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Introduce An Experimental Approach to Accurately Model Delivery Sequence and Beam Delivery Time Based On a Cyclotron Accelerator Proton Therapy System

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INTRODUCTION

The pencil beam scanning (PBS) technique has become a key planning and treatment modality in proton beam therapy. Proton spot delivery sequence is critical to the accurate evaluation of the motion interplay effect. Unfortunately, this research area related to machine-specific delivery sequence modeling has not been systematically explored by the particle therapy community yet, except for the two reports on standard delivery sequence using a simplified IBA ProteusPlus cyclotron system from West German Proton Therapy Essen (WPE)[1] and a HITACHI ProBeat synchrotron accelerator system from Mayo Clinic Arizona[2].

AIM

We proposed an experimental approach to build a precise machine-specific beam delivery time (BDT) prediction and delivery sequence model for standard, volumetric, and layer repainting delivery based on a cyclotron accelerator system.

The total beam delivery time T_{BDT} can be split into three categories: spot drill time (T_{SDT}), spot switching time (T_{SSW}), and the layer switching time (T_{LSW}). The model to predict beam delivery time can therefore be written as :

$$T_{BDT} = N_{vol}(T_{SDT} + T_{SSW} + T_{LSW}) + \sum_{v=1}^{N_{vol}-1} t_{vsw}^{v}$$

where N_{vol} is the total number of volumetric repaintings; t_{vsw}^{v} is the volumetric repainting switching time between volumetric repainting v and v+1. We aim to model each time component accurately.

METHOD

Combine both the experiment and theoretical derivation:

- Conduct the experiment to measure the spot scanning speed for y and diagonal direction. To quantitatively model the y-direction speed (spot positions with the same x-coordinate), we designed the test fields that the spot with 0.02 MU travels in y-direction only ($|x_{i,j,k+1} - x_{i,j,k}| = 0$) at thirty-four different y-distance interval $|y_{i,j,k+1} - y_{i,j,k}| = 1,2,3,\ldots,7,8,9,10 + 5n\ (n = 0,1,2,\ldots 16), 107, 119, 155, 175, 176, 177, 180, 225$ (mm). A series of rectangular diagonal test fields with spot patterns are designed to test the spot travels in different x, y diagonal direction and distance when it switches line during the scanning. We repeat the y-direction and diagonal experiments for different energy as 70, 100, 150, 200, and 220 MeV.

- Analysis the data from both experiment and clinic by curve fitting and other technique.

- The beam delivery time and other parameters are independently imported from the log file with a modified MATLAB package based on the REGGUI.

RESULTS

A: Spot switching time (SSWT) modeling (Figure 1)

For the SSWT in the x-direction t_x can be described by a piecewise linear function with respect to its scan distance x (mm):

$$t_x = \begin{cases} 1 & (x < 1\,mm) \\ 0.2412x + 0.7096 & (1mm < x \le 50mm) \\ 0.3694x - 5.7096 & (x > 50mm) \end{cases}$$

The SSWT along the y-direction only (t_y) can be linearly fitted by :

$$t_y = 0.3274y + 2.882 \quad \text{(ms)}$$

the diagonal switching time or line switching time can be written as:

$$t_{RSW} = \max(t_{x\_rsw}, t_{y\_rsw})$$

$$T_{SSW} = \sum_{i=1}^{N_{layer}} \left[\sum_{j=1}^{N_{paint}^{i}-1} (t_{psw}^{i,j} + T_{SSW}^{i,j}) + T_{SSW}^{i,N_{paint}^{i}}\right] \text{ (ms)}$$

B: Energy layer switching time (ELST) modeling (Figure 2)

$$t_{lsw}^{i} = \begin{cases} \mu\left[4\left(T_{SDT}^{i} + T_{SSW}^{i} + T_{PSW}^{i}\right) + T_{SDT}^{i+1} + N_{spot}^{i+1}\right] + 1 & if\,\Delta E_i < 0 \\ 9.468 - 0.0239E_i & if\,\Delta E_i > 0 \end{cases}$$

C: Layer repainting modeling

The presumed MU for plan *k*th spot in layer *i* is $mu_{pre}^{i,k} = \frac{mu_{plan}^{i,k}}{N_{paint}^{i}}$

