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Evaluation of Deformable Image Registration and Dose Accumulation Using Histogram Matching Algorithm between kVCT and MVCT with Helical Tomotherapy

Masahide Saito*, Yuki Shibata, Naoki Sano, Kengo Kuriyama, Takafumi Komiyama, Kan Marino, Shinichi Aoki, Hiroshi Onishi

Department of Radiology, University of Yamanashi, Yamanashi, Japan
Email: *masahides@yamanashi.ac.jp

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Abstract

Purpose: To evaluate the accuracy of deformable image registration (DIR) between the planning kVCT (pCT) and the daily MVCT combined with the histogram matching (HM) algorithm, and evaluate the deformable dose accumulation using a suggested method for adaptive radiotherapy with Helical Tomotharapy (HT). **Methods:** For five prostate cancer patients (76 Gy/38 Fr) treated with HT in our institution, seven MVCT series (a total of 35 series) acquired weekly were investigated. First, to minimize the effect of different HU values between pCT and MVCT, this image-processing method adjusts HU values between pCT and MVCT images by using image cumulative histograms of HU values, generating an HM-MVCT. Then, the DIR of the pCT to the HM-MVCT was performed, generating a deformed pCT. Finally, deformable dose accumulation was performed toward the pCT image. **Results:** The accuracy of DIR was significantly improved by using the HM algorithm, compared with non-HM method for several structures ($p < 0.05$). The mean dice similarity coefficient of the non-HM method was 0.75 ± 0.05, 0.83 ± 0.06, and 0.90 ± 0.04 for the CTV, rectum, and bladder, respectively, while that of the HM method was 0.81 ± 0.06, 0.81 ± 0.04, and 0.92 ± 0.06, respectively. For the deformable dose accumulation, some difference was observed between the two methods, particularly for the small calculated regions, such as rectum V60 and V70. **Conclusion:** Adapting the HM method can improve the accuracy of DIR. Furthermore, dose calculation using the deformed pCT using HM methods can be an effective tool for adaptive radiotherapy.

Keywords

Radiotherapy, Tomotherapy, MVCT, Histogram-Matching, Deformable Image

Registration

1. Introduction

Intensity modulated radiotherapy (IMRT) using helical tomotherapy (HT) (Accuray, Sunnyvale, CA) reduces the radiation dose to organs at risks (OAR) while maintaining conformity of the tumor [1]. Meanwhile, image-guided radiotherapy using HT uses mega-voltage computed tomography (MVCT) images [2], which have been used routinely for patient setup in HT treatments. Understanding daily anatomical changes and calculating the radiation dose are imperative. Therefore, some studies on adaptive radiotherapy using the daily MVCT and deformable image registration (DIR) have been published [3] [4] [5] [6].

Recently, Branchini *et al.* suggested a method of planning CT (pCT) for daily MVCT deformation and evaluated its accuracy [7]. They suggested that the method might be sufficiently fast and reliable for daily delivered dose evaluations in clinical strategies for adaptive radiotherapy using HT. However, the use of the daily MVCT is generally limited due to significant photoelectric interaction components and the presence of noise resulting from low detector quantum efficiency of megavoltage x-rays. The poor image quality of MVCT might decrease the accuracy of DIR and dose calculation. Although several authors introduced denoising methods [3], further evaluation for more accurate ART methods using MVCT is needed.

Some authors have investigated the improvement of image quality using Hounsfield unit (HU) modification methods, such as histogram matching (HM) method [8] [9] [10]. Although previous studies investigated kV-CBCT, no reports on improving the quality of MVCT images have been published. Furthermore, the deformable dose accumulation using this method was not investigated sufficiently. Therefore, the purpose of this study was to evaluate the accuracy of DIR between the pCT and the daily MVCT combined with the HM algorithm. In addition, we evaluated the deformable dose accumulation using a suggested method for adaptive radiotherapy with HT.

