**Original Article**

# Impact of the Respiratory Motion and Longitudinal Profile on Helical Tomotherapy

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The TomoTherapy® beam-delivery method creates helical beam-junctioning patterns in the dose distribution within the target. In addition, the dose discrepancy results in the particular region where the resonance by pattern of dose delivery occurs owing to the change in the position and shape of internal organs with a patient's respiration during long treatment times. In this study, we evaluated the dose pattern of the longitudinal profile with the change in respiration. The superior-inferior motion signal of the programmable respiratory motion phantom was obtained using AbChes as a four-dimensional computed tomography (4DCT) original moving signal. We delineated virtual targets in the phantom and planned to deliver the prescription dose of 300 cGy using field widths of 1.0 cm, 2.5 cm, and 5.0 cm. An original moving signal was fitted to reflecting the beam delivery time of the TomoTherapy®. The EBT3 film was inserted into the phantom movement cassette, and static, without the movement and with the original movement, was measured with signal changes of 2.0 s, 4.0 s, and 5.0 s periods, and 2.0 mm and 4.0 mm amplitudes. It was found that a dose fluctuation within ±4.0% occurred in all longitudinal profiles. Compared with the original movement, the region of the gamma index above 1 partially appeared within the target and the border of the target when the period and amplitude were changed. Gamma passing rates were 95.00% or more. However, cases for a 5.0 s period and 4.0 mm amplitude at a field width of 2.5 cm and for 2.0 s and 5.0 s periods at a field width of 5.0 cm have gamma passing rates of 92.73%, 90.31%, 90.31%, and 93.60%. TomoTherapy® shows a small difference in dose distribution according to the changes of period and amplitude of respiration. Therefore, to treat a variable respiratory motion region, a margin reflecting the degree of change of respiration signal is required.

Keywords: TomoTherapy®, 4D CT, Moving phantom, Period, Amplitude

## Introduction

Intensity modulated radiation technique of Tomo-Therapy® is specified by binary multi-leaf collimator (MLC) and simultaneously synchronous motion of gantry rotation and couch movement.[1] Through this beam delivery technique, conformity and homogeneity of target has been increased, while the dose of near-by organ at risk (OAR) decreased. Therefore, the effectiveness of radiation therapy becomes better and more efficient.[2] In addition, equipped with dynamic jaws in the unit, TomoEDGE®, the region of longitudinal penumbra has dramatically been reduced, which improves the dosimetric advantages and conformal dose distribution as well.[3] Owing to helical beam delivery, however, the dose distribution in target has junctioning patterns and threaded effect. Moreover, compared with

volumetric arc therapy (VMAT), treatment time is usually longer, which would affect the dose distribution, and especially be sensitive to respiratory motion.

The tumor motion attributed to respiration provides the differences between treatment planning and actual delivered dose distribution because of its complexity and interplay.[4-6] Accordingly, target margin would be widely applied. The field margin is occasionally considered because the difference of dose distribution by the organ motion is caused by field width of the TomoTherapy®.[7] The characteristics of dose distribution can be revised using the machine parameters and treatment planning. In the other hands, the deformation and reposition of organs by respiratory motion would provide dose uncertainty, thereby, discrepancy between planned and actual dose. Furthermore, the resonance of periodic motions of gantry, couch, and respiration would sometimes give a worse influence as well. In IMRT beam delivery that consists of small sub-fields of beamlets, besides, dose uncertainty from respiratory motion could be enhanced.

In this study, we evaluated the longitudinal dose profile attributed to respiratory motion in the treatment using TomoTherapy®.

## Materials and Methods

### 1. Acquisition of respiratory signal and beam delivery on moving phantom

For the phantom study, QUASAR™ programmable respiratory motion phantom (Modus Medical Devices Inc. London, Ontario, Canada) was used. 4D CT scan was performed with 3 mm-thick slice and respiratory signal was programed and transferred to Toshiba CT scanner (Toshiba Medical Systems, Otawara, Japan) using the signal generated by Abches system (APEX Medical Inc., Tohyo, Japan) as shown in Fig. 1. 4D CT scan was reconstructed with the 10 phases. In order to obtain the moving images and to delineate the target, the wire was inserted within the film cassette to indicate targets. Based on the acquired CT scan, treatment plan was computed with TomoTherapy H™ Series planning station (TomoTherapy Inc., Madison, WI, USA). Especially, 4D plan was considered by the delineations of two targets on every 10 phases' CT scans, which had cylindrical shapes with the diameter of 3 cm and height of 6 cm, which were named by target 1 and 2 (Fig. 2(a)). The target 2 was just used for the beam modulation,



