



Assessing Stereotactic Body Proton Therapy Treatment Plan Robustness for Right-Sided Liver Lesions

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I. Introduction

Stereotactic body radiation therapy (SBRT) has become an increasingly important treatment option for primary and metastatic liver malignancies because of its excellent local control and favorable toxicity profile. Despite these advantages, as the liver is a relatively radiosensitive organ, treatment-related toxicities have been associated with the volume of uninvolved liver receiving low and intermediate radiation doses, with metrics such as liver V_{15Gy} and V_{30Gy} being important treatment planning objectives when attempting to maximize the therapeutic ratio of a given treatment. Towards minimizing these low doses to the liver, proton therapy can be an attractive option, as in this setting the finite range of the proton Bragg peak can dramatically reduce the low-dose bath delivered to healthy liver, particularly in tissues distal to the target.

However, proton therapy introduces additional uncertainties arising from setup variation and uncertainty in proton range estimation, and in the context of treatment planning, this often requires us to irradiate effectively larger treatment volumes to ensure robust target coverage. Thus, in the context of stereotactic body proton therapy (SBPT), where highly conformal plans with tight margins are highly desirable due to the large doses per fraction used, it is not obvious *a priori* whether the additional margins required to robustly cover the target will negate the intrinsic normal tissue sparing afforded by the protons. Thus, the objective of this study was to evaluate the dosimetric performance and robustness of multiple proton beam arrangements for treatment of right-sided liver lesions to identify proton SBPT planning strategies for the liver.

II. Methods

Patients with right-sided liver lesions previously treated with breath-hold photon SBRT and CT-on-Rails image guidance (Figure 7), providing a unique opportunity to evaluate the performance of proton plans on actual daily anatomical changes. Future work will retrospectively accumulate proton dose across daily CT alignment images to determine whether currently used robustness criteria adequately account for observed anatomical variations. These analyses will ultimately support the development of evidence-based liver SBPT planning guidelines and identify scenarios where adaptive proton therapy may be required.

Robustness evaluation was performed by incorporating ± 2 mm setup and $\pm 3.5\%$ range uncertainty. Dose distributions were recalculated for all uncertainty scenarios and both target coverage and organ-at-risk metrics were reanalyzed. Comparisons between proton and photon plans were performed using PTV50 coverage, GTV60 coverage, liver mean dose, liver V_{15Gy} and V_{30Gy} , and chest wall D_{30cc} . Nominal and worst-case robustness scenarios were evaluated for all patients.

