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A Predictive Irradiation Time Calculator for Pencil Beam Scanning Proton Therapy

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Abstract

In proton therapy treatment planning, several free parameters impact both plan quality and delivery time. These include spot and energy layer spacing, MU per spot or layer, and in some systems, utilization of adaptive apertures (AA)[1]. Decreasing delivery time while maintaining plan quality maximizes patient comfort and clinical efficiency.
To better understand the impact of treatment planning approaches, an irradiation time calculator was developed based on delivery log files.

Methods and Materials

Machine logs from a single irradiation for 32 subjects over 12 months were acquired from two matched clinical synchrocyclotron treatment vaults, totaling 36 plans and 116 fields. Disease sites included breast, central nervous system, craniospinal axis, esophagus, head and neck, pelvis, spine, and thorax. 17 plans utilized dynamic apertures and 19 utilized static apertures. The timestamp, energy, spot index, spot position, charge, and AA coordinates were fit using linear-least squares, fitting coefficients for AA movement, spot position and charge, and setting energy layer switch time as constant. The plans were divided into training and testing (14) and validation (22) plans. The model was evaluated by correlation between actual and predicted delivery time.

32 Subjects
Jan 2025-Dec 2025

36 Plans
116 Fields

17 dynamic apertures
19 static apertures

Disease Sites:
Breast, CNS, CSA, Esophagus, HN, Pelvis, Spine, Thorax

14 Testing
22 Validation

Delivery Time =
AA movement + Spot Position Scanning + Charge Delivery + Energy layer switch time

