Dosimetric Impact of Anatomical Change on VHEE and VMAT Plans: A Comparative Robustness Study

VHEE'25

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Prior Work & The Knowledge Gap

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Hypothesis: VHEE is **more robust** to anatomical change

Why that's plausible?

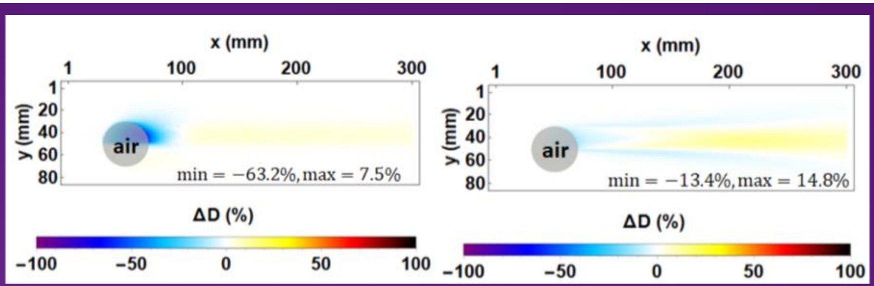
Simulations: MC (DesRosiers, Papiez, others) → VHEE **less sensitive inhomogeneities.**

Experimental: Lagzda et al. → VHEE profiles **stable** across inserts vs photons/protons.

Treatment Planning: High-quality VHEE plans; **can outperform VMAT** in plan quality & OAR sparing (on static anatomy).

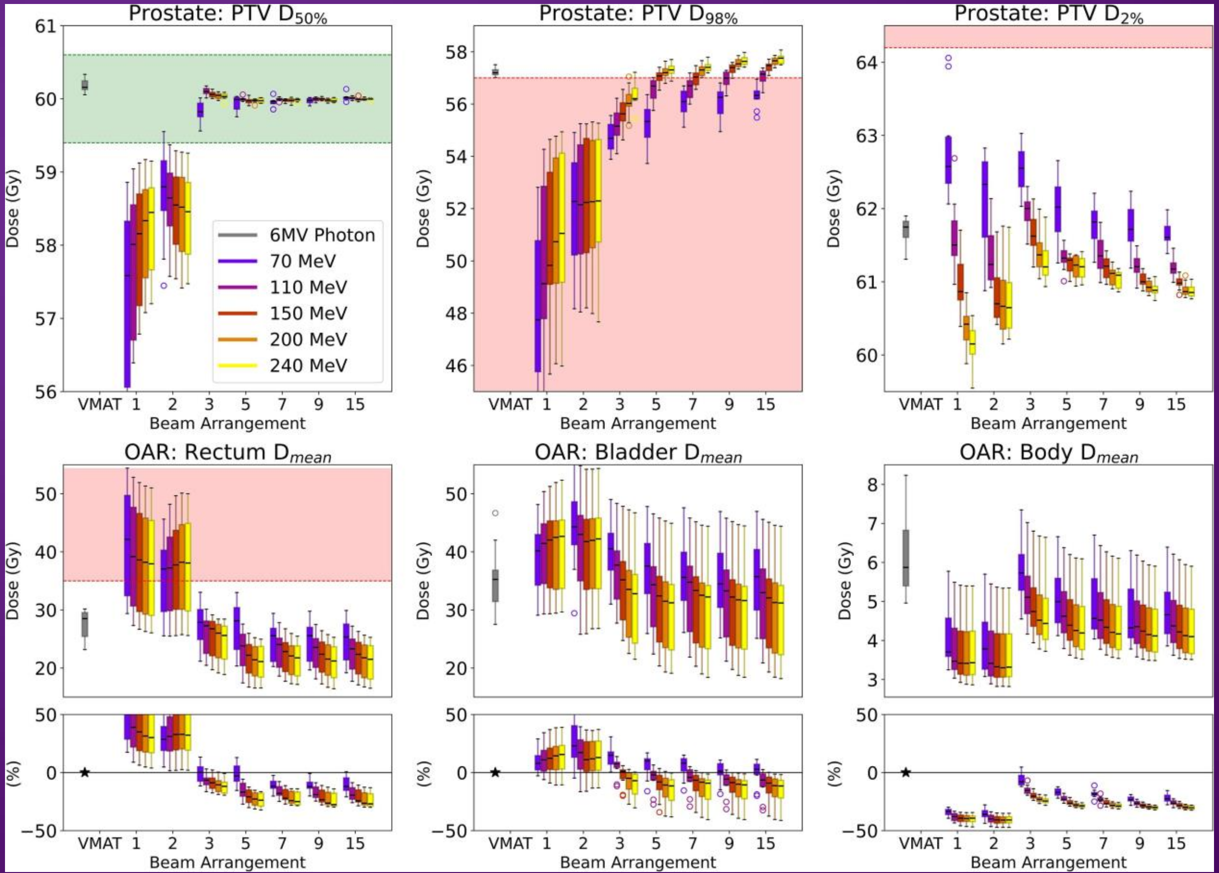
Gap: No direct VHEE vs VMAT under **real patient** changes.

