In this study, we developed an automated method for determination of robust beam directions against the patient setup error based on the electron (ED)-based beam's eye view (BEV) in the beam direction in the particle therapy. The basic idea of our approach was to find the robust beam directions, whose ED-based BEV has low special frequency variation with small amplitude.

**Electron density based beam's eye view:** The ED-based BEV was produced by projection of the 3D electron density map derived from the CT image from a beam source to the distal end of a planning target volume (PTV). Figure 1 (a) shows PTV region from BEV and Figure 1 (b) shows the ED-based BEV including "simulated irradiation field" with a PTV shape from the beam's eye view and non-irradiation field (black region). The simulated irradiation field was considered as the irradiation field if the particle therapy was performed to the patient.

**Determination of robust beam directions against patient setup errors using gradients of power spectra:**
We assume that as the spatial frequency and amplitude of the variation in the ED-based BEV in a beam direction is lower and smaller, respectively, the gradient of the power spectrum becomes larger, which means the robust beam direction. Before calculating power spectrum, some preprocesses were applied to ED-based BEV images. First, a circumscribed quadrangle of the ED-based BEV was cropped, and it was enlarged to 512x512 for applying fast Fourier transformation. Second, the pixel values outside the non-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. Third, a Gaussian filter was applied to inside and outside of 10 pixels 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. Fourth, a power spectral image was calculated by using two-dimensional Fourier transformation from the preprocessed image. Fifth, the 2D power spectral image in Cartesian coordinate system was converted to the polar coordinate system, which has the horizontal axis of angle and the vertical axis of spatial frequency. The power spectral value of the image was integrated by the angle direction. We obtained a relationship between the spatial frequency and the integral of the 2D power spectral image by the angle, i.e., 1D power spectrum. Sixth, the gradient of the 1D power spectrum was calculated as the slope of a one-order polynomial with the power spectral values for all frequencies until a Nyquist frequency. The gradients were calculated in all directions (0 to 355 degree) with an interval of 5 degree. Finally, the robust beam directions against patient setup errors were determined by selecting the directions corresponding to the three largest gradients of 1D power spectra for all beam directions.

**Important results:**
We applied the proposed method to four head and neck cancer cases and detected beam directions. Figure 2 (a) shows the gradients of 1D power spectra in beam directions of 0 to 355 degree, and Figure 2 (b) 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 beam path. In this case, 80, 85, and 275 degrees were considered as the robust beam directions. As a discussion of the results with a radiological oncologist, they agreed with most beam directions determined by the proposed method, which seems to be robust against patient setup errors.
Fig. 1 (a) Digital reconstructed radiography (DRR) including a PTV projection (red) from a beam's eye view when the gantry angle was 0 degree. (b) An ED-based BEV including “irradiation” field with a PTV shape from a beam's eye view and non-irradiation field (black region) when the gantry angle was 0 degree.

Fig. 2 (a) Gradients of 1D power spectra in beam directions of 0 to 355 degree. (b) Robust beam directions determined by the proposed method on three CT slices for a case. In this case, 80, 85, and 275 degrees were considered as the robust beam directions.