Investigation of on-line tumor edge detection using multiple Bragg peak detection in carbon therapy.

Marta F. Dias

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1. Motivation and Aim

Challenges in charged particle therapy

→ Charged particles, e.g. carbons are highly sensitive to tissue density variations.

e.g.:
400MeV/u carbon beam crosses 27.3cm of water but only 16.4cm of bone
So 1mm of bone in a water medium causes an error of 0.6mm
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→ Tumor shifts/shrinkage
  geographical miss and/or high-dose deposition at OARs.

Image from Mori et al. [2013]
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It is crucial to have on-line/precise knowledge of edges/interfaces along carbon's path!

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Image from Mori et al. [2013]
Possible Solution: Carbon Imaging

→ Carbon CT/Radiography
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Diagram:
- Pencil Beam
- Stickman
- Range detector
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![Pencil Beam](image1.png)

Stickman

![Range detector](image2.png)

Bragg Curve
1. Motivation and Aim

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→ Carbon CT/Radiography

Bragg Peak position is converted into total WET crossed.

Pencil Beam

Stickman

Bragg Curve

Range detector
1. Motivation and Aim

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→ Carbon CT/Radiography

Bragg Peak position is converted into total WET crossed.

Range detector

→ Carbons travel near straight paths (less than 1mm error for WET of 20cm) Fekete et al. [2016]

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1. Motivation and Aim

Each peak contains information about the crossed materials

Range detector signal

$$-\frac{\partial E}{\partial z}$$

Beam propagation axis

$z (a.u.)$
1. Motivation and Aim

It is crucial to have on-line/precise knowledge of edges/interfaces along carbon's path!

**Hypothesis:** we can detect on-line (during treatment) tumor edges using information from the detected multiple Bragg peaks.

- Reduced number of irradiation beams in order to reduce dose delivered to the patient.
- No imaging reconstruction methods.
2. Materials and Methods

We can decompose the peak into pristine Bragg peaks.
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**Assumptions:**

1. Straight path;
2. Materials and Methods

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3. Gaussian Beam, this is assumed to be valid at any depth along the beam trajectory.
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4. \( R_1 = \alpha E_0 \) (Bortfeld and Schlegel, [1996])
2. Materials and Methods

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**Assumptions:**
1. Straight path;
2. No tails due to secondary particles.
3. Gaussian Beam, this is assumed to be valid at any depth along the beam trajectory.
4. \( R_1 = \alpha E_0^p \) (Bortfeld and Schlegel, [1996])

The dose deposit at any point \( z < R \):

\[
- \frac{\partial E}{\partial z} = \frac{(R - z)^{1/p} - 1}{p\alpha^{1/p}}
\]

![Diagram showing the energy loss profile with the assumptions mentioned.]
We can decompose the peak into pristine Bragg peaks.

\[
\Delta I = \frac{\partial E(R_2) - \partial E(R_1)}{\partial E(R_1)}
\]

Range detector signal

\( \partial E \), total detected signal

\( \partial E_1 \)

\( \partial E_2 \)

\( z \) (a.u.)

\( R_1 \) and \( R_2 \)

\( \Delta WET \)
We can decompose the peak into pristine Bragg peaks.

\[ \Delta I = \frac{\partial E(R_2) - \partial E(R_1)}{\partial E(R_1)} \]

**Theoretical \( \Delta I - \Delta WET \) curve**

\[ \Delta I = \lambda^{1 - \frac{1}{p}} \Delta WET^{\frac{1}{p} - 1} + \left( \frac{W_2}{W_1} - 1 \right) \]
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\( W_1 \rightarrow \) percentage of carbons crossing above the interface
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**Theoretical \( \Delta I - \Delta WET \) curve**

\[ \Delta I = \lambda^{1-\frac{1}{\nu}} \Delta WET^{\frac{1}{\nu}} - 1 + \left( \frac{W_2}{W_1} - 1 \right) \]

\( W_1 \rightarrow \) percentage of carbons crossing above the interface

\[ W_2 = 1 - W_1 \rightarrow W_1 = \frac{1 - \text{erf} \left( \frac{Y}{\sigma \sqrt{2}} \right)}{2} \]
2. Materials and Methods

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We scan the interface for three irradiation spots (known spacing).
2. Materials and Methods

- We can decompose the peak into pristine Bragg peaks.

\[ \Delta I = \frac{\partial E(R_2) - \partial E(R_1)}{\partial E(R_1)} \]

**Theoretical \( \Delta I - \Delta WET \) curve**

\[ \Delta I = \lambda^{1-\frac{1}{\beta}} \Delta WET^{\frac{1}{\beta}-1} + \left( \frac{W_2}{W_1} - 1 \right) \]

- \( W_1 \rightarrow \) percentage of carbons crossing above the interface

- We scan the interface for three irradiation spots (known spacing).

