

Development of a PETG-based 3D-printed lumbar spine phantom for bone mineral density assessment

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ABSTRACT

Background: Recent advances in three-dimensional printing technology have enabled the development of customized phantoms for quantitative imaging applications, including bone mineral density assessment.

Objectives: This study aimed to develop and validate a 3D-printed lumbar spine phantom by comparing its radiological characteristics with those of the commercial anthropomorphic RSD RS-113T pelvic phantom and evaluating its performance against the GE Lunar iDXA quality control (QC) phantom.

Materials and methods: A commercial RSD RS-113T pelvic phantom was scanned using CT and DXA to obtain reference CT numbers and BMD values. Lumbar spine structures were segmented from CT images to design a 3D-printed lumbar spine phantom using fused deposition modeling (FDM). Polyethylene terephthalate glycol (PETG; densities 1.24 and 1.27 gm/cm³), combined with calcium carbonate powder, was used to simulate bone mineral content. CT number and BMD measurements of the developed phantoms were compared with those of the RSD RS-113T pelvic phantom using Bland-Altman agreement analysis. BMD repeatability of the developed phantoms was subsequently validated using the GE Lunar iDXA QC phantom.

Results: The PETG black phantom (1.27 gm/cm³) showed closer agreement with the RSD RS-113T pelvic phantom than the PETG white phantom (1.24 gm/cm³), with smaller Bland-Altman mean biases for CT number (8.65 vs -297.10 HU) and BMD (0.22 vs 0.84 gm/cm²). The RSD RS-113T pelvic phantom exhibited BMD CV values of less than 2%. The PETG black phantom also demonstrated better BMD repeatability (CV: 0.58%-2.92%) than the PETG white phantom, although some measurements exceeded the 2% precision criterion.

Conclusion: The PETG black 3D-printed lumbar spine phantom demonstrated superior BMD repeatability compared with the PETG white phantom. It also showed good agreement with the RSD RS-113T pelvic phantom and satisfactory BMD performance when validated using the GE Lunar iDXA QC phantom.

Introduction

Recent advances in three-dimensional (3D) printing have created new opportunities for developing customized phantoms in medical imaging and radiological physics.¹ Additive manufacturing techniques enable precise control over anatomical geometry, internal structure, and material composition, allowing the fabrication of phantoms with tunable radiological properties.^{2,3} In particular, fused deposition modeling (FDM) combined

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with polymer-based materials⁴ and mineral additives offers a promising approach for simulating bone-equivalent attenuation and density characteristics relevant to both dual-energy X-ray absorptiometry (DXA) and computed tomography (CT) imaging.⁵⁻⁷

DXA is a widely used quantitative imaging modality for assessing bone mineral density (BMD) based on the differential attenuation of X-ray photons at two distinct energy spectra. BMD values expressed in grams per square centimeter (gm/cm^2) serve as a fundamental parameter for the diagnosis, classification, and longitudinal monitoring of osteoporosis and other metabolic bone disorders.⁸ Owing to its high precision, low radiation dose, and short acquisition time, DXA is regarded as the reference standard for clinical BMD evaluation.⁹ However, the accuracy and reproducibility of DXA-derived BMD measurements depend on rigorous quality assurance procedures, which rely heavily on standardized phantoms to ensure measurement consistency across time and imaging systems.^{10,11} Variations in geometry and material composition across manufacturers restrict cross-system comparability.¹² In computed tomography (CT), phantoms are similarly essential for evaluating system performance, including image quality, CT number accuracy, and measurement consistency. They provide standardized references for calibration and validation of quantitative imaging metrics under controlled conditions.^{13,14}

In this context, 3D printing offers a flexible platform for developing customized phantoms with controlled structural and material properties. Nevertheless, the extent to which 3D-printed phantoms can accurately replicate the densitometric characteristics of established reference phantoms remains insufficiently explored. We hypothesize that optimizing filament density and material composition will yield a 3D-printed phantom with CT number and BMD values comparable to those of a reference phantom.

