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Scientific Article

Virtual Patient-Specific 3-Dimensional Specimen Maps for Adjuvant Radiation Therapy Planning in Mucosal Head and Neck Squamous Cell Carcinoma

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Purpose: Adjuvant radiation therapy planning for mucosal head and neck squamous cell carcinoma is challenging due to postoperative anatomic changes, contributing to variability in clinical target volume (CTV) delineation and risk of geographic miss or unnecessary dose expansion. Patient-specific 3-dimensional (3D) specimen maps may offer a novel approach to improve the localization of high-risk margins and facilitate multidisciplinary communication.

Methods and Materials: In this prospective, noninterventional feasibility study, 3D scanning and virtual pathologic mapping of surgical specimens were performed as part of routine pathologic processing. Annotated 3D maps were integrated into the radiation therapy planning workflow and reviewed by the multidisciplinary team. Two adjuvant radiation therapy plans were prepared: 1 per standard of care and 1 with a 3D specimen map added. Changes in CTV primary or CTV boost delineation, dosimetric parameters for organs at risk, and clinician-reported confidence were assessed.

Results: Thirteen patients were treated by 5 radiation oncologists. Changes in CTV primary and CTV boost delineation occurred in 3 cases each. 3D specimen mapping enabled focal expansion or reduction of boost volumes, reflecting improved localization of high-risk surgical margins. Small dosimetric changes were observed for organs at risk, but none exceeded clinically significant thresholds. Radiation oncologists reported increased confidence in treatment volumes (mean score increased from 64.5 to 84.9; $P = .02$) and improved ability to localize positive margins (mean score increased from 51.6 to 75.4; $P = .02$).

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Data Sharing Statement: Research data are stored in an institutional repository and will be shared on request to the corresponding author.

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Conclusions: Integration of patient-specific 3D specimen maps into adjuvant radiation therapy planning for head and neck squamous cell carcinoma is feasible and can meaningfully influence target delineation, particularly for boost volumes. This strategy improves margin localization, multidisciplinary communication, and clinician confidence, with the potential to optimize oncologic coverage.

Introduction

According to the National Comprehensive Cancer Network guidelines, adjuvant radiation with or without concurrent chemotherapy is indicated following surgical resection of mucosal head and neck squamous cell carcinoma (SCC) when intermediate- and high-risk features, such as advanced pathologic tumor stage, close or positive margins, positive lymph nodes, extranodal extension (ENE), lymphovascular invasion (LVI), and/or perineural invasion (PNI), are present.[1,2] The clinical target volume (CTV) for the primary site (CTV_p) is typically treated to 60 Gy and includes the operative bed, with a margin to account for microscopic disease. In cases of positive margins or ENE, the radiation oncologist may consider a localized boost up to 66 Gy to the anatomic area of concern.[3,4] Accurate identification of the boost volume (CTV_b) is critical, as uncertainty in margin location may affect both target coverage and dose to adjacent organs at risk (OARs), which can contribute to suboptimal locoregional control and increased late-term side effects.

Adjuvant radiation treatment planning for mucosal head and neck cancer is challenging due to significant postsurgical anatomic changes, including the loss of native tissue planes, postoperative inflammation, fluid collection, and surgical manipulation or reconstruction.[5,6] The current standard of care involves a multidisciplinary approach, including review of preoperative imaging, operative reports, and expert consensus, to ensure precise targeting and minimize toxicity. However, these methods have notable limitations that can impact accuracy and consistency. Written operative reports vary in quality and may lack precise anatomic details or be misinterpreted. This makes it difficult to reconstruct the exact location of close/positive margins or the extent of resection, which can increase the risk of geographic miss.[7,8] Preoperative computed tomography (CT), magnetic resonance imaging, and positron emission tomography/CT will not reflect postsurgical anatomic distortion, and errors in imaging acquisition or fusion can affect the entire treatment plan. Moreover, there is substantial variability in treatment decisions among radiation oncologists, particularly in the absence of consensus guidelines for target volume delineation in the adjuvant setting. While consensus guidelines exist for primary tumor CTV delineation in the definitive setting, no standardized recommendations are currently available in the postoperative context.[6,7,9]

Prior studies have shown that ex vivo optical 3-dimensional (3D) scanning and virtual 3D specimen maps can improve communication among surgeons, medical oncologists, radiation oncologists, and pathologists in multidisciplinary care.[10-13] Unlike preoperative imaging, which defines gross tumor extent prior to resection, 3D specimen mapping is designed to spatially contextualize microscopic margin status after resection within the distorted postoperative anatomy. However, the use of 3D specimen maps to specifically improve the delineation of adjuvant radiation treatment volumes has not been evaluated. This study evaluates whether incorporating 3D tumor specimen maps into multidisciplinary care alters CTV_p and CTV_b delineation and directly influences radiation oncologist decision-making.