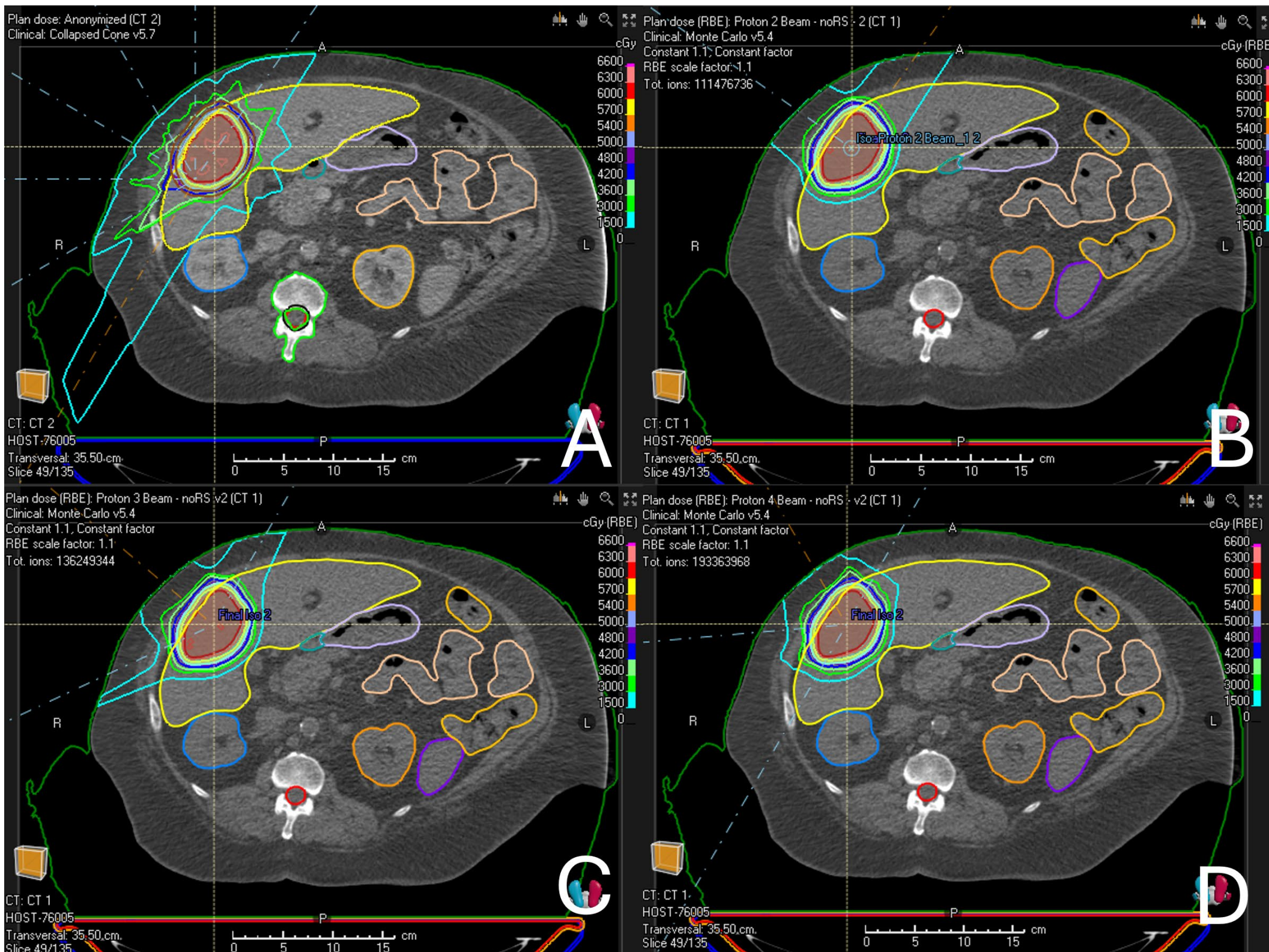


Figure 1. Representative treatment plans generated for a right-sided liver lesion. (A) Clinical photon SBRT plan. (B) Two-beam proton plan. (C) Three-beam proton plan. (D) Four-beam proton plan.

III. Results: Target Coverage

Across all proton beam arrangements, clinically acceptable target coverage was achieved while maintaining plan robustness (Figure 2).