**Fig. 1.** The setup of QUSAR phantom and Abches system for acquiring the motion signal.
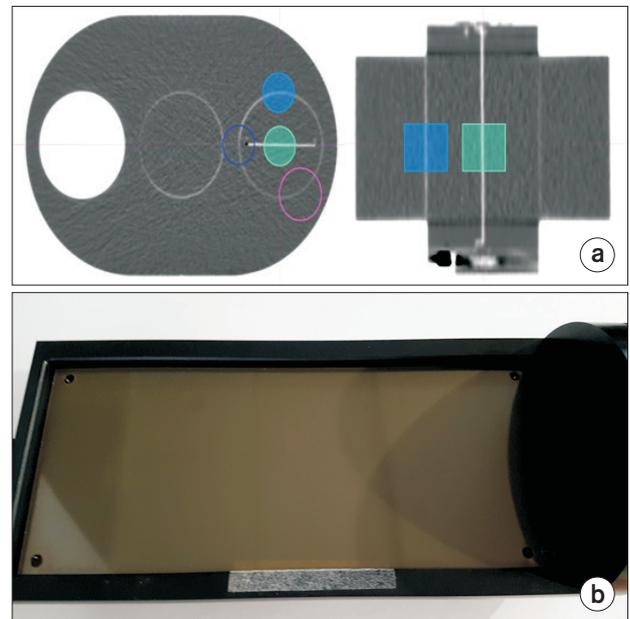


**Fig. 2.** (a) Target 1 and Target 2 of 3.0 cm diameter and 6.0 cm length in a QUASAR™ phantom film cassette and Organs at Risk (OARs); (b) EBT3 film inserted in film cassette.

and was not for the dose distribution. In addition to the delineation of targets, adjacent organ at risk (OAR) was contoured as well. Treatment plans was computed with field width of 1.0, 2.5, 5.0 cm and every plans with 0.287 pitch and 2 modulation factor. Prescribed dose was 3.0 Gy on both targets with 10 fractions.

Generally, the TomoTherapy® takes a long time than the computed tomography (CT) simulation. To consider the real treatment environment, instead of programed signal, we were applied the surrogation obtained from AbChes, which were re-processed using Matlab version R2010a (The MathWorks Inc., Natick, MA) to cover the time range of treatment with the same respiratory period and fitted by up to $7^{th}$ order of Gaussian function as follows:

$$f(t) = a_0 + a_1\cos(t+\omega) + b_1\sin(t+\omega) + a_2\cos(2t+\omega) + b_2\sin(2t+\omega) + ... + a_6\sin(6t+\omega) + b_6\cos(6t+\omega) + a_7\sin(7t+\omega) + b_7\cos(7t+\omega) \quad (1)$$

where coefficients, $a_0$-$a_7$ and $b_1$-$b_7$ can be determined by fitting, t and $\omega$ mean the time and angular frequency.