This work: Proof of concept - **Patient-based** robustness comparison under clinically observed change.



Left: Photons vs VHEE - VHEE dose profiles remain comparatively stable across air inserts (Lagzda et al., 2020; adapted [1]).

Bottom: Prostate parameter study (n=10) - boxplots across beam numbers and energies comparing 6 MV VMAT with VHEE (420 dose distributions; D'Andrea et al., 2025 [2]).



[1] Lagzda et al. Influence of heterogeneous media on Very High Energy Electron (VHEE) dose penetration and a Monte Carlo-based comparison with existing radiotherapy modalities. Nuclear Instruments and Methods in Physics Research B (2020). https://doi.org/10.1016/j.nimb.2020.09.008

[2] D'Andrea et al. Comparative treatment planning of very high-energy electrons and photon volumetric modulated arc therapy: Optimising energy and beam parameters. Physics and Imaging in Radiation Oncology (2025). https://doi.org/10.1016/j.phro.2025.100732

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Why does this matter?

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Plans built on a planning CT; delivered over many weeks:

Anatomy changes (inter- & intra-fraction):

- **Tumour** regression *(shrinkage, oedema, baseline drift)*
- **OAR** volume change & motion *(bladder filling, rectal gas, bowel peristalsis)*
- ***Patient weight / body-contour change***