2. Materials and Methods

2.1. Planning kVCT and MVCT Images

For five prostate cancer patients (76 Gy/38 Fr) treated with HT in our institution, seven MVCT series (a total of 35 series) acquired weekly were investigated. These images were used for routine patient setup and acquired with the pitch of 4 mm and reconstruction thickness of 2 mm. For the pCT, the settings for image acquisition were 120 kV, 250 mA, 0.50 s, and a 2.0 mm slice thickness.

For the pCT image and each MVCT image, anatomical contours of the CTV (prostate + seminal vesicle), rectum, and bladder were described by an experimental oncologist and medical physicist. However, the scan range of each MVCT

was insufficient to describe the whole anatomical volume of the rectum and bladder in some patients.

2.2. DIR Using Histogram Matching Algorithm

In this study, the scan range of the daily MVCT was smaller than the pCT as mentioned previously. To perform DIR between pCT and MVCT normally, we generated a merged MVCT, as shown in Figure 1. First, the rigid image registration was performed between pCT and each MVCT image. Then, the image region outside the MVCT was replaced with pCT, resulting in the merged MVCT.

The algorithm between the pCT and the fractional MVCT was applied to improve the accuracy of pCT to MVCT deformation. Figure 2(a) shows the procedure of the HM method. To minimize the effect of different HU values between pCT and MVCT, this image-processing method adjusts HU values between pCT and MVCT images by using image cumulative histograms of HU values, generating an HM-MVCT. The HM method was performed by a script generated using MATLAB 2016a (Mathworks Inc., Natick, MA).

Then, the DIR of the pCT to the HM-MVCT was performed, generating a deformed pCT, as shown as Figure 2(b). In this study, this method was also applied to the original MVCT and the result was compared with that of the HM method. All DIRs were performed using the MIM Maestro ver.6.6.8 (MIM Software, Inc., Cleveland, OH) with intensity-based free form deforamtion algorithm.

2.3. Dose Accumulation

Figure 3 demonstrates the workflow of the deformable dose accumulation in

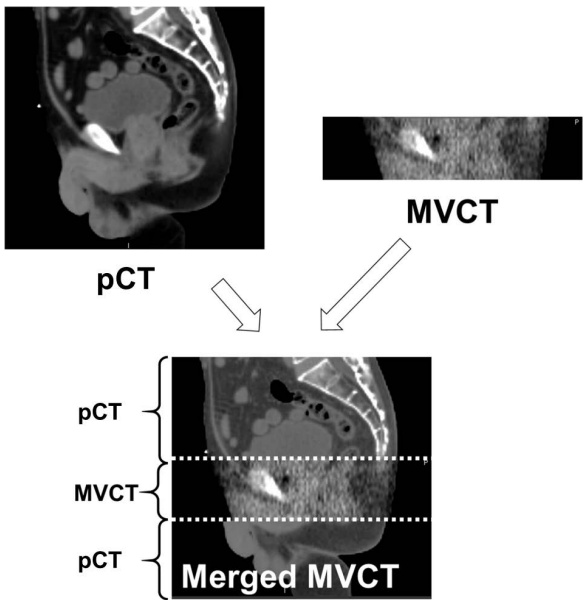

Figure 1. Concept of a merged MVCT. First, the rigid image registration was performed between the pCT and each fractional MVCT image. Then, the image region outside the MVCT was replaced with that of the pCT.