## 2. Measurement and analysis of the profile along longitudinal direction

The EBT3 film was inserted into film cassette of QUASAR™ phantom described in Fig. 2(b). The measurement were made with the condition of "static" which represents no respiratory motion and "dynamic" which consists of 6 different conditions: phantom original movement acquired from CT simulation, movement changed of 3 respiratory periods (2.0, 4.0, 5.0 second) and 2 amplitudes (2.0, 4.0 mm). Moreover, we applied 3 different field width (1.0, 2.5, 5.0 cm) where 3 different monitor units (MU), 5198 MU, 2703 MU, and 1898 MU were delivered respectively. Measured films were analyzed by RIT113 ver. 6.3 software (@2014, USA) with constant region of interest (ROI), 3 cm×3 cm square. The longitudinal profiles by dynamic
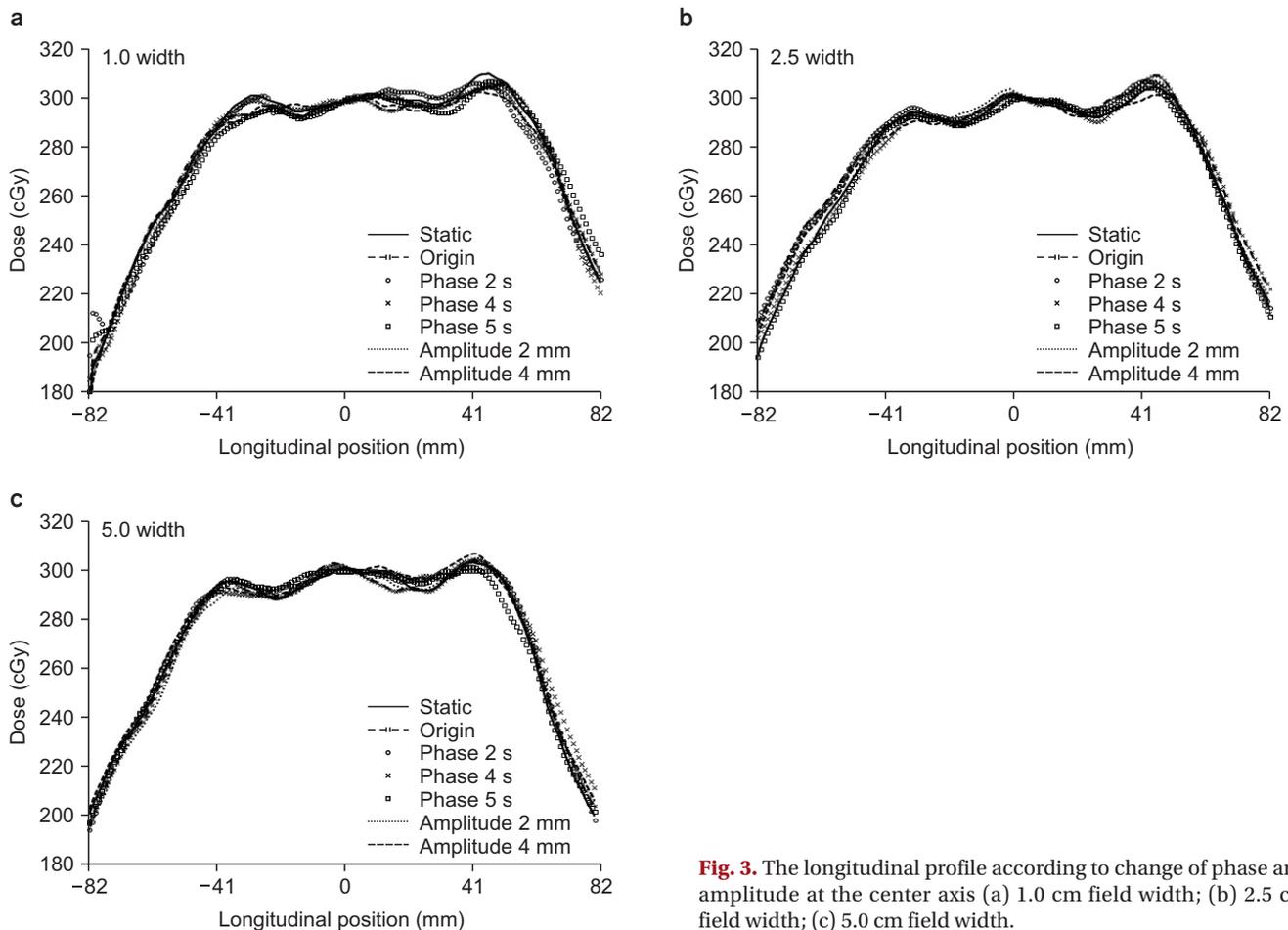


**Fig. 3.** The longitudinal profile according to change of phase and amplitude at the center axis (a) 1.0 cm field width; (b) 2.5 cm field width; (c) 5.0 cm field width.

conditions were compared with the static condition. And then, to evaluate the effects of dose distributions according to the change of motion signal, the original movement and modified movement were compared by using gamma passing rate and gamma index. The gamma passing rate with the criteria of 3.0%/3.0 mm and gamma index were analyzed. The gamma index above 1 means that there were 3.0% or more dose differences between both dose distributions.

## Results

### 1. Longitudinal profile of QUASAR phantom

The residual sum of square (R-square) was obtained from the respiratory curve fitted by equition1. The R-square was 0.992 as goodness of fit that the fitting curve was similar to the original curve. Compared with static, the longitudinal

profiles of dynamic movements were measured with a little dose fluctuation less than 4% within target 1. In Fig. 3, longitudinal profile crossing a center of target is shown, where, (−) and (+) mean the superior and inferior direction of phantom, respectively. When the amplitude was changed, the variation of profiled along central axis was compared with static case. That had been found up to 3.04%, −3.77% and −3.97% in the target border area corresponding to 1.0, 2.5, and 5.0 cm field widths, respectively. In addition, two profiles measured with different amplitudes showed the percentage differences of up to −2.02%, −4.00% and −3.31% for the jaw field sizes of 1.0, 2.5, and 5.0 cm, respectively.

