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Quantitative Evaluation of Patient Positioning Error Using CBCT 3D Gamma Density Analysis in Radiotherapy

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Radiotherapy patients should maintain their treatment position as patient setup is very important for accurate treatment. In this study, we evaluated patient setup error quantitatively according to Cone-Beam Computed Tomography (CBCT) Gamma Density Analysis using Mobius CBCT. The adjusted setup error to the QUASAR™ phantom was moved artificially in the superior and lateral direction, and then we acquired the CBCT image according to the phantom setup error. To analyze the treatment setup error quantitatively, we compared values suggested in the CBCT system with the Mobius CBCT. This allowed us to evaluate the setup error using CBCT Gamma Density Analysis by comparing the planning CT with the CBCT. In addition, we acquired the 3D-gamma density passing rate according to the gamma density criteria and phantom setup error. When the movement was adjusted to only the phantom body or 3 cm diameter target inserted in the phantom, the CBCT system had a difference of approximately 1 mm, while Mobius CBCT had a difference of under 0.5 mm compared to the real setup error. When the phantom body and target moved 20 mm in the Mobius CBCT, there are 17.9 mm and 13.5 mm differences in the lateral and superior directions, respectively. The CBCT gamma density passing rate was reduced according to the increase in setup error, and the gamma density criteria of 0.1 g/cc/3 mm has 10% lower passing rate than the other density criteria. Mobius CBCT had a 2 mm setup error compared with the actual setup error. However, the difference was greater than 10 mm when the phantom body moved 20 mm with the target. Therefore, we should pay close attention when the patient's anatomy changes.

Keywords: Mobius CBCT, Setup error, 3D Gamma Density Analysis, Gamma density passing rate, CBCT

Introduction

Radiotherapy goes through various stages, such as acquisition of patient images, a treatment plan, verification of patient setup, radiotherapy, etc. To accurately and precisely deliver dose to tumor, the patient position is an important element in each stage of the process. Currently, intensity-modulated radiotherapy (IMRT) and similar methods that deliver a dose to a tumor are optimized for its size and shape. Stereotactic body radiotherapy (SBRT), stereotactic radiosurgery (SRS), and similar technologies that deliver dose to tumor for each fraction are premised on the accuracy of the patient's position so that the risks from radiotherapy are minimized and the treatment efficiency is high.[1,2)]

When radiotherapy was first being used, film or two-dimensional images were used to check the accuracy of the patient treatment setup. Currently, the patient position and treatment setup is evaluated in 3 dimensions using Cone Beam Computerized Tomography (CBCT) images acquired through an On-board Imager (OBI). Differences in the X, Y, and Z axes, as well as yaw, are supplied, and the treatment table is moved as required. The axis directions and angles considered are used simultaneously in the treatment plan and radiotherapy.[3-11)] Further, body surface outline scanning based patient position setup technologies have been developed by C-RAD Corporation's Sentinel 4DCT (C-RAD AB, Uppsala, Sweden), VisionRT Corporation's AlignRT (VisionRT, London, United Kingdom), etc., and are used to verify the patient treatment position, but image matching using CBCT images is primarily used in the radiation therapy field. However, CBCT uses manual operations or automatic algorithms on the CT images used in treatment plans. Differences are produced through image matching. The disadvantage is that only information on the axis directions is given, and the difference cannot be evaluated quantitatively. More recently, using the method of Gamma Density Analysis on these types of CBCT images, algorithms have been developed that can quantitatively analyze CT images and CBCT images used for treatment planning. In addition, the technology has become commercialized.[12)] In this paper, a quantitative analysis of patient position errors using the existing method of Gamma Density Analysis was compared with existing CBCT image correction programs.

