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Dosimetric Impact of MLC Backlash on CSRS and SBRT Treatment Plans

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INTRODUCTION

Numerous planning studies have shown inaccurate MLC positioning to be clinically significant, as summarized in Barnes 2025 [1]. These studies typically simulate simple stylized errors not representative of real-world MLC failure modes.

MLC backlash, whereby MLC components in the drive train wear causing mechanical play, is a real-world failure mode that causes MLC positional error [2, 3]. See Figure 1.

MLC positional error due to backlash has been characterized [2] for VMAT delivery and is theoretically dependent on both direction of motion (push vs pull) and gravity (gantry angle). The linac does not interlock at magnitudes approaching recommended [4] tolerances.

This study primarily aims to theoretically assess the dosimetric impact of MLC backlash on Cranial Stereotactic Radiosurgery (CSRS) and Spine Stereotactic Body Radiotherapy (SBRT) treatment plans at both realistic and worse-case magnitudes.

Secondarily, dependencies for which backlash induced errors have increased clinical significance are investigated.

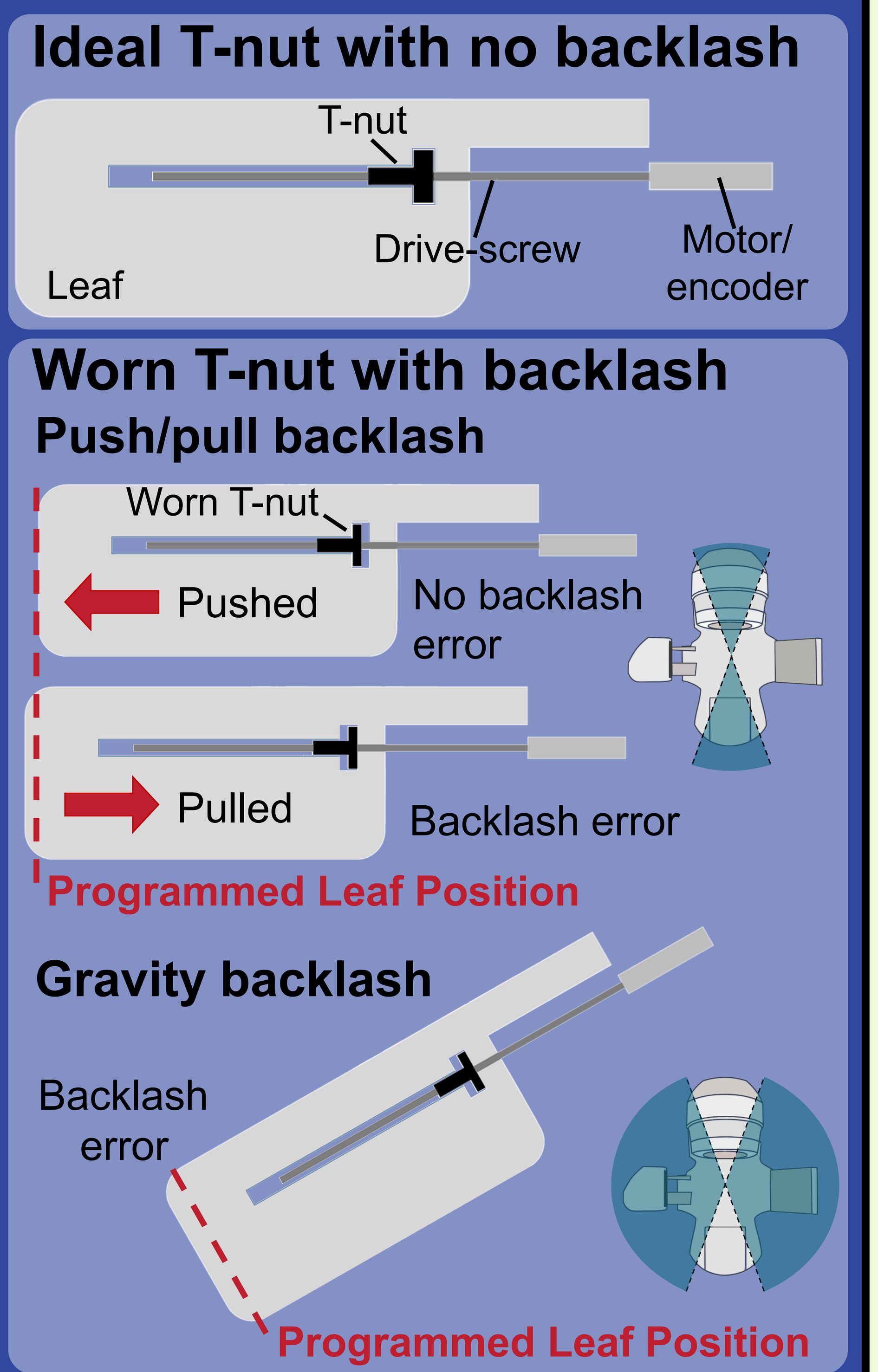

Figure 1: MLC leaf depicting a worn MLC T-nut resulting in two forms of backlash induced positional error.

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METHODS AND MATERIALS

MLC backlash was introduced into clinical treatment plans by editing leaf positions at each control point using an Eclipse (Varian Medical Systems, Palo Alto, CA, USA) ESAPI script. Backlash error comprised of push-pull and gravity dependencies, as experimentally characterized [2] and depicted in Figure 1. Gravity backlash is assumed for ±20° away from vertical for no collimator rotation, and with the equivalent gravity vector in the direction of leaf travel otherwise, push/pull backlash was modelled.

45 CSRS and 30 Spine SBRT plans sourced from two clinics (Clinical Plans) were recalculated without and with simulated backlash across all leaves. Changes to dosimetric metrics were compared.