Dose difference (X, −X) in the longitudinal profile of regions, where were shifted 1.5 cm left and right from center of the target, showed the values of up to (3.07%, −4.05%), (−3.71%, −4.02%) and (−3.97%, −2.02%), respectively (Fig. 4, 5).
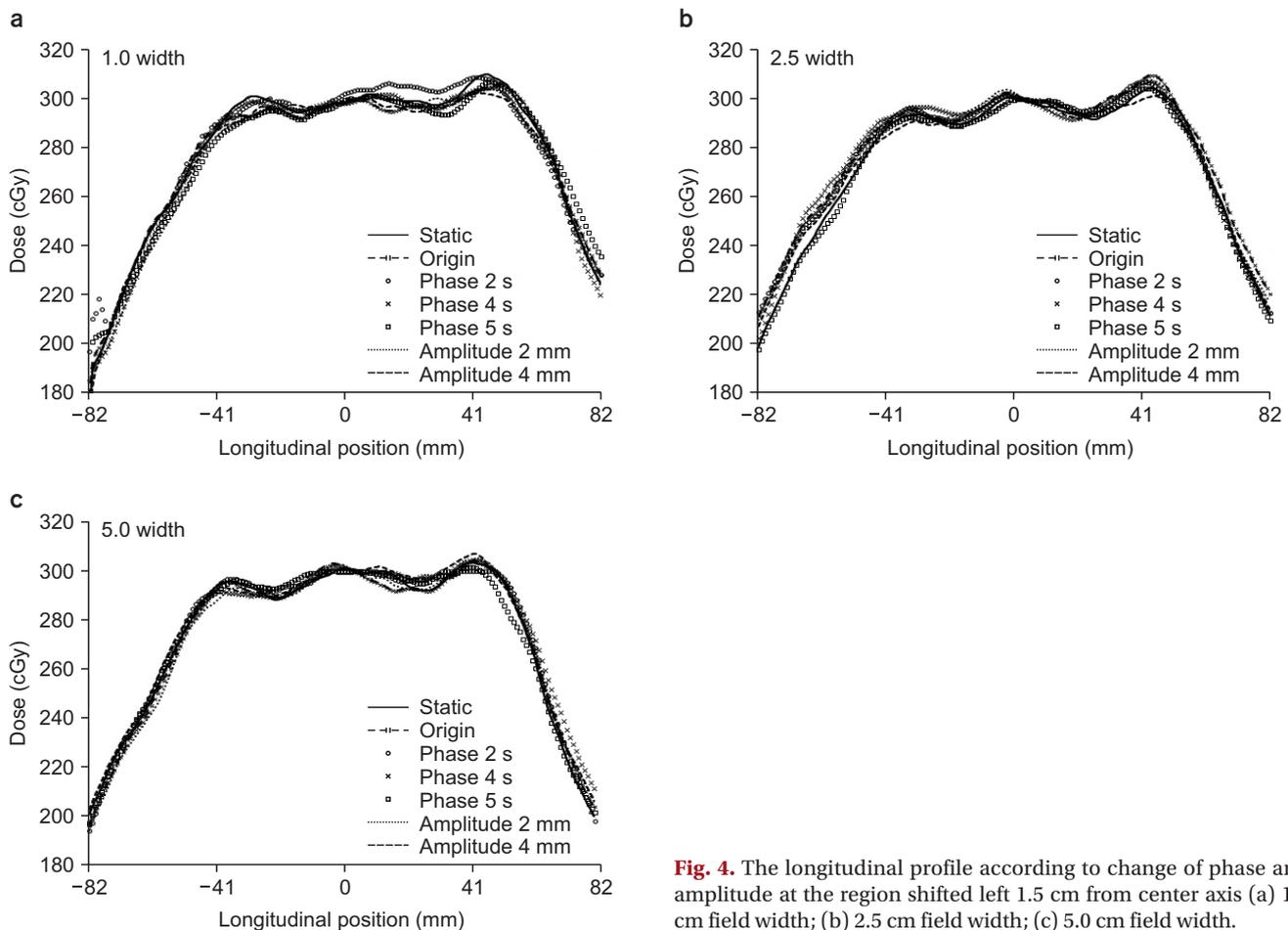


