Evaluation of dose error distribution caused by spot position error in spot scanning proton beam therapy

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1. Introduction

Spot scanning proton beam therapy system enables to deliver conformal dose to the target tumors while sparing surrounding healthy tissues by controlling the beam position and dose spot by spot. However, this method has a potential to generate hot and/or cold dose regions if non-negligible position error has been arisen for each spot during the irradiation (Fig.1). We have developed a simple method to estimate the dose distribution error caused by spot position error based on the statistical model and evaluated the deviation of dose distribution corresponds to the spot position error results from the actual beam delivery.

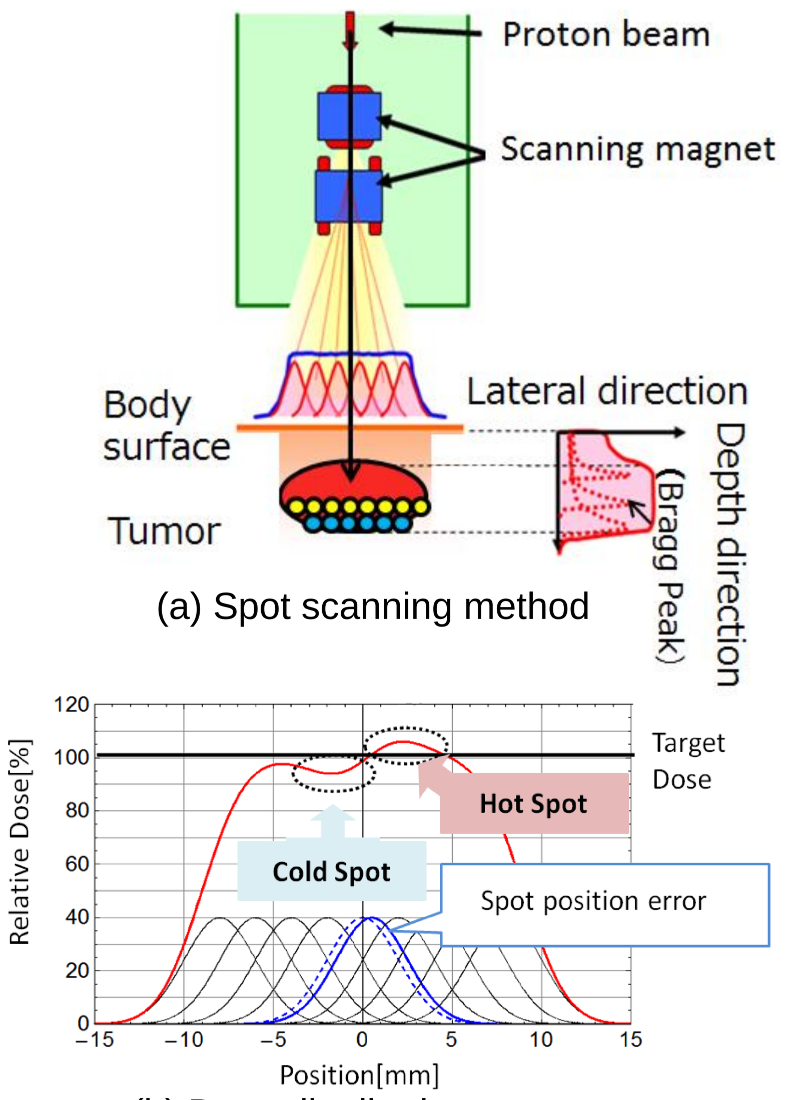


Fig.1 Spot scanning method and typical dose distribution error caused by spot position error

2. Materials and Methods

We have developed a statistical method to calculate the standard deviation of the dose distribution error for the target region by superpositioning each spot dose which has previously given statistical position errors. Physical dose for each spot is calculated by using the approximation formulas, i.e. Bortfeld equation[1)] for the depth-dose distribution and Gaussian approximation for the lateral distribution with Highland formula of beam width calculation[2)]. All spot doses are superposed in the lateral x and y directions and overlapped in each energy layers for beam direction z. Finally we get the three dimensional integrated dose distributions and their standard deviations. The following equation shows the 3D dose distribution D(x,y,z).

