the lower neck and supraclavicular fossa (SCF) is a recurring source of morbidity in head and neck (H&N) chemoradiation. Flattening filter-free (FFF) beams produce a softer photon spectrum, shallower build-up, and increased surface dose compared with conventional flattened beams. The primary aim of this technical note is to characterise the magnitude of FFF-related lower-neck skin dose elevation on an O-gantry (Halcyon 6 MV FFF) system and to define a practical mitigation framework.

Methods and Materials: A 57-year-old woman with pT3N3b oral-tongue squamous cell carcinoma underwent postoperative IMRT to 60 Gy/54 Gy in 30 fractions (simultaneous integrated boost) with concurrent weekly cisplatin, delivered on an O-gantry system (6 MV flattening filter-free [FFF]). Grade III ARD developed over the left lower neck at fraction 20, coincident with treatment-related weight loss and extension of the planning target volume (PTV) beyond the body surface contour. Adaptive replanning with re-simulation, mask remoulding, and 4 mm PTV-to-skin cropping was performed. The skin dose was compared between FFF and non FFF beams.

Results: At iso-coverage, FFF plan delivered higher skin dose than the non-FFF plan across nearly all metrics: skin Dmax 70.58 vs 66.73 Gy (+5.8%), Dmean 12.85 vs 12.01 Gy (+7.0%), V25 Gy 173.09 vs 147.63 cc (+17.2%), V30 Gy 137.14 vs 115.67 cc (+18.6%), and V50 Gy 59.0 vs 54.08 cc (+9.1%). Body Dmax was 70.50 Gy on Halcyon versus 69.20 Gy on TrueBeam. After PTV-to-skin cropping and re-simulation on Halcyon, skin Dmax fell to 68.25 Gy (−3.3%) and V20–V30 Gy decreased by approximately 5–7%, confirming that mitigation strategies substantially reduce the FFF surface-dose excess. Clinically, ARD resolved within two weeks of treatment completion.

Conclusions: In this single-patient matched comparison delivery on an o-gantry, 6 MV FFF was associated with measurably higher lower-neck skin dose than an equivalent arm, 6 MV flattened plan. The skin-dose excess arises primarily from the softer FFF-only photon spectrum, the in-line beamline (no bending magnet) and the lower mean primary electron energy. Anatomical change during treatment can amplify this baseline difference. A practical mitigation framework — accurate body contouring, 3–5 mm PTV-to-skin cropping, optimised positioning, explicit skin DVH constraints, and a low threshold for adaptive replanning — is proposed as the primary clinical response to FFF-related surface dose elevation on o-gantry platforms.

Keywords: o-gantry; flattening filter-free; surface dose; skin dose mitigation; radiation dermatitis; head and neck cancer; adaptive radiotherapy; PTV-to-skin cropping; flattened beam.

1. Background

Acute radiation dermatitis (ARD) remains one of the most frequent and clinically significant toxicities of chemoradiation for head and neck (H&N) squamous cell carcinoma (SCC). Across modern cooperative-group randomised trials using IMRT-based chemoradiation, grade ≥3 ARD occurs in approximately 5–15% of cisplatin-treated patients, rising to 23–35% with cetuximab-containing regimens, with some institutional series reporting rates as high as 49% depending on patient selection, fractionation, and grading criteria.[1,2,3,4]

Unlike organs such as the parotid glands or pharyngeal constrictors, the skin overlying the lower neck and SCF is anatomically inseparable from the relevant nodal target volumes. Standard PTV expansions, combined with anatomical features specific to this region — skin folds, loss of subcutaneous tissue, and proximity to the cutaneous surface — produce increased surface dose and a correspondingly higher risk of clinically significant dermatitis. Flattening filter-free (FFF) beams produce a softer photon spectrum, shallower build-up, and increased surface dose compared with conventional flattened beams

The primary aim of this technical note is to characterise the additional impact of FFF beams' skin dose on lower-neck skin dose, quantify that elevation in a representative clinical case, and propose a structured mitigation framework for routine clinical practice.