Additionally, multi-lesion CSRS was also assessed with plans using spherical targets of varying size and off-axis distance for the purpose of isolating variables (Test Plans). Two magnitudes of backlash error were investigated for all plans:

- 0.3 mm, representing standardly encountered backlash [2]
- 0.5 mm, a realistic worse case-scenario.

Results are presented for the change in target coverage (PTV D100%) and for OAR near-maximum doses (D0.1cc) relative to the prescription dose.

Spearman's rank correlation coefficient was used to assess correlation between changes in target coverage and the following parameters/variables:

- PTV volume size
- PTV margin size
- Lesion number
- Lesion off-axis distance
- Complexity metrics
- Clinic

RESULTS

Figure 2 indicates that as PTV volume decreases PTV coverage reduces due to MLC backlash for CSRS plans. PTV D100 changes for lesions <1 cc averaged -3.0% and -5.3% for clinical plans with 0.3 mm and 0.5 mm simulated backlash, respectively. The dosimetric impact increases with backlash magnitude. Volume dependence is not observed for Spine SBRT cases, which typically feature larger target volume. (results not presented)

Figure 3 indicates that the CSRS volume dependence is clinic dependent with a strong, statistically significant ($p<0.05$) correlation observed for clinic 1, but weak and insignificant correlation is observed for clinic 2.

Figure 4 indicates that OAR doses are universally reduced, but to varying magnitude by MLC backlash.

Table 1 shows statistically significant correlation between the impact of MLC backlash on PTV coverage and the meanMLC gap and Tongue-and-Groove index (TGi) metrics as described by Vieillevigne et al [5] for CSRS for both the test plans and clinical plans from clinic 1, but not for clinic 2. Clinic dependency was reversed for SBRT-Spine. Correlation was not observed with lesion number, lesion off-axis distance nor the following complexity metrics: GSmodulation, MCS, MI, MLCspeedModulation, PI, PM, Rrmodulation, mean GS, mean MLCspeed, mean RR.