Actual MU calculation:

$$\widehat{N_{paint}^{i}} = \begin{cases} \left\lfloor \frac{mu_{plan}^{i,k}}{tol} \right\rfloor & (mu_{plan}^{i,k} \ge tol) \\ \left\lceil \frac{mu_{plan}^{i,k}}{tol} \right\rceil & (mu_{plan}^{i,k} < tol) \end{cases} \quad and \quad mu^{i,j,k} = \frac{mu_{plan}^{i,k}}{\widehat{N_{paint}^{i}}}$$

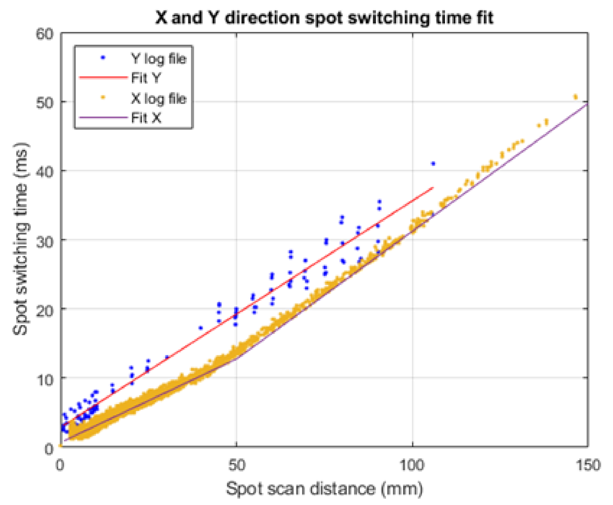

Figure 1: Spot scanning time modeling in x and y directions: X-direction data fitted by the piecewise linear from ten clinical cases and Y-direction experimental data fitted by linear.

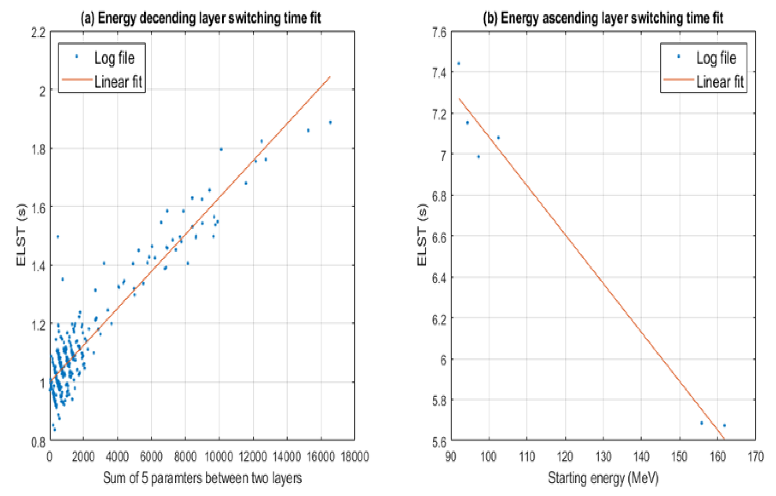

Figure 2: Linear regression for descending ELST through ten clinical IMPT beam cases and for ascending through 6 volumetric repainting switching cases.