Materials and Methods

1. 3 Dimensional CBCT gamma density analysis

Currently, the role of adjusting the patient's treatment position is being performed by measuring the treatment position and any geometric changes in interior organs through CBCT images. These images are gathered within a scan time of about 60 seconds. Recently, the Mobius CBCT (Mobius Medical Systems, Texas, USA) has been developed by Mobius Medical Systems. This system can evaluate the accuracy of the patient treatment position and region of interest (ROI) through 3D-CBCT Gamma Density Analysis, which compares the image density difference (DD) between the Planning CT image and CBCT image. CBCT Gamma Density Analysis is analyzed through Equation 1 below.

$$r\left(\vec{r}_e\ \vec{r}_r\right)=\sqrt{\frac{r^2\left(\vec{r}_e,\vec{r}_r\right)}{\Delta d^2}+\frac{\rho^2\left(\vec{r}_e,\vec{r}_r\right)}{\Delta P^2}} \quad (1)$$

Here $r\left(\vec{r}_e,\vec{r}_r\right)$ is the spatial distance between the image reference point and the measured point. $\rho\left(\vec{r}_e,\vec{r}_r\right)$ refers to the image DD criterion between the reference point and the measured point. Also, the difference in distance, Δd is the distance to agreement (DTA) criterion, and ΔP is the image DD criterion. The Gamma Density Analysis formulas published by Low DA, Dempsey JF, etc. were modified and used in the Gamma Density Analysis. In particular, instead of the dose difference criterion, the image DD criterion was applied. For each difference in distance, the image DD criterion (g/cc) was used, and the passing rate of the Gamma density criteria was calculated. Using the isodose curve and all target ROI (PTV, CTV, GTV, etc.), the CBCT Gamma density passing rate can be analyzed inside a constant radius from the center of the image. This is different from the method of adjusting the patient's treatment position based on the subjective judgment of an observer of the patient's body structure. Through 3D-CBCT Gamma Density Analysis, changes in the patient treatment position can be measured directly. Also, there is the advantage that the optimized movement distances in the lateral, longitudinal, and vertical directions according to Gamma Density Analysis can be checked. In this research, the Moibus CBCT was used to confirm the technical utility of the patient position setup errors.

2. Phantom experiments

In order to analyze the treatment setup errors in a Mobius CBCT, a QUASAR™ Phantom (Modus Medical Devices Inc., ON, Canada) was moved in the superior and lateral directions for 5, 10, and 20 mm, and a CBCT image was gathered. To artificially generate QUASAR™ phantom setup errors, experiments were carried out in the following three cases. First, the phantom position was fixed, and then the target in the center of the phantom was moved 5, 10, and 20 mm (T_{5mm}, T_{10mm}, and T_{20mm}, respectively) only in the superior direction. Second, the target was fixed, and the phantom's Body was moved 5, 10, and then 20 mm (B_{5mm}, B_{10mm}, and B_{20mm}, respectively) in both the superior and lateral directions. Finally, the phantom's target and the target and body were moved together in the superior and lateral directions for 5, 10, and 20 mm (TB_{5mm}, TB_{10mm}, and TB_{20mm}, respectively). After each translation, a CBCT image was gathered (Fig. 1).

For a quantitative evaluation of the setup error using the Mobius CBCT, in the phantom's artificial setup errors, the gathered CBCT images and the error-free phantom treatment plan-use CT images were matched, and a three-dimensional Gamma Density Analysis was performed. The CBCT Gamma Density Analysis criterion was applied at a DTA criterion of 1, 2, and 3 mm and a DD criterion of 0.1, 0.2, and 0.3 g/cc. The setup errors according to the criteria and changes in the Gamma Density Passing Rate were confirmed. In order to evaluate the suggested setup error analysis function of the Mobius CBCT, a CBCT System from Varian Corporation was used to analyze the proposed setup errors in the acquired CBCT image.

Results

1. Analysis of setup errors

The setup error differences between the CBCT System and the Mobius CBCT system were analyzed. The results show that at the setup origin and at T_{5mm}, T_{10mm}, T_{20mm}, the CBCT System and Mobius CBCT did not produce setup errors. An approximate difference of 1 mm was observed at B_{5mm}, B_{10mm}, and B_{20mm} and at TB_{5mm}, TB_{10mm}, and TB_{20mm} in the CBCT System. In the Mobius CBCT, at B_{5mm} and TB_{5mm}, the difference was under 1 mm. However, a difference of over 1 mm was observed in the case of B_{10mm}, B_{20mm}, TB_{10mm}, and TB_{20mm}. Further, at TB_{20mm}, a difference with real setup errors of 17 mm in the left direction and 11.8 mm in the inferior direction was observed. When the CBCT System and Mobius CBCT moved together by 20 mm, the difference with real setup errors was greatest, and in particular, when they moved to the right, the difference