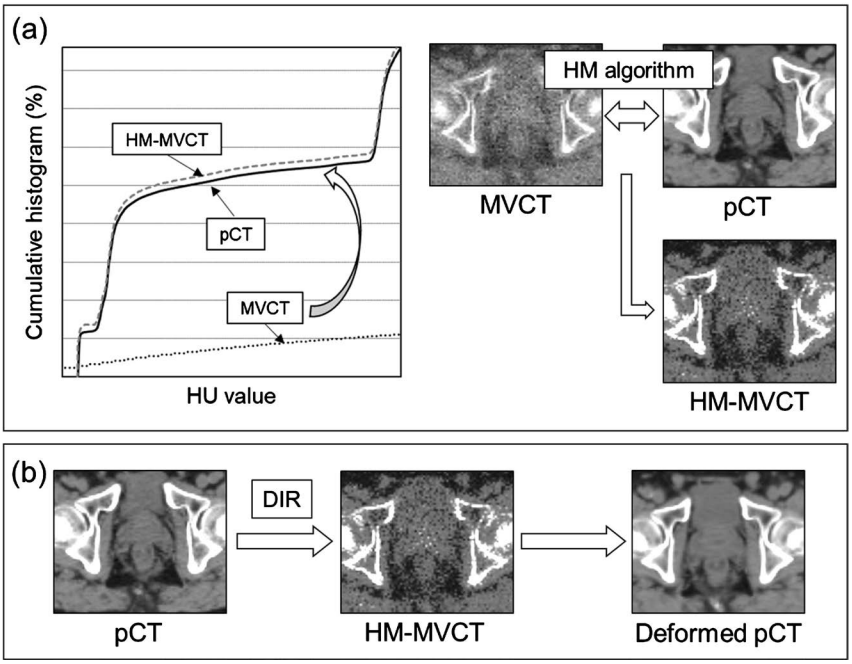

Figure 2. The procedure of deformable image registration combined with the HM method. First, to minimize the effect of different HU values between pCT and MVCT, this image-processing method adjusts HU values between pCT and MVCT images by using image cumulative histograms of HU values, generating an HM-MVCT (a). Then, the DIR of the pCT to the HM-MVCT was performed, generating a deformed pCT (b).

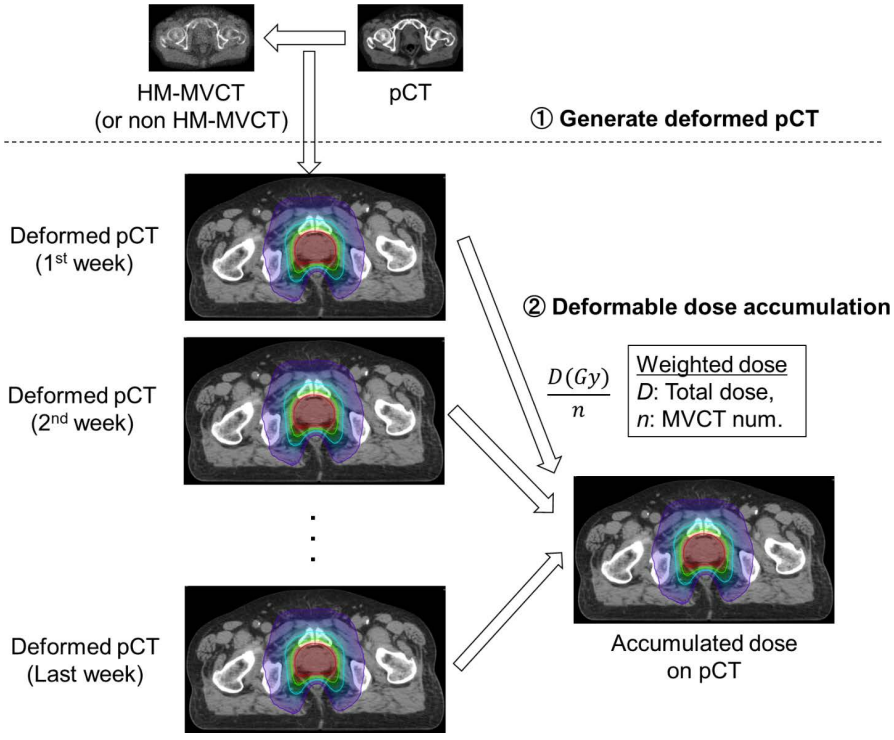

Figure 3. The workflow of the deformable dose accumulation in this study. First, each fractional deformed pCT was generated by using HM-MVCT (or non HM-MVCT). Then, the dose of the weekly deformed pCT was calculated. Finally, the deformable dose accumulation was performed toward the pCT image.

this study. First, each fractional deformed pCT was generated by using HM-MVCT (or non HM-MVCT). Then, the dose of the weekly deformed pCT was calculated as following condition. The target prescribed dose that was calculated by using each weekly MVCT image was scaled to 10.86 Gy, which was divided by the total dose (76 Gy) by 7 weeks. Finally, the deformable dose accumulation was performed toward the pCT image using MIM software. The dose calculation of the reference pCT image was performed using Tomotherapy planning station ver. 5.1.0.2, and each fractional dose of the deformed pCT was calculated via Tomotherapy DQA station ver. 5.1.0.4 with the fine condition of dose grid size.