Methods and Materials

Study population

Following approval from the University-affiliated institutional review board (number 221597), patients with biopsy-proven head and neck cancer who underwent primary resection at any mucosal head and neck anatomic subsite (oral cavity, oropharynx, hypopharynx, or larynx) scheduled to receive standard-of-care adjuvant radiation at the institutional medical center were considered for accrual in the study. Cutaneous malignancies were excluded. Patients were included only if all study components (Fig. 1) were completed. Patients and treating radiation oncologists provided consent prior to participation. All mucosal histopathology types were included; patients with cutaneous malignancies were excluded. Patient characteristics were extracted from the electronic medical record. Chart review was performed to assess patient age, tumor histology, pathologic tumor and nodal stage, anatomic subsite, surgical procedure, and pathologic features (PNI, LVI, ENE, and final margin status). All staging was reported according to the eighth edition of the American Joint Committee on Cancer staging system.

3D Scanning and Visual Pathology Report Protocol

As previously described, resected oncologic specimens were scanned by research personnel prior to standard-of-

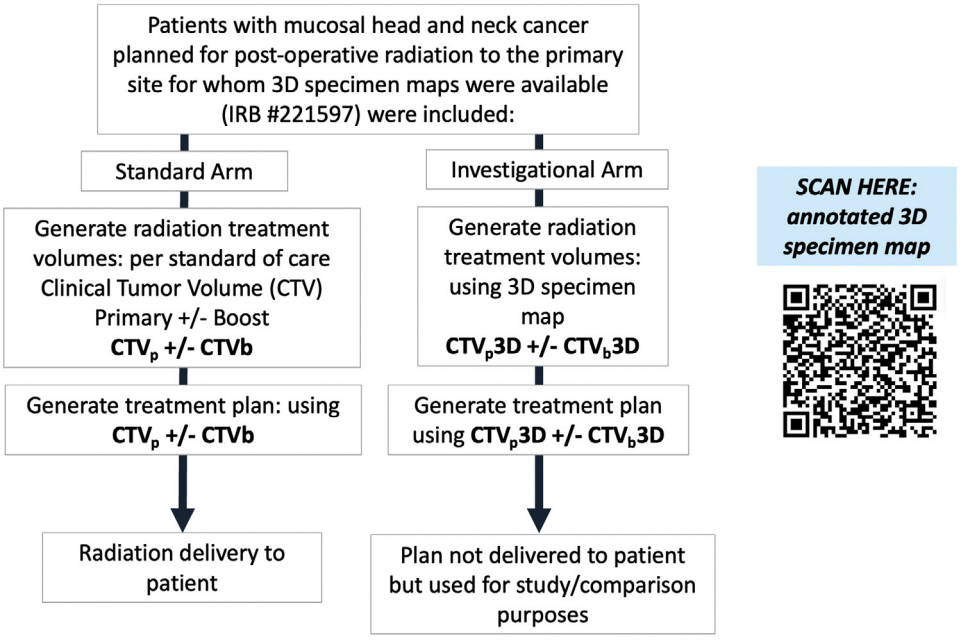

Figure 1 Study protocol. Each patient had 2 plans drawn (1 standard arm and 1 investigational arm). Only the standard-of-care plan was used to treat the patient.
Abbreviations: 3D = 3-dimensional; CTV, clinical tumor volume; CTV_b, clinical tumor volume boost; CTV_p, clinical tumor volume primary; CTVp3D = clinical tumor volume primary with 3D model; CTVb3D = clinical tumor volume boost with 3D model; IRB = institutional review board.

care pathologic processing. Specimens were transported from the operating room to the pathology laboratory, rinsed with water, and patted dry to reduce glare or reflective surfaces.[11,12] All specimens included in this study were submitted en bloc to reflect native anatomic orientation prior to scanning. Piecemeal resections were excluded from this study. A commercially available structured-light 3D scanner (EinScan SP, Shining 3D) and its accompanying software (EXScan, Shining 3D) were set up on a mobile cart immediately outside the operating room and used to capture the 3D topography of the ex vivo specimen. The specimen was placed on a turntable in the enclosed cart to reduce light exposure, and the top face of the specimen was scanned 360 degrees. The specimen was then manually flipped to scan the second face. The 2-point cloud matrices were manually aligned using 3-point cross-registration, yielding a virtual 3D model of the surgical specimen. The 3D scan was exported as a watertight, high-quality 3D mesh model and saved as 3MF and OBJ files. The entire process took an average of 8 minutes, and the specimen was then returned to the pathologist for standard-of-care processing.

