

# Computerized Determination of Robust Beam Directions Against Patient Setup Errors in Hadron Particle Therapy

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**Abstract.** We have proposed a computerized method for determination of robust beam directions against patient setup errors using electron density (ED)-based beam's eye view (BEV) in hadron particle therapy. The basic idea of our proposed method was to find the robust beam directions, whose ED-based BEV image has spatial fluctuations with low spatial frequency and small amplitude. The proposed method was applied to four head and neck cancer patients for evaluation of the proposed method. As a preliminary result, radiation oncologists agreed with most beam directions, which seem to be robust against patient setup errors, suggested by the proposed method. Our proposed method could be feasible to determine the robust beam directions against patient setup errors in hadron particle therapy.

**Keywords:** hadron particle therapy, robust beam direction, electron density (ED)-based beam's eye view (BEV) image, Fourier analysis

## 1 Introduction

Proton therapy or heavy ion therapy (carbon ion) has the physical ability to increase the high dose delivered to tumors while achieving a very low dose to normal tissue [1,2]. In particular, the highly-ionizing property of the heavy ion charged particles, i.e., higher linear energy transfer (LET), leads to eventual tumor cell death with higher tumor control probability than conventional radiotherapy of X-rays or electrons from the biological point of view.

In the hadron particle therapy, the distal end shape of dose distribution is modulated by a passive or active beam shaping method according to beam's eye view (BEV) of a 3D electron density (ED) map of a computed tomography (CT) image for each patient. However, the accurate dose distributions produced by the hadron particles

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may be very sensitive to patient setup errors [3-9] occurring in a lateral direction orthogonal to the beam direction. If the patient setup errors are not taken into account during the treatment planning, the actual dose distribution that would occur in the patient during treatment could be strongly degraded compared with the planned dose distribution. In other words, due to patient setup errors, the distal end of the dose distribution in a beam direction could not be fitted with that of a tumor shape if the ED-based BEV in the beam direction changed more abruptly (high frequency fluctuation) with large amplitude fluctuation. This incident could lead to significant tumor underdose, but fatal overdose in organs at risk.

The goal in this study was to develop a computerized method for determination of robust beam directions against the patient setup errors based on the ED-based BEVs in the beam direction in the hadron therapy.

## **2 Materials and methods**

### **2.1 Overall procedure**

The proposed method mainly consisted of the following two steps: (1) production of a beam's eye view (BEV) image by projecting a 3D electron density image from a particle source to a planning target volume (PTV) distal end, (2) determination of robust beam directions against patient setup errors by using the slope of the power spectrum.

### **2.2 Clinical cases**

Radiation treatment planning (RTP)-CT (referred to as planning CT) images of four head and neck cancer patients (ages: 48-85; median: 64.5) who had undergone conventional x-ray radiotherapy at our institution were selected for determination of the robust beam directions. All patients were scanned to acquire planning CT images (pixel size: 0.59 mm x 0.59 mm, depth bits per pixel: 16) using a 4-slice CT scanner (Mx 8000, Philips, Amsterdam, The Netherlands) with a slice thickness of 3.0 mm. Contours of clinical target volumes (CTV) of head and neck cancers were manually outlined by radiation oncologists on the planning CT images using a commercially available RTP system (Eclipse, Varian Medical Systems Inc., Palo Alto, USA).

### **2.3 Determination of robust beam directions against patient setup errors by using the slope of the power spectrum**

The fundamental idea of our proposed method was to find the robust beam directions whose ED-based BEV images had spatial fluctuations with low spatial frequency and small amplitude. A BEV image was produced by projecting a 3D electron density image in a beam direction from a particle source to the distal end of a planning target

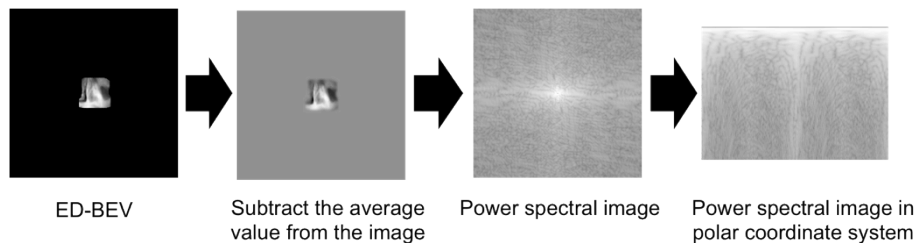
volume (PTV). Power spectra of the ED-based BEV images in all directions, i.e., 0 to 355 degrees, with an interval of 5 degrees were calculated for evaluation of the spatial fluctuations in the ED-based BEV images in a beam direction. We assumed that as the average spatial frequency and amplitude of the fluctuation in the ED-based BEV images in a beam direction become lower and smaller, respectively, the absolute value of the slope of the power spectrum becomes larger. Therefore, the slopes of one-order polynomial of the power spectra were calculated for determination of the robust beam directions.