$$D(x,y,z) = \sum_{k=1}^{l}\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{w_k \cdot D_k(z, E_k + \Delta E_k)}{2\pi\sigma(z, E_k + \Delta E_k)^2}\cdot g(x,y,z)\right)$$

$$g(x,y,z) = \exp\left[-\left\{\frac{\left(x-\mu_{xij}+\Delta\mu_{xij}\right)^2}{2\sigma(z,E_k+\Delta E_k)^2}+\frac{\left(y-\mu_{yij}+\Delta\mu_{yij}\right)^2}{2\sigma(z,E_k+\Delta E_k)^2}\right\}\right]$$

(w_k : beam weight, i:spot number of X axis, j:spot number of Y axis, k:layer number, $\Delta\mu_{xij}$:position error in X axis , $\Delta\mu_{yij}$:position error in Y axis, ΔE_k:energy error caused by minute difference of accelerator)

The values of spot position errors caused by actual bean delivery indicates the accuracy of the spot scanning system and which can be considered as the typical performance of the system. We categorize them into two possible position errors, (1) lateral position error caused by spot scanning magnet control and (2) range error caused by minute difference of accelerated energy. The reference values and ranges of the errors for (1) and (2) have been determined by the actual measurement. Target region is defined to be a cube (5x5x5cm) in the homogeneous water. The number of spots is 11x11 for lateral direction and the typical number of energy layers is 19.

We assumed spot position errors (1) and (2) follows the normal distributions and set the parameter of standard deviation of spot position errors as σ_s and σ_a for lateral and depth directions. We calculated the 3D dose distributions with the spot position errors statistically enough times and then evaluated their standard deviations σ_d. Fig.2 shows the schematic view of dose distribution calculation.