Following 3D image acquisition, the 3MF file was exported to computer-aided design software (Meshmixer, Autodesk Inc). After overnight formalin fixation, the tissue specimens were sectioned and stained according to the routine standard-of-care protocol. A member of the research team closely observed the pathology assistant as they sampled perpendicular and shave sections based on areas of concern. The virtual ink colors corresponded to the actual ink on the gross specimen, and the virtual letters corresponded to each cassette. The computer-aided design file was saved and exported as a 3MF file. The completed 3D specimen map and 3D image of the specimen were uploaded to a presentation (Microsoft PowerPoint, Microsoft Corporation) and animated to rotate, revealing each face of the specimen. Research personnel added a legend to clarify the ink colors and their corresponding anatomic positions, as well as the perpendicular and shave margins. The 3MF file of the annotated 3D specimen map was 3D-printed on a Stratasys J-730 printer and delivered to the treating radiation oncologist for reference during treatment planning. The time required to prepare the annotated 3D specimen map was approximately 30 minutes of hands-on time, depending on the specimen's complexity, plus an additional 5 to 10 minutes to prepare the digital model. The model was left unattended overnight for 3D printing.[13,14] The cumulative hands-on time was approximately 45 minutes to 1 hour per case. In summary, the treating radiation oncologist was provided with both a digital 3D file and a 3D-printed model of the resected cancer and its pathologic processing.

Radiation therapy procedures

Patients underwent CT-based radiation therapy planning per standard of care, with immobilization using a long thermoplastic mask, typically with the addition of intravenous contrast. The bite block was optional,

depending on the primary tumor site. All treating radiation oncologists routinely treat head and neck malignancies at a high-volume academic center, with a median of 8.5 years (IQR, 4-19) of posttraining clinical experience. Standard clinical treatment plans underwent routine departmental peer review prior to delivery. The comparison plans incorporating the 3D specimen map were generated for study purposes and were not used for treatment. The treating radiation oncologist first generated CTVs in accordance with standard practice, including any of the following: pathology review, pre- and postoperative imaging review, operative notes, discussions with the surgical team, or a multidisciplinary tumor board. CTV_p was required and typically encompassed the postoperative tumor bed, while CTV_b was optional, based on the discretion of the treating radiation oncologist for certain high-risk features, including positive margins or bone invasion. While CTVs could also be delineated for nodal regions per standard of care, 3D specimen maps were limited to primary tumors; thus, nodal CTV volumes were neither altered nor investigated in this study. A second set of CTVs ($CTV_p3D \pm CTV_b3D$) was generated using the standard-of-care method in conjunction with the digital and 3D-printed specimen map model. Planning tumor volumes (PTVs) were generated by expanding the CTVs by a margin to account for setup uncertainty, organ motion, and daily variation between treatments. The magnitude of the PTV margin was determined by institutional protocols, image guidance, and immobilization technique. All patients received intensity modulated radiation therapy or volumetric arc modulated therapy. Doses to the PTVs were prescribed according to the standard of care at the discretion of the treating radiation oncologist. Patients were commonly treated with 60 Gy to the primary postoperative bed and high-risk nodal levels, and 54 Gy to the low-risk neck, with or without a boost to 66 Gy. Only the radiation plans generated without the 3D specimen maps were used for treatment delivery. The radiation plans derived from the 3D specimen maps were used only for study comparison purposes.

OARs

The parotid glands, submandibular glands, and pharyngeal constrictors are routinely delineated as OARs due to their association with late toxicities, including xerostomia and dysphagia. Clinical and dosimetric studies have demonstrated that the mean dose (D_{mean}) to the parotid and submandibular glands correlates with salivary function and patient-reported xerostomia, whereas D_{mean} to the pharyngeal constrictors is predictive of dysphagia and swallowing dysfunction.[15,16] For comparative analysis, D_{mean} for each OAR was extracted from the treatment plans designed with and without the aid of the 3D specimen map. Clinical significance was defined as a change in D_{mean} to OARs that resulted in reclassification of the dose category, specifically a shift between "ideal," "acceptable variation," or "deviation unacceptable," when evaluated using the 3D specimen map. In this analysis, if the D_{mean} of an OAR crossed a threshold that altered its dose category due to differences in CTV delineation with and without the intervention, it was considered clinically significant.

Qualitative survey experience

All participating radiation oncologists completed a custom survey prior to designing the treatment plan, with and without the 3D specimen map, and then repeated the survey after completing the treatment plan (Fig. E1). Provider perceptions of improved understanding of tumor characteristics, including tumor size and sites of positive and close surgical margins, as well as multidisciplinary communication when using the 3D specimen map, were assessed using the survey. The survey included questions specifically designed to evaluate these domains, with each item rated on a 0 to 100 Likert scale (0 = “strongly disagree” and 100 = “strongly agree”) to quantify provider perceptions. Survey data were collected using the Research Electronic Data Capture database and distributed by research team personnel.

