Development of anthropomorphic multi-modality pelvic phantom for quantitative evaluation of deep-learning-based synthetic computed tomography image generation technique

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Purpose: The objective of this study was the fabrication of an anthropomorphic multi-modality pelvic phantom to evaluate a deep-learning-based synthetic computed tomography (CT) image generation technique for magnetic resonance-guided radiotherapy (MRgRT).

Methods: Three polyurethane materials and one silicone-based material were prepared with various silicone oil concentrations to determine the tissue surrogate. The cylinders containing these materials were scanned using low field 0.35 T magnetic resonance (MR) and CT scanners. Five tissue surrogates were determined by comparing the organ intensity with patient CT and MR images. Patient-specific organ modeling for three-dimensional (3D) printing was performed by manually delineating the structures of interest. The phantom was finally fabricated by casting materials for each structure. For the quantitative evaluation, the mean and standard deviations were measured within the regions of interest on the MR, simulation CT (CT_{sim}), and synthetic CT (CT_{syn}) images. Intensity-modulated radiation therapy plans were generated to assess the impact of different electron density assignments on plan quality using CT_{sim} and CT_{syn}. The dose calculation accuracy was investigated in terms of gamma analysis and dose–volume histogram parameters.

Results: For the prostate site, the mean MR values for the patient and phantom were 78.1 ± 13.8 and 86.5 ± 19.3, respectively. The intensity of the synthetic image was 30.9 ± 10.1, which was comparable to that of the real CT phantom image. Between the phantom and patient cases, the soft tissue surrogate only exhibited discrepancies of 5.8 and 9.2 HU using the CT and MR, respectively. The original and synthetic CT values of the fat tissue in the phantom were −105.8 ± 4.9 and −107.8 ± 7.8, respectively. For the target volume, the difference in $D_{95\%}$ was 0.32 Gy using CT_{syn} with respect to CT_{sim} values. The V_{65Gy} values for the bladder in the plans using CT_{sim} and CT_{syn}

were 0.31% and 0.15%, respectively. The gamma analysis of the dose distribution in CT_{sim} and CT_{syn} exhibited a 99.6% pass rate within 2%/2 mm at a 10% dose threshold.

Conclusion: This work demonstrated that the anthropomorphic pelvic phantom fabricated using 3D printing technology was physiologically and geometrically similar to the patient organ and was employed to evaluate the deep-learning-based synthetic CT algorithm quantitatively. This phantom is anticipated to be a useful tool for the quality assurance of emerging image processing techniques for MRgRT.

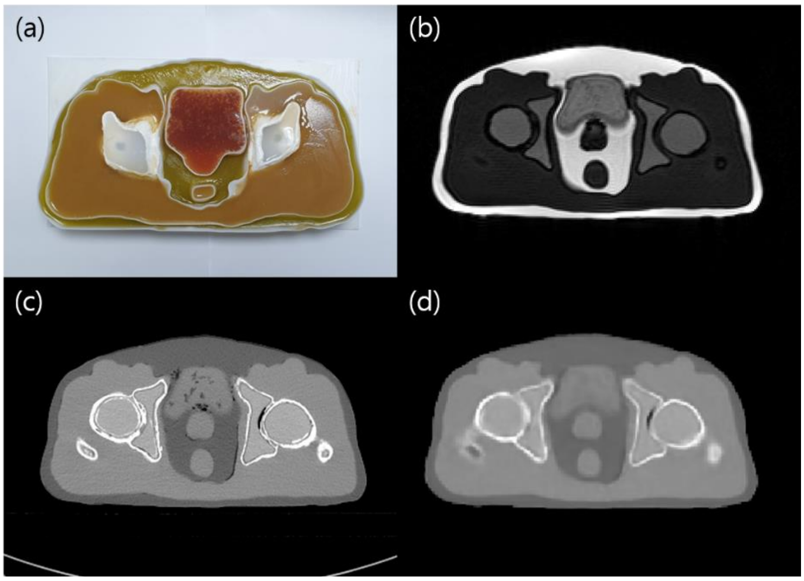

Figure 1. (a) Multi-modality anthropomorphic pelvic phantom; Phantom images scanned using (b) 0.35-T TRUFI MRI and (c) CT simulator; (d) image derived from the image in (b) using synthetic CT generation model.

Table 1. Dose–volumetric parameters of plans calculated based on simulation CT and synthetic CT images of phantom.

	CT_{sim}	CT_{syn}	Difference
PTV			
$D_{1\%}$ (Gy)	76.83	76.74	0.09
$D_{2\%}$ (Gy)	76.36	76.23	0.13
$D_{95\%}$ (Gy)	69.68	69.36	0.32
$D_{98\%}$ (Gy)	68.88	68.60	0.28
$D_{99\%}$ (Gy)	68.48	68.15	0.33
Bladder			
Maximum dose (Gy)	8.46	8.08	0.38
$D_{55\%}$ (Gy)	29.96	30.00	−0.04
$D_{30\%}$ (Gy)	40.37	40.57	−0.20
$D_{25\%}$ (Gy)	43.26	43.22	0.04
V_{65Gy} (%)	0.31	0.15	0.16
V_{60Gy} (%)	3.04	2.90	0.14
V_{55Gy} (%)	8.00	7.85	0.15
Rectum			
Maximum dose (Gy)	10.96	11.32	−0.36
$D_{50\%}$ (Gy)	27.71	27.75	−0.04
$D_{20\%}$ (Gy)	36.93	36.95	−0.02
V_{65Gy} (%)	0.27	0.23	0.04
V_{60Gy} (%)	1.35	1.37	−0.02
V_{55Gy} (%)	4.39	4.18	0.21
Femoral heads			
Maximum dose (Gy)	7.86	8.10	−0.24

Abbreviations: PTV: planning target volume; Dn%: highest dose received by at least n% volume of a structure; VnGy: percent volume receiving n Gy