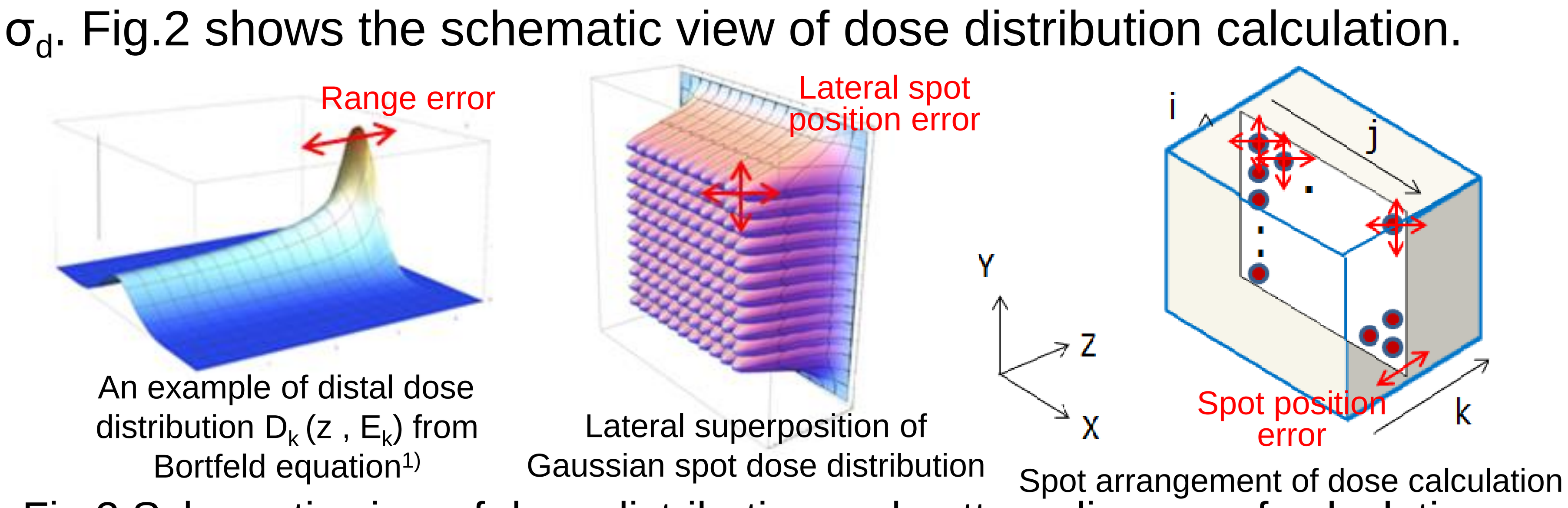
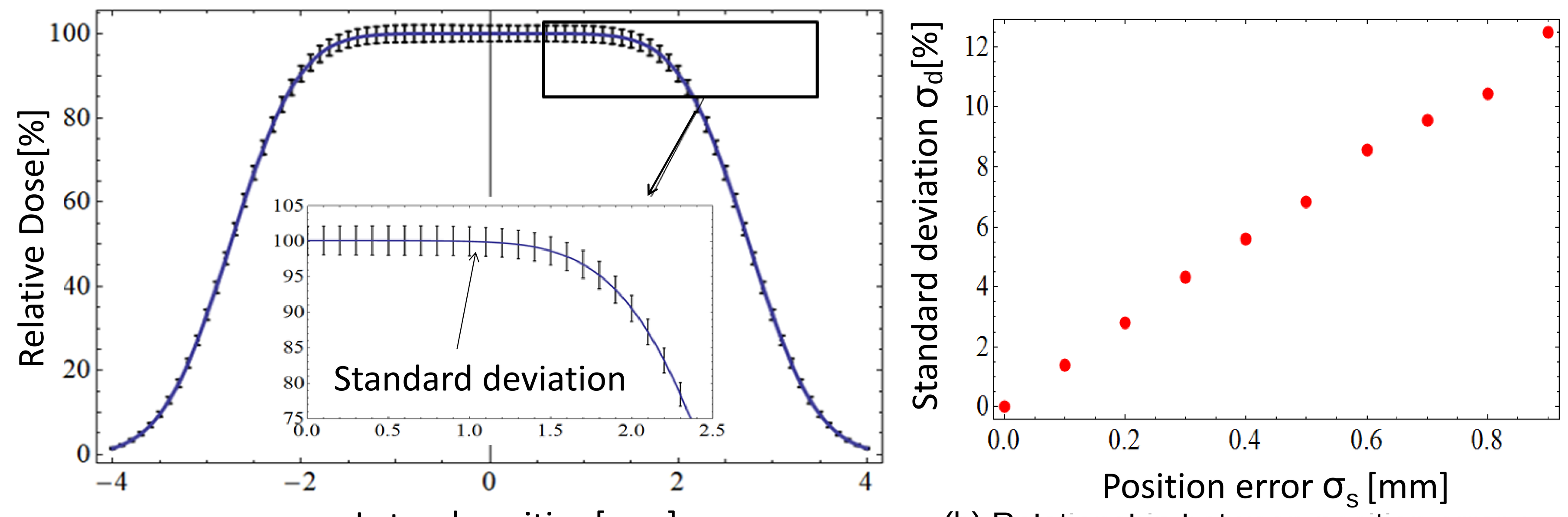


Fig.2 Schematic view of dose distribution and pattern diagram of calculation

3. Results and Discussion

Fig. 3 shows the result of lateral dose distribution and standard deviations. Fig. 3(a) shows the typical result of lateral dose distribution with position error σ_s = 0.5 mm. Error bar shows the standard deviation of the dose distribution σ_d. It becomes about 2% in flat dose region. Relationship between position error σ_s and lateral dose distribution error σ_d is shown in Fig. 3(b). Almost linear relationship is observed.