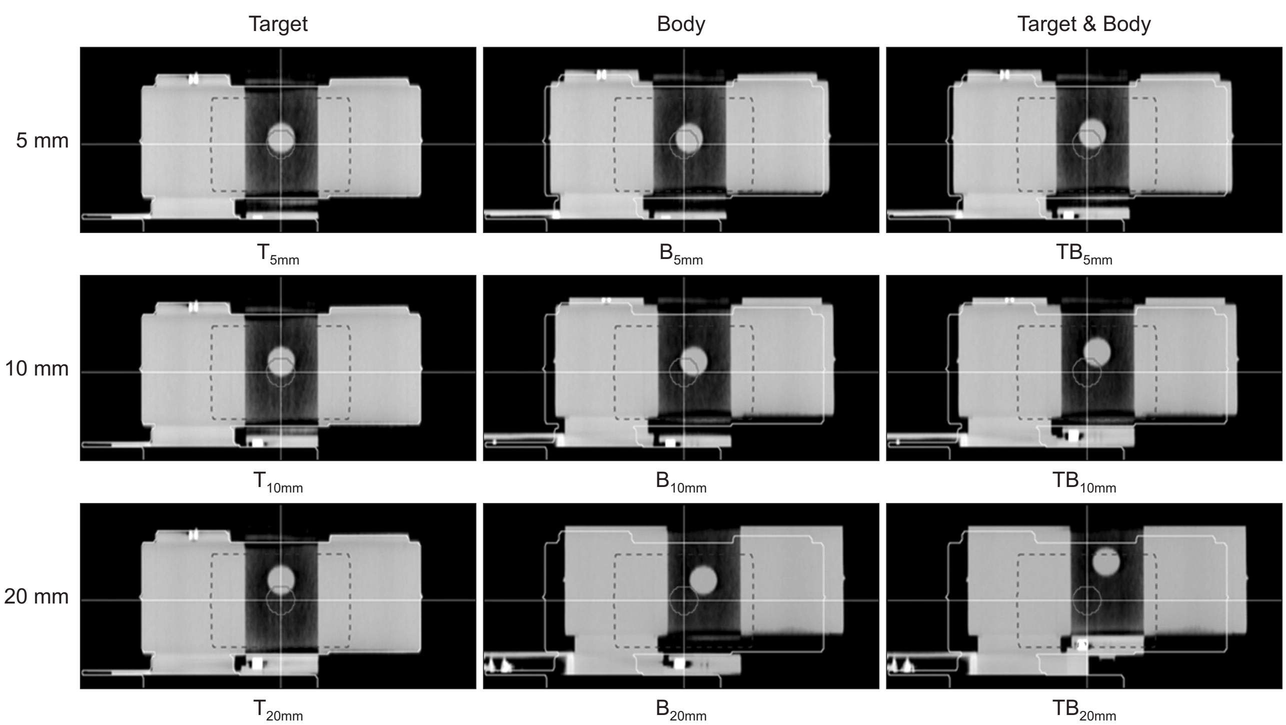

Fig. 1. The CBCT images according to target and phantom movement. Red solid line and blue dashed line indicate the target ROI and CBCT gamma ROI, respectively.

was greatest (Table 1).

In the Mobius CBCT, results from analyzing the setup errors according to the Gamma Density Analysis criterion, DD criteria (0.1, 0.2, 0.3 g/cc), and DTA criterion (1, 2, 3 mm) show that in the case of T_{5mm}, T_{10mm}, and T_{20mm}, and B_{5mm}, B_{10mm}, and B_{20mm}, there was no change in the values of the presented setup errors. However, at TB_{10mm} and TB_{20mm}, for 17 mm in the left direction and 11.8 mm in the inferior direction, there was no change in the values of the proposed setup error. For TB_{5mm}, the value of the proposed setup error was 0 mm with an image DD criterion of 0.1 g/cc and DTA criterion of 1, 2, and 3 mm (Table 2).