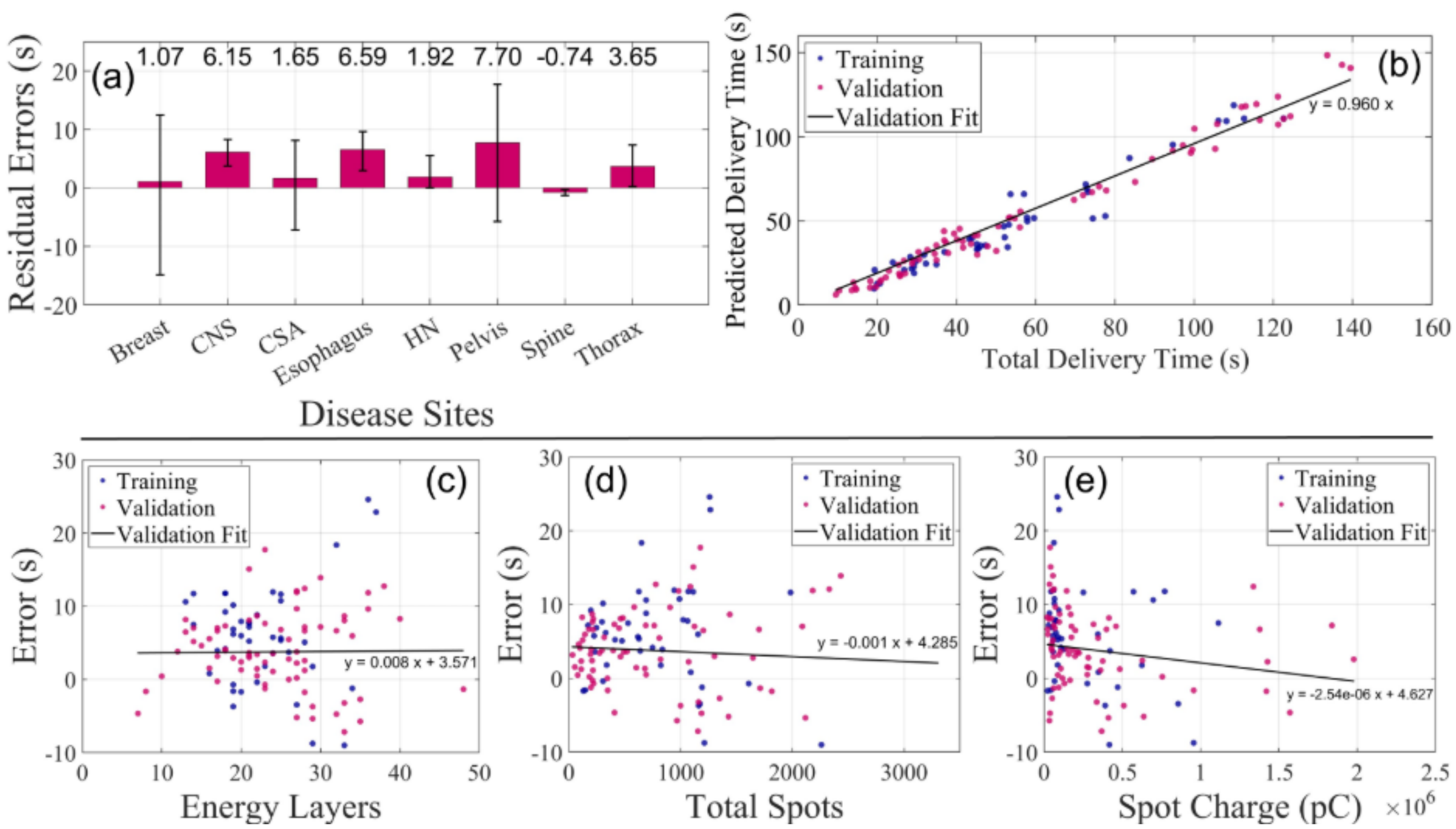

Fig. 1. Comparison plots generated for the delivery time model. The bars on (a) show mean residual errors per disease site, with error bars spanning max-min. (b) shows predicted versus total delivery times for training and validation spots. (c-e) show training and validation errors as a function of delivery parameters. All fit lines shown are calculated on the validation data only.

Results

Predicted delivery times had an absolute mean regression error of 7.47±5.40 seconds in the training set and an absolute mean residual error of 5.53±4.01 seconds in the validation set. Breast plans had the lowest absolute regression error of 3.68±2.64 seconds, and pelvis had the highest absolute regression error of 15.64±9.73 seconds.

AA movement: 0.09 m/s

Scanning target speed: 1.28 m/s

Charge delivery: 144.44 pC/s

Energy layer switch: 242.07 ms

The model was trained using all unique spots from 43 treatment fields comprising 34,279 data points. The model was trained in a piecewise manner, first fitting coefficients for scanned spot position, spot charge, and the center-of-mass of the adaptive apertures (AA COM). Different coefficients were fit for spot position and AA COM because the carriage that moves the AA has been found to be a time limiting step in the delivery process.
The HYPERSCAN synchrocyclotron system modulates energy by inserting variable thickness range shifters in the nozzle in a binary manner. Delivery is optimized to minimize the number of range shifters moving into and out of the beam between layers. Thus, energy layer switching was modeled as a constant, solving for layer switch time after fitting all data points without energy layer switches.
The model was trained using only static apertures, only dynamic apertures, and separately with both delivery modes combined to account for possible differences in carriage and MLC movement, however the combined model performed best.
When compared to actual delivery time, the model underpredicted with a mean regression error of 5.47±7.45 seconds (13.37±15.73%) and a mean residual error of 3.77±5.71 seconds (10.95±13.89%). Fig. 1 shows no significant correlation between residual error in the validation cohort and spot charge delivered. The validation cohort showed a mean residual error decrease of 1 second per 1,000 additional spots and an increase of 0.008 seconds per additional energy layer. All residual errors are less than 20 seconds, and the mean residual errors by disease site range from -0.74-7.70 seconds, and the total and predicted delivery times for the validation cohort correlated within 4%.

Discussion

Substantial decreases in delivery time for proton beam therapy reduce patient discomfort, decreasing the probability of patient movement. A treatment delivery time calculator was generated based on detailed log file analysis. This calculator could be used to optimize scanning parameters during treatment plan optimization and could be further leveraged to generate accurate estimates of dose rate. This tool can be used to predict total delivery times and allow for exploration on the impact of treatment planning parameters on delivery time.

References

1. Zhu M, Flampouri S, Stanforth A, et al. Effect of the initial energy layer and spot placement parameters on IMPT delivery efficiency and plan quality. *J Appl Clin Med Phys*. 2023;24(9):e13997. doi:10.1002/acm2.13997