Improved Delta Radiomic Fidelity with HyperSight CBCT Compared to Conventional CBCT in Pelvic Radiotherapy

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ABSTRACT

INTRODUCTION

Radiomics-based biomarkers are sensitive to acquisition and reconstruction variability, making cross-fraction consistency a prerequisite for reliable longitudinal modeling. In pelvic radiotherapy, CBCT radiomics can be confounded by dose-dependent coverage changes and image quality variations, complicating interpretation when features are used for adaptive decision support. HyperSight CBCT has been introduced to improve CBCT quality; however, its impact on preserving CT-derived radiomic characteristics during treatment requires quantitative validation.

PURPOSE

To test whether HyperSight CBCT (HS-CBCT) improves CT-consistency of longitudinal radiomics versus conventional CBCT in pelvic radiotherapy.

METHODS AND MATERIALS

Ten pelvic cancer patients with planning CT (pCT), HS-CBCT, and conventional CBCT were analyzed longitudinally. All CBCTs were rigidly registered to pCT and resampled to 1-mm isotropic resolution before radiomics extraction (PyRadiomics v3.0.1) in the CTV and femoral head. Radiomic features were computed in the clinical target volume (CTV) and femoral head using PyRadiomics (v3.0.1). In the CTV, CT-referenced normalized deviation (δ) was modeled versus per-fraction CTV D95 using feature-wise linear mixed-effects models with patient random intercepts and a modality×D95 interaction.

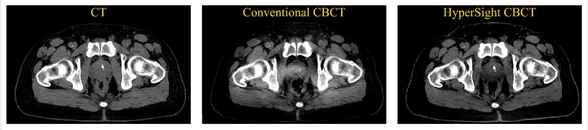

Figure 1. Representative pelvic axial slice comparison across modalities. Planning CT (left), conventional CBCT (middle), and HyperSight CBCT (right)

Let $f_{i,t,m,k}$ denote the value of feature k for patient i at fraction t for modality $m \in \{\text{CBCT}, \text{HS-CBCT}\}$and $f_{i,\text{CT},k}$ denote the patient-specific pCT reference value. To quantify modality-dependent deviation from CT-like radiomics in the CTV while accounting for per-fraction dosimetric variation, a CT-referenced normalized deviation (delta) was defined as $\Delta f_{i,t,m,k} = (f_{i,t,m,k} - f_{i,\text{CT},k})/(|f_{i,\text{CT},k}| + \varepsilon)$, where ε is a small constant for numerical stability. For each feature k, the relationship between Δf_(i,t,m,k)and CTV coverage was modeled using a linear mixed-effects model with patient-specific random intercepts:

$$\boldsymbol{\Delta f_{i,t,m,k} = \beta_{0k} + \beta_{1k}\widehat{D95}_{i,t,m} + \beta_{2k}\mathbb{I}(m = \text{HS-CBCT}) + \beta_{3k}\widehat{D95}_{i,t,m}\mathbb{I}(m = \text{HS-CBCT}) + b_{ik} + e_{i,t,m,k}} \quad \textbf{(1)}$$

where $D95_{i,t,m}$ is the per-fraction dosimetric coverage metric, $\widehat{D95}$ denotes its standardized form to stabilize estimation, $\mathbb{I}(\cdot)$ is an indicator function, $b_{ik} \sim \mathcal{N}(0, \sigma^2_{b,k})$ captures between-patient heterogeneity, and $e_{i,t,m,k} \sim \mathcal{N}(0, \sigma^2_{e,k})$ is the residual error. In this specification, β_{1k}represents the dose-delta association for conventional CBCT and β_{3k} tests whether

HyperSight CBCT modifies the dose dependence of radiomic deviation relative to CT; multiple-comparison control was applied across features using false discovery rate adjustment within each modeled term.

Longitudinal stability was evaluated in the femoral head as a comparatively dose-insensitive reference region while accommodating unequal numbers of available fractions. For each patient and modality, the first available fraction was treated as the within-modality baseline (t=0), and treatment progress was normalized as $p_{i,t,m} = t/\max_t t \in [0,1]$ to support aggregation across heterogeneous fraction counts. To summarize multifeature temporal change as a single stability metric, features were standardized within modality as

$$\boldsymbol{z_{i,t,m,k} = (f_{i,t,m,k} - \mu_{m,k})/\sigma_{m,k}}, \quad \textbf{(2)}$$

where $\mu_{m,k}$and $\sigma_{m,k}$were computed over all samples for modality m. "Texture drift" at fraction $t$was then defined as the Euclidean distance from the baseline point in standardized feature space,

$$\boldsymbol{d_{i,t,m} = \| z_{i,t,m} - z_{i,0,m} \|_2 = \sqrt{\sum_k (z_{i,t,m,k} - z_{i,0,m,k})^2}}, \quad \textbf{(3)}$$