- Apply the fit
2. Materials and Methods

We can decompose the peak into pristine Bragg peaks.

\[ \Delta I = \frac{\partial E(R_2) - \partial E(R_1)}{\partial E(R_1)} \]

Theoretical \( \Delta I - \Delta WET \) curve

\[ \Delta I = \lambda^{1 - \frac{1}{p}} \Delta WET^{\frac{1}{p} - 1} + \left( \frac{W_2}{W_1} - 1 \right) \]

At the edge:

\[ \Delta I = \lambda^{1 - \frac{1}{p}} \Delta WET^{\frac{1}{p} - 1} \]
2. Materials and Methods

Validation: Monte Carlo Simulations

- 400 MeV carbon beam with n=10^6 particles
- Geant4 (v 4.9.6.p02) (Agostinelli et al. [2003]). Ion packages (Lechner et al. [2010]).
- FWHM = 4mm, 8mm and 10mm
2. Materials and Methods

Parametric phantoms:

- Rectangular bone insert
- Semi-cylindrical bone insert

 Beam position: [-3,-2,-1,0,1,2,3]mm above and below the interface
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**Range dilution effects**, due to carbons from the same beam crossing different

- Beam position: [-3,-2,-1,0,1,2,3] mm above and below the interface
3. Materials and Methods

Edge detection through multiple BP: lung tumor example

→ X-ray CT prior knowledge for peak identification
→ The WET crossed and expected BP can be computed.
Parametric phantoms:

Parallel interface

\[ \Delta I = \lambda^{1-\beta} \Delta \text{WET}^{1/\beta-1} - 1 + \frac{W_2}{W_1} \]

Semi-cylindrical

\[ \Delta I = \lambda^{1-\beta} \Delta \text{WET}^{1/\beta-1} - 1 + \frac{W_2}{W_1} \]
4. Results and Discussion

Parametric phantoms:

Parallel interface:

\[ \Delta I = \lambda^{1-\frac{1}{p}} \Delta WET^{\frac{1}{p}-1} + \frac{W_2}{W_1} \]

Semi-cylindrical:

\[ \Delta I = \lambda^{1-\frac{1}{p}} \Delta WET^{\frac{1}{p}-1} + \frac{W_2}{W_1} \]

Zero at: 0.001mm
4. Results and Discussion

**Parametric phantoms:**

**Parallel interface**

- $\Delta I = \lambda^{1/\beta} \Delta W E T^{1/\beta-1} + \frac{W_2}{W_1}$

- Edge

→ Same error for all FWHM

→ Larger FWHM easier to identify the peaks

**Semi-cylindrical**

- $\Delta I = \lambda^{1/\beta} \Delta W E T^{1/\beta-1} + \frac{W_2}{W_1}$

- Edge
Clinical environment: Lung tumor

\[
\Delta l = \lambda^{\frac{1}{\beta}} \Delta W ET^{\frac{1}{\beta'-1}} - 1 + \frac{W_2}{W_1}
\]
Clinical environment: Lung tumor

\[ \Delta I = \lambda^{\frac{1}{p}} \Delta W E T^{\frac{1}{p} - 1} - 1 + \frac{W_2}{W_1} \]

Zero at: 0.001/-0.015 mm
Edge detection within <0.01mm accuracy using multiple BP information.

→ Carbon imaging is worse than helium imaging [Fekete et al. 2016];
5. Conclusions and Future work

Edge detection within <0.01mm accuracy using multiple BP information.

→ Carbon imaging is worse than helium imaging [Fekete et al. 2016];

→ Difficult to change particle type and if two beams available, it is possible on-line detection;
Edge detection within <0.01mm accuracy using multiple BP information.

→ Carbon imaging is worse than helium imaging [Fekete et al. 2016];
→ Difficult to change particle type and if two beams available, it is possible on-line detection;
→ Low dose to the patient;
Edge detection within <0.01mm accuracy using multiple BP information.

→ Carbon imaging is worse than helium imaging [Fekete et al. 2016];

→ Difficult to change particle type and if two beams available, it is possible on-line detection;

→ Low dose to the patient;

→ Prior-knowledge strategies are required for the identification of the relevant peaks;

→ Future work will consider applying the same methods to other tumor areas and structures which can be used for patient positioning.
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References


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Thank you so much for your attention/time!

Questions?
3. Results and Discussion

Edge detection through two Bragg peaks: theoretical formulation

Semi-cylindrical insert

- Smeared BP
- Different BP position
- Larger FWHM → Larger the ΔWEPL
- Larger FWHM → easier BP identification
4. Materials and Methods

Validation: Validation with ray-tracing

→ HU-RSP calibration curve
→ Patient CT data (Cancer Imaging Archive)
→ FWHM=4mm
→ Beam position: [-3,-2,-1,0,1,2,3]mm above and below the interface

\[ WET = \sum (RSP_i \times a_i) \]

Measured signal with range dilution effects