3. Case Description

4.1 Patient Presentation and Initial Treatment

A 57-year-old woman with squamous cell carcinoma of the left lateral border of the tongue underwent hemiglossectomy, left modified radical neck dissection (MRND), and free radial-artery forearm-flap (FRAFF) reconstruction. Histopathology confirmed pT3N3b disease with metastatic involvement of ipsilateral nodal levels II, III, and IVa.

Adjuvant IMRT was planned as a simultaneous integrated boost: 60 Gy in 30 fractions to the tumour bed and involved nodal regions, and 54 Gy in 30 fractions to elective nodal volumes, with concurrent weekly cisplatin (40 mg/m²). The clinical plan was delivered on the Halcyon system (6 MV FFF, dual-layer MLC, coplanar VMAT).

4.2 Clinical Course and Adaptive Intervention

After 20 fractions of radiotherapy and four cycles of cisplatin, the patient developed grade III ARD over the left lower neck (Figure 3, left). Clinical and on-treatment imaging review identified two compounding geometric problems: treatment-related weight loss had reduced subcutaneous tissue volume in the lower neck (Figure 1), and the high-dose PTV was extending to or beyond the skin surface on recalculated dose mapping.

Management comprised CT re-simulation with a freshly moulded thermoplastic mask, full re-contouring, and cropping of the high-dose PTV by 4 mm from the body surface (Figure 2). The patient completed treatment without further interruption; skin reactions had substantially resolved within two weeks of treatment completion (Figure 3, right).

4.3 Figures: Geometric Trigger and Clinical Course

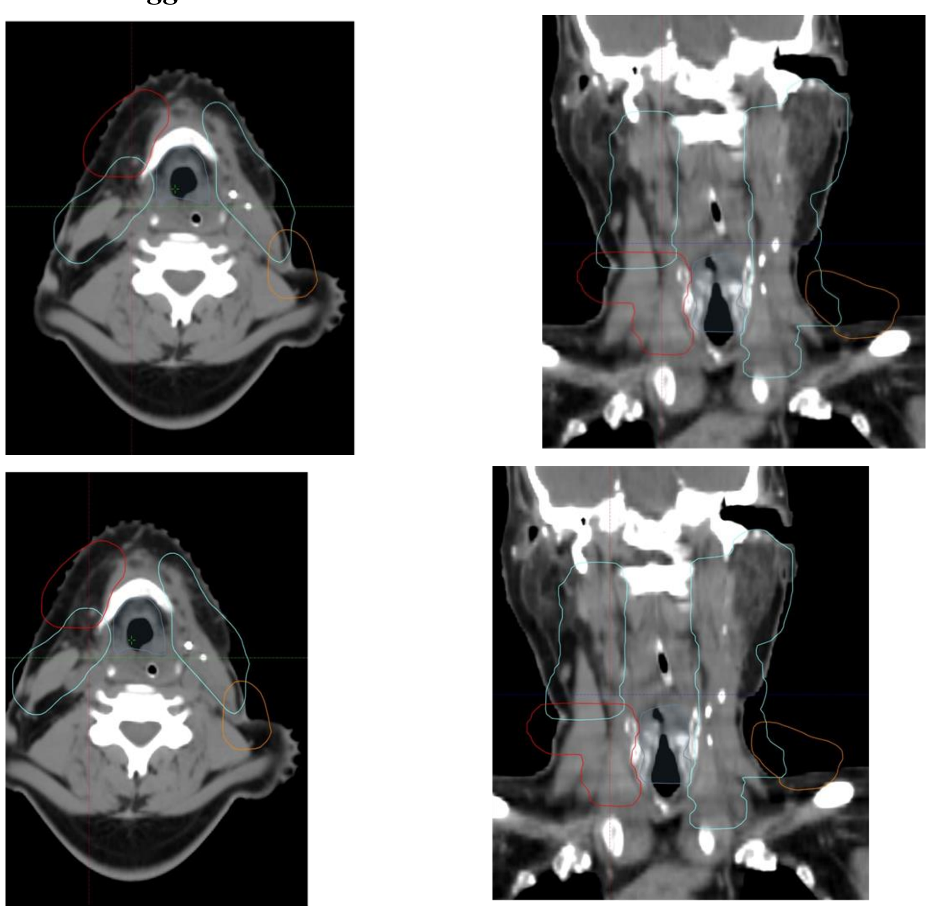

Figure 1. Geometric consequence of weight loss. Axial (top) and coronal (bottom) CT views demonstrating the effect of treatment-related weight loss in the index patient. The body contour (green) no longer matches the patient's anatomy after significant subcutaneous volume loss, and the high-dose PTV (red) now extends outside the current body surface in the lower neck — a configuration that drives excessive superficial fluence and is a formal trigger for adaptive replanning.