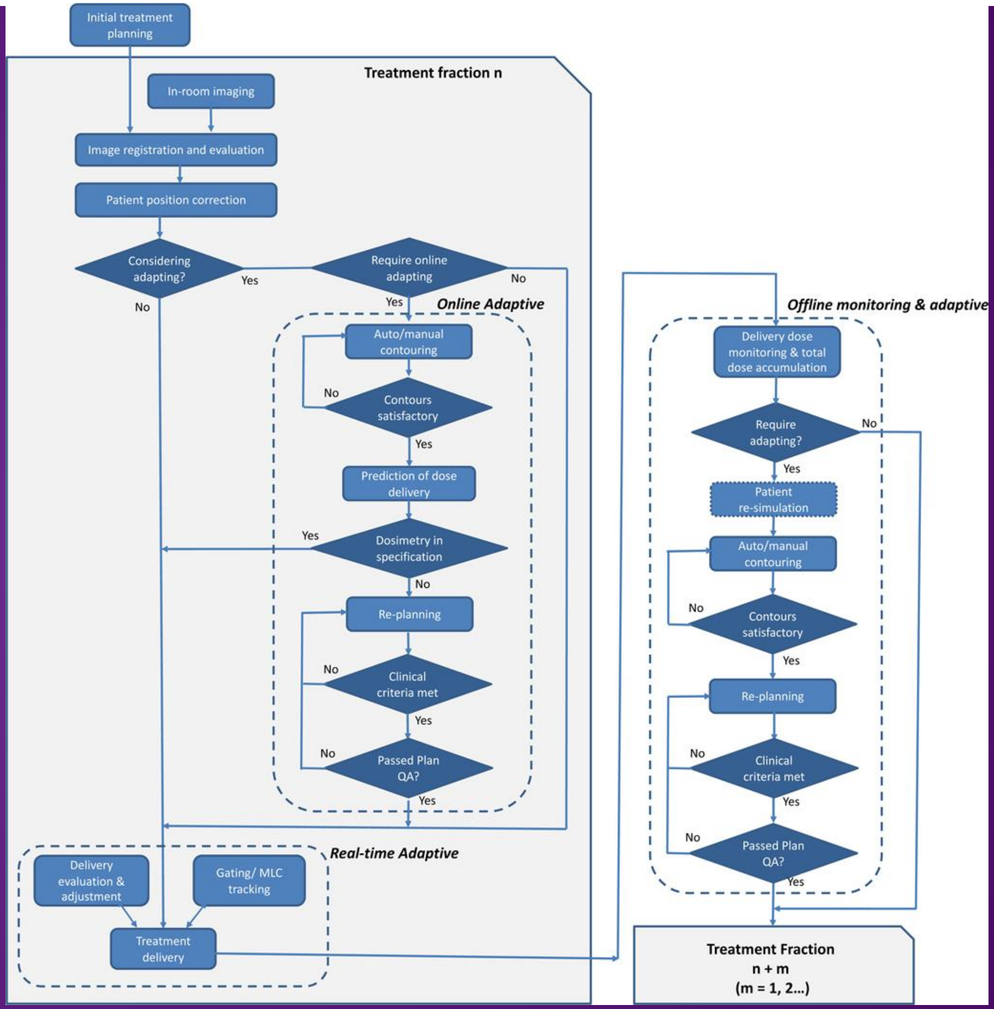
Quick implications:

- **Risk:** CTV **underdose** : ↓ local control
- **Risk:** OAR **overdose**: ↑ toxicity / limits breached

Action: IGRT/ART triggers → repeat imaging, plan adapt, re-fit devices

- Resource intensive
- May introduce treatment break / continue on inferior plan while replanned.

A modality with **intrinsic robustness** → less reliance on **ART**



Adaptive radiotherapy workflow showing online, offline, and real-time adaptation across fractions (imaging, registration, contouring, dose prediction/accumulation, re-planning, and plan QA). Adapted from Glide-Hurst (2021).

Method: Cases & Anatomical Change

Retrospective, preliminary, proof-of-concept cohort *(n=4)*
→ each **triggered mid-course replan**

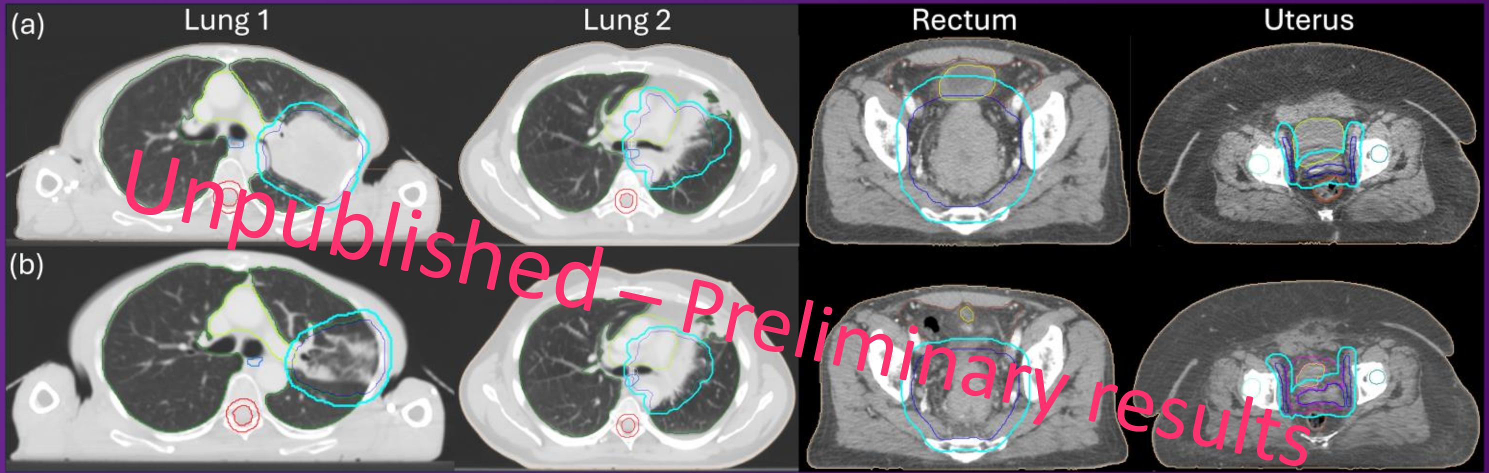
Clinical VMAT context: Approved plans; **dosimetric review**; **replanned**