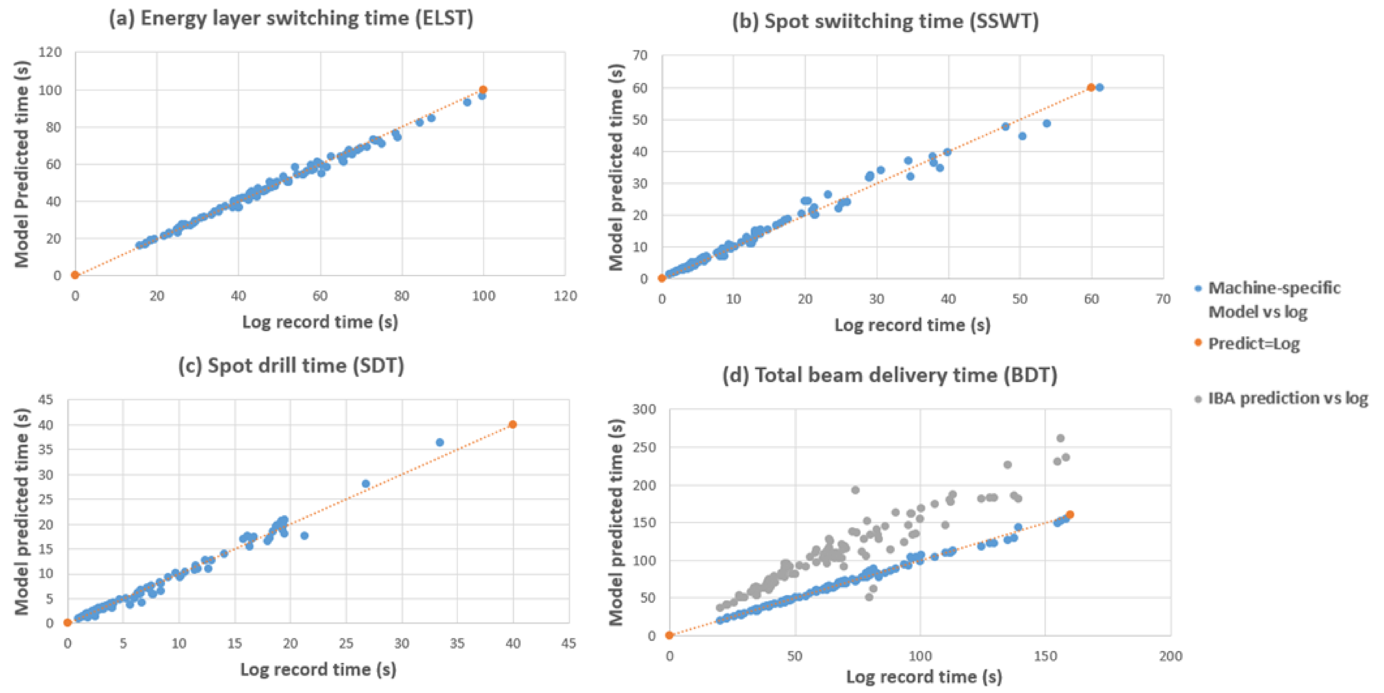

Figure 3: The validation result of BDT each component and total BDT compared with IBA ProteusPlus® prediction.

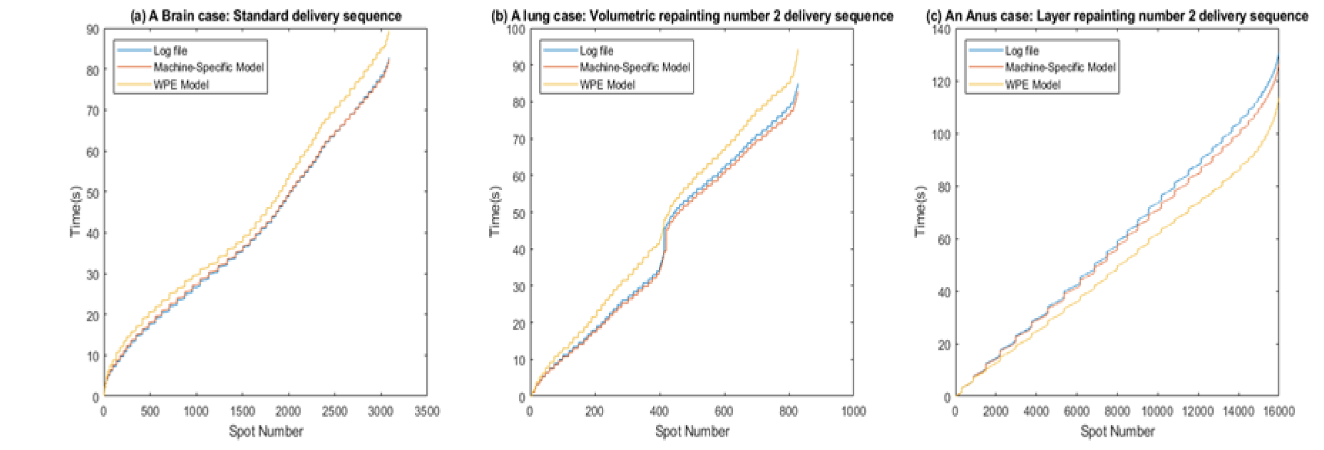

Figure 4 : Comparison of spot-scanning delivery sequence with log file among different clinical IMPT plans from various disease sites. (Red) the machine-specific model; (Yellow) WPE model and (Blue) log file. (a) Standard delivery sequence: A brain cancer case. (b) volumetric repainting delivery sequence (N_{vol}=2): A Lung cancer case (c) layer repainting delivery sequence (N_{paint}^{i}=2): An anus cancer case.

CONCLUSIONS

An experimental approach for beam delivery sequence modeling was developed to determine the related proton therapy operational parameters that affect PBS beam delivery time for the cyclotron accelerator proton beam therapy system, IBA ProteusPLUS®. This precise machine-specific beam delivery time prediction model could be used in the clinic to evaluate the motion interplay effect.

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