Statistical analysis

Patient characteristics were summarized using descriptive frequencies and medians (IQRs). For survey data, the normality of pre−post difference scores was assessed using histograms, skewness/kurtosis, and the Kolmogorov-Smirnov test. Because the distribution met the assumption of normality, paired sample t tests were used to compare pre- and postintervention responses. For unpaired questions, the data were summarized using the mean and SD to describe the distribution of responses. Statistical significance was defined as $P < .05$. All statistical analyses were conducted using GraphPad Prism version 10.4.1.

A priori sample size calculations were performed for the paired CTV data. Prior published data by Wiens et al[17] describing within-pair differences in treatment volume with and without intervention showed that these differences follow approximately a normal distribution, with an SD of 7.00. Using this estimate and assuming a true mean paired difference of 6.00, 13 patients with matched pre- and postintervention data were required to achieve 80% power to detect this effect with a 2-sided paired t test and a type I error rate of .05.

Results

Patient cohort

Thirteen patients and 5 radiation oncologists were included between January 2023 and March 2025. Table 1

Table 1 Patient demographics

No.	Patient	Anatomic site	Surgery	Path stage	LVI	PNI	ENE	Final margin status	Maximum dimension of specimen (cm)
1	55 M	Mandibular alveolus	R mandibulectomy	T4aN0	N	N	N	Close	7.4
2	68 M	Maxilla	L maxillectomy	T4aN0	N	Y	N	Negative	9.3
3	62 M	Mandibular alveolus	L mandibulectomy	T4aN2b	N	Y	N	Close	9.3
4	37 M	Tongue	L hemiglossectomy	T2N0	N	Y	N	Negative	5.8
5	63 M	Maxillary alveolus	L maxillectomy	T4bN0	N	Y	N	Positive	8.3
6	80 F	Buccal mucosa	R oral cavity composite resection	T4aN2b	N	Y	N	Negative	7.9
7	49 M	Anterior palate	Maxillectomy	T4aN1	N	N	N	Close	7.7
8	57 M	Alveolar ridge	R oral cavity composite resection	T4aN0	N	N	N	Close	9.0
9	43 F	Tongue	L hemiglossectomy	T2N3b	N	Y	Y	Close	6.5
10	55 M	Mandible	R oral cavity composite resection	T3N1	N	N	N	Close	9.0
11	42 M	Larynx	Total Laryngectomy	T3N0	N	N	N	Positive	9.6
12	56 M	Tongue	R hemiglossectomy	T4aN2c	Y	Y	N	Close	9.5
13	73 M	Mandible	R mandibulectomy	T4aN2a	N	Y	Y	Positive	9.2

Abbreviations: ENE = extranodal extension; F = female; L = left; LVI = lymphovascular invasion; M = male; N = no; PNI = perineural invasion; R = right; Y = yes.

shows the baseline characteristics of patients who met the inclusion criteria. Most patients were male (n = 11, 85%), and the median age was 56 years (IQR, 46-66). All patients had mucosal SCC, and most (n = 12, 92%) had a primary lesion of the oral cavity. One patient underwent upfront total laryngectomy for advanced laryngeal SCC. Eleven patients (85%) had advanced pathologic tumor stage, 8 (54%) had lymph node involvement, 1 (8.3%) had LVI, 7 (62%) had PNI, and 2 (15%) had ENE on the final pathology report. Three patients (23%) had positive final margins, 7 (54%) had close margins, defined as invasive carcinoma <5 mm from the surgical ink, and 3 had negative margins. Four patients (31%) required a boost; 3 had positive margins and 1 had bony invasion.

The CTV_p and CTV_b changed in 3 cases each when using the 3D specimen map (Table 2). Changes in D_{mean} to OARs were observed in 4 of 13 cases (31%) when using the 3D specimen map (Table 3). In these cases, the D_{mean} either decreased, indicating improved sparing of the OARs, or increased, reflecting a higher D_{mean} with the 3D map compared with the original plan. However, none of these changes met the criteria for clinical significance, as

Table 2 Radiation doses and clinical target volumes

No.	Primary dose (Gy)	CTV_p (cm^3)	CTV_p3D (cm^3)	ΔCTV_p	Boost dose (Gy)	CTV_b (cm^3)	CTV_b3D (cm^3)	ΔCTV_b
1	60	251.3	253.6	+2.3 (0.9%)	-	-	-	-
2	60	225.3	225.3	0	65.1	0	15.4	+15.4
3	60	277	297.9	+20.9 (7.5%)	-	-	-	-
4	60	32.5	33.9	+1.4 (4.3%)	-	-	-	-
5	60	300.9	300.9	0	66	132.4	93.7	−38.7 −(29.2%)
6	60	176.4	176.4	0	-	-	-	-
7	60	95.3	95.3	0	-	-	-	-
8	60	281.6	281.6	0	-	-	-	-
9	60	23.2	23.2	0	-	-	-	-
10	54	190.4	190.4	0	-	-	-	-
11	61.05	331.2	331.2	0	66	189.0	98.7	−90.3 −(47.8%)
12	60	279.3	279.3	0	-	-	-	-
13	60	171.19	171.19	0	66	17.63	17.63	0

Abbreviations: ΔCTV_b = change in ΔCTV_b; CTV_b = clinical target volume boost; ΔCTV_p = change in CTV_p; CTV_p = clinical target volume primary site; CTVp3D = clinical tumor volume primary with 3D model; CTVb3D = clinical tumor volume boost with 3D model.

