Beyond 2D Evaluation: MRI Polymer Gel-Based 3D DVH Verification for VMAT Lattice Radiotherapy

Yugo Ebinuma[1], Tenyoh Suzuki[1], Yoshihiko Hoshino[2], Ryo Takahashi[1], Kenji Hotta, PhD[1], Kouta Hirotaki, PhD[1], Sina Mossahebi, PhD[3], Robabeh Rahimi, PhD[3], Byong Yong Yi, PhD[3], Hidenobu Tachibana, PhD[1]

[1]Radiation Safety and Quality Assurance Division, National Cancer Center Hospital East, Kashiwa, Japan; [2]Department of Radiology, Gunma University Hospital, Maebashi, Japan; [3]Department of Radiation Oncology, University of Maryland School of Medicine, Baltimore, MD, USA

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INTRODUCTION

Lattice radiotherapy (LRT) intentionally creates a heterogeneous 3D dose distribution by placing multiple high-dose vertices within a bulky target. This heterogeneity is evaluated using the peak-to-valley dose ratio (PVDR), and agreement between planned and measured PVDR is desirable because its relationship with antitumor immune responses has been suggested.

Volume-based PVDR has been defined as GTV D10/D90 [1]; however, 1D and 2D dosimetry cannot generate a measured DVH for the entire GTV, making direct verification difficult. Because the biological effect of LRT may depend on the entire peak-valley dose architecture, accurate verification of volumetric dose delivery may be required in addition to individual vertex evaluation.

MRI-readout gel dosimetry enables 3D dose measurement with high dose resolution [2], but to our knowledge it has not been applied to LRT. This study proposes an MRI-readout gel-based QA method for LRT DVH verification.

METHODS AND MATERIALS

Equipment

- vGEL dosimeter (VIPET-based; 12 × 12 × 12 cm^3 cubic phantom; Triangle Products, Japan) (Fig. 1)
- MRI readout: 1.5 T Avanto (Siemens Healthineers)

VMAT-LRT planning

- TPS: RayStation 2024B (16.0.0.847)
- Lattice geometry: 27 spherical ROIs (sphere_all), 3 × 3 × 3 arrangement in GTV (482.6 cm^3)
- Sphere diameter / spacing: 1.0 cm / 3 cm (Fig. 1)
- Prescription: 12 Gy / 1 fr, sphere_all D95 ≥ 100%

Irradiation

- Beam: 6 MV FFF photon beam
- Linacs: TrueBeam (Varian) and OXRAY (Hitachi High-Tech, Japan) (Fig. 2)

Evaluation

- 3D dose: Plan (TPS) vs Measurement (MRI gel)
- DVH endpoints: PVDR for the GTV (D10/D90), vertex-level ΔD95 and ΔD5
- Global gamma analysis: 3%/1.5 mm [3], 10% dose threshold

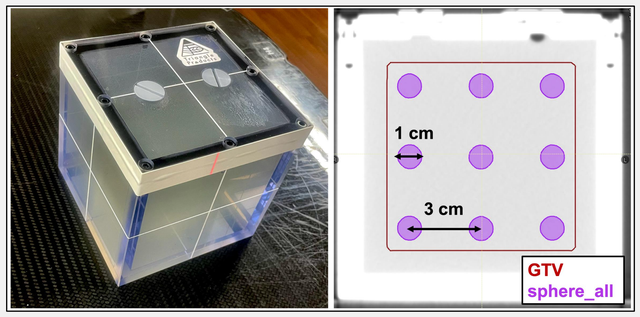

Fig. 1. vGEL phantom and 27-vertex lattice geometry.