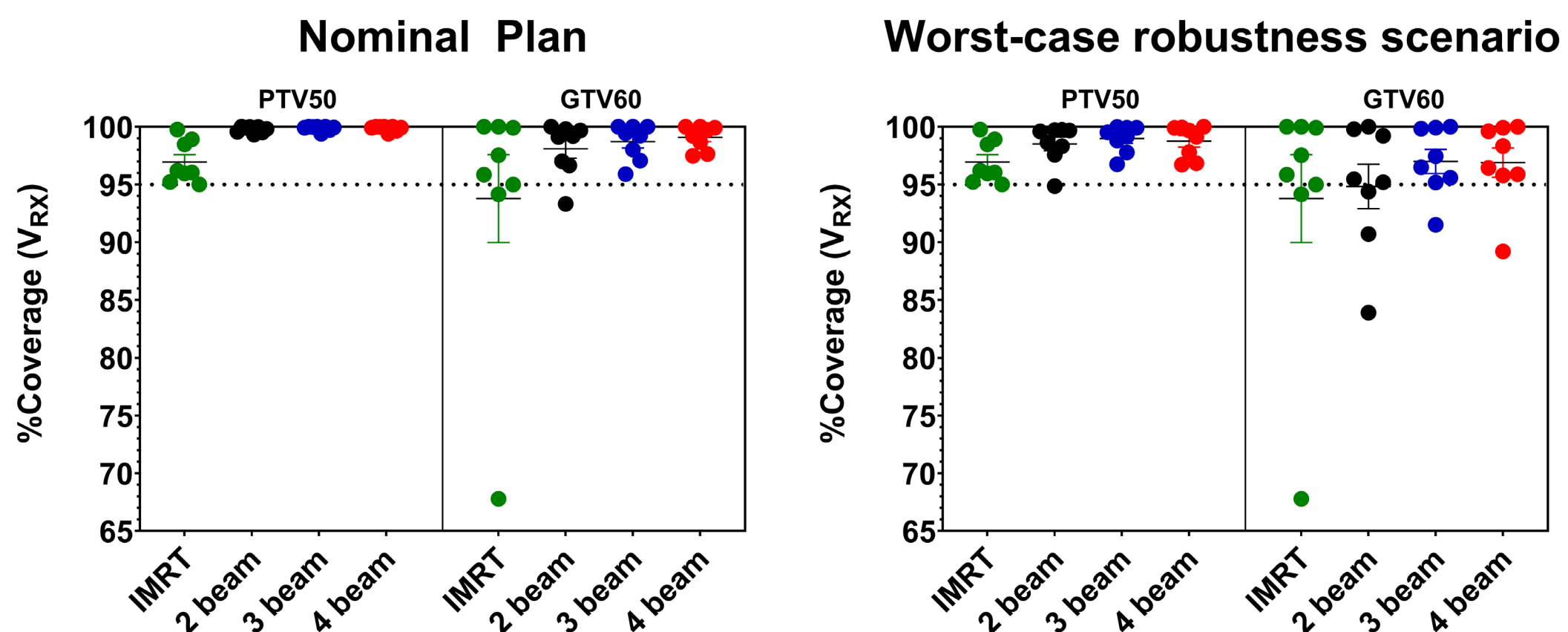


Figure 2. Target coverage achieved by photon and proton plans. All proton beam arrangements maintained clinically acceptable target coverage for both PTV50 and GTV60 objectives despite setup and range uncertainties.

Relative to the photon plans, the proton plans generally improved PTV50 coverage while producing comparable or modestly improved GTV60 coverage. These trends held even under the worst-case robustness scenarios, demonstrating that robust SBPT plans can be generated for right-sided liver lesions without sacrificing target coverage (Figure 3).