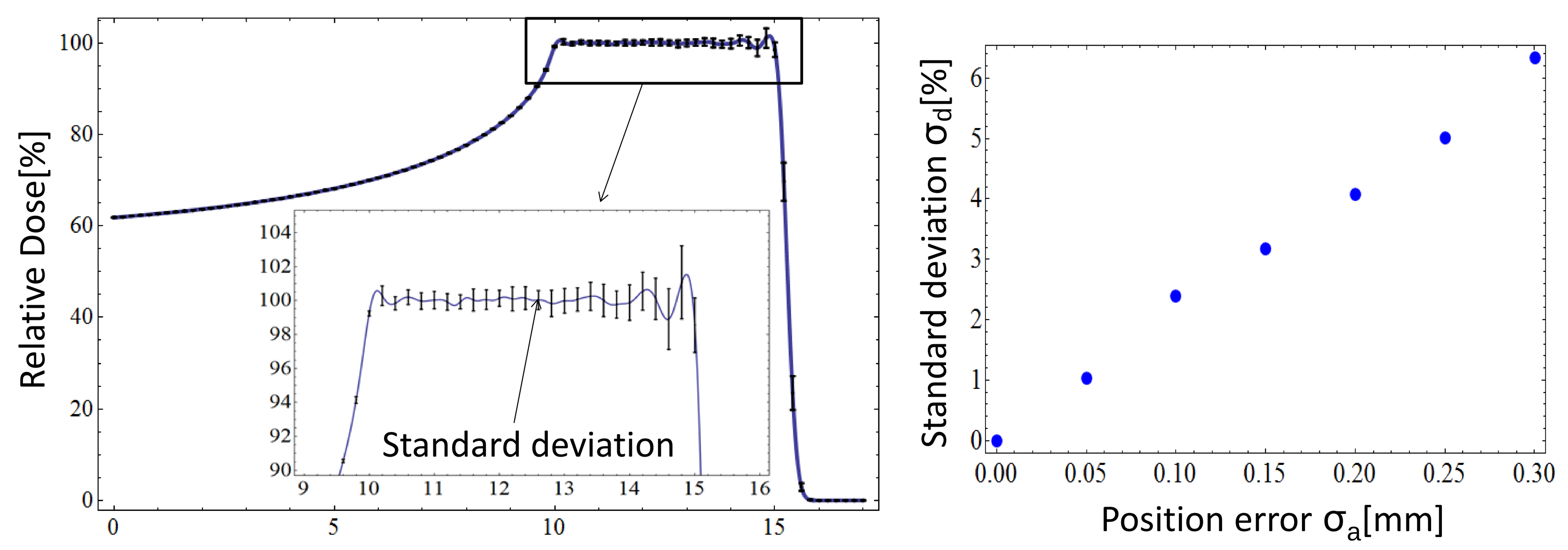
Fig. 4 shows the result of depth dose distribution and standard deviations. In this case, 19 energy layers was adopted to form 5cm SOBP. Fig. 4(a) shows the typical result of depth dose distribution with range error σ_a = 0.2 mm. Again error bar shows the standard deviation of the dose distribution σ_d. It gradually becomes larger and is up to 4% in the deepest region. It is because beam weight w_k becomes larger for the deeper layers with small number of overlaps of other layers. Relationship between range error σ_a and depth dose distribution error σ_d is shown in Fig. 4(b). Almost linear relationship is observed.



(a) An example of lateral dose distribution and standard deviations with position error σ_s = 0.5mm

(b) Relationship between position error σ_s and lateral dose distribution error σ_d at the center of target region

Fig. 3 Result of lateral dose distribution and standard deviations



(a) An example of depth dose distribution and standard deviations with position error σ_a = 0.2mm

(b) Relationship between position error σ_a and depth dose distribution error σ_d at the deepest position of SOBP region

Fig. 4 Result of depth dose distribution and standard deviations

4. Conclusions

We have developed a statistical method to calculate the standard deviation of the dose distribution error caused by spot position error in the target region. Typical results are shown for both lateral and depth dose distributions. Relationship between spot position error and dose distribution error becomes almost linear and standard deviations of the dose distribution errors are estimated quantitatively. This method can be used for evaluation of the system performance and robustness and also used for performance assessment and QA of the spot scanning system.

References

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