2.4. Evaluation and Analysis

To evaluate the accuracy of the DIR, dice similarity coefficients (DSC) between deformed contours described in deformed pCT and manual contours described in original MVCT were calculated for CTV, rectum, and bladder, respectively. The DSC results of the HM method were compared with that of the non-HM method.

In addition, the accumulated dose using the HM method was compared with that of non-HM method and the reference planned dose for each organ (CTV: mean dose, maximum dose, and D50; rectum: V20, V60, and V70; bladder: V60 and V70). All statistical analyses were performed using JMP ver.11.2.1 (SAS Institute, Cary, North Carolina).

3. Results

3.1. DIR Using HM Algorithm

First, the DIR of pCT to HM-MVCT (or non-HM-MVCT) was performed. Figure 4 shows a typical case of improving the accuracy of deformation using HM method for CTV. The accuracy of DIR was evaluated using DSC between pCT

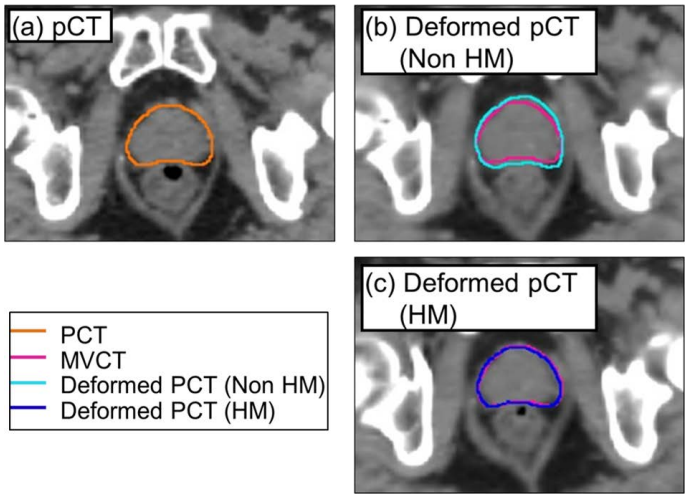

Figure 4. A typical case of improving the accuracy of deformation using HM method for CTV.

and MVCT, comparing with the results of the non-HM method, as shown in Figure 5. The mean DSC of the non-HM method was 0.75 ± 0.05, 0.83 ± 0.06, and 0.90 ± 0.04 for the CTV, rectum, and bladder, respectively, while that of the HM method was 0.81 ± 0.06, 0.81 ± 0.04, and 0.92 ± 0.06, respectively. The accuracy for CTV and bladder was significantly improved compared with non-HM MVCT ($p < 0.05$).

3.2. Dose Accumulation

The dose calculation was performed for each fractional deformed pCT. Figure 6 shows the fractional scaled dose changes of patient 1, showing (a) CTV, (b) rectum, and (c) bladder for non-HM method (solid line) and HM methods (dash line). For all five patients, the maximum dose deviations of a same fraction between non-HM and HM methods were 0.16 Gy (CTV mean dose), −0.19 Gy (CTV maximum dose), −0.16 Gy (CTV D50), −2.20 Gy (rectum V20), −1.62 Gy (rectum V60), −1.23 Gy (rectum V70), 1.9 Gy (bladder V60), and 1.23 Gy