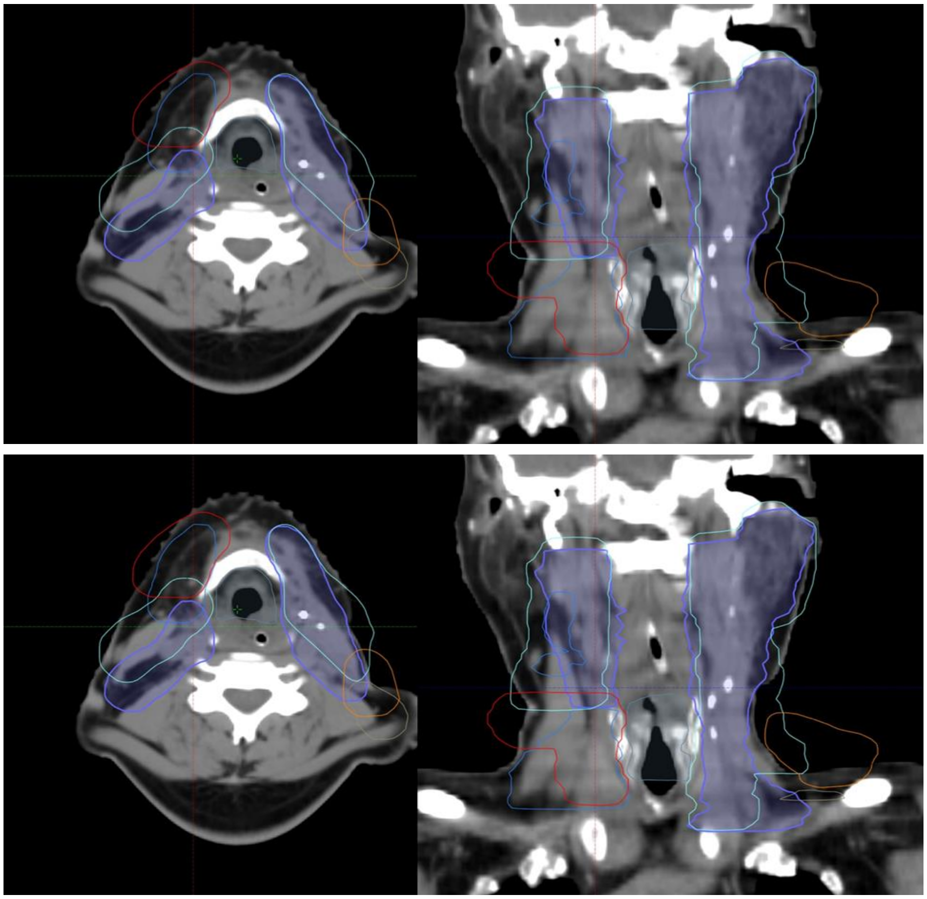

Figure 2. Dosimetric correction after adaptive replanning. Axial (top) and coronal (bottom) CT views following CT re-simulation with a new thermoplastic mask and formal re-contouring. The body contour has been updated to reflect the patient's current anatomy and the PTV has been cropped 4 mm from the corrected body surface. Compare with Figure 1: the PTV no longer exceeds the skin boundary, and the optimiser is no longer under pressure to deliver high-dose fluence at the surface.

Figure 3. Clinical skin reactions before (left) and after (right) adaptive intervention in the index patient. Left panel: grade III radiation dermatitis (confluent moist desquamation) over the left lower neck at fraction 20, prior to adaptive replanning. Right panel: degree of resolution observed at treatment completion following implementation of the adapted plan.