Table 3 Organs at risk dose

No.	Δ Ipsilateral parotid (D_{mean} ≤ 2000 cGy), %	Δ Contralateral parotid (D_{mean} ≤ 2000 cGy), %	Δ Pharyngeal constrictors (D_{mean} ≤ 5000 cGy), %	Δ Ipsilateral submandibular gland (D_{mean} ≤ 2600 cGy), %	Δ Contralateral submandibular gland (D_{mean} ≤ 2600 cGy), %
1	−1.64	−7.9	−2.4	−0.23	−4.8
2	−0.81	−1.4	+1.7	+0.71	−3.5
3	+0.53	−6.9	−0.45	+0.24	−1.1
4	−2.5	−1.0	+0.1	-	-
5	−6.2	+0.3	+1.4	−1.6	−0.73
6	-	-	-	-	-
7	-	-	-	-	-
8	-	-	-	-	-
9	-	-	-	-	-
10	-	-	-	-	-
11	−0.1	−1.9	−1.5	−1.35	−0.70
12	-	-	-	-	-
13	-	-	-	-	-

Abbreviation: D_{mean}, mean dose.

the dose category for each OAR (ideal, acceptable variation, and unacceptable deviation) remained unchanged.

Case vignettes

In the first case (patient 3), a 62-year-old man with pathologic stage pT4aN2b SCC of the left mandibular alveolus underwent mandibulectomy, and final pathology revealed PNI. During pathologic processing, sections H and M were identified as areas with close margins in the superior and medial soft tissue. A 3D specimen map was generated and shared with the radiation oncologist. This facilitated precise localization of the close margins and informed multidisciplinary discussion regarding adjuvant treatment planning. As a result, the CTV_p volume increased by 7.5% from 277.0 to 297.9 cm^3 in the 3D model. A representative image is demonstrated in Fig. 2A.

In the second case (patient 11; Fig. 2B), a 42-year-old man underwent total laryngectomy for pT3N0M0 SCC of the larynx, with final pathology revealing focal carcinoma involvement of the anterolateral margin. A 3D specimen map was generated to mirror the grossing of the total laryngectomy specimen, and section Z denoted the cassette with a positive margin. Because this patient had a positive margin, a radiation boost to the involved region was indicated. During discussion with the treating radiation oncologist, a 3D model was used to localize the region of focal involvement, resulting in a 47.8% decrease in CTV_b from 189.0 to 98.7 cm^3. The area of positive margin was included within the original boost volume; however, the 3D model enabled more precise localization, allowing the reduction of unnecessary surrounding tissue.

In the third case (patient 2; Fig. 2C), a 68-year-old man underwent left maxillectomy for pT4aN0 SCC. Final pathology revealed PNI and bony invasion. Final margins revealed close margins <1 mm at sections D, E, and F. Because the exact site of the bony invasion and the close margin could not be confidently localized using standard-of-care planning, CTV_b was not initially planned by the radiation oncologist for this anatomically complex resection. After using the 3D specimen map, CTV_b3D was boosted to 15.4 cm^3 in the inferior resection bed.

Qualitative surveys

Each radiation oncologist treated at least 1 patient in this study and completed both the pre- and postsurvey. Prior to using the 3D specimen map, radiation oncologists reported a mean confidence score of 64.5 (SD, 18.8) in the treatment volumes created with standard-of-care tools for treatment planning (Table 4). After using the 3D specimen map, the mean response to this statement increased to 84.9 (SD, 16.8; 95% CI, 3.12-37.8; P = .02). Regarding their ability to locate the site with a positive margin, providers reported an increase in the score from 51.6 (SD, 23.5) to 75.4 (SD, 20.7; 95% CI, 4.04-43.5; P = 0.02) after using the specimen map. Providers also reported improved communication among the surgeon, pathologist, and radiation oncologist for adjuvant treatment planning, as well as improved understanding of tumor size and characteristics when using 3D specimen maps

