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Development of a Range Probe to Improve Dose Delivery Accuracy in Proton Beam Therapy

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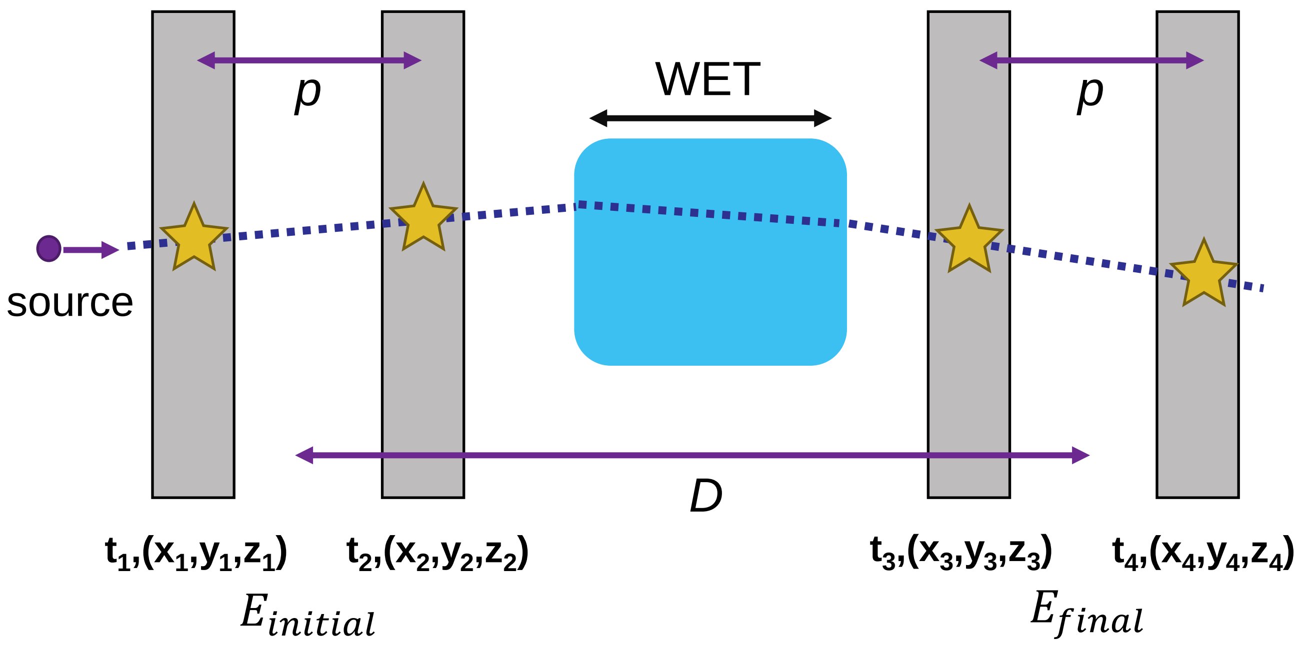
Introduction

- There is currently no method of in-vivo range verification in clinical use.
- A proton range probe is defined as a small number of proton pencil beams that pass through the patient to measure stopping power (SP) or water equivalent thickness (WET).
- Range probes could be a simple, low-dose method to provide range information and verify calculations from X-ray CT.
- Time-of-flight (TOF) detectors could be used to build a compact, sensitive range probe for range verification.



Schematic of the TOF proton range probe

Methods: Calibration Curves

Monte Carlo simulations (Geant4, version 11.0.3) were performed to investigate a TOF proton range probe.

The probe consists of two sensors upstream and two sensors downstream of the object to be measured. The sensors within each pair are separated by plane separation, *p,* and the two pairs are separated by a flight distance, *D*.

A calibration curve was generated by simulating a proton beam passing through a water block:

1. Each proton's hit time and position on all four sensors was recorded.
2. The initial proton energy was calculated with the data from sensors 1 and 2, and the final proton energy from the data from sensors 3 and 4, using the relativistic energy equation:
$$E = m_p c^2 \left(\frac{1}{\sqrt{1-\frac{1}{c^2}\left(\frac{|x_2-x_1|}{t_2-t_1}\right)^2}} - 1 \right)$$
3. The change of energy, ΔE, was calculated for each proton.
4. The distribution of ΔE values was fitted to find the average.
5. Steps 1-4 were repeated with water blocks of different thicknesses.

Methods: Parameter Investigation

Detector parameters were varied to investigate their effect on WET measurement accuracy and precision.

Parameter	Values
Sensor timing resolution (σ_t)/ps	0,20,30,50,60,100
Sensor spatial resolution (σ_{xy})/mm	0.1, 0.5, 1.5
Plane separation (p)/cm	5, 10, 15, 20
Flight distance (D)/m	0.5, 1, 1.5
Number of protons (n)	10^5, 10^6, 10^7

Results: Homogeneous Materials

Measurements were simulated in homogeneous blocks of water, PMP and Teflon. The average ΔE was calculated and the corresponding WET value was found using the calibration curve. Each measurement was repeated 100 times to obtain a mean WET estimate.