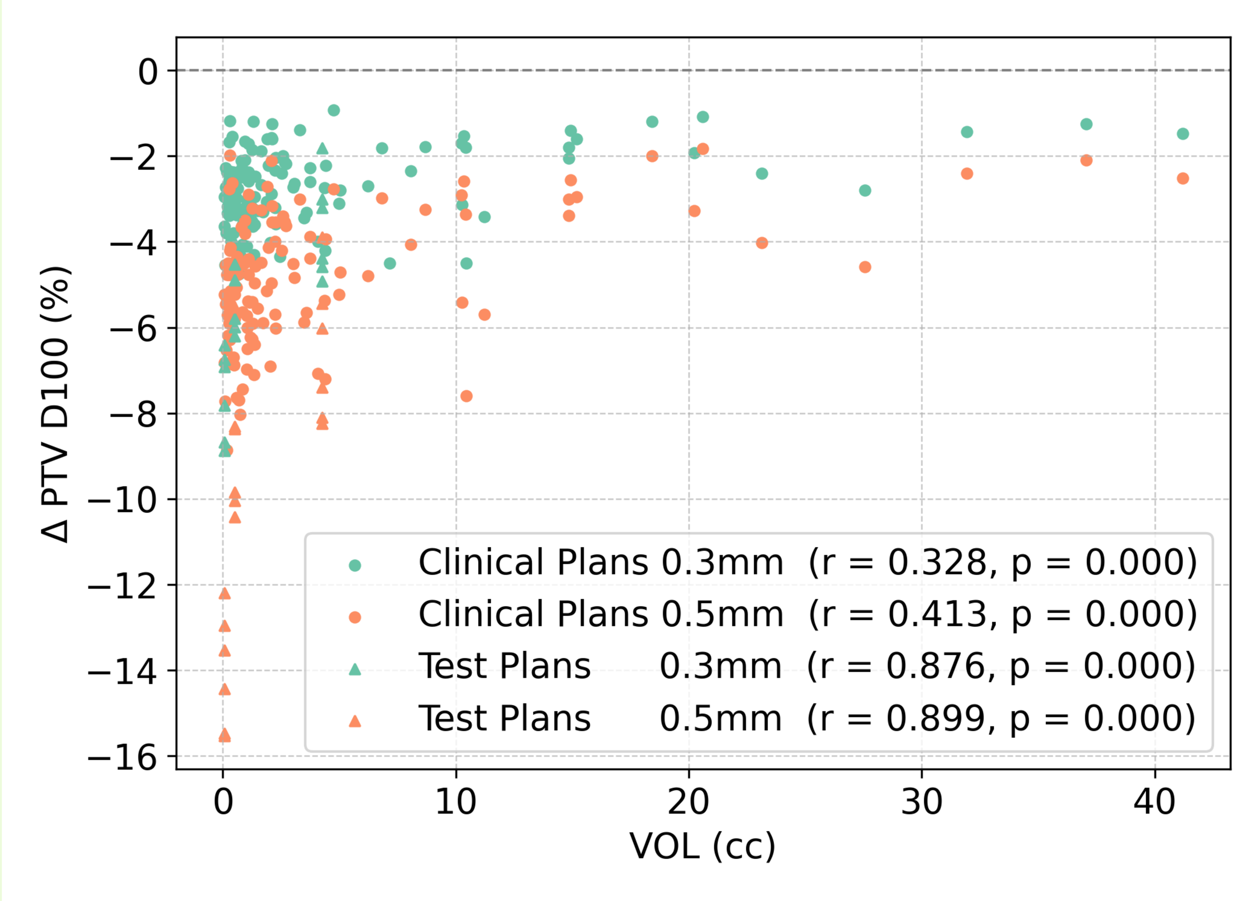

Figure 2: Change in PTV D100% coverage (relative to prescription dose) with lesion volume for CSRS at two magnitudes of backlash (0.3 mm and 0.5 mm)