Table 1. Additional position shift suggested in CBCT system and Mobius CBCT.

Motion	CBCT system		Mobius CBCT	
	Left (mm)	Inferior (mm)	Left (mm)	Inferior (mm)
Origin	No shift	No shift	No shift	No shift
T_{5mm}				
T_{10mm}				
T_{20mm}				
B_{5mm}	4.0	6.0	5.7	5.4
B_{10mm}	9.0	11.0	10.6	9
B_{20mm}	19.0	21.0	21.3	18.8
TB_{5mm}	4.0	5.0	5.5	5.5
TB_{10mm}	9.0	11.0	11	8.8
TB_{20mm}	19.0	21.0	3	8.2

Origin: No movement, T: target movement, B: body movement, TB: target & body movement, 5: 5 mm movement, 10: 10 mm movement, 20: 20 mm movement.

2. Analysis of the gamma density passing rate

The dependence of the gamma density passing rate on the inter-image density of CBCT images and CT images in the Mobius CBCT was analyzed. For all the cases of T_{5mm}, B_{5mm}, and TB_{5mm} and image DD criteria of 0.2 and 0.3 g/cc, a gamma density passing rate of over 90% was seen. At 0.1 g/cc, a passing rate of over 73% was seen. When the setup error was over 10 mm, the DD criterion was 0.1 g/cc, and the gamma density passing rate was 82%. In particular, in the case of B_{20mm} and TB_{20mm}, it was confirmed that the minimum value was under 10%, while at 0.2 and 0.3 g/cc, it was over 87% (Table 3).

When analyzing CBCT gamma density results, the Mobius Corporation recommends 0.2 g/cc for the image DD criterion and 2 mm for the DTA criterion[16]. Using those recommended values, changes in the gamma density passing rate according to the criteria were verified (Fig. 2).

Table 2. Additional position shift for Target & Body movement 20 mm according to Gamma Density Analysis criteria and DTA suggested in Mobius CBCT.

Density (g/cc)	DTA (mm)	Mobius CBCT	
		Left	Inferior
0.1	1	0.00	0.00
	2	0.00	0.00
	3	0.00	0.00
0.2	1	3.00	8.20
	2	3.00	8.20
	3	3.00	8.20
0.3	1	3.00	8.20
	2	3.00	8.20
	3	3.00	8.20

Table 3. The CBCT gamma density passing rate about Target (T), Body (B) and Target & Body (TB) movement according to DTA and DD.

DD (g/cc)	DTA (mm)	CBCT gamma density passing rate (%)								
		T_{5mm}	B_{5mm}	TB_{5mm}	T_{10mm}	B_{10mm}	TB_{20mm}	T_{20mm}	B_{20mm}	TB_{10mm}
0.1	1	81.4	76.4	73.7	77.9	59.7	40.1	48.6	5.9	5.5
	2	83.2	78.7	76.2	80.1	62.9	43.8	52.4	9.3	8.7
	3	85.1	81.2	79.1	82.5	67.2	50.1	59.1	12.6	11.9
0.2	1	93.7	92.6	92.8	94.1	87.6	87.3	95.5	74.7	73.7
	2	94.8	94.2	94.4	95.3	89.2	88.8	96.5	76.3	75.3
	3	95.8	95.4	95.6	96.2	90.5	90.1	97.3	77.6	76.7
0.3	1	98.2	96.2	96.3	98.3	90.1	89.8	98.5	77.3	76.5
	2	99.0	97.4	97.5	99.1	91.5	91.1	99.2	78.7	78
	3	99.4	98.3	98.4	99.5	92.6	92.2	99.4	80	79.3

When artificial setup errors were applied on the target (T), variation in the gamma density passing rate increased from 15.8 to 46.8% due to the increase in the image DD criterion. Even in the case when the body (B) and the target and body (TB) moved together, the gamma density passing rate increased 18.7~69.4%, and 21.3~69.3%, respectively. This result is due to the increase in the image DD criterion. It could be seen that the observed increases were due to the increase in the artificial setup errors. When 20 mm artificial setup errors were applied to B and TB, a 5 mm setup error