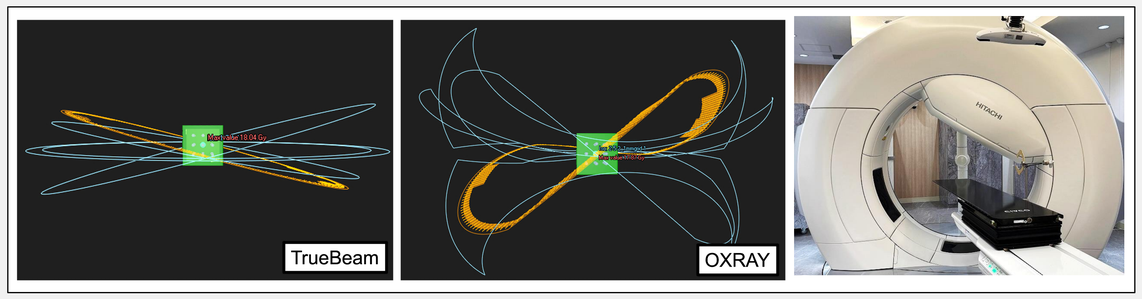

Fig. 2. Beam arrangements for TrueBeam (left) and OXRAY (center), and OXRAY system exterior (right). OXRAY is an O-ring linac platform with couch-free non-coplanar VMAT capability.

RESULTS

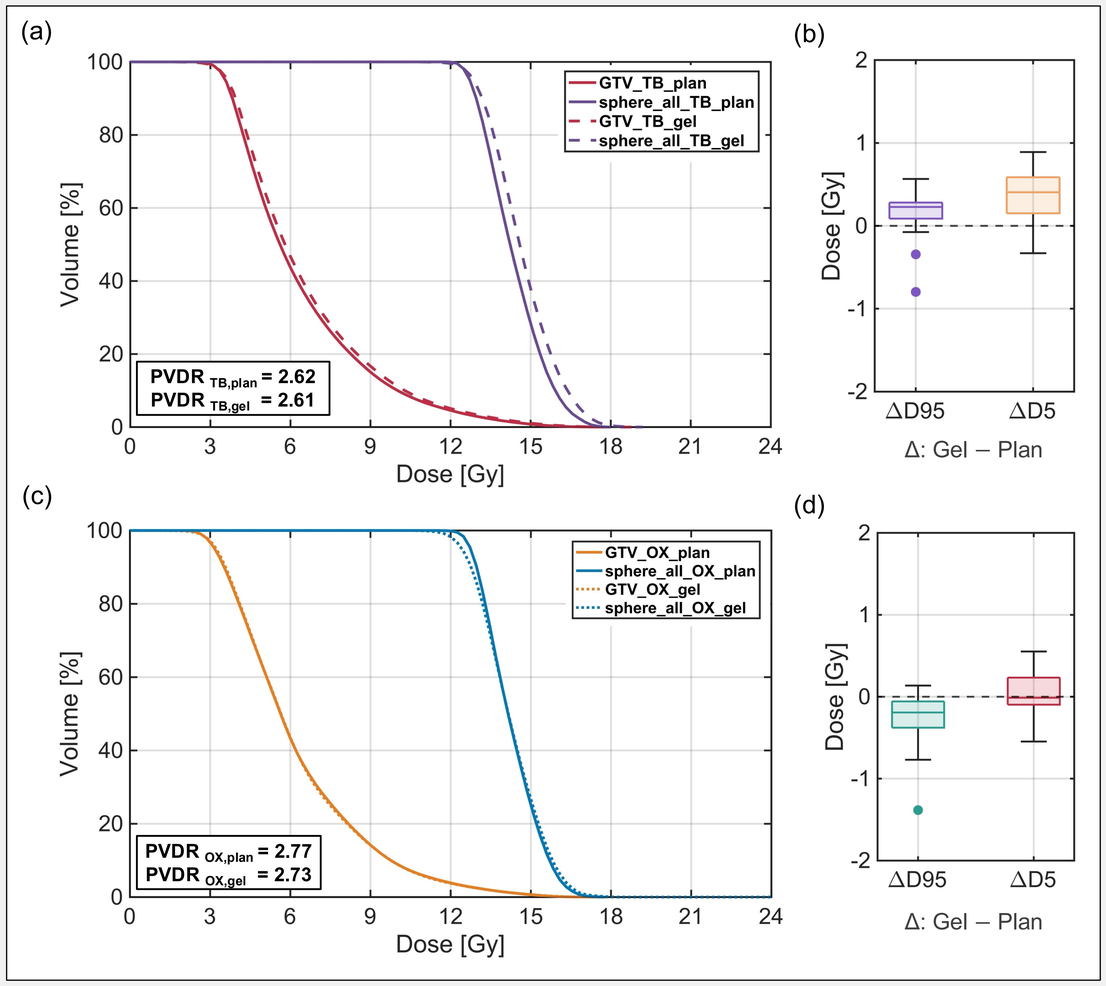

Fig. 3. DVH-based verification of PVDR (GTV D10/D90) and per-vertex ΔD95 and ΔD5. (a) TrueBeam (TB) DVH, (b) TB per-vertex ΔD95 and ΔD5 boxplots, (c) OXRAY (OX) DVH, and (d) OX per-vertex ΔD95 and ΔD5 boxplots. Delta = gel – plan; evaluated vertices: TB n = 21, OX n = 22.