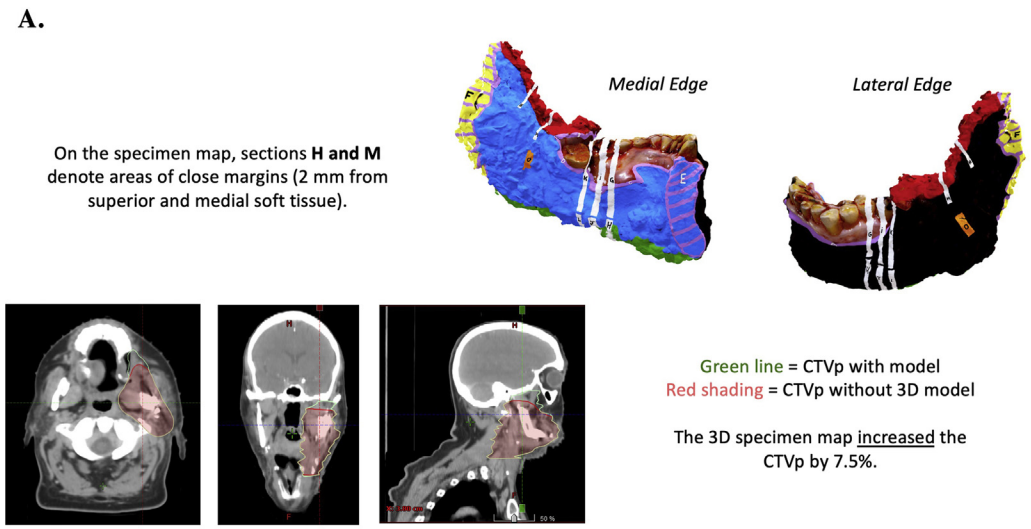

Figure 2 Representative 3-dimensional (3D) models of patients and images of the radiation plan. (A) A patient with stage IVA cancer of the mandible was planned for adjuvant radiation therapy to 60 Gy. The 3D models demonstrated areas with close margins at sections H and M. The clinical tumor volume primary site (CTV_p), as designed per standard of care, is denoted by the red line, while CTV_p with the addition of the 3D model is denoted by the green line. There was a 7.5% increase in CTV_p volume when using the 3D model. (B) A patient with stage III laryngeal cancer was planned for adjuvant radiation therapy to the primary site to 61.05 Gy with a boost to 66 Gy for positive final margins. There was no change in CTV_p. The clinical tumor volume boost (CTV_b) is denoted by the orange line, while CTV_b3D is denoted by the purple line. There was a 47.8% decrease in the boost volume at the site of the positive margin in the anterolateral soft tissue, denoted by section Z. (C) A patient with stage IVA squamous cell carcinoma of the maxilla was planned to receive 60 Gy. CTV_p did not change. CTV_b3D increased by 15.4 cm^3 from a CTV_b of 0 cm^3 with the addition of the 3D model due to improved localization of the close margin and bony invasion at the inferior resection bed.
Abbreviations: CTVb3D = clinical tumor volume boost with 3D model.

alongside standard-of-care tools. However, these responses were not significant when comparing the pre- and postsurveys. At the conclusion of the study, radiation oncologists reported that the 3D specimen maps were easy to use and manipulate (mean [SD], 93.9 [7.7]) and useful for generating treatment plans (mean [SD], 76.1 [15]). Providers also reported that they would use the 3D specimen map during future treatment planning (mean [SD], 90 [11.6]).

Discussion

In this feasibility study, we evaluated whether patient-specific 3D specimen maps could be integrated into the postoperative radiation therapy planning workflow for head and neck cancer and whether they meaningfully influenced treatment decisions. We found that incorporating 3D specimen maps was feasible and altered target delineation in select cases, primarily affecting CTV_b rather than CTV_p. In these cases, 3D mapping enabled either focal expansion or meaningful reduction of the CTVb, reflecting improved localization of high-risk surgical margins. Although small dosimetric changes were observed for OARs, none exceeded clinically significant thresholds beyond D_{mean} constraints. Radiation oncologists reported improved confidence in treatment volumes and margin localization after using the 3D maps.

Postoperative radiation planning following surgical resection with or without reconstruction and neck dissection is frequently complicated by loss of native tissue planes, reconstruction, and ambiguous documentation of margin status.[18] Unlike the definitive setting, where consensus guidelines inform target delineation, no standardized recommendations exist for the adjuvant setting, contributing to substantial variability in practice. The case vignettes in this study highlight cases in which radiation oncologists expanded or reduced either CTV_p or CTV_b when using the 3D specimen map for treatment planning, underscoring the dual potential to improve oncologic coverage while avoiding unnecessary radiation exposure. This study builds on our previous work using 3D scanning to enhance communication in a multidisciplinary setting and, for the first time, extends it to real-time radiation treatment planning decisions.[12]

Locoregional recurrence is strongly associated with poor overall survival in head and neck cancer, underscoring the importance of precise and comprehensive target coverage in the adjuvant setting.[19,20] Inadequate coverage due to imprecise delineation or excessive sparing can compromise outcomes, and unnecessary dose expansion