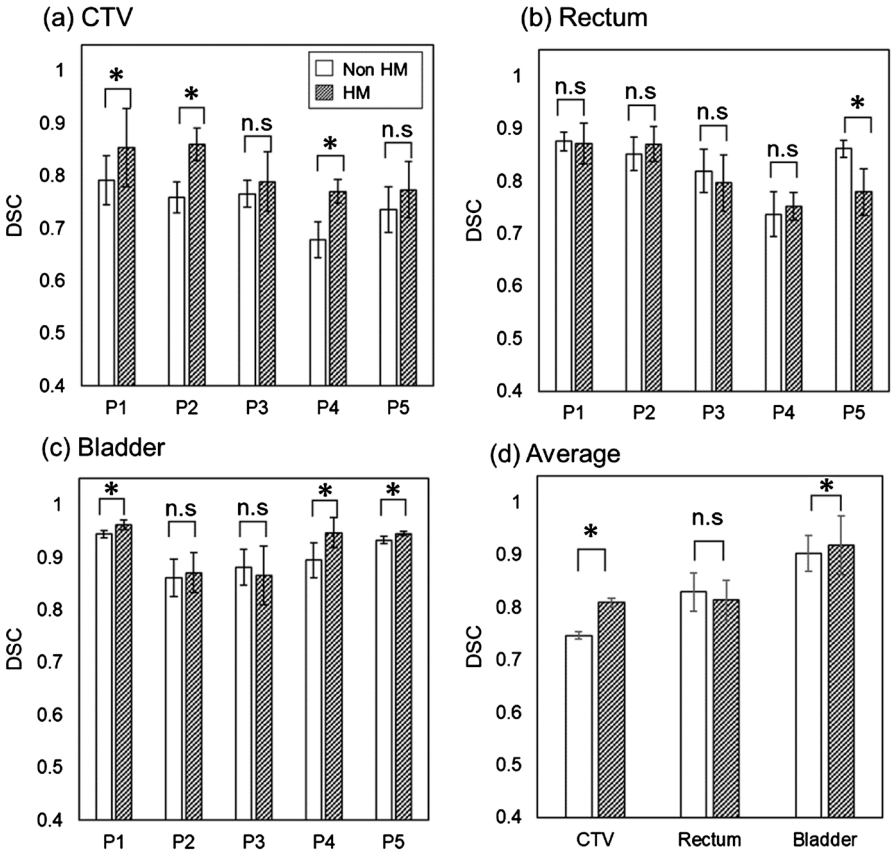

Figure 5. Patient individual dice similarity coefficient (DSC) between manual contours on the each fractional MVCT and deformed contours on the deformed pCT for (a) CTV, (b) rectum, and (c) bladder, and the average DSCs of all patients are shown in (d). Asterisk symbols (*) indicates a significant difference between two methods ($p<0.05$). The mean DSC of the non-HM method was 0.75 ± 0.05, 0.83 ± 0.06, and 0.90 ± 0.04 for the CTV, rectum, and bladder, respectively, while that of the HM method was 0.81 ± 0.06, 0.81 ± 0.04, and 0.92 ± 0.06, respectively.

