Total Variation Regularization of Fluence Fields for 3D Printed Compensators in Small Animal IMRT

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INTRODUCTION

There is significant interest in the development of highly conformal small animal radiation techniques by 3D printed compensator based intensity modulated radiation therapy (IMRT) technique. It provides the benefits of low cost, superior dose coverage and short treatment delivery time.

However, traditional IMRT optimization leads to highly-modulated fluence patterns that can be difficult for 3D printers.

AIM

In this work, a Total Variation Regularization based IMRT (TVR-IMRT) was proposed and experimentally verified to reduce compensator modulation while keep overall dose conformity acceptable.

METHOD

- DuringTVR-IMRT optimization, an L1 norm gradient operator is defined on nearby beamlet intensities in both column-wise and row-wise directions, and a mixed L1/L2 norm optimization with non-differentiable and convex cost functions is approximated and solved efficiently by an in-house software.

$$\begin{aligned} &\text{minimize} \quad h(y) + \beta\|Gx\|_1 \\ &\text{subject to} \quad y = Dx, \;\; l_x \preceq x \preceq u_x, \end{aligned}$$

  where $\|Gx\|_1$ is the gradient operator representing total variation (TV).

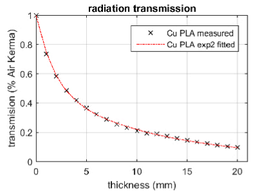
- The attenuation coefficient of Copper/Polylactic-acid (80/20%) filament used for compensator fabrication was empirically determined for XRad225Cx (Precision X-ray Inc.) small animal irradiation system. This enables conversion from optimized beamlet intensity to local compensator thickness.

- Five-field plans were generated with both traditional IMRT and TVR-IMRT to conformally treat a murine tumor with a simultaneous integrated boost to hypoxic tumor.

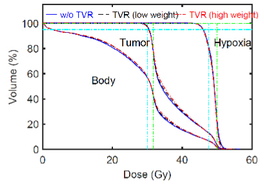
- Dose delivered to a phantom using 3D-printed compensator IMRT was measured with calibrated gafchromic film. Gamma analysis was used to compare measured to planned dose per-field.

RESULTS

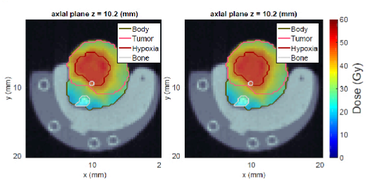
Figures from (C) to (I), left plot: IMRT; right plot: TVR-IMRT



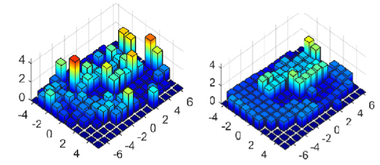
(A) Attenuation of compensator material



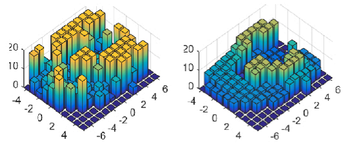
(B) DVH curves (blue: IMRT; red: TVR-IMRT)



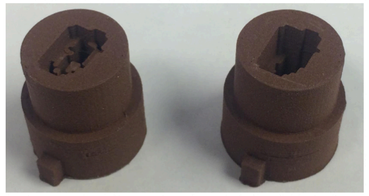
(C) Dose distribution



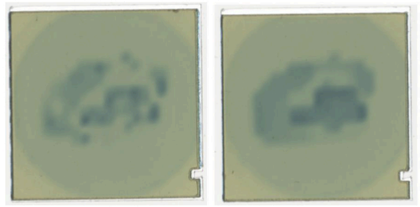
(D) Beamlet intensity



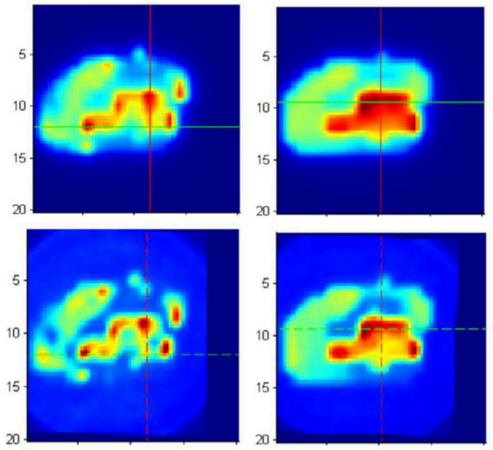
(E) Compensator thickness



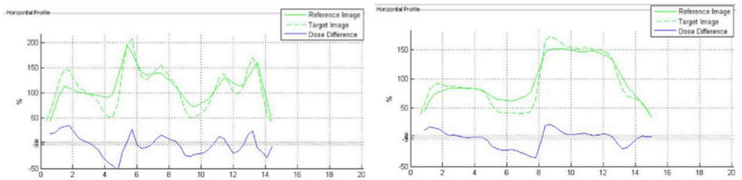
(F) 3D printed compensators



(G) Film measurement



(H) Dose distribution (top: planned, bottom: measured)



(I) Gamma Analysis: difference between planned and measured dose profiles

1. TVR-IMRT reduced
   - beamlet intensity TV by 48-58%
   - compensator thickness TV (a measure of smoothness of a surface) by 45-54%
   - sum of compensator thickness by 20-28%
   - radiation beam-on time by 22-28%
2. Gamma analysis: 3%/0.7mm passing rate was comparable at 95.7% with TVR-IMRT and 94.0% with IMRT.

Note that reducing beam-on time reduces overall treatment time and non-focal dose to normal tissue from leakage and scatter. Reduced compensator thickness decreases printing time/material.

CONCLUSIONS

This work uses TVR-IMRT to reduce fluence map complexity for 3D printed compensators. Experimental results show TVR-IMRT can produce more easily printable compensators, which reduce printing time, save costs in material usage, and reduce treatment times while maintaining the planning advantages of IMRT.

ACKNOWLEDGEMENTS

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