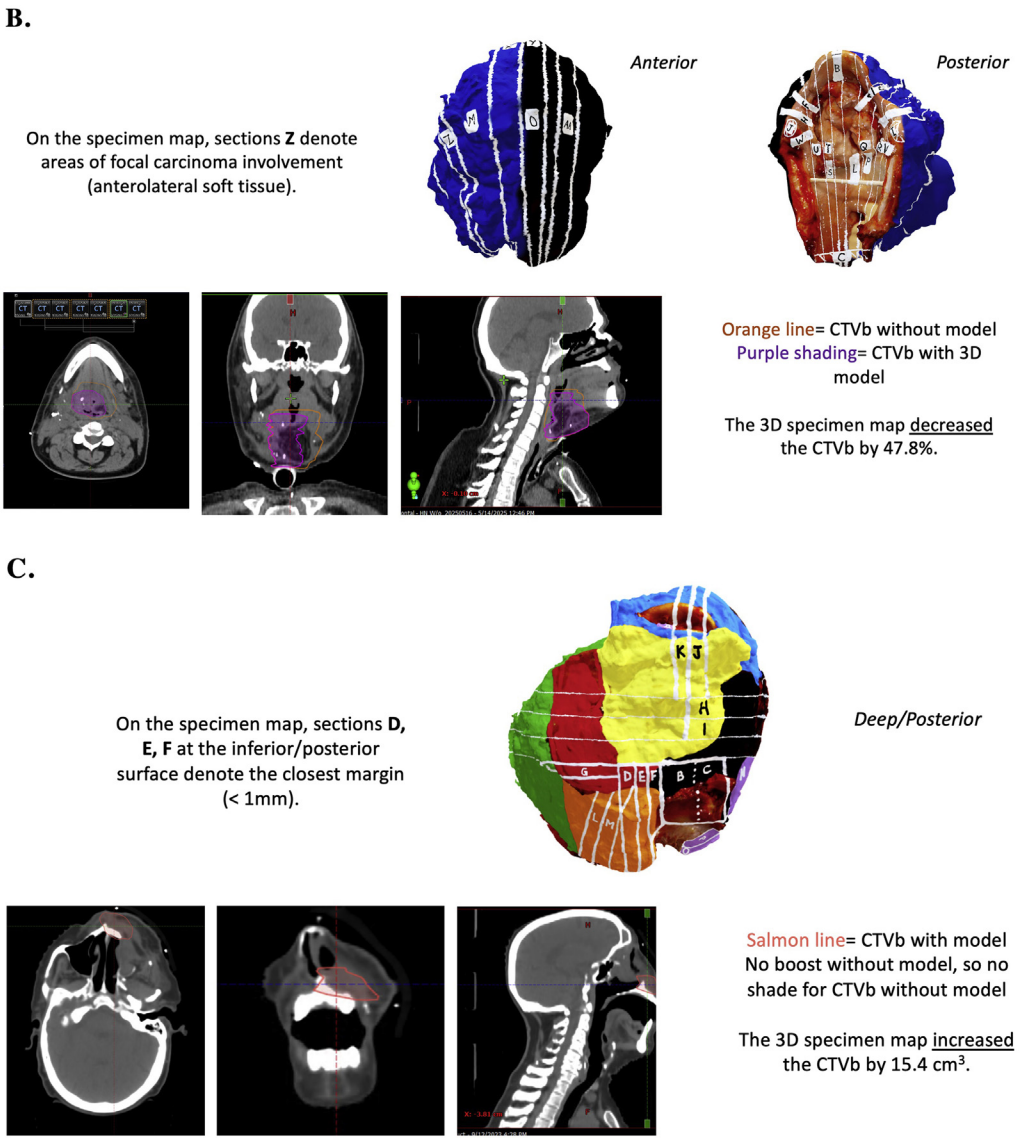

Figure 2 **Continued.**

increases morbidity. Therefore, radiation oncologists may prioritize comprehensive target coverage over small dosimetric trade-offs.[3,4] Even modest uncertainty about margin location may therefore drive radiation oncologists to err on the side of expanded CTVs to avoid undertreatment, particularly in cases with pathologic risk factors such as close/positive margins and bony invasion. While this approach may increase radiation dose to adjacent normal tissues, the potential morbidity from xerostomia, dysphagia, or fibrosis is typically considered acceptable when weighed against the morbidity and mortality of recurrent disease. This study reveals that 3D specimen maps may help reduce this uncertainty, thereby reducing the need for physicians to unnecessarily expand volumes. By more accurately contextualizing high-risk areas, these models may enable sparing of uninvolved structures while maintaining oncologic coverage.

