Using a Novel Hybrid Computational Phantom to Calculate Out-of-Field Dose and Equivalent Dose in Proton Therapy

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INTRODUCTION

With the modern increase in cancer survivorship[1], long term quality of life is likewise of increasing importance. Specifically, secondary primary malignancies due to radiation therapy are estimated to affect 1/100 patients[2]. These secondary cancers frequently appear on the fringes of or outside the treatment field[3]. Out-of-field dose, and neutron dose in particular, is not adequately accounted for in clinical treatment planning[4]. Neutrons produced in proton therapy have variable biological effectiveness, and travel far from the treatment field, leading to unaccounted dose within the patient. There is a gap in knowledge regarding the risk from out-of-field neutron dose from treatment plans on an individual patient level.

AIMS

1) Design a method of creating a patient-specific whole body hybrid representation utilizing scaled adult mesh-type reference computational phantoms (MRCP)[5] and individual in-field CT images.

2) Create a Monte Carlo framework able to separate neutron dose from therapeutic dose, and calculate the neutron weighting factor, equivalent dose, and risk of secondary cancer to specific organs.

3) Validate the method by comparing the proposed hybrid representation along with the currently available MRCP (scaled and unscaled) with respect to a reference whole body patient CT.

METHODS

Build a hybrid phantom with three major segments:

- In-field: Taken directly from a whole body CT (WBCT)
- Out-of-field: A mesh-type reference phantom (MRCP) scaled to patient measurements (spine length, pelvis width/depth)
- Transition: A voxelized blending area made by registering the MRCP to the patient CT, and applying that deformation with a gradient to match the edge of the patient CT to the boundary of the MRCP

Create a custom scorer to separate therapeutic and neutron dose, as well as enable equivalent dose calculation:

- Neutron Dose: All dose attributed to neutrons or neutron descendants
- Therapeutic Dose: All other dose
- Neutron Energy Fluence: Get the mean fluence-averaged neutron energy per voxel to calculate the energy dependent neutron weighting factor (ICRP 92 model[6])

Analyze hybrid performance and apply a baseline Linear Non-Threshold (LNT) risk model:

- Design a hypothetical proton prostate treatment plan
- Simulate treatment plan on the WBCT, hybrid, scaled MRCP, and unscaled MRCP
- Isolate the dose/equivalent dose to individual organs using DICE score validated organ masks as well as contours from the treatment planning system
- Calculate excess relative risk (ERR) for cancer risk using the BEIR VII estimated tissue risk coefficients[7]

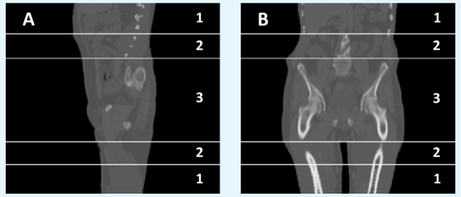
RESULTS

The Hybrid Phantom

- A male hybrid phantom was created for a hypothetical proton treatment case of a prostate tumor **(Figure 1)**.

Figure 1

Sagittal (A) and coronal (B) images of the male hybrid. The regions are separated into the scaled MRCP (1), the voxelized transition area (2), and the original patient CT image (3).

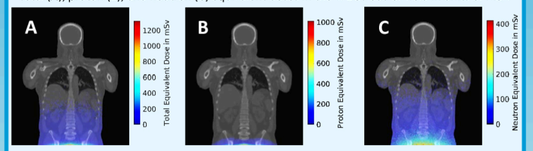


Contributions to Equivalent Dose Out-of-Field

- Outside the treatment field, the equivalent dose was dominated by the neutron contribution **(Figure 4)**. Equivalent dose from neutrons ranged from ~50-100 mSv in the out-of-field low dose bath.

Figure 4

Total (A), proton (B), and neutron (C) equivalent doses in the WBCT out-of-field in units of mSv.



Application of Linear Non-Threshold Risk Model

- ERR calculations made assuming the patient was age 45 at exposure and 65 attained age **(Table 3)**.
- Hybrid is able to reasonably approximate the risk of cancer incidence found in the WBCT.

Table 3

ERR and EAR for organ-specific cancer risk in the WBCT and the hybrid

	WBCT	Hybrid
Organ	ERR	ERR
Prostate	17.4	17.0
Bladder	24.5	24.5
Colon	2.3E-02	3.0E-02
Heart	6.4E-04	7.0E-04
Brain	1.7E-05	1.7E-05

Total Dose, Neutron Dose, and Neutron Weighting Factor Throughout The Body

- Neutron dose was mostly concentrated in the treatment area, but still spreads out-of-field to areas where the energy dependent neutron weighting factor was the greatest **(Figures 2 and 3)**.