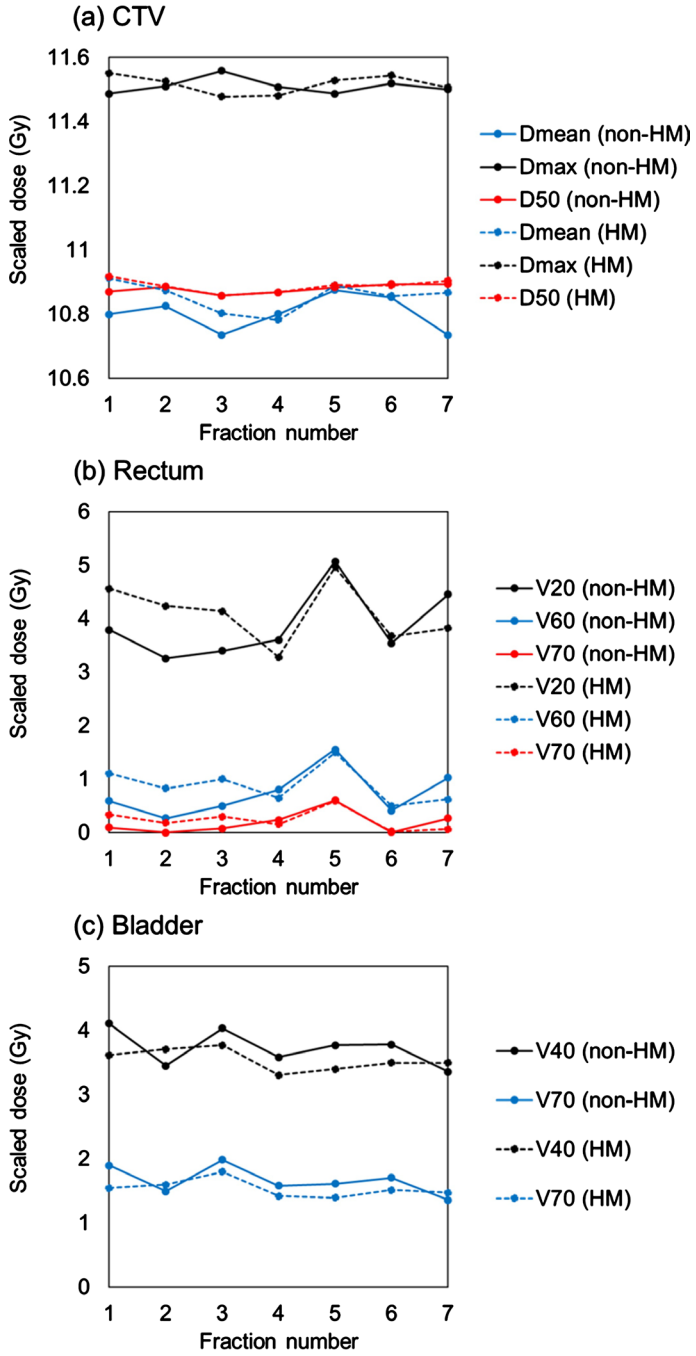

Figure 6. Fractional scaled dose changes of patient 1, showing (a) CTV, (b) rectum, and (c) bladder for non-HM method (solid line) and HM methods (dash line).

(bladder V70).

Meanwhile, the dose accumulation for all fractional MVCT was performed using the HM method. Table 1 shows the comparison of the reference calculated dose on pCT with the cumulative dose using two deformed pCT datasets. Some difference was observed between the two methods, particularly for the small calculated regions, such as rectum V60 and V70.

The DIR between two CT images is an effective tool to perform a more accurate

Table 1. Comparison of the reference calculated dose on pCT with the cumulative dose using two deformed pCT datasets. All p-values were calculated with Wilcoxon test.

		calculated accumulate dose (Gy, mean ± s.d.)				
		pCT	deformed pCT (non-HM-method)	*p-value*	deformed pCT (HM-method)	*p-value*
CTV	Dmean	76.5 ± 0.1	76.4 ± 0.8	0.71	76.6 ± 0.9	0.77
	Dmax	79.7 ± 0.7	79.1 ± 0.8	0.08	79.3 ± 0.9	0.37
	D50	76.6 ± 0.1	76.6 ± 0.8	1.00	76.7 ± 0.9	0.70
rectum	V20	41.1 ± 8.7	40.1 ± 8.1	0.26	43.1 ± 8.4	0.08
	V60	11.3 ± 5.4	7.1 ± 4.5	0.01	11.1 ± 5.0	0.77
	V70	5.0 ± 3.8	2.1 ± 3.2	0.01	4.3 ± 3.4	0.34
bladder	V40	40.4 ± 14.0	38.5 ± 14.1	0.17	40.4 ± 15.7	0.99
	V70	15.2 ± 3.1	11.7 ± 3.3	0.01	15.7 ± 3.5	0.47

adaptive radiotherapy. It is usually applied to two kV CT images (two pCT images or pCT image-daily CBCT image). Several authors evaluated their accuracy by using DSC and target registration error (TRE) [11] [12] [13] [14] [15]. Although various DIR algorithms were used for these validations, the accuracy of DIR usually depends on the parameter setting of each software. In this study, we used the intensity-based DIR implemented in MIM software. Kadoya *et al.* investigated the algorithm and found that the 3D registration error was 2.17 mm to 3.61 mm in 10 theoretical images [14]. Although their results were not focused on the pelvic images, the accuracy of the deformation using MIM software was comparable with that of the other commercial DIR software.

