Synthetic Fluoroscopic Image Generation for Tracking Accuracy Validation of Marker-Less Tumor Tracking in Radiotherapy

JULY 12–16 2020 VIRTUAL JOINT AAPM | COMP MEETING EASTERN TIME [GMT-4]

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INTRODUCTION

One of the difficulties associated with developing a marker-less tumor tracking algorithm is validation of its tracking accuracy. Some studies validated with a phantom experiment[1], but it tends to easy to track a tumor phantom because there is no inner body motion. Others validated with patients' fluoroscopic images[2]. In these cases, ground truth positions of the tumor on fluoroscopic images were manually entered. However, it is hard to define the tumor positions accurately due to low contrast on fluoroscopic image. So there could be uncertainty about the ground truth positions[2]. We assume this situation reduces reliability of an algorithm and hinders its clinical implementation.

Therefore, we propose a new validation scheme that uses synthetic fluoroscopic images of a patient and a 3D printed tumor. The overview is shown in Fig. 1. By synthesizing the 3D printed tumor's fluoroscopic images onto the patient's fluoroscopic images as if the 3D printed tumor was inside the patient's body, we can evaluate the tracking accuracy by tracking the 3D printed tumor as an alternative of the real tumor. In this scheme, generation of the realistic synthetic images of separately taken two objects' fluoroscopic images is important.

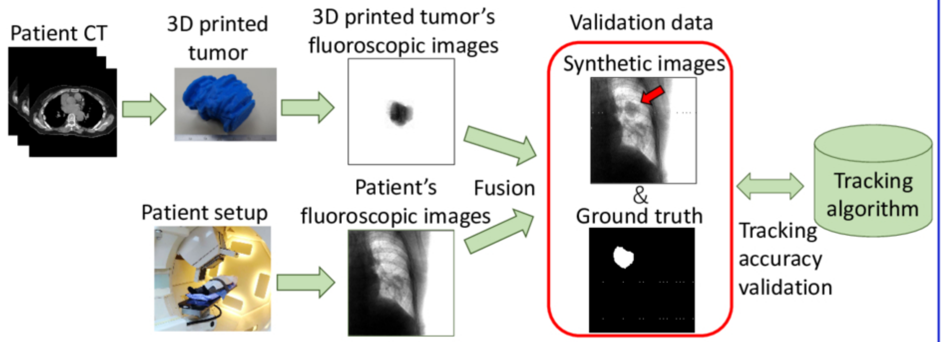

Fig. 1. The Overview of the proposed validation scheme.

A synthetic method of fiducial markers was proposed in [3], however this ignored the beam hardening effect and noise difference, so the contrast of the tumor was not well reproduced. Fig. 2 shows an example of a synthetic image made by [3]. The contrast around the 3D printed tumor was higher and the noise level was lower than those of the fluoroscopic image taken two objects together. This may lead to overestimation of the tracking accuracy in our validation scheme.

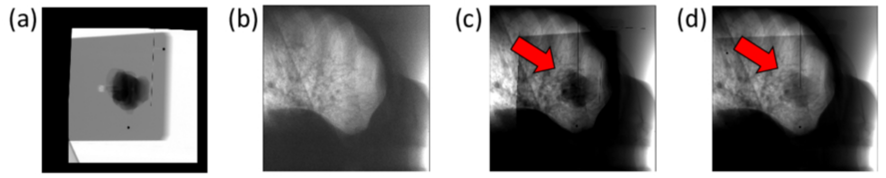

Fig. 2. Fluoroscopic images of (a) a 3D printed tumor, (b) a chest phantom and (d) both together. (c) is a synthetic image of (a) and (b) made by [3].

AIM

The aim of this study is to establish a realistic synthetic image generation method of separately taken two objects' fluoroscopic images and to evaluate the synthetic image quality in a phantom experiment.