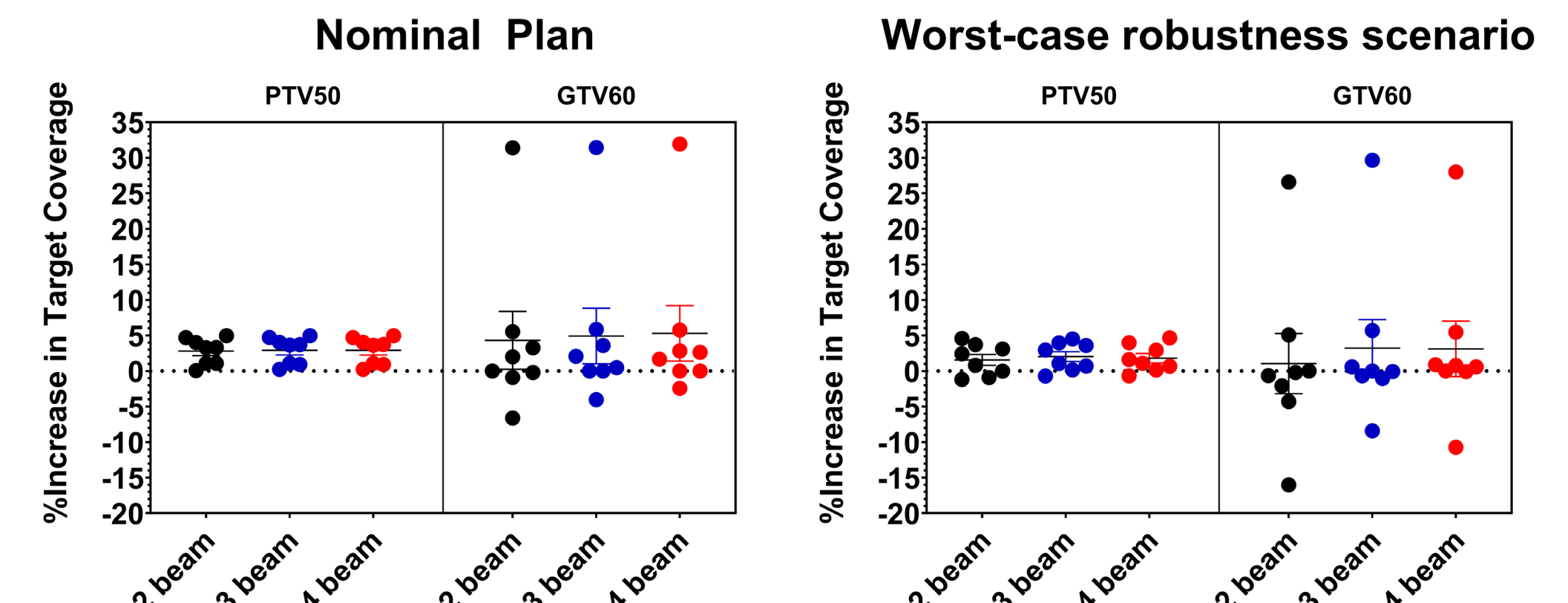


Figure 3. Relative change in target coverage compared with photon SBRT. Proton beam arrangements improved PTV50 coverage by approximately 2–3% while generally maintaining or improving GTV60 coverage. Similar trends persisted in worst-case robustness scenarios.

IV. Results: Liver Sparing

Substantial reductions in liver dose were observed for all proton beam arrangements. Mean liver dose and liver V_{15Gy} were consistently reduced relative to photon plans, while liver V_{30Gy} generally remained comparable between modalities (Figures 4 and 5, Table 1). These benefits persisted across worst-case robustness scenarios suggesting that the dosimetric benefits of proton therapy remain clinically meaningful despite potential treatment delivery uncertainties.