O-gantry (Halcyon 6 MV FFF) and arm (TrueBeam MV flattened, non-FFF) VMAT plans were generated for the index patient on a single simulation CT using identical target volumes, organ-at-risk contours, prescription dose, and acceptance criteria. This comparison serves the secondary study objective: to quantify the dosimetric benefit of conventional flattened beams on an arm platform relative to FFF o-gantry delivery. Both plans were optimised to the same target coverage (V95% ≥ 95%) and normalised identically. Skin and body dose-volume metrics are summarised in Table 2 and visualised in Figures 4–7. The findings are presented as a single-patient illustrative comparison rather than a multi-patient controlled study, and are intended to indicate the order of magnitude of the platform- and filter-related skin-dose difference encountered in clinical practice.

Parameter	FFF (Initial)	Non FFF (Initial)	FFF (Post-Adapt)	Non FFF (Post-Adapt)
Skin (Gy / cc)				
D_{max} (Gy)	70.58	66.73	68.25	69.2
D2% (Gy)	61.64	61.54	61.64	62.1
D50% (Gy)	2.53	2.38	2.54	5.7
D95% (Gy)	0.35	0.21	0.35	0.233
D98% (Gy)	0.30	0.17	0.30	0.179
D_{mean} (Gy)	12.85	12.01	15.15	14.26

Parameter	FFF (Initial)	Non FFF (Initial)	FFF (Post-Adapt)	Non FFF (Post-Adapt)
D2cc (Gy)	65.00	64.30	68.71	66.14
V10 Gy (cc)	308.4	299.0	276.0	280.9
V20 Gy (cc)	214.1	194.94	203.0	169.6
V25 Gy (cc)	173.09	147.63	172.0	141.2
V30 Gy (cc)	137.14	115.67	135.0	116.32
V50 Gy (cc)	59.0	54.08	57.0	55.7
Body (Gy)				
Body D_{max} (Gy)	70.50	69.20	70.5	69.87
Body D_{mean} (Gy)	12.20	11.15	15.3	14.2

Table 2. Patient 1 — comparative skin and body dose metrics for the Halcyon (o-gantry, 6 MV FFF) and TrueBeam (arm, 6 MV flattened, non-FFF) plans. The TrueBeam comparison serves the secondary study objective of quantifying the skin-sparing benefit of flattened beams. Initial plans (pre-adaptation) and post-adaptation plans for both platforms are shown. The post-adaptation TrueBeam (arm, Non-FFF) plan with 4 mm PTV-to-skin cropping is now included.

5.1 Key Quantitative Findings

- Skin Dmax was 5.8% higher on Halcyon than on TrueBeam (70.58 vs 66.73 Gy).
- Skin Dmean was 7.0% higher on Halcyon (12.85 vs 12.01 Gy).
- Skin V25 Gy, V30 Gy and V50 Gy— the volume metrics most strongly correlated with grade ≥2 dermatitis in published series — were 17.2% ,18.6% and 9% higher on Halcyon respectively.
- Skin V50 Gy (high-dose surface volume) was 9.1% higher on Halcyon (59.0 vs 54.08 cc).
- Body Dmax was 1.9% higher and Body Dmean was 9.4% higher on Halcyon.
- After 4 mm PTV-to-skin cropping, the Halcyon skin Dmax fell from 70.58 Gy to 68.25 Gy (−3.3%) and skin V20–V30 Gy fell by approximately 5–7%, confirming that geometric correction is the dominant lever for surface-dose reduction even on an O-ring platform.

