Quantifying Undetected Dosimetric Deviations in Multi-Fraction Interstitial HDR Brachytherapy Without Adaptive Replanning: A Retrospective Analysis

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EXECUTIVE SUMMARY

Study Objective: To quantify the physical magnitude of interfraction catheter displacement in multi-fraction interstitial high-dose-rate (HDR) brachytherapy and evaluate its biological dosimetric consequences on target coverage and organs-at-risk (OARs).

The Problem: In many multi-fraction regimens, adaptive replanning is not routinely performed. Catheter movement between fractions can lead to clinically significant underdosages to the tumor or overdosages to surrounding healthy tissues.

Key Findings

Physical Catheter Movement: Catheters shifted by a mean of 1.69 ± 0.26 mm across all cases, but maximum deviations reached up to 11.03 mm (mean maximum: 4.87 ± 2.35 mm).

Systematic Directional Trends: Catheter movement is not entirely random. The largest shifts occurred in the superior-inferior direction (mean retraction ΔZ of -0.74 ± 0.22 mm) and tended to occur in the posterior sector of the implant geometry.

Target Underdosage: Due to displacement, the high-risk clinical target volume (HR-CTV D90) decreased by an average of 0.18 ± 0.77 Gy (EQD2), with similar downward trends for the GTV and IR-CTV.

OAR Dose Escalation: The worst-affected OAR per case saw a biologically equivalent dose increase of 2.63 ± 1.22 Gy (EQD2)
. Specifically, the rectum was the most vulnerable structure, experiencing a mean dose increase of 2.18 ± 1.38 Gy (EQD2).

The Rectal Gas Effect: In the inpatient setting, gas build-up in the rectum systematically displaces the anatomy. This results in an increased rectal dose, but conversely causes a clinically meaningful dose reduction to the sigmoid (mean decrease of 1.21 ± 1.87 Gy EQD2) as it is pushed further away

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INTRODUCTION

Interfraction catheter displacement in multi-fraction high-dose-rate (HDR) brachytherapy is a recognized concern, yet its dosimetric impact when adaptive replanning is generally not performed and remains poorly quantified. This study evaluates the magnitude of catheter deviations between fractions and their consequences on target coverage and organ-at-risk (OAR) doses using biologically equivalent dose (EQD2) metrics.

METHODS AND MATERIALS

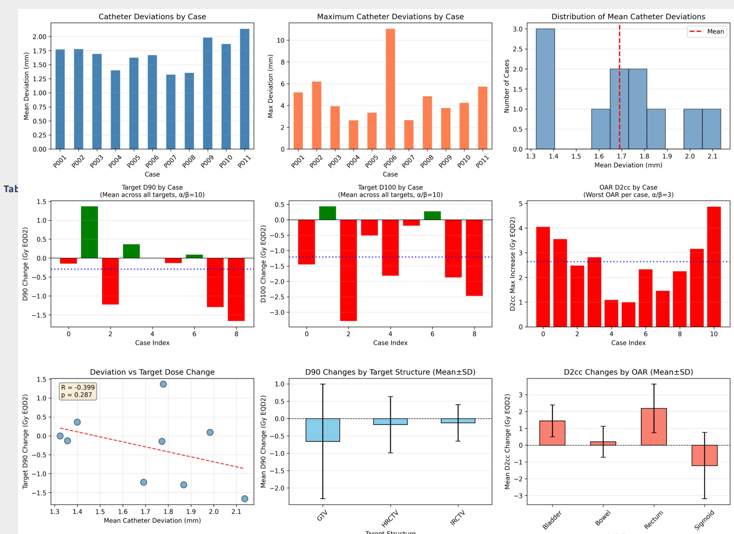
Eleven interstitial HDR brachytherapy cervical cancer patients (median 10 catheters/case, range = 7-20) treated with multi-fraction regimens were retrospectively analyzed. For each case, CT imaging from the initial fraction (Fx1) and subsequent fraction (Fx2) were registered using rigid alignment. Original Fx1 catheter positions were digitally reconstructed on Fx2 anatomy to represent the "undetected" scenario (no adaptive replanning). Actual Fx2 catheter positions were independently digitized to quantify displacement. Three-dimensional catheter deviations were calculated for each channel, including overall magnitude, directional components (ΔX, ΔY, ΔZ), and angular distribution relative to patient anatomy. All structures were contoured on the Fx2-CT images. Dose distributions were recalculated using identical dwell times and a TG-43 calculation engine for both scenarios. Target structures (HR-CTV, IR-CTV, GTV) and OARs (bladder, rectum, sigmoid, bowel) were analyzed using D90, D100 (targets) and D2cc (OARs), with all doses converted to EQD2 (α/β=10 for targets, α/β=3 for OARs) to account for fractionation effects.

CONCLUSIONS

Interfraction catheter displacement without adaptive replanning leads to substantial, often undetected dosimetric deviations in multi-fraction interstitial HDR brachytherapy. When expressed in EQD2, target underdosage and OAR overdosage may reach clinically significant thresholds. In the in-patient setting, gas often builds-up in the rectum, generally increasing rectal dose and perhaps, unintuitively, seems to decrease the dose to the sigmoid from resultant displacement by rectal gas. Directional patterns suggest anatomical factors may contribute to systematic displacement. These findings underscore the critical need for adaptive replanning workflows in brachytherapy where inpatient workflow is necessary.

RESULTS

Mean catheter displacement across all cases was 1.69 ± 0.26 mm (range: 1.32-2.14 mm), with maximum deviations of 4.87 ± 2.35 mm (range: 2.64-11.03 mm). Directional analysis revealed systematic shifts: ΔX (lateral) = 0.03 ± 0.33 mm, ΔY (anterior-posterior) = 0.10 ± 0.56 mm, ΔZ (superior-inferior) = -0.74 ± 0.22 mm. Angular distribution analysis demonstrated the largest deviations tend to occur in the posterior sector of the implant geometry. HRCTV CTV D90 decreased by 0.18 ± 0.77 Gy (EQD2) on average, with similar trends for the GTV and IRCTV. OAR D2cc increased by 2.63 ± 1.22 Gy (EQD2) for the worst-affected OAR per case. Correlation analysis revealed moderate association between catheter displacement magnitude and target D90 deterioration (Pearson R = -0.399, p = 0.287). Structure-specific analysis identified the rectum as most vulnerable to dose escalation, with mean D2cc increase of 2.18 ± 1.38 Gy (EQD2). Conversely, the sigmoid experience a clinically meaningful dose reduction, with mean D2cc decrease of 1.21 ± 1.87 Gy (EQD2).



Cohort Catheter Displacement Analysis