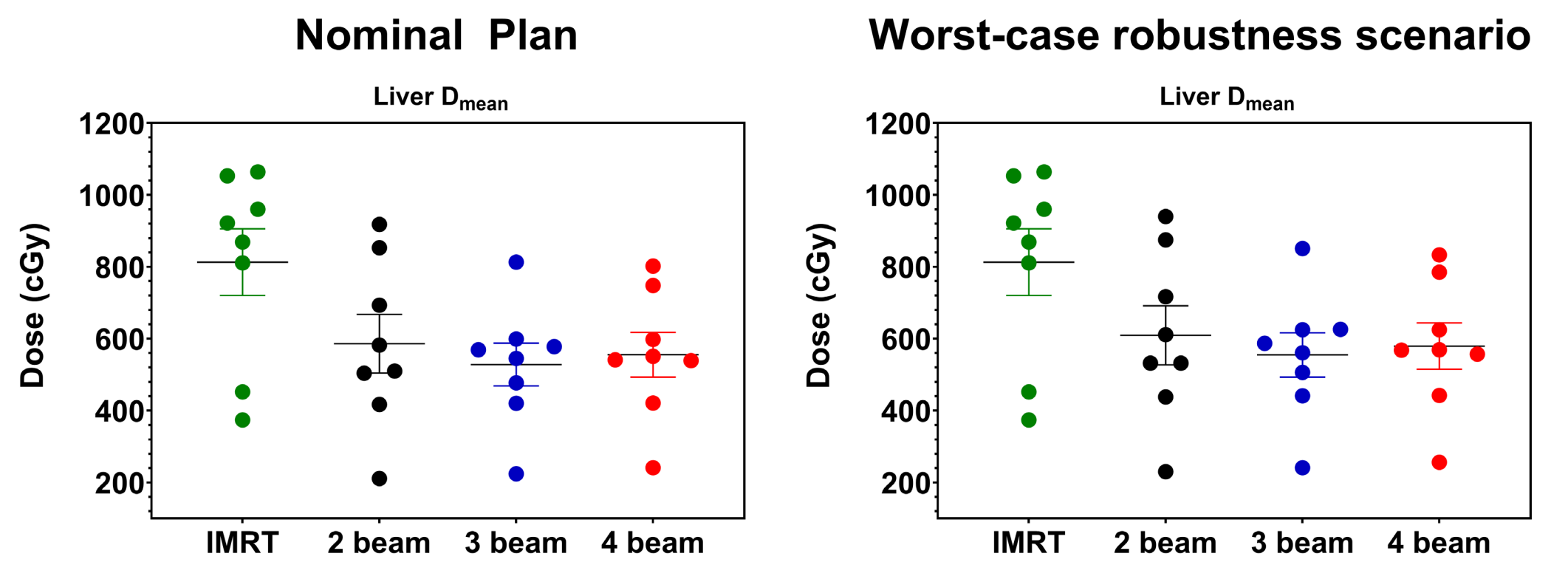


Figure 4. Mean dose to uninvolved liver. All proton beam configurations generally reduced liver mean dose relative to photon IMRT, with greater reductions seen for three- and four-beam arrangements.