METHOD

Proposed synthetic method

Fig. 3 shows the overview of the proposed synthetic method. We extended the previous method[3] and newly introduced beam hardening (BH) correction factor $\alpha(x, y; \mathrm{kV})$ and additional noise $\eta_{\mathrm{add}}(x, y; \mathrm{kV})$. Generally, the attenuation of the X-ray is expressed as an exponential function, so the attenuation map of a 3D printed tumor $A_{\mathrm{t}}(x, y; \mathrm{kV})$ and that of a patient $A_{\mathrm{p}}(x, y; \mathrm{kV})$ are calculated using pixel value of a 3D printed tumor $P_{\mathrm{t}}(x, y; \mathrm{kV})$, that of a patient $P_{\mathrm{p}}(x, y; \mathrm{kV})$ and background pixel value $P_0(\mathrm{kV})$ as follows

$$A_{\mathrm{t}}(x, y; \mathrm{kV}) = -\ln \frac{P_{\mathrm{t}}(x, y; \mathrm{kV})}{P_0(\mathrm{kV})}, \qquad A_{\mathrm{p}}(x, y; \mathrm{kV}) = -\ln \frac{P_{\mathrm{p}}(x, y; \mathrm{kV})}{P_0(\mathrm{kV})}.$$

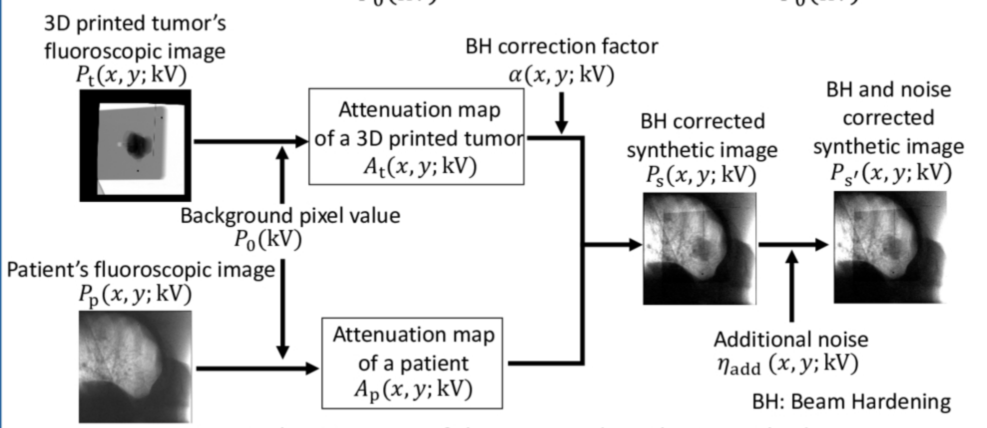

Fig. 3. The Overview of the proposed synthetic method.

Then the BH corrected synthetic image $P_{\mathrm{s}}(x, y; \mathrm{kV})$ is calculated as follows

$$P_{\mathrm{s}}(x, y; \mathrm{kV}) = P_0(\mathrm{kV}) \exp\left(-A_{\mathrm{p}}(x, y; \mathrm{kV}) - \alpha(x, y; \mathrm{kV}) A_{\mathrm{t}}(x, y; \mathrm{kV})\right).$$

The X-ray passed thorough an object is hardened (known as BH) and the attenuation by an object behind ($A_{\mathrm{t}}(x, y; \mathrm{kV})$ in this case) is decreased. BH correction factor $\alpha(x, y; \mathrm{kV})$ is introduced to consider this effect, and its value range is (0, 1). Finally, the BH and noise corrected synthetic image $P_{\mathrm{s'}}(x, y; \mathrm{kV})$ is calculated as follows

$$P_{\mathrm{s'}}(x, y; \mathrm{kV}) = P_{\mathrm{s}}(x, y; \mathrm{kV}) + \eta_{\mathrm{add}}(x, y; \mathrm{kV}).$$

$\alpha(x, y; \mathrm{kV})$ and $\eta_{\mathrm{add}}(x, y; \mathrm{kV})$ were measured by comparing the synthetic image and the image taken two objects together in a preliminary experiment.

Phantom Experiment

Phantom experiments were conducted to take fluoroscopic images of (a) a 3D printed tumor, (b) a chest phantom and (c) both together. Fig. 4 shows an experimental setup of (c). Our goal is to minimize differences between the image taken at (c) and the synthetic image of (a) and (b). We tested two types of tube voltage settings, the tube parameters were summarized in Table 1.