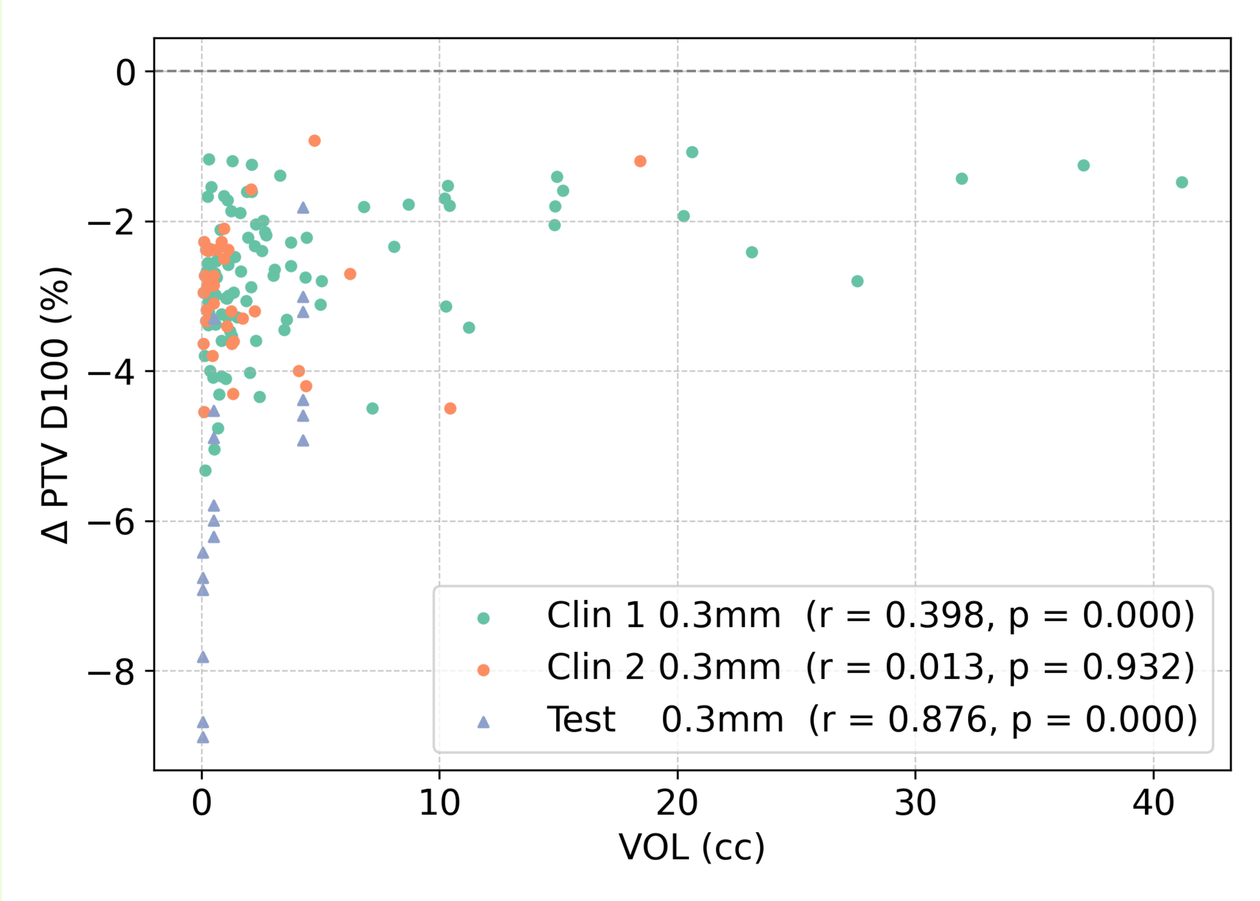

Figure 3: Change in PTV D100% coverage (relative to prescription dose) across two clinics for CSRS at 0.3 mm backlash.