and drift trajectories were summarized across patients using median and interquartile ranges as functions of fraction (or normalized progress). When inferential comparison of drift patterns was required, a mixed-effects model with a smooth function of progress and patient random intercepts was used to compare modality-specific longitudinal trends:

$$\boldsymbol{d_{i,t,m} = s(p_{i,t,m}) + \gamma\,\mathbb{I}(m = \text{HS-CBCT}) + s_\Delta(p_{i,t,m})\,\mathbb{I}(m = \text{HS-CBCT}) + u_i + \eta_{i,t,m}}, \quad \textbf{(4)}$$

where $s(\cdot)$denotes the baseline drift trajectory, $s_\Delta(\cdot)$captures the modality-specific deviation in trajectory, $u_i \sim \mathcal{N}(0, \sigma_u^2)$, and $\eta_{i,t,m}$is residual noise

RESULTS & DISCUSSION

Conventional CBCT showed stronger dose-associated drift in the CTV (steeper δ-D95 trends and greater dispersion), whereas HS-CBCT showed smaller dose dependence. Across 93 CTV features, 39/93 showed a significant modality×D95 interaction after FDR correction (q<0.05), and HS-CBCT reduced the absolute δ-D95 slope for 38/39 (median |slope| 0.247→0.059 per 1 SD D95; 76% reduction). Representative slopes (CBCT→HS) included first-order interquartile range 0.989→0.278 ($q=8.6\times10^{-5}$), uniformity -0.247→-0.097 ($q=6\times10^{-5}$), and GLCM IDMN -0.100→-0.012 ($q=1.1\times10^{-6}$).

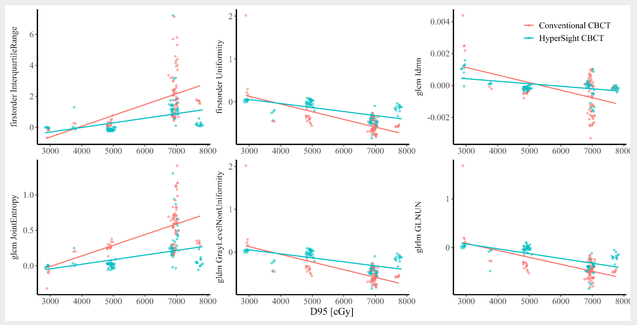

Figure 2. Dose-conditioned CT-referenced delta radiomics in the CTV. Scatter plots show CT-referenced normalized deviation (Δf) vs. per-fraction CTV D95 (cGy) for representative radiomic features. Points correspond to individual fractions across patients; solid lines denote linear trend fits for conventional CBCT and HyperSight CBCT.

Based on Figure2, HyperSight CBCT demonstrates reduced dose-conditioning (smaller slope magnitude) and decreased dispersion compared with conventional CBCT, indicating improved preservation of CT-like radiomic behavior in the target region.

In the femoral head, among patients with ≥2 fractions in both modalities (n=8), end-of-treatment drift was 3.61 (IQR 3.02-4.19) for HS-CBCT vs 7.98 (3.01-9.94) for CBCT (55% lower). Integrated drift over normalized progress (AUC) was also reduced: 1.50 (1.11-1.92) vs 2.85 (2.05-6.21); one-sided paired Wilcoxon p=0.027. This analysis further supports improved radiomic stability for HyperSight CBCT.

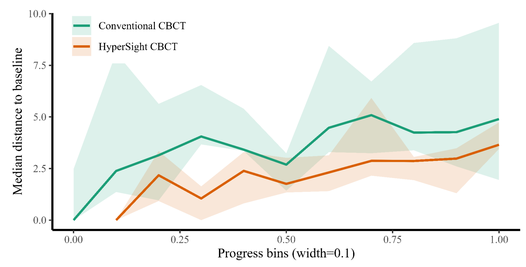

Figure 3. Longitudinal radiomic stability in the femoral head quantified by texture drift. The median Euclidean distance-to-baseline in standardized radiomic feature space is plotted versus normalized treatment progress (bin width = 0.1) for conventional CBCT and HyperSight CBCT; shaded regions represent interquartile ranges across patients. HyperSight CBCT exhibits consistently lower drift and narrower variability across treatment progress, supporting improved longitudinal radiomic consistency in a dose-insensitive bony reference region.

Because the femoral head is comparatively dose-insensitive, this provides complementary evidence that improved fidelity with HyperSight is not solely attributable to target-dose effects but reflects enhanced longitudinal consistency of the image-derived radiomic signature.

CONCLUSIONS

HS-CBCT provides more CT-consistent, dose-robust radiomics than conventional CBCT in pelvic radiotherapy, supporting its use for adaptive workflows and longitudinal radiomics studies.

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