The MVCT is usually used for daily patient setup for image-guided HT treatment instead of kV-CBCT implemented in a conventional linac. Some authors investigated the use of daily MVCT to adaptive radiotherapy, for example, the dose calculation and the deformation between kVCT to MVCT [5] [6]. However, kVCT and MVCT have some differences, namely, imaging noise, contrast resolution, and field of view, worsening the accuracy for intensity-based deformation compared with kV-kV registration. Therefore, to improve the accuracy of DIR, we applied HM algorithm between pCT and MVCT.

The HM algorithm is a method used to adjust HU values between pCT and CBCT images by using image cumulative histograms. Van Zijtveld *et al.* showed that the percentage of points with a gamma value < 1 (2%/2 mm) between pCT and modified CBCT was 98% using the HM algorithm in five patients [10]. However, these reports focused on kV-CBCT, and reports on MVCT combined with the HM algorithm have not been evaluated. Our results indicating that the HM algorithm was effective in improving the accuracy of DIR between pCT and MVCT for almost all anatomical structures are similar to that of the previous kV-CBCT studies [8] [9] [13]. However, some cases had rectal gas and volume change of the bladder, resulting in more variations in the accuracy of DIR. In addition, one of the limitations of this study was the use of the merged MVCT

images because the routine MVCT have usually limited field of view and number of slices to reduce irradiation, increasing the uncertainty in the accuracy. Therefore, our results of the merged MVCT can be useful for performing more accurate adaptive radiotherapy.

The dose calculation using daily image was investigated by some authors [16] [17] [18]. However, the noisy image, such as kV-CBCT, cannot usually adapt to high-accuracy dose calculation. Onozato *et al.* evaluated the accuracy of dose calculation of CBCT using DIR combined with the HM method [9]. They concluded that the method using HM significantly improved accuracy compared with conventional CBCT dose calculation. Arai *et al.* also evaluated the dose calculation using HM methods for proton therapy and showed that it could improve the accuracy of the proton dose calculation [8]. In our study, we referenced and modified the previous study by Branchini *et al* [7], that is, we incorporated the HM method to their method to improve the DIR accuracy because of improving image contrast between organs on the CT image. These process leads to improvement of deformable image registration between multi-modalities. Therefore, a more accurate image for adaptive dose calculation can be generated than that of the previous study.

Several authors have evaluated the deformable dose accumulation [19] [20] [21] [22]. Janssen *et al.* evaluated the deformable dose accumulation using MOSFET measurement and showed the effectiveness of deformable dose accumulation [21]. Although some reports of deformable dose accumulation using kV-CT images have been published, no studies have evaluated the dose accumulation of MVCT. Our results showed that each fractional dose can be changed by using the HM method. In particular, for the small calculated dose index, such as rectum V60 and V70, the effect was significant. The HM method can transform the original MVCT image to a high-contrast image; thus, the deformation of these high-dose regions in the organ boundary tended be affected. Similarly, the accumulated dose of these regions was significantly different. However, almost all dose indices were note significantly different between the two methods.

Our study included some limitations. First, only a small number of patients and fractional MVCT were used. Second, the accuracy of DIR was evaluated by only using DSC, which is not ideal because only the edge of the specific organ can be evaluated and not the whole region. Therefore, we will use the TRE, which is defined as the anatomical structure point, in future studies to possibly yield more accurate results. Third, a lack of ground truth value of the accumulated dose was of concern in this study. In future studies, the accuracy of deformable dose accumulation in pelvic region should be investigated further and the results referenced to previous report [23] [24].

4. Conclusion

In this study, we evaluated the dose accumulation method using the HM method for tomotherapy MVCT. Adapting the HM method can improve the accuracy of

DIR. Furthermore, dose calculation using the deformed pCT using HM methods can be an effective tool for adaptive radiotherapy.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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