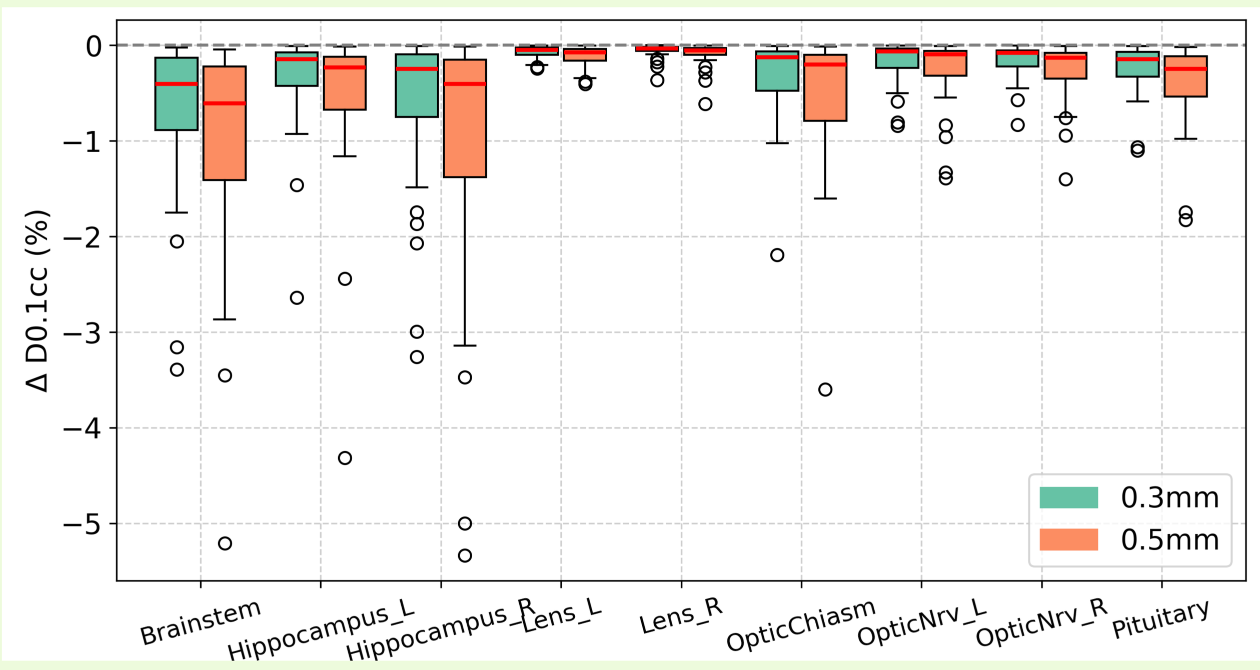

Figure 4: Change in OAR near-max doses at 0.3 mm backlash.

Table 1: Correlation of impact of backlash on PTV D100 coverage for CSRS plans with the mean MLC gap and TGi plan complexity metrics [5]. Green = p-value < 0.05.

Department	Plan Type	meanMLCgap		meanTGi	
		P-value	Effect size (r)	P-value	Effect size (r)
Clinic 1	SABR_SPINE	0.752	0.089	0.550	-0.168
	SRS	0.000	0.527	0.000	-0.458
	SRS_MULTI	0.004	0.417	0.001	-0.484
	SRS_SINGLE	0.009	0.650	0.001	-0.839
Clinic 2	SABR_SPINE	0.000	0.800	0.001	-0.775
	SRS	0.427	0.126	0.221	-0.193
	SRS_MULTI	0.749	0.056	0.285	-0.186
	SRS_SINGLE	0.500	0.309	0.908	-0.055
Test Plans	SRS_MULTI	0.000	0.842	0.000	-0.829

DISCUSSION

The effect of MLC backlash is to close the aperture. As such, it is theoretically expected that backlash will be detrimental to target coverage, but advantageous for OAR sparing.

As lesion volumes decrease, smaller MLC apertures can be expected, for which MLC positional error will have an outsized influence. Hence, the volume dependency observed for clinic 1 is expected. That this is not the case for clinic 2 is under investigation but is suspected to be due to the choice of collimator angle. For collimator angles around 90 degrees, which clinic 2 utilizes frequently, gravity does not work in the direction of leaf motion and hence gravity induced backlash error is not present.

The reduction in OAR doses due to backlash potentially provides an added safety margin, especially for critical OARs such as the spinal cord, when in close proximity to the target as is the case for Spine SBRT.

Correlation between backlash impact on target coverage and varying complexity metrics suggest that dependencies are complex and likely multi-variate. That such correlations are not consistent between clinics limit the potential for standardized use of complexity metrics as a predictor of backlash significance.

While a uniform backlash of 0.5 mm across all MLC leaves is unlikely to occur in clinical practice, service procedures suggest that such magnitudes are possible in poorly serviced MLCs. Also, from service records a uniform backlash of 0.3 mm is considered a more realistic representation of this failure mode.

CONCLUSIONS

The dosimetric impact of MLC positional error due to backlash has been simulated for CSRS and Spine SBRT plans from 2 institutions. Target coverage degradation is observed for small lesions but is clinic dependent whilst OAR doses are universally improved. MLC positional error due to backlash is ever present to magnitudes of 10^{th}'s of millimeters for Varian single stacked MLCs.

REFERENCES

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