5.2 Visual Comparison: Dose-Wash Color Maps

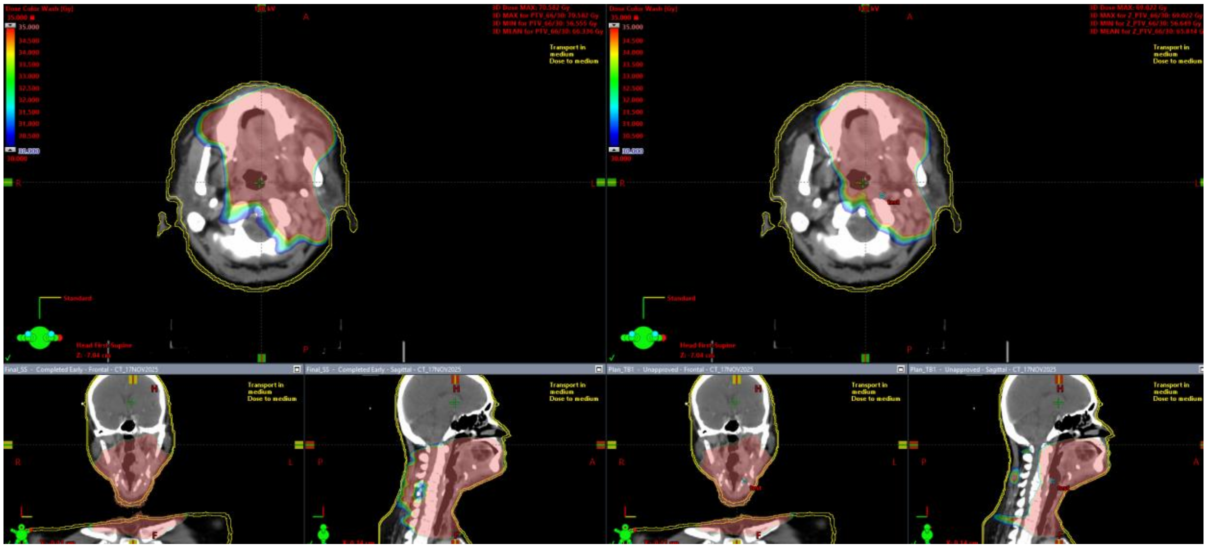

Figure 4. Halcyon (left) versus TrueBeam (right) — dose-wash color maps thresholded at 30–35 Gy on representative axial, coronal, and sagittal slices for the index patient (initial plans). The 30 Gy isodose envelope (yellow contour) is visibly larger on Halcyon, particularly across the anterior neck and SCF skin.

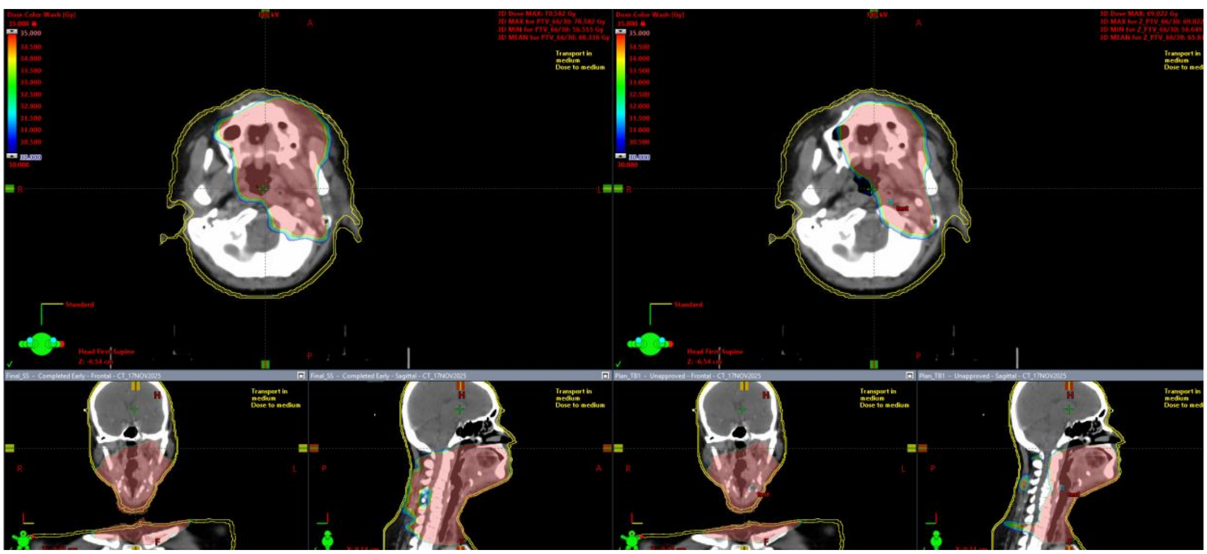

Figure 5. Halcyon (left) versus TrueBeam (right) — dose-wash color maps thresholded at 30–35 Gy after adaptive replanning for the index patient. Note the reduction in superficial 30 Gy envelope on the adapted Halcyon plan, but persistent excess relative to the TrueBeam comparator at the lower-neck skin.