The key results were:

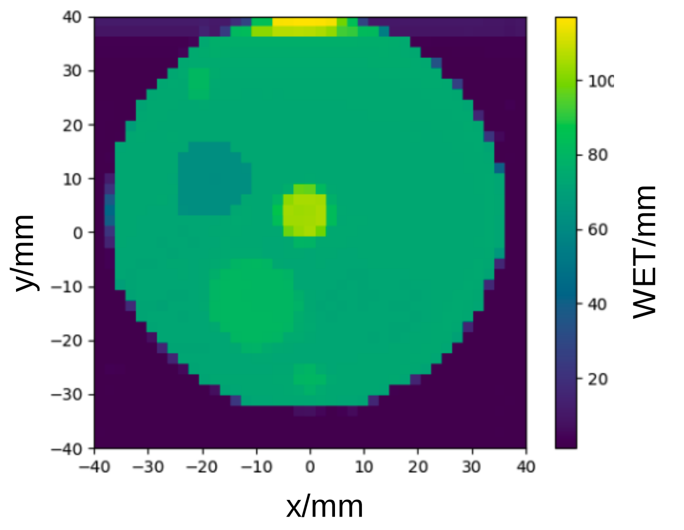
- The mean WET error was below 1% for measurements of WET ≥ 100mm with sensor timing resolution ≤ 60ps.
- The WET resolution was below the range straggling limit (1.2%) for measurements of WET ≥ 50mm with sensor timing resolution ≤ 60ps.
- Results were consistent between materials.
- Sensor spatial resolution and flight distance did not affect the results.

Results: Inhomogeneous Phantom

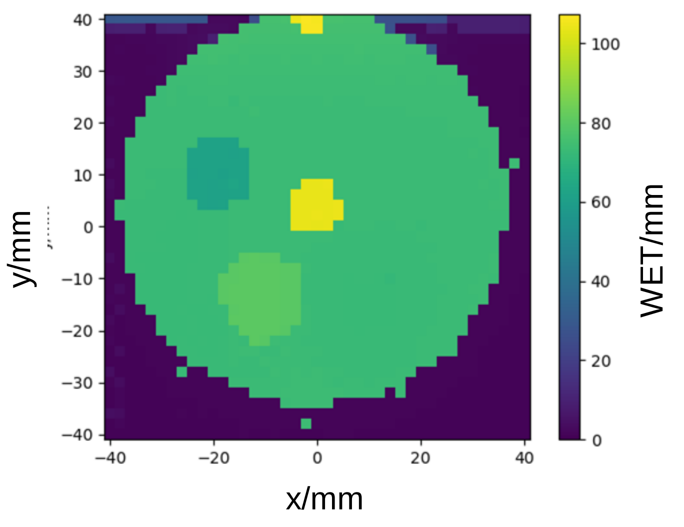
Measurements through an inhomogeneous phantom were also simulated.

A 2D WET projection was simulated by changing the probe x, and y positions. This was compared to a 'ground truth' WET projection that was generated from the X-ray CT. The key findings were:

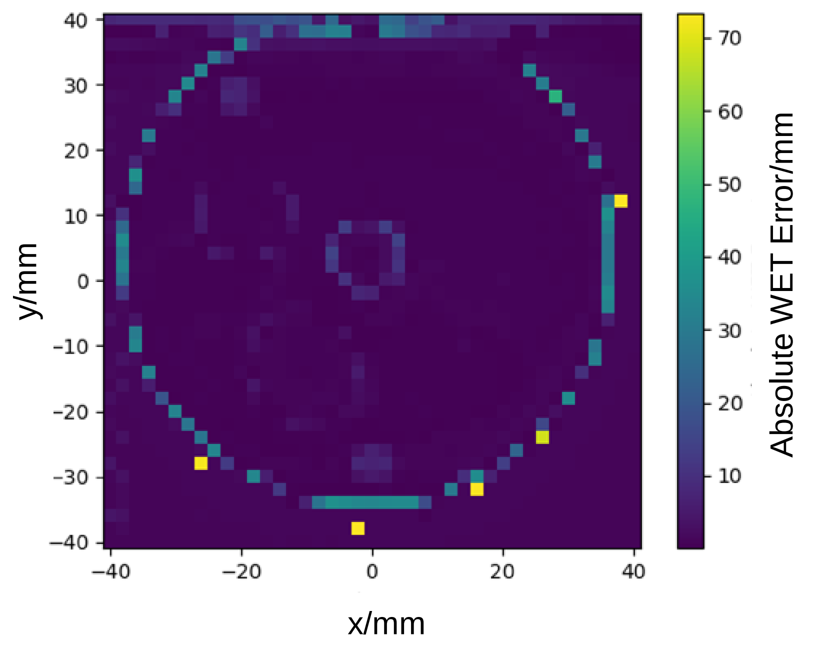
- Range error was greatest at the boundaries of different media.
- With non-perfect sensor timing resolution, cannot accurately measure WET in smaller structures.



WET projection from CT



Simulated WET projection



Map of absolute WET error

Conclusions and Next Steps

- TOF range probe can measure WET with accuracy and resolution better than 1%
- WET measurement accuracy depends on sensor timing resolution, inhomogeneity and spot size
- The next step is to test detectors (e.g. diamond, low-gain avalanche diodes) and build a prototype
- Need to consider clinical application: how many measurements are needed? How will the probe position be chosen? How will measurements be used?

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