Prior to calculation of the power spectral images, the ED-based BEV images were preprocessed as follows. First, the pixel values outside the irradiation field were assigned the average pixel value of the ED-based BEV inside the simulated irradiation field for decreasing the difference in the pixel value between inside and outside of the irradiation field. Second, a Gaussian filter was applied to inner and outer narrow bands (10 pixels) apart from the edge of the ED-based BEV for reducing the higher frequency components in the power spectrum, which were not related to the ED-based BEV. Third, a mean value in the ED-based BEV image was subtracted from the image to remove the influence of the mean value of the power spectral image.

Fourth, a power spectral image was calculated by using two-dimensional Fourier transformation from the preprocessed image. The power spectral image in the Cartesian coordinate system was converted to the polar coordinate system, which has the horizontal axis of the angle and the vertical axis of the spatial frequency. The power spectral image was integrated over a range of angles from 0 to 360 degrees to calculate the slope of an average power spectrum by using the following equation:

$$G(f) = \int_0^{360} \ln P(f, \theta) d\theta, \quad (1)$$

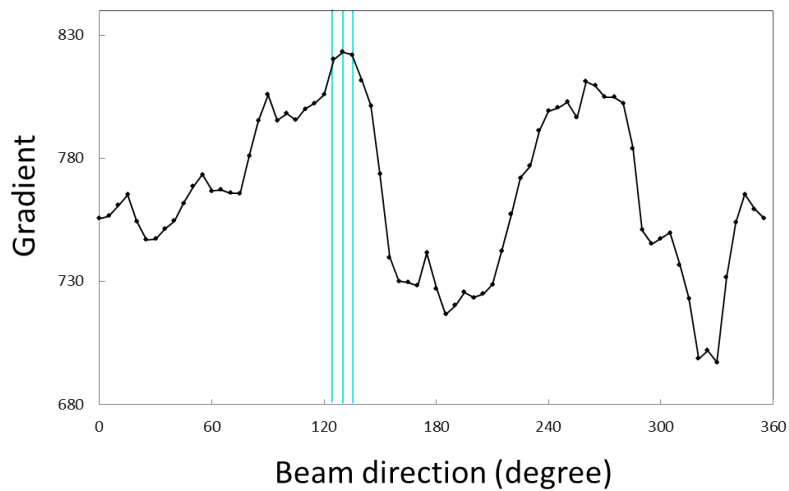
where  $f$  is the spatial frequency (mm<sup>-1</sup>), and  $\theta$  is the angle (degree) in the power spectral image. The slope of the average power spectrum was evaluated as the slope of a one-order polynomial of the power spectrum from 0.0195 mm<sup>-1</sup> to a Nyquist frequency, which was calculated by a least square method. The slopes were calculated in all directions (0 to 355 degrees) with an interval of 5 degrees. Finally, the robust beam directions against patient setup errors were determined by selecting the directions corresponding to the several largest gradients of average power spectra for all beam directions. Figure 1 shows the resulting images in the major steps of the proposed method.



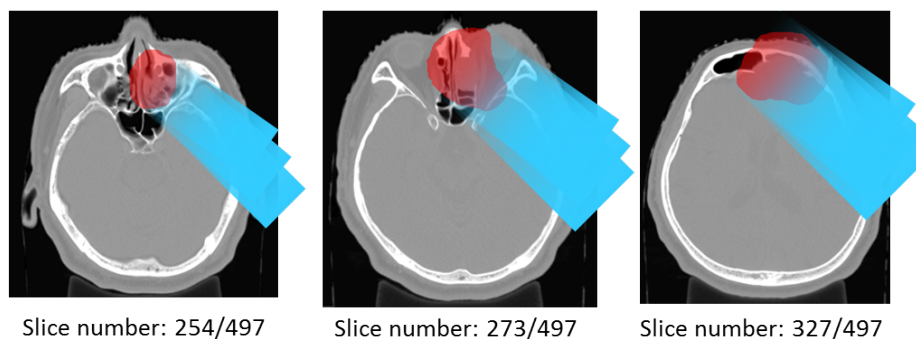
**Fig. 1.** Resulting images in the major steps of the proposed method.

### 3 Results and discussion

We applied the proposed method to four head and neck cancer cases and detected the beam directions. Nine beams of 13 beams (69%), which were used for the four patients in clinical practice, would be theoretically acceptable from the robustness point of view against the patient setup error. Figure 1 shows an example of the slope of the average power spectra as a function of beam direction, and the detected beam directions of 0 to 355 degrees are indicated by blue lines. Figure 2 shows the robust beam directions determined by the proposed method on three CT slices for a case. Each red region shows a PTV region, and each light blue region shows the beam path. In this case, 125, 130, and 135 degrees were considered as the robust beam directions. In a discussion of the results with radiological oncologists, all the oncologists agreed with most of the optimum beam directions determined by the proposed method. The suggested beam directions were close to those employed as one of beam directions in clinical practice.



**Fig. 2.** Slope of average power spectral value as a function of the beam direction (0 to 355 degree).



**Fig. 3.** Robust beam directions determined by the proposed method on three CT slices for a case by selecting the directions corresponding to the three largest slopes of average power spectra for all beam directions.

## 4 Conclusions

We have proposed a computerized determination of robust beam directions against patient setup errors based on Fourier analysis of ED-based BEVs in hadron particle therapy. The proposed method could be useful to select the robust beam directions against patient setup errors in hadron particle therapy such as carbon ion therapy.

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