Figure 2

Total dose (A) and neutron dose (B) throughout the WBCT in Gray.

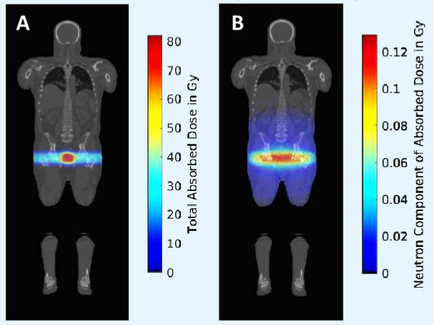
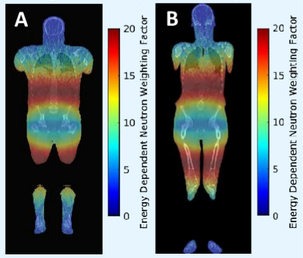


Figure 3

The energy dependent neutron weighting factor throughout the WBCT (A) and the hybrid (B).



- The neutrons with the largest weighting factor for equivalent dose calculations are concentrated outside of the treatment field (distance of ~12 cm, energy of ~1 MeV) **(Figure 3)**.

Dose and Equivalent Dose Comparison for Individual Organs

Table 1

Absorbed dose (Gy) and equivalent dose (Sv) in individual organs in the ground truth WBCT

		Whole Body CT Reference			
	Organ	Abs. Dose	Std. Dev.	Eq. Dose	Std. Dev.
In Field	Prostate	80.7	9.3	161.9	18.6
	Bladder	27.2	25.5	54.8	51.1
Near Field	Colon	6.3E-03	2.4E-02	4.1E-02	7.5E-02
Far Field	Heart	2.9E-04	2.3E-04	3.0E-03	2.9E-03
	Brain	2.8E-05	7.1E-05	8.1E-05	2.3E-04

- While the equivalent dose is close to double the absorbed dose in-field, the eq. dose is more than 6x greater in the colon and 10x greater in the heart, reflecting the higher impact of heavily weighted neutrons **(Table 1)**.
- The hybrid provided the closest estimate of dose in the WBCT compared to the generic reference phantoms **(Table 2)**.
- The colon has a much higher deviation than the other organs due to the complexity of the contour and anatomical variability between patient models

Table 2

Percent differences in dose and equivalent dose between the WBCT and the three tested phantoms

		Hybrid		Scaled MRCP		MRCP	
		Abs. Dose	Eq. Dose	Abs. Dose	Eq. Dose	Abs. Dose	Eq. Dose
In Field	Prostate	2.0	2.0	15.1	15.0	13.5	13.4
	Bladder	0.2	0.2	24.1	24.0	14.8	14.7
	Average	1.1	1.1	19.6	19.5	14.1	14.1
Near Field	Colon	19.1	29.9	69.0	40.0	256.9	111.1
Far Field	Heart	2.6	8.8	3.3	12.0	8.9	8.6
	Brain	3.6	4.4	17.5	14.0	30.8	29.4
	Average	3.1	6.6	10.4	13.0	19.8	19.0

CONCLUSIONS

The hybrid whole body patient representation provides better estimates of dose at all points in the patient compared to the generic scaled and unscaled MRCP. With the exception of the colon, all organs in the hybrid had a <10% difference in dose and equivalent dose compared to the WBCT.

Protons contributed most to equivalent dose in-field, but the out-of-field was dominated by the neutron contribution. The calculated equivalent dose for organs such as the colon and heart were 6 times in excess of the absorbed dose, reflecting the heavy weighting factor attributed to the neutrons outside of the treatment field, and their importance when calculating secondary cancer risk.

This kind of CT-MRCP hybrid can be flexibly created for male or female patients, for a variety of treatment sites, allowing the preservation of the known patient in-field while supplementing missing anatomy with an individually tailored out-of-field. Hybrid phantoms could have applications in cases where there is a stronger consideration for secondary cancer risk, such as in pediatric patients, and for dose reconstruction purposes for patients presenting for re-irradiation.

More thorough knowledge of the risk an individual patient faces can inform the treatment planning process. In conjunction with risk models, secondary cancer risk could be used in the treatment planning objective function itself to create risk-optimized treatment plans.

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