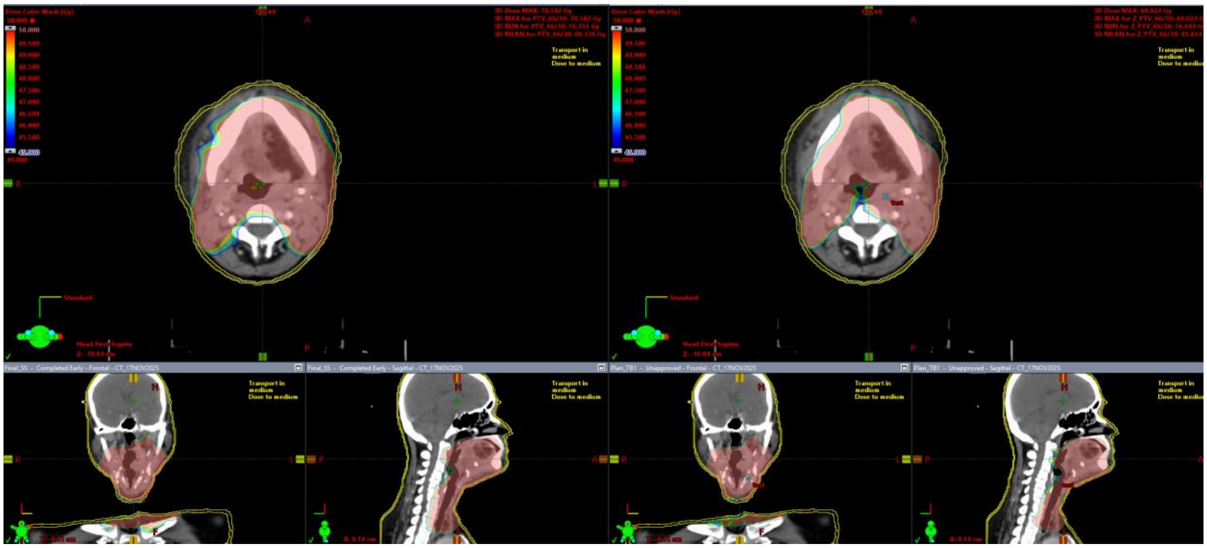

Figure 6. Halcyon (left) versus TrueBeam (right) — dose-wash color maps thresholded at 45–50 Gy. The 45 Gy isodose reaches closer to the anterior skin surface on Halcyon than on TrueBeam at matched coverage.