Thorax

- **Lung1** (60 Gy): **marked regression**; re-aeration.
- **Lung2** (55 Gy): **regression.**

Pelvis

- **Uterus** (46 Gy): CTV stable; **Bladder -67%,** rectum -46%
- **Rectum** (45 Gy): **PTV −24%, bladder −32%;** Bowel stable



Planning and mid-treatment anatomy across the four cases. (a) Planning CTs and (b) mid-treatment CTs for Lung1, Lung2, Rectum, and Uterus. The PTV is shown in light blue; other contours denote the re-contoured regions of interest used for evaluation

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Method: Treatment Planning

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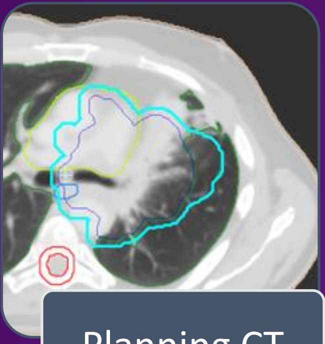
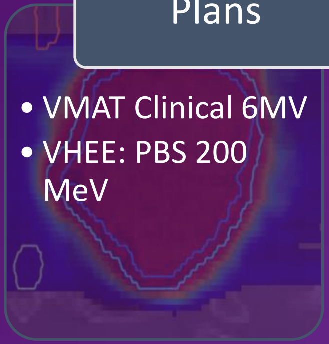
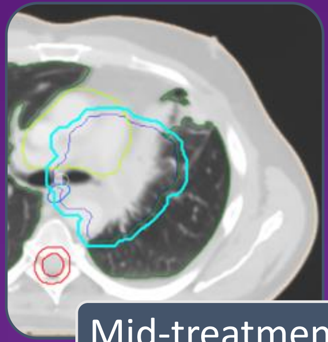


Planning CT

Plans

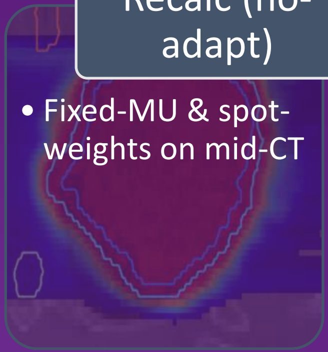


- VMAT Clinical 6MV
- VHEE: PBS 200 MeV



Mid-treatment CT

Recalc (no-adapt)



- Fixed-MU & spot-weights on mid-CT

- Target & Key OARs
- Pass/Fail vs constraints
- Δ = mid − plan

Metrics & Δ

Compare

- VMAT should degrade
- Does VHEE degrade less?
- Mode of failure

	VMAT	**VHEE**
Delivery	Clinical 6 MV arcs (*as-delivered, approved*)	200 MeV, PBS, static fields
Geometry	**Pelvis:** full arcs **Thorax:** half-arc (*ipsilateral*)	**Thorax:** $n = 5$ beams, equidistant over 200° **Pelvis:** $n = 7$ beams, equidistant around 360°
Spot size	—	$\sigma = 4\,\mathrm{mm}$; spacing $1.5\,\sigma$;
Validation	Clinical TPS; dosimetrically reviewed & approved	MC (GATE/Geant4); validated (prev. work) Single-spot $\gamma \geq 98\%$ (1%/1 mm)