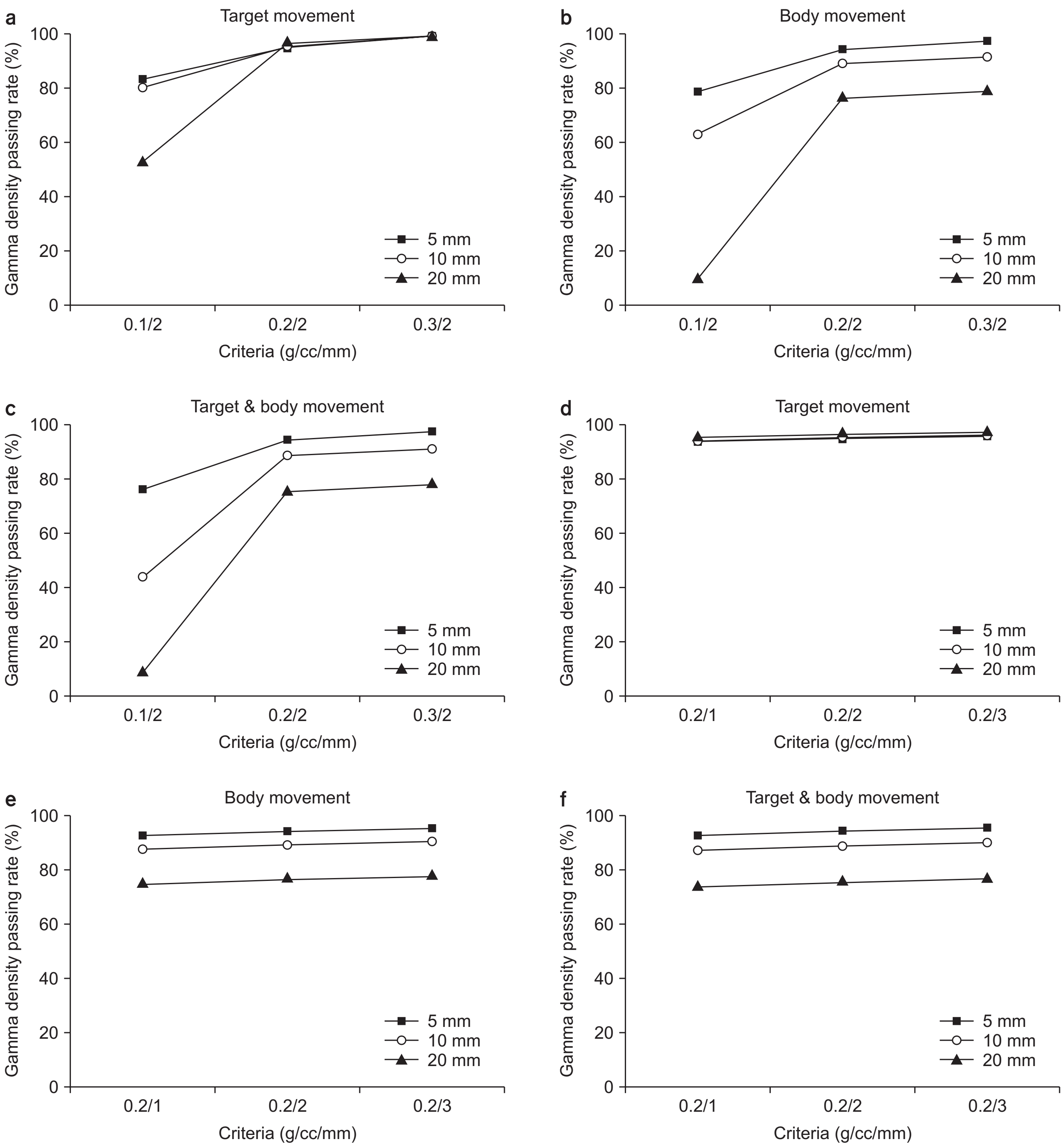

Fig. 2. Plot (a)-(c) illustrate for CBCT gamma density passing rate about Target, Body and Target & Body movement according to DD and plot (d)-(f) is CBCT gamma density passing rate according to DTA.