**Fig. 4.** The longitudinal profile according to change of phase and amplitude at the region shifted left 1.5 cm from center axis (a) 1.0 cm field width; (b) 2.5 cm field width; (c) 5.0 cm field width.

a



b

c
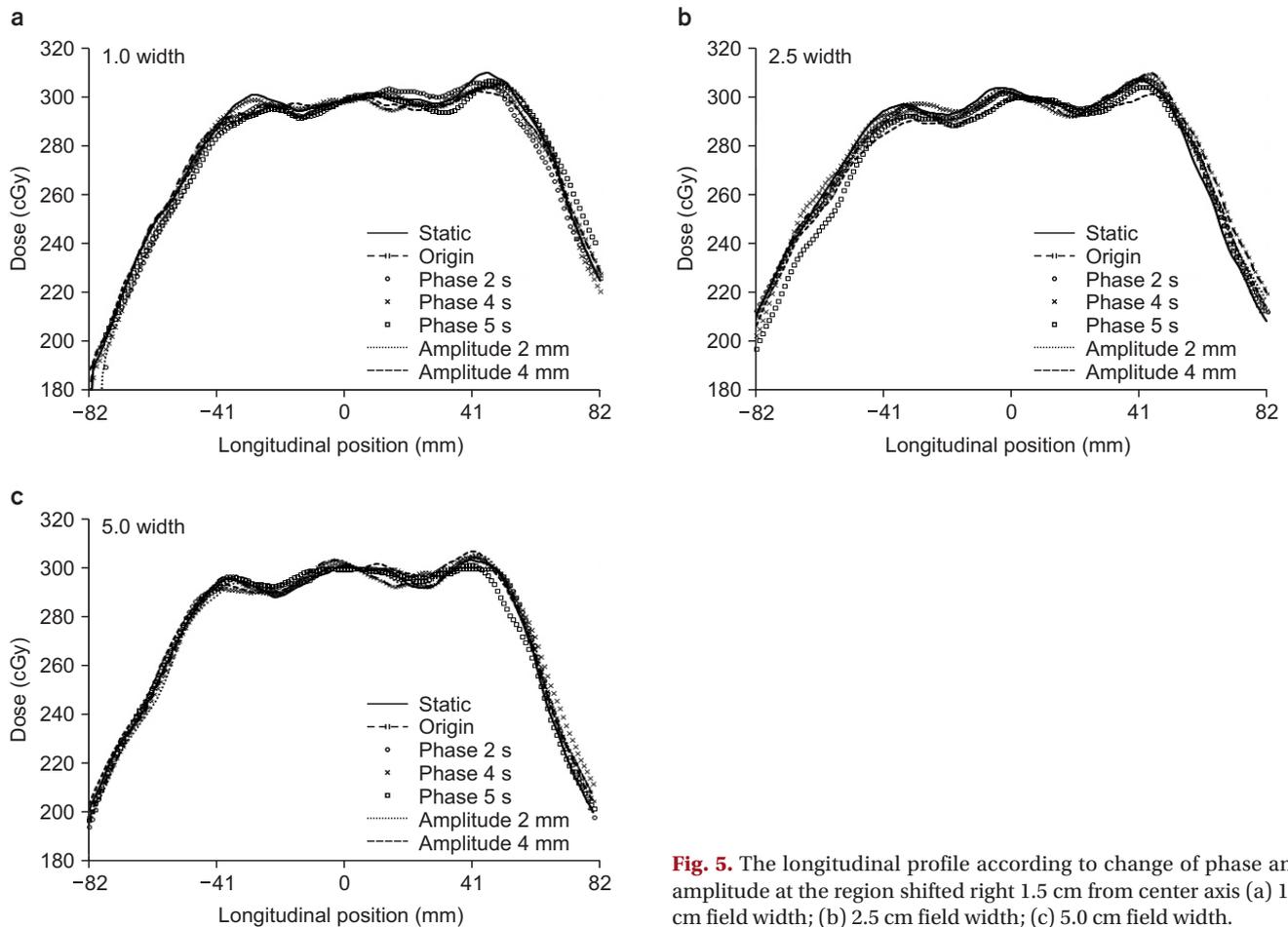


**Fig. 5.** The longitudinal profile according to change of phase and amplitude at the region shifted right 1.5 cm from center axis (a) 1.0 cm field width; (b) 2.5 cm field width; (c) 5.0 cm field width.