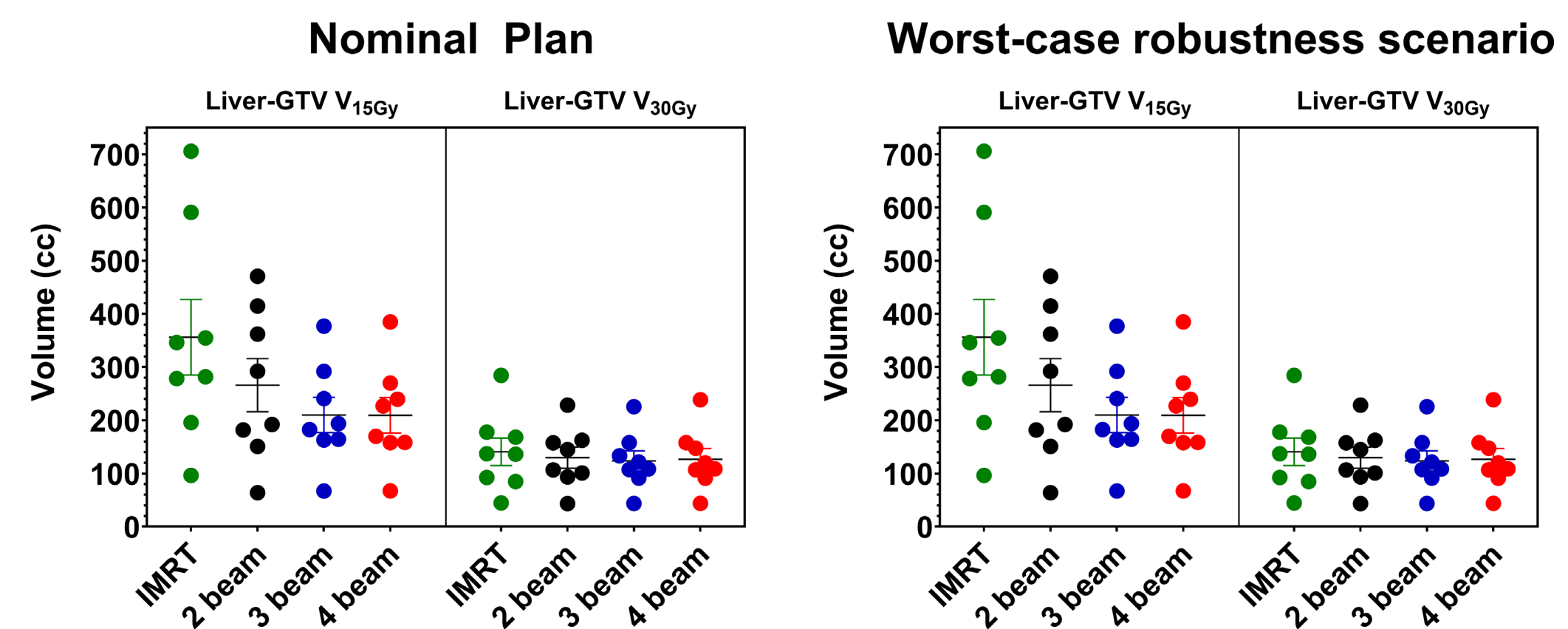


Figure 5. Liver V_{15Gy} and V_{30Gy} dose metrics. Substantial reductions in liver V_{15Gy} were observed for all proton beam arrangements, while liver V_{30Gy} generally remained comparable between modalities. The largest reductions were achieved using three- and four-beam proton plans

V. Results: Chestwall Sparing

Beam arrangement had the strongest impact on chest wall sparing. Two-beam plans generally produced chest wall doses similar to photon SBRT, whereas three-beam and four-beam plans reduced chest wall D_{30cc} by approximately 18% and 25%, respectively (Figure 6, Table 1). The three-beam arrangement consistently provided a favorable balance among robustness, plan quality, and plan complexity.