Although no clinically significant changes in OAR dosimetry were observed, this study was not designed or powered to evaluate functional outcomes. Additionally, radiation therapy plans were optimized to maintain target coverage while minimizing doses to OARs. Importantly, advances in organ-preservation trials have shown that dysphagia, xerostomia, and speech remain critical endpoints, and interventions that improve the accuracy of radiation delivery may contribute meaningfully to reducing treatment-related morbidity.

This study has several limitations. The sample size was small and limited to a single institution, limiting generalizability and precluding subgroup analysis. The follow-up time was short, precluding assessment of long-term oncologic or functional outcomes. The workflow required additional time and resources for 3D scanning, processing, and printing, potentially limiting scalability in

Table 4 Radiation oncologists' subjective opinions

	Presurvey	Postsurvey	Preintervention survey responses, mean (SD)	Postintervention survey responses, mean (SD)	95% CI	*P* value
1	The surgery, pathology, and radiation oncology teams can easily communicate and understand tumor characteristics to support adequate postoperative radiation therapy planning.	The 3D specimen map helped improve communication among the surgeon, pathologist, and radiation oncologist for postoperative treatment planning.	74.6 (21.9)	82.3 (17.9)	−9.28 to 24.7	.343
2	The current tools used for radiation therapy treatment planning (ie, operative reports, pathology reports, verbal discussions with surgeons and pathologists, and pre- and postoperative imaging) help me understand the tumor size and characteristics.	The 3D specimen map helped me understand the tumor size and characteristics, as well as the current tools used for radiation therapy.	63.6 (24.6)	80.8 (18)	−2.3 to 36.6	.07
3	I feel confident in the treatment volumes created using the current tools for treatment planning.	I feel confident in the treatment volumes created using the 3D specimen map and current treatment planning tools.	64.5 (18.8)	84.9 (16.8)	3.12-37.8	**.02**
4	I can locate the site of a positive margin using the current tools for treatment planning.	The 3D specimen map improved my ability to locate the site of positive margins for postoperative radiation therapy treatment planning.	51.6 (23.5)	75.4 (20.7)	4.04-43.5	**.02**
	-	The specimen map was easy to use and manipulate.	-	93.9 (7.7)	-	-
	-	The 3D specimen map was a useful tool for creating a treatment plan.	-	76.1 (15)	-	-
	-	I would use the 3D specimen scan again during treatment planning.	-	90 (11.6)	-	-

Bold P values indicate $P < 0.05$.

resource-constrained settings. Scalability may be enhanced by selectively implementing the workflow in cases where margin localization is most clinically impactful (eg, positive margins) and by using digital models without routine 3D printing. Importantly, the protocol remains feasible and adaptable, with implementation at other institutions estimated to require approximately 30 minutes of additional hands-on time per case.[21] In

addition, treatment planning was performed by a small group of radiation oncologists familiar with the study protocol, which may introduce potential cognitive bias. Given the small sample size, this study was not powered to assess differences in contour modification by physician experience level. However, contour changes were observed across multiple physicians, suggesting the effect was not driven by a single individual. Finally, while the models altered target volumes in selected cases, the clinical significance of these changes remains uncertain without prospective correlation with toxicity or disease control in this patient cohort. If validated across larger, more diverse cohorts of other solid organ tumors, 3D specimen mapping may represent a scalable adjunct to postoperative target delineation, particularly in the setting of anatomically complex resections and pathologic risk factors.

Although only a small proportion of our cohort had positive margins or bony invasion (4 patients), the 3D specimen maps were found to be most clinically meaningful in these cases. Because CTV_b is focal and more explicitly driven by margin status, improving providers' understanding of margin localization can yield proportionally greater effects. Because CTV_p coverage is designed to account for the entire surgical bed and therefore encompasses a wider region, small differences in the precise location of a positive/close margin rarely shift the boundaries enough to substantially change CTV_p. Future trials will focus exclusively on patients with positive margins, and study designs may also involve registering the 3D model directly to the postoperative preradiation planning CT, allowing the treating radiation oncologist to visualize the 3D model on the 2D axial planning CT with greater anatomic accuracy. This integration would reduce reliance on cognitive fusion between ex vivo models and in vivo postresection anatomy. Surface-based or deformable registration techniques may facilitate further alignment of the specimen contour with the resection cavity, thereby improving spatial concordance. These studies will further refine the anatomic precision and clinical utility of 3D specimen maps within the adjuvant radiation planning workflow.

Conclusions

Patient-specific 3D specimen maps enable precise reconstruction of resected tumor volumes, which is especially valuable in the context of altered anatomy following surgical resection, reconstruction, and neck dissection. These maps, when integrated with preoperative imaging and operative reports, may help localize high-risk areas and guide postoperative target delineation when there is loss of native tissue planes and anatomic distortion.

Disclosures

None.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.adro.2026.102067.

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