## 2. Gamma passing rates on target area with respiratory motions

Table 1 shows the gamma passing rates for the target region when the signal is changed compared to the original phantom movement. Gamma passing rates almost have 95.00% or more. However, cases for 5.0 s period and 4.0 mm amplitude at 2.5 cm field width represent the gamma passing rate of 92.73% and 90.31%, cases for 2.0 s and 5.0 s period at 5.0 cm in field width have 90.31% and 93.60% respectively. Fig. 6 shows the 2D gamma index map with 5.0 s period and 4.0 mm amplitude which have the greatest change in period and amplitude. When the period changes, the regions with gamma index above 1 appear (red) within the target. At the time of amplitude change, the area of gamma index 1 or more appears at the border of the target region except for the case of 4.0 mm amplitude on the 2.5 cm field width.

**Table 1.** Gamma passing rates within the target for each period and amplitude according to field width compared with original movement.

|  | Field width | | |
|---|---|---|---|
|  | 1.0 cm | 2.5 cm | 5.0 cm |
| 2.0 s Period | 95.50% | 97.87% | 90.31% |
| 4.0 s Period | 97.79% | 96.11% | 97.08% |
| 5.0 s Period | 95.52% | 92.73% | 93.60% |
| 2.0 mm Amplitude | 97.92% | 97.10% | 98.71% |
| 4.0 mm Amplitude | 96.15% | 90.31% | 95.21% |

## Discussion and Conclusion

TomoTherapy® improves the conformity and homogeneity within the target through continuous movement of couch, gantry and MLC. It also reduces the dose to adjacent OARs.

In addition, accurate positioning and setup of the patient is possible using MVCT. However, since TomoTherapy®
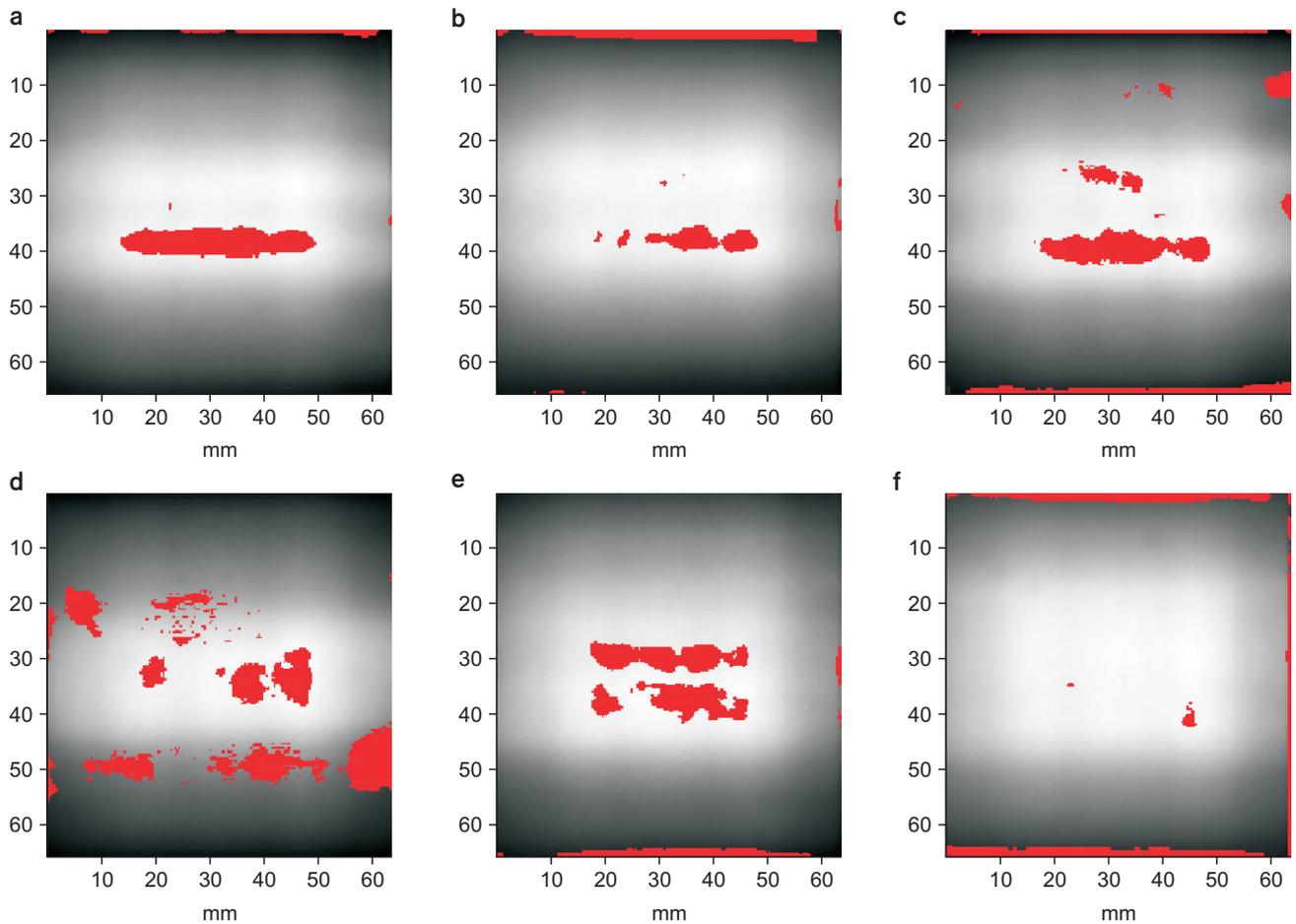
**Fig. 6.** 2D gamma index map (a) 5.0 s period, 1.0 cm field width; (b) 4.0 mm period, 1.0 cm field width; (c) 5.0 s period, 2.5 cm field width; (d) 4.0 mm period, 2.5 cm field width; (e) 5.0 s period, 5.0 cm field width; (f) 4.0 mm period, 5.0 cm field width; Red (dark): Gamma index >1.