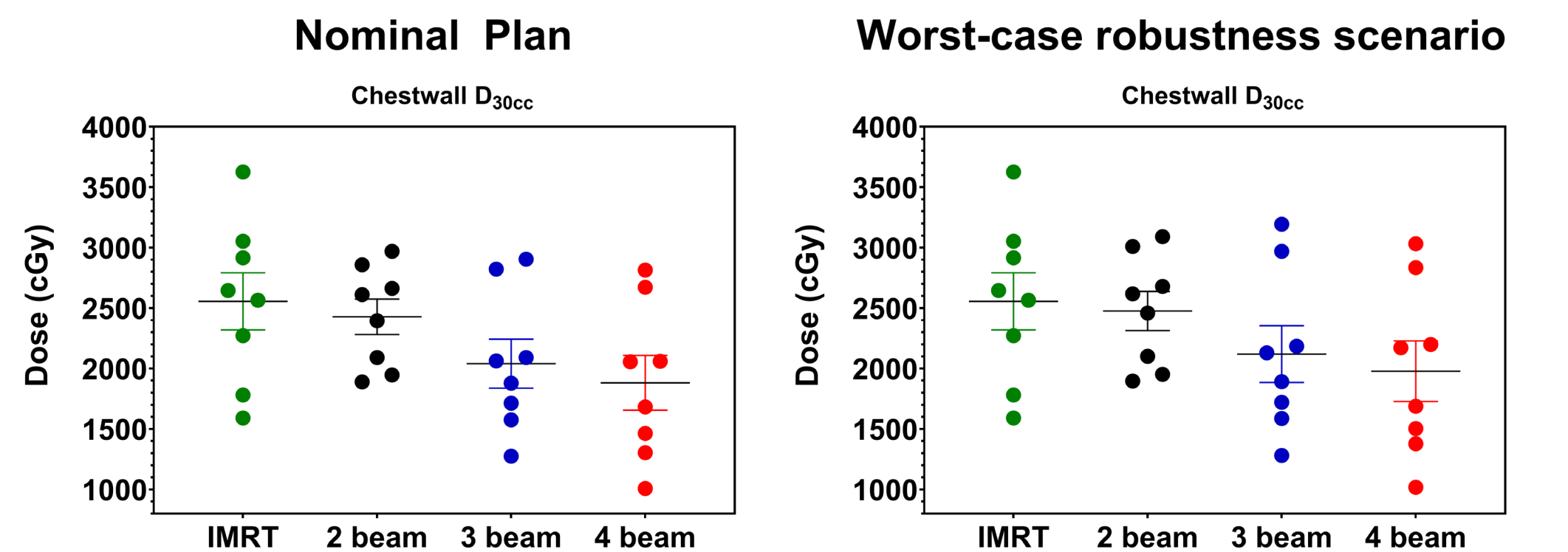


Figure 6. Chest wall D_{30cc} comparison. Two-beam proton plans produced chest wall doses comparable to photon IMRT. Three-beam and four-beam configurations substantially reduced chest wall D_{30cc} , with four-beam plans generally achieving the greatest sparing.

VI. Conclusions

Relative to photon SBRT, proton therapy consistently reduced mean liver dose and liver V_{15Gy} while maintaining robust target coverage. While all proton beam arrangements could meet clinical planning objectives for right-sided liver lesions, three- and four-beam arrangements provided the greatest chest wall sparing, with the three-beam approach offering the best overall balance among robustness, plan complexity, ease of optimization, and organ-at-risk sparing (Table 1). These findings support the clinical feasibility of SBPT for appropriately selected liver patients and provide a framework for future implementation of liver proton stereotactic body radiotherapy.

Table 1. Changes in target coverage and organ-at-risk metrics relative to clinical photon SBRT plans. Values represent mean percentage differences under nominal and worst-case robustness scenarios. Positive values indicate improved target coverage, while negative values indicate reduced normal tissue dose.

Nominal Plan						
Metric	PTV50 %Coverage (V _{Rx})	GTV60 %Coverage (V _{Rx})	Liver-GTV D _{mean}	Liver-GTV V _{15Gy}	Liver-GTV V _{30Gy}	Chestwall D _{30cc}
Plan						
2-beam	2.8±0.7%	4.3±4.1%	-28.4±4.9%	-24.2±6.1%	-4.6±5.5%	-1.5±4.9%
3-beam	2.9±0.7%	4.9±3.9%	-33.7±4.5%	-36.4±5.3%	-9.8±6.4%	-17.6±3.4%
4-beam	2.9±0.7%	5.3±3.9%	-30.6±4.0%	-36.8±4.9%	-7.9±7.0%	-24.8±4.6%

Worst Case Scenario						
Plan						
2-beam	1.6±0.8%	1.1±4.2%	-25.2±4.8%	-20.6±6.1%	1.5±5.5%	-0.7±4.8%
3-beam	2.0±0.7%	3.2±4.0%	-30.3±4.7%	-32.1±5.6%	-2.4±6.6%	-17.5±3.0%
4-beam	1.8±0.7%	3.1±3.9%	-27.4±4.3%	-32.3±5.2%	-0.4±7.3%	-24.0±3.9%

VII. Future Work

All patients in this study were originally treated using CT-on-Rails image guidance (Figure 7), providing a unique opportunity to evaluate the performance of proton plans on actual daily anatomical changes. Future work will retrospectively accumulate proton dose across daily CT alignment images to determine whether currently used robustness criteria adequately account for observed anatomical variations. These analyses will ultimately support the development of evidence-based liver SBPT planning guidelines and identify scenarios where adaptive proton therapy may be required.