Redacted

Results: Pelvis exemplar - Uterus

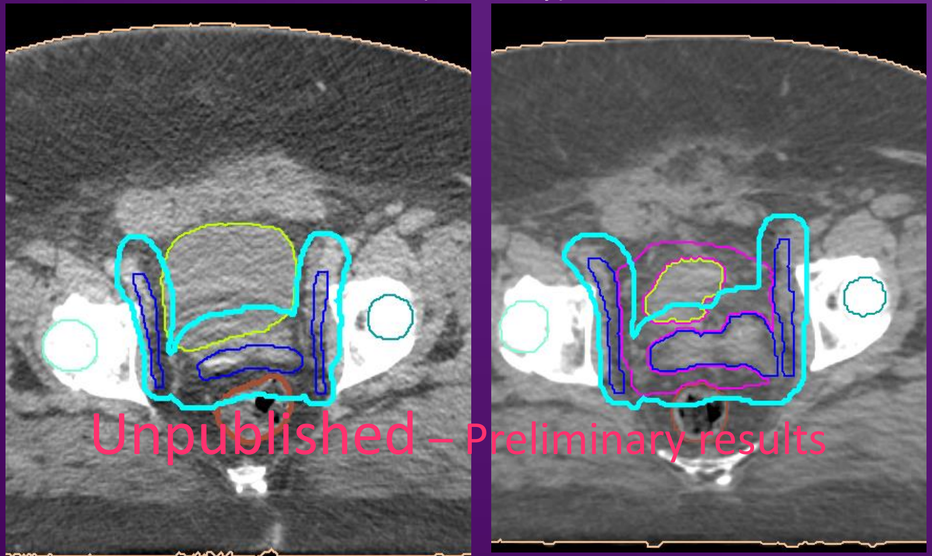
Scenario: Weight-loss, bladder −67%, rectum −46%