was observed, thus showing a 70% decrease in the passing rate. However, at a DD criterion of 0.1 g/cc, the gamma density passing rate decreased by about 31% in the case of T. At 0.2 and 0.3 g/cc, the variation in the gamma density passing rate was under 2%. Changes in the gamma density passing rate according to the DTA criterion were about 2% when using the 0.2 and 0.3 g/cc DD criterion. A maximum change of 10% was confirmed at 0.1 g/cc.

Discussion

From IMRT, SBRT, SRS, and similar technologies from treatment planning to treatment preparation, setup errors have to be minimized for each treatment. The coincidence of these types of errors has to be maintained. Further, in order to maximize the technical utility of new setup error evaluations, verification is needed.

In order to carry out a quantitative evaluation of setup errors at a standard accurate setup position, it was confirmed that the CBCT images of the CBCT System and Mobius CBCT all had no errors. In the case of T_{5mm}, there were also no setup errors for the two proposed systems. Setup errors under 1 mm were seen for B_{5mm} and TB_{5mm}, and over 1 mm errors were seen for B_{10mm}, B_{20mm}, TB_{10mm}, and TB_{20mm}. In particular, for the case of TB_{20mm}, differences with real setup errors were at a 1 mm maximum in the CBCT system. In contrast, errors were 17 mm in the lateral direction, and 8.2 mm in the longitudinal direction in the Mobius CBCT., the setup errors when using the acquired CBCT images when setting up the patient's position are reported to be about 2 to 3 mm when using the CBCT system.[14,15] The CBCT system can automatically match images and evaluate setup errors, but a situation in which it cannot perform an accurate matching can cause errors. Setup errors are adjusted through manual image matching based on anatomical features seen with the naked eye. To compensate for this, Mobius CBCT's Gamma Density Analysis calculates 3-dimensional image density changes and evaluates the setup errors. Individual gamma density analyses on the surface and important organs are possible, and this can be included in radiotherapy. However, a difference greater than 1 mm is observed when setup errors are larger than 10 mm. Thus there are difficulties in using only a Mobius CBCT for evaluation. So, when using a Mobius CBCT and adjusting a patient's setup errors, the patient's setup errors should be maximally adjusted first through the CBCT system, followed by performing the CBT Gamma Density Analysis with the Mobius CBCT. Results on the CBCT Gamma density passing rate confirmed that changes in the gamma density passing rate due to setup errors showed a similar trend at 0.2 g/cc and 0.3 g/cc DD criterion. At 0.1 g/cc, compared to other DD criteria, a low gamma density passing rate was seen. It is thought that the small changes in volume ROI position confirmed through gamma mapping can be useful when evaluating patient treatment position and location at 0.1 g/cc.

Conclusion

In this research, setup errors in a Mobius CBCT patient setup evaluation system were quantitatively evaluated and were found to depend on the CBCT image density. The results showed that the CBCT gamma density passing rate decreased depending on the increase in setup errors, and that there was no gamma density passing rate change in the DTA criterion. In the case of 0.2 and 0.3 g/cc, the gamma density passing rate changes were low. However, under the image density difference criterion of 0.1 g/cc, the passing rate was under 80% despite a low 5 mm setup error. In the case of 20 mm setup error, it was confirmed that the passing rate decreased to 5.5%. For the setup errors proposed by the Mobius CBTC, it was confirmed that there was a greater than 1 mm difference with real setup errors when the artificial setup errors were greater than 10 mm. Therefore, it is insufficient to analyze patient setup errors using only a Mobius CBCT. When preparing the patient, the CBCT system should be used first. After adjusting the maximum setup errors, it's thought that performing a Gamma Density Analysis with a Mobius CBCT will improve the accuracy of the patient setup. Additional research should be conducted on the Mobius CBCT proposed setup error changes following differences in the image density. A dose analysis of a treatment plan's quality management will be performed according to the results on patient setup errors using the CBTC image density.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

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

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