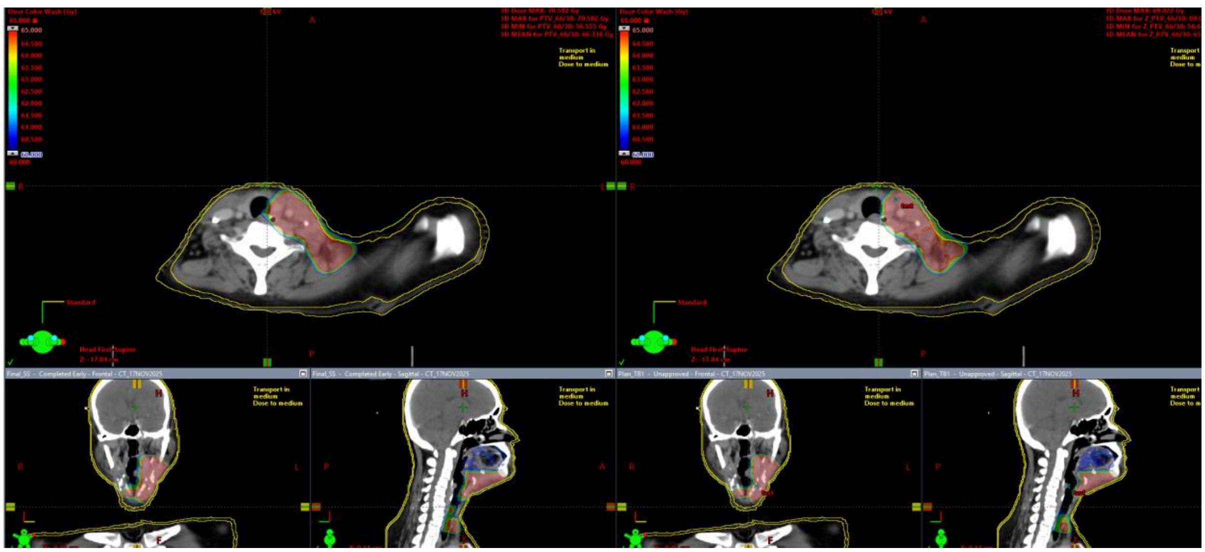

Figure 7. Halcyon (left) versus TrueBeam (right) — dose-wash color maps thresholded at 60–65 Gy showing the high-dose envelope at the lower-neck skin. The high-dose envelope tracks the skin contour more closely on Halcyon.

6. Discussion

The lower neck and SCF represent a particularly challenging region for skin-toxicity management in H&N radiotherapy. The case described and the matched dosimetric comparison together suggest three converging mechanisms by which severe ARD develops in this region:

(i) FFF beam characteristics (primary driver). O-gantry 6 MV FFF beam — generated from a shorter waveguide, driven by a magnetron rather than a klystron, and without the momentum filtration provided by a 270° achromatic bending magnet — has a softer primary electron spectrum (reported mean ≈5.6 MeV vs ≈6.1 MeV on TrueBeam) and a lower mean photon energy than either TrueBeam FFF or TrueBeam flattened beams. Crucially, the removal of the flattening filter on both FFF platforms eliminates a key beam-hardening element; on TrueBeam, operators may select the flattened 6 MV mode to partially recover this hardening effect and reduce surface dose. The build-up region on Halcyon FFF is correspondingly shallower, surface dose is higher, and contiguous skin volumes receiving 25–30 Gy are larger. In the present secondary comparison against arm flattened (non-FFF) beams, this translated into an 18.6% higher V30 Gy and a 5.8% higher Dmax on Halcyon FFF at matched target coverage.

(ii) Geometric and anatomical effects. Anterior neck skin folds act as self-bolus, eliminating the build-up region in the lower neck irrespective of platform. Treatment-related weight loss exceeding 10% of body weight is reported in a substantial proportion of H&N chemoradiation patients and progressively alters the PTV-to-skin relationship, representing the most common trigger for adaptive replanning in published ART protocols.[13,14,15]

(iii) Treatment-planning and contouring effects. Inaccurate body contouring may artificially extend the PTV toward or beyond the skin surface, and air gaps between the immobilisation mask and skin can cause the treatment-planning system to overestimate skin sparing.

Adaptive radiotherapy (ART) — defined here as CT re-simulation and formal replanning in response to anatomical change rather than purely on-treatment clinical assessment — has been shown to correct dosimetric degradations caused by such changes. Prospective data confirm that appropriately timed replanning, typically triggered around the third to fourth week of treatment, can restore PTV coverage and reduce unintended dose to OARs including the skin.[16,17,18] The DARTBOARD phase II randomised trial recently confirmed that daily adaptive H&N radiotherapy reduces skin toxicity and improves quality of life.[19]

In the present secondary comparison, the post-adapt FFF skin Dmax (68.25 Gy) approached pre-adapt flattened (non-FFF) skin Dmax (66.73 Gy) and all skin dose metrics from V10-V50 were further reduced in comparison to the initial plan. This indicates that geometric correction (PTV cropping, body re-contouring) can help reduce the skin dose.

6.4 Limitations

Several limitations should be acknowledged. First, the dosimetric comparison is restricted to a single patient and is intended as illustrative rather than definitive; multi-patient and multi-centre validation is required. Second, both plans were generated with current-generation algorithms and clinically realistic constraints, but inter-planner variability cannot be excluded. Third, body-contour and skin-segmentation accuracy at the lower-neck/shoulder transition is technically demanding, and small variations in skin-ring definition can affect absolute V_x Gy values. Fourth, although the case provides clinical correlation between high skin DVH metrics and grade III ARD, causal attribution of the toxicity to the platform alone is not possible in the presence of concurrent geometric drivers. The post-adaptation arm (TrueBeam, Non-FFF) plan with 4 mm PTV-to-skin cropping has now been generated and included in Table 2 for direct comparison.