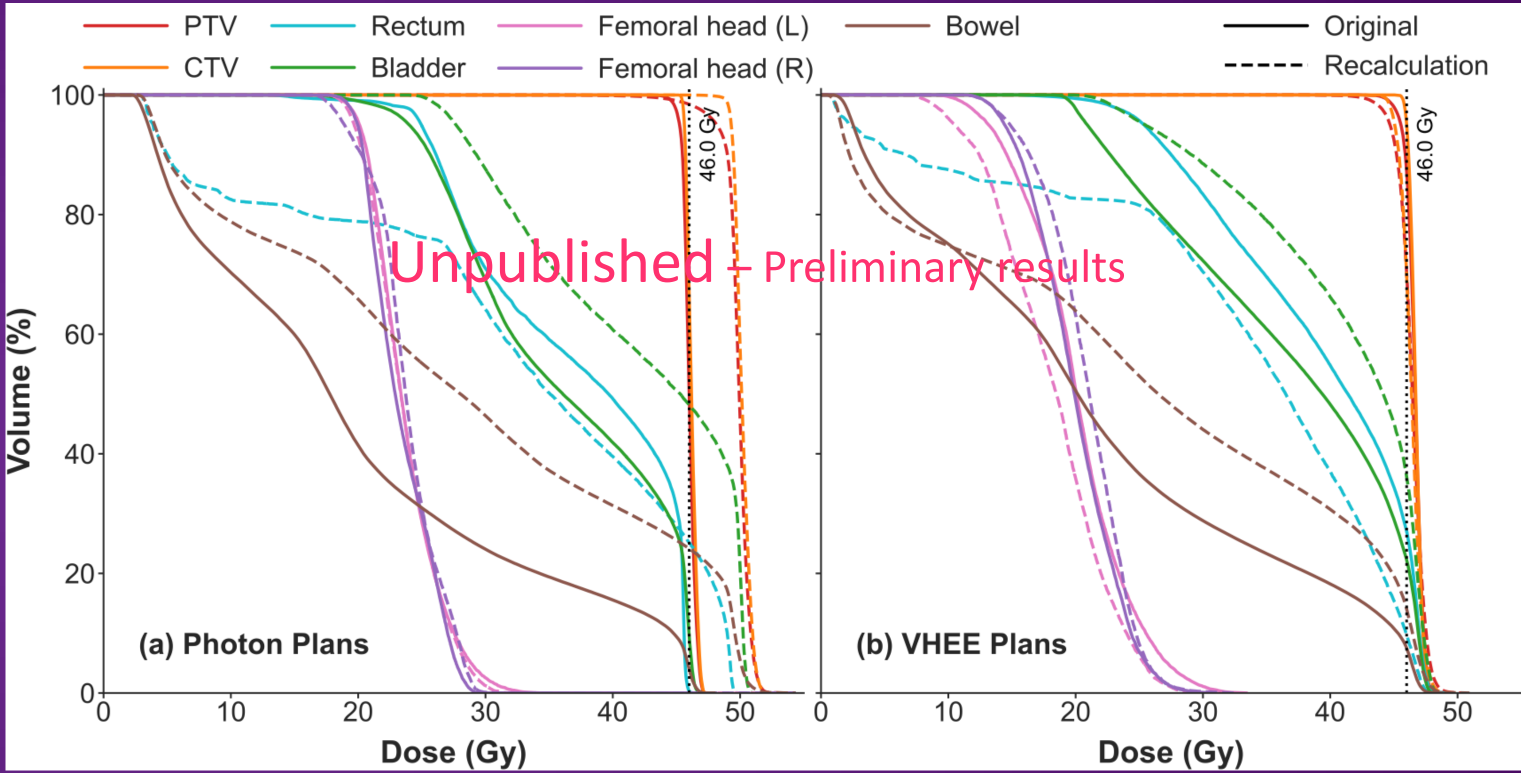
VMAT: (Plan → Mid, tolerance):

- PTV D95 [% Rx] (≥ 97%): 98.4 → 104.7 (pass)
- PTV D1cc [%] (≤ 110%): 102.5 → 113.3 (fail)
- Bowel V100 [cm³] (advisory): 51.3 → 259 .3↑↑

VHEE: (Plan → Mid, tolerance):

- PTV D95 [% Rx] (≥ 97%): 99.0 → 97.2 (pass)
- PTV D1cc [%] (≤ 110%): 104.6 → 107.4 (pass)
- Bowel V100 [cm³](advisory): 96.5 → 150.1 ↑





Uterus: combined DVHs for planning-CT optimisation and mid-treatment recalculation.

Results: Thorax exemplar – Lung 1

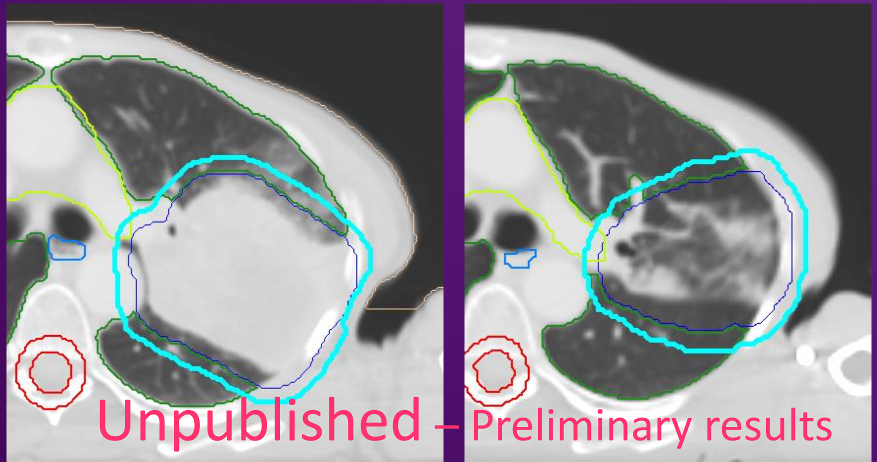
Scenario: ≈34% tumour regression + lung re-aeration;