Fig. 4. Experimental setup.

Table 1. X-ray tube parameters.

Item	High dose setting	Low dose setting
Tube voltage (V)	110	60
Tube current (mA)	50	50
exposure time (ms)	5	5

RESULTS

Synthetic image quality evaluation

The visual comparison of the synthetic and the fluoroscopic image for high dose and low dose settings are shown in Fig. 5. The subtraction of the synthetic and the fluoroscopic image is almost noise level. Fig. 6 shows the pixel value profile of the high dose setting along the red dashed line shown in Fig. 5. For the conventional method, the pixel value around the 3D printed tumor is lower than the that of the reference, this means the contrast of the 3D printed tumor is higher for the conventional method. On the other hand, the pixel value is consistent with the reference for the proposed method because of the consideration of the BH effect.

We calculated the structural similarity (SSIM) and the mean squared error (MSE) to quantitatively evaluate the image quality. We defined noise reproducibility (NR) to evaluate the noise level of the synthetic image. NR is calculated as follows

$$\mathrm{NR} = \frac{\mathrm{SD_s}}{\mathrm{SD_r}},$$

where $\mathrm{SD_s}$ and $\mathrm{SD_r}$ are standard deviations of the synthetic and the reference image around the 3D printed tumor. If NR is smaller than 1, the noise level of the synthetic image is lower than that of the reference. Table 2 shows the results. By adding the noise, SSIM and MSE are slightly decreased but NR is closer to 1 compared to not added case.

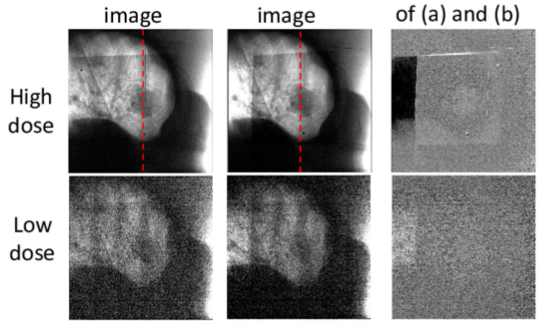

Fig. 5. Comparison of the synthetic and the fluoroscopic image.

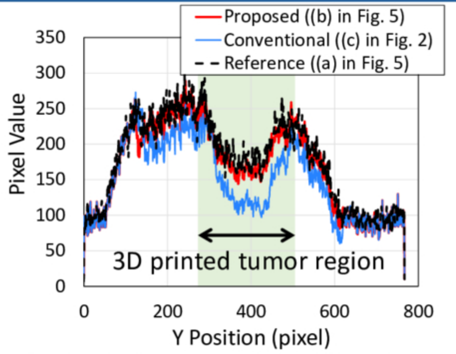

Fig. 6. Pixel value profile of high dose setting along red dashed lines in Fig. 5.

Table 2. Summary of the evaluation metrics.

Synthetic method		High dose setting			Low dose setting		
		SSIM	MSE	NR	SSIM	MSE	NR
Proposed	Noise added	0.930	390.6	0.92	0.461	58.0	0.82
	Not added	0.940	327.2	0.63	0.504	47.6	0.51
Conventional		0.885	1723.4	0.65	0.468	66.6	0.50

DISCUSSION

In this study, we evaluated our method only by phantom experiments. We have already applied our method to the patient's images taken during treatment, but the result was not shown here because image quality evaluation was impossible for the patient case. However the principle of the X-ray attenuation in an object is the same for the phantom case and the patient case, so our method is applicable for the patient case as well.

The deformation of the tumor shape was not considered in this study. In some clinical cases, the tumor may deform due to patient's respiration.

CONCLUSIONS

- ✓ We extended a synthetic image generation method to consider the beam hardening effect and noise difference. The method was validated with phantom experiments and the pixel value profile of the synthetic image was well matched to the reference image.
- ✓ The ground truth position of the synthesized 3D printed tumor is calculated precisely, so we can evaluate the tracking accuracy of a marker-less tumor tracking algorithm without positional uncertainty on the ground truth position.

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ACKNOWLEDGEMENTS

This research is partially supported by Hitachi, Ltd,.

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