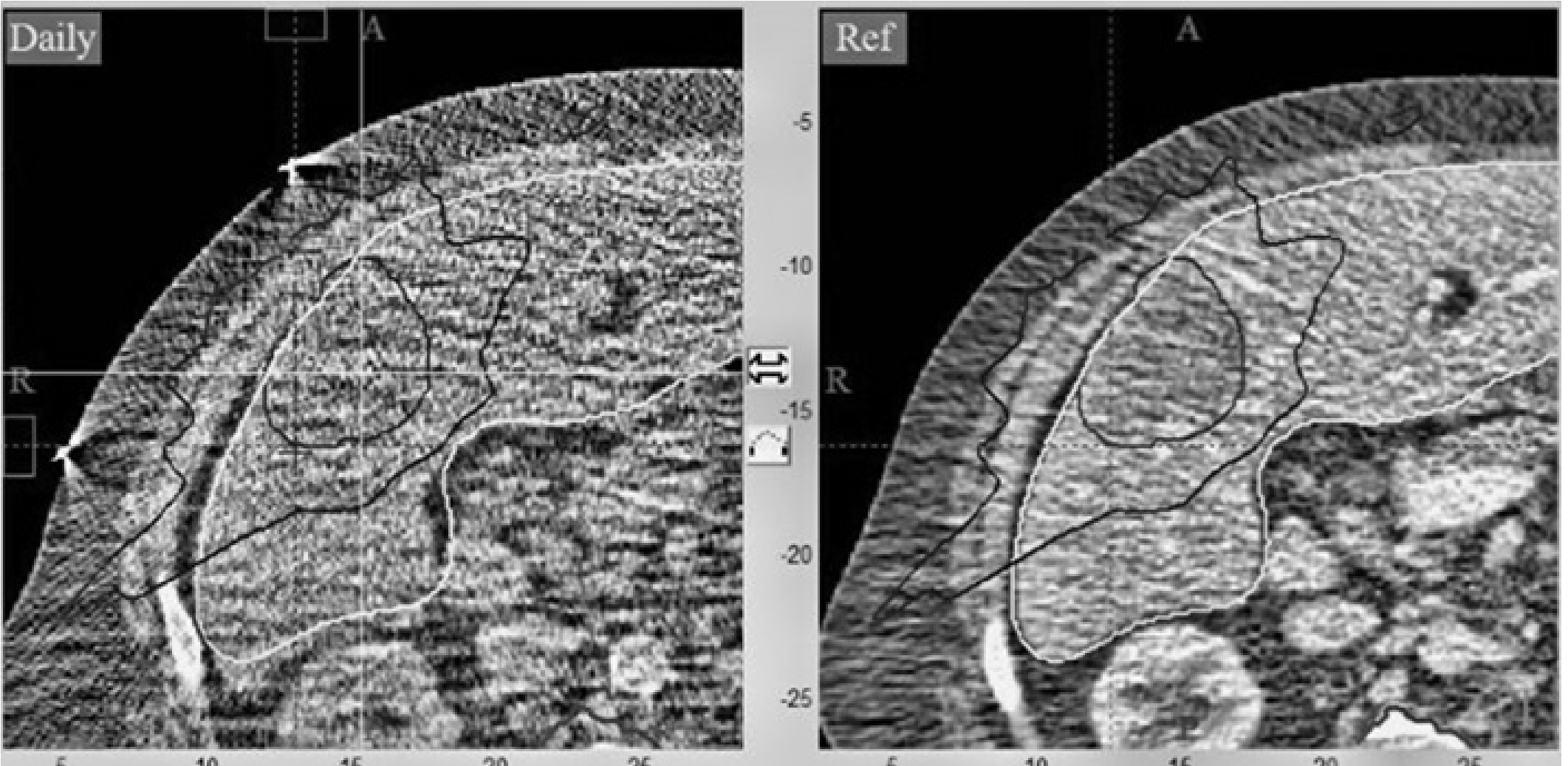


Figure 7. Example CT-on-Rails daily alignment image. Future studies will use daily CT datasets to evaluate accumulated delivered dose and determine whether current robustness assumptions adequately reflect observed anatomical variation.

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