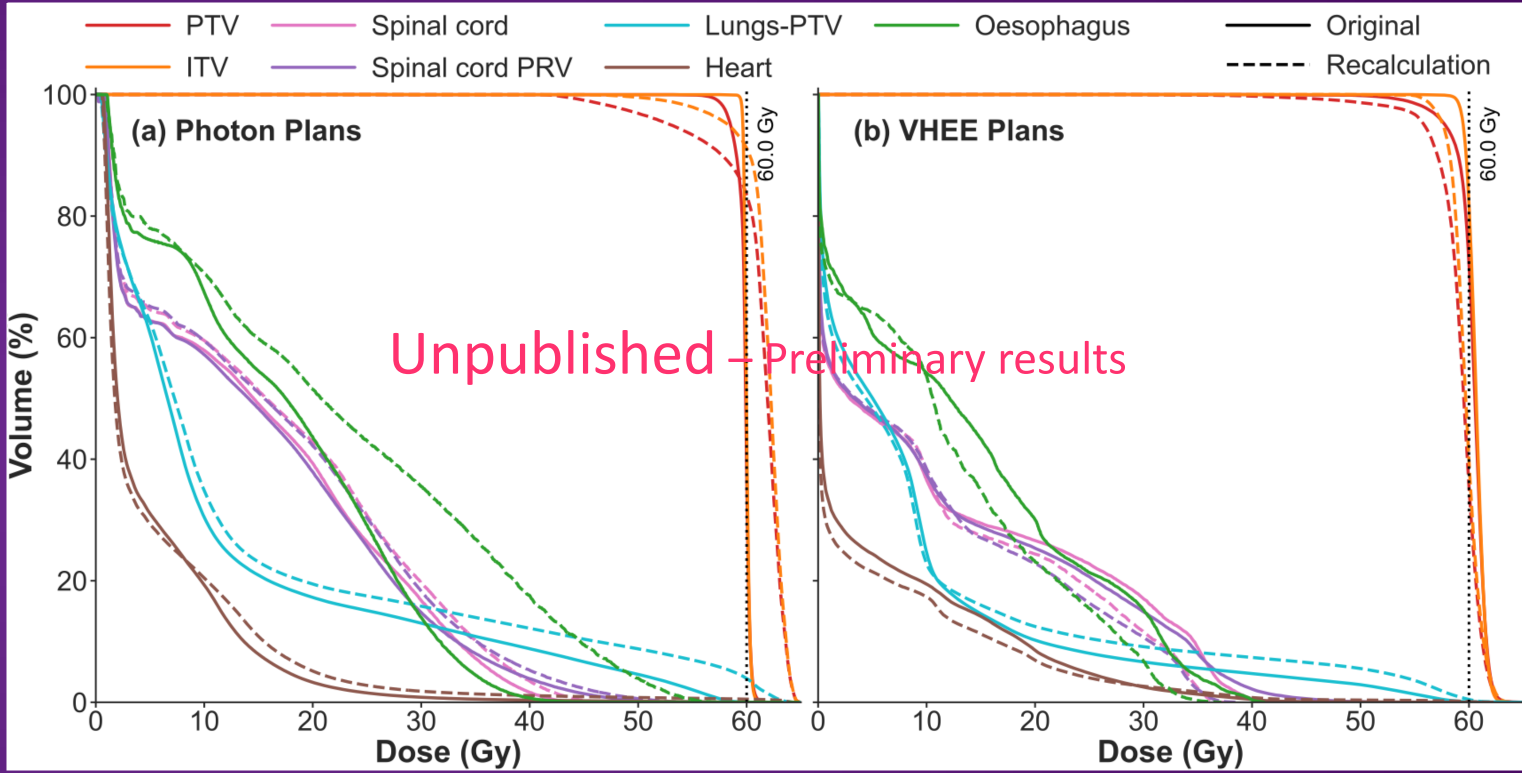
VMAT (Plan → Mid, tolerance):