7. Practical Mitigation Framework

Drawing on the dosimetric evidence reviewed above and on the matched plan comparison presented in Section 5, the following structured framework is proposed for routine clinical use, with particular relevance to centres treating H&N patients on the Halcyon platform.

7.1 Mask Fit and Immobilisation

- Ensure optimal thermoplastic mask fitting in the lower neck and SCF region at the time of CT simulation.
- Minimise air gaps between mask and skin; air gaps impair accurate surface-dose calculation and cause the skin-sparing effect to be over-stated in the planning system.

7.2 Contouring Accuracy

- Carefully review body-surface contours to eliminate artefacts or discontinuities that could artificially extend the PTV toward the skin.
- Ensure accurate representation of the skin surface at all levels, particularly in the lower neck where the contour may be affected by positioning artefacts or shoulder shadow.

7.3 PTV-to-Skin Relationship at Planning

- Crop the PTV 3–5 mm from the skin surface where oncologically safe (NIMRAD, PATHOS, JAVELIN protocols).[19,20]
- Reassess cropping feasibility carefully in postoperative or high-risk nodal regions where skin involvement may be a genuine oncological concern.

7.4 Patient Positioning

- Maintain a neutral or slight chin-up position to limit anterior neck skin folds; folds act as self-bolus, eliminating skin sparing and raising surface dose to prescription level.
- Verify positioning at every fraction with kV-CBCT; consistent reproduction prevents progressive changes in fold geometry during treatment.

7.5 Adaptive Radiotherapy

- Combine weekly clinical skin review with formal geometric assessment of weekly CBCT images. PTV extension outside the body contour is an established replanning trigger.[21]
- Consider formal adaptive replanning when: weight loss exceeds approximately 10% of body weight; tissue shrinkage reduces the PTV-to-skin distance; or grade ≥2 dermatitis emerges in the lower neck before fraction 20.

7.6 Planning Technique Optimisation

- On the FFF beam, incorporate explicit skin DVH constraints (e.g. mean skin dose, V40–V60 Gy to a 3 mm skin-ring structure) into the optimisation objective set, particularly in patients with prior neck surgery, flap reconstruction, or anticipated significant weight loss.

8. Conclusions

Clinically significant ARD in the lower neck and SCF is not an inevitable consequence of target proximity to the skin. It arises from an identifiable combination of FFF beam characteristics and treatment-planning factors, several of which are tractable to clinical and dosimetric intervention. The primary finding of this technical note is that FFF beams produce measurably higher lower-neck skin dose through a softer photon spectrum, shallower build-up, and constrained coplanar geometry — and that this excess can be substantially mitigated through accurate body contouring, PTV-to-skin cropping, optimised positioning, explicit skin DVH constraints, and adaptive replanning. These observations should not be interpreted as a reason to avoid FFF delivery. The dose-rate advantages of FFF beams — reduced beam-on time, lower intrafraction motion risk, decreased out-of-field scatter, and improved departmental throughput[23] — remain compelling and are well-supported in the literature. The mitigation framework proposed here is intended to preserve these benefits while addressing the specific vulnerability of the lower-neck skin in FFF-treated head and neck patients.

A structured approach incorporating accurate body contouring, 3–5 mm PTV-to-skin cropping, optimised positioning, explicit skin DVH constraints, and a low threshold for formal adaptive replanning provides a practical, evidence-supported framework for reducing severe ARD without compromising oncological intent.

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Conflict of Interest Statement

Sushil Beriwal and Luca Cozzi are employed by Varian Medical System, Inc., a Siemens Healthineers company. The other authors declare that they have no relevant conflicts of interest. Halcyon and TrueBeam are products of Varian Medical Systems (Palo Alto, CA), the employer of Beriwal and Cozzi. The other authors have no financial relationship with the manufacturer.

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Patient Consent

Written informed consent was obtained from the patient for the use of de-identified clinical photographs and dosimetric data for educational and publication purposes.

Data Availability

De-identified treatment-planning DICOM-RT data supporting the dosimetric comparison are available from the corresponding author on reasonable request.

9. References

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