has not control system which is possible to considering the respiration of patients such as gating radiotherapy, it is necessary to consider the margin of target or the system for respiration control such as Deep-inspiration Breath Hold (DIBH). In this study, we assessed the dose effect of TomoTherapy® on the longitudinal direction of the target when different respiratory periods or phases were applied to the original respiration according to each field width. The period of 2.0 s, 4.0 s, 5.0 s and amplitude of 2.0 mm and 4.0 mm were changed in the original respiratory, respectively. Analysis results of the measured EBT3 film showed that non-uniform profile was formed regardless of the field width when the same respiration signal was given. This is because the narrow slit beam of TomoTherapy® crosses the target of the patient. M.W. Kissick et al.[8] have proposed a factor of 0.86 to reduce the thread effect of the

"ripple" (peak to trough relative to the average) and helical beam junctioning patterns occurring in the beam-axis profile. However, this factor is reflected in TomoTherapy® planning system. In actual treatment, patient's respiratory pattern can act as a modulation factor in dose distribution. However, from the results of gamma passing rates of more than 95.0%, there is no significant difference in dose distribution, even though there may be dose fluctuations in one axis of the longitudinal direction by change in respiration relative to the original respiratory signal. When the motion was changed by 2.0 s period applied to the 2.5 cm field width, the dose difference of longitudinal profile of the center axis within the target is assumed to be a random error in the gamma passing rate range of 97.87% (Fig. 2(a), Table 1). It was confirmed that the gamma index in the target showed a value of 1 or more when the period

was changed. The reason is considered to be a regional resonance phenomenon that can occur when the target motion frequency and the helical beam frequency coincide with each other. When the amplitudes were changed, it was confirmed that 1 or more gamma index were mainly shown in the border region of the target except one or more gamma index in the target of 2.5 cm field width. However, it is difficult to identify a uniform pattern through this study. Because the change of respiration was selectively variated, the dose distribution around the target was not analyzed due to the size limitation of the film cassette in the phantom. In addition, phantom motion was restricted to the superior-inferior direction and did not show anterior-posterior and left-right changes. Study showed that changes in the original respiratory motion signal do not significantly affect overall dose delivery. However, even though TomoTherapy® plan defines target and movement in 10 phases of respiration, changes in respiratory period and amplitude can make areas under or over dose in target area.

Therefore, in order to treat a variable-motion region using TomoTherapy®, a target margin reflecting the degree of change of periode and amplitude from original respiratory signal may be considered for the accurate radiation treatment.

## Acknowledgements

## Conflicts of Interest

The authors declare no conflict of interest.

## Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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