- PTV D95 [% Rx] (≥ 90%): 97.5 → 88.4 (fail)
- PTV D1cc [%] (≤ 107%): 102.20 → 107.7 (fail)
- Cord PRV Dmax¹cc [Gy] (≤ 48): 44.5 → 49.4 (fail)
- Oesophagus Dmean [Gy] (advisory): 16.9 → 22.2
- Lung V20 [%] (≤ 35): 17.3 → 19.5 (pass)

VHEE (Plan → Mid, tolerance):

- PTV D95 [% Rx] (≥ 90%): 96.3 → 93.1 (pass)
- PTV D1cc [%] (≤ 107%): 105.4→ 105.2 (pass)
- Cord PRV Dmax¹cc [Gy] (≤ 48): 44.4 → 36.2 (pass)
- Oesophagus Dmean [Gy] (advisory): 13.3 → 11.6
- Lung V20 [%] (≤ 35): 10.2 → 12.5 (pass)





Uterus: combined DVHs for planning-CT optimisation and mid-treatment recalculation.

Clinical takeaways & next steps

Overall: In this small stress test, results suggest VHEE was more robust than VMAT.

What could this mean?

- Fewer unscheduled replans and clinical interventions
- Potential for tighter PTV margins (site-selective)
- Higher delivery confidence? (FLASH etc.)

Limitations:

- Retrospective, small cohort (n=4); proof-of-concept.
- Comparator VMAT plans were standard, not robust-optimised

Next steps:

- Larger cohorts across more sites
- Benchmarks vs robust-optimised VMAT and protons (both transmission & SOBP?)

Case	**VMAT outcome**	**VHEE outcome**
Pelvis — Uterus	! **Breach:** PTV $D_{1cc} = 113.3\%$ ($\leq 110\%$); V_{100}^{bowel} : $51 \to 259$ cm^3	✓ **Met:** D_{95} : $99.0 \to 97.2\%$ ($\geq 97\%$); $D_{1cc} = 107.4\%$; V_{100}^{bowel} : $97 \to 150$ cm^3
Pelvis — Rectum	✓ **Met:** coverage OK; large OAR drift (V_{100}^{bowel} : $30.6 \to 280$, V_{100}^{bladder} : $6 \to 42$ cm^3)	✓ **Met:** smaller drifts (V_{100}^{bowel} : $60 \to 126$, V_{100}^{bladder} : $29 \to 21$ cm^3)
Thorax — Lung 1	! **Breach:** PTV D_{95} : $97.5 \to 88.4\%$ ($\geq 90\%$); cord PRV $D_{1cc}^{\max}$: $44.5 \to 49.4$ Gy (≤ 48); hotspot $= 107.7\%$ ($\leq 107\%$)	✓ **Met:** D_{95} : $96.3 \to 93.1\%$ ($\geq 90\%$); cord PRV $D_{1cc}^{\max}$: $44.4 \to 36.2$ Gy; oesophagus mean ↓
Thorax — Lung 2	! **Breach:** D_{95} : $98.9 \to 92.3\%$ ($\geq 95\%$); hotspot $= 110.2\%$ ($\leq 107\%$)	! **Minor:** hotspot $= 110.0\%$ ($\leq 107\%$); coverage preserved $99.4 \to 99.6\%$

Unpublished – Preliminary results

Thanks for listening!

Questions?

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References:

[1] Lagzda *et al. Influence of heterogeneous media on Very High Energy Electron (VHEE) dose penetration and a Monte Carlo-based comparison with existing radiotherapy modalities. Nuclear Instruments and Methods in Physics Research B* (2020). https://doi.org/10.1016/j.nimb.2020.09.008

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[3] Glide-Hurst *et al. Adaptive Radiation Therapy (ART) Strategies and Technical Considerations: A State of the ART Review From NRG Oncology. International Journal of Radiation Oncology • Biology • Physics* (2021). https://doi.org/10.1016/j.ijrobp.2020.10.021