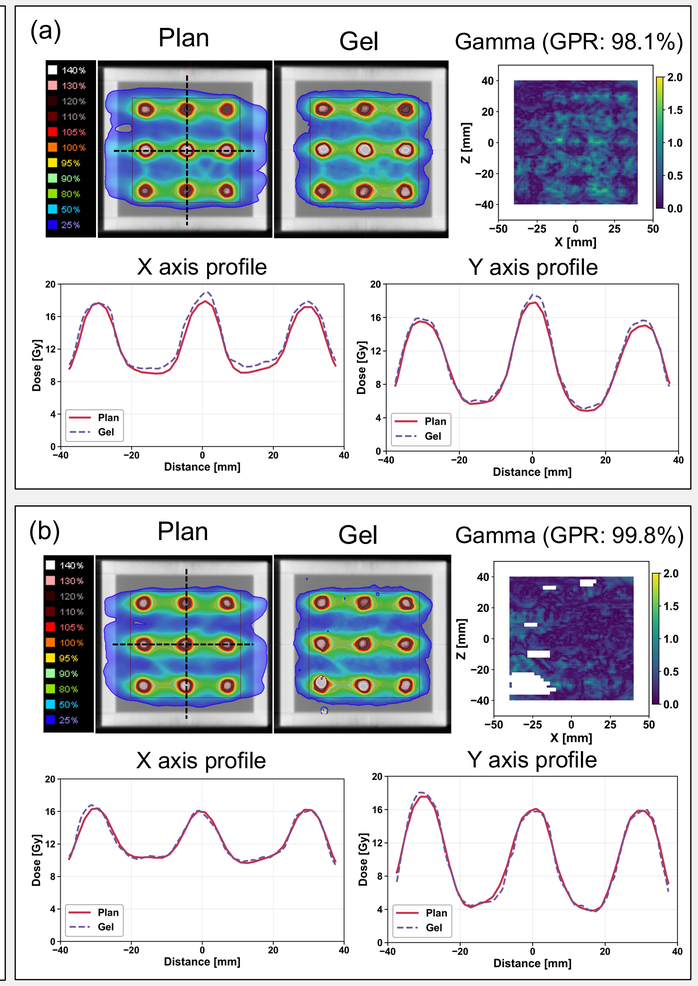

Fig. 4. Central coronal-plane plan, gel, gamma-index map, and X- and Y-axis dose profiles for (a) TrueBeam and (b) OXRAY. GPR: gamma passing rate.

DISCUSSION

- MRI gel dosimetry enabled direct 3D verification of VMAT LRT dose distributions, overcoming limitations of conventional 2D QA methods that cannot reconstruct volumetric dose information.
- Small differences in PVDR and vertex-level D95 and D5 observed on both platforms indicate accurate evaluation of both global dose heterogeneity and local dose delivery at individual high-dose vertices.
- As future LRT strategies incorporate increasingly complex geometries and biologically guided vertex placement, verification of individual vertex dose delivery may become critical, potentially exceeding the capability of conventional QA approaches.
- Because the workflow requires time-intensive gel preparation, MRI acquisition, and post-processing, it is better suited for commissioning or end-to-end validation. Remaining limitations include bubble formation and registration-related uncertainty.

CONCLUSIONS

This approach may provide a commissioning framework for emerging highly heterogeneous radiotherapy techniques that cannot be adequately verified using conventional 2D dosimetry. Small plan-gel differences in PVDR and vertex-level D95 and D5 on TrueBeam and OXRAY support its potential use for LRT commissioning.

REFERENCES

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CONTACT

Yugo Ebinuma (e-mail: yebinuma@east.ncc.go.jp)
Radiation Safety and Quality Assurance Division, National Cancer Center Hospital East, Chiba 277-8577, Japan

NCCJ National Cancer Center Japan