Accordingly, this study aimed to develop and quantitatively validate a 3D-printed lumbar spine phantom by comparing its radiological characteristics with those of the anthropomorphic RSD RS-113T pelvic phantom and evaluating its BMD performance using the GE Lunar iDXA QC phantom as the reference.

Materials and methods

The RSD RS-113T pelvic phantom was initially scanned using both a CT system and a DXA system to obtain baseline imaging and bone density data. For CT analysis, regions of interest (ROIs) with an area of 7.34 mm^2 were placed at three specific locations (one central and two lateral) on axial CT images of the lumbar vertebral bodies of L1-L5 to measure CT number values. Subsequently, bone mineral density (BMD) measurements of the same vertebrae were performed using the DXA system to provide corresponding reference values. Following this, the lumbar spine phantom was fabricated using FDM with filaments

(eSUN, China; IEMA, China) and Creality 3D printers (Shenzhen Creality 3D Technology Co., Ltd. China), specifically the Creality K1 Max and Creality Ender-3 V3 models. The printing materials included polyethylene terephthalate glycol (PETG) filaments with densities of 1.24 and $1.27 \text{ gm}/\text{cm}^3$ and polylactic acid (PLA) filament with a density of $1.23 \text{ gm}/\text{cm}^3$. BMD measurements were conducted using a GE Lunar iDXA Prodigy system (GE Healthcare, USA) operated at 76 kV, 3 mA.

CT imaging was performed with a PHILIPS Ingenuity scanner (Philips Healthcare, The Netherlands) following a standardized lumbar spine protocol set at 120 kV, 30 mA, and 1 mm slice thickness, balancing adequate X-ray penetration and spatial resolution to ensure precise bone structure assessment. This methodology enabled a comprehensive comparison of the imaging and bone density characteristics of the developed 3D-printed lumbar spine phantom with those of the reference phantom.

For radiological characterization, the CT number and BMD measurements of the developed 3D-printed phantom were compared with those of the commercial anthropomorphic RSD RS-113T pelvic phantom using Bland-Altman agreement analysis to assess measurement agreement. Subsequently, the BMD performance of the developed 3D-printed phantom was validated using the GE Lunar iDXA QC phantom.

3D block sample design

Firstly, a rectangular prism (cuboid) model was designed in Autodesk Fusion 360 with dimensions of $15 \text{ mm} \times 15 \text{ mm}$ in width and length, and a thickness of 21 mm, corresponding to the L3 vertebral body. Block samples were then printed using two commonly used filament materials: PETG and PLA. For each material, samples were fabricated at infill densities of 80% and 100%, utilizing two infill patterns: Gyroid, selected for its flexibility and mechanical strength, and Crosshatch, selected for its printing efficiency and economical material usage. To evaluate their radiological properties, CT scans were performed on the samples, with a single ROI of 7.34 mm^2 placed at the center of each block sample to measure CT numbers. Additionally, BMD values were obtained via DXA. Based on clinically reported DXA ranges, a BMD value of $0.50 \text{ gm}/\text{cm}^2$ was defined as low-density, $1.00 \text{ gm}/\text{cm}^2$ as intermediate-density, and $1.50 \text{ gm}/\text{cm}^2$ as nominal density target, and were selected for this study. The resulting CT number and BMD values from the block samples were then compared with those of the RSD RS-113T pelvic phantom to assess similarity.

In the second phase, the block samples were redesigned as box-shaped phantoms with lids, maintaining overall dimensions consistent with the L3 vertebral body ($15 \times 15 \times 21 \text{ mm}$). The lids and edges were printed at 100% infill density to enhance structural integrity. Samples were fabricated using PETG and PLA at infill densities of 0%, 20%, and 40%, and printed

with three infill patterns: Grid, Crosshatch, and Gyroid (Figure 1). To evaluate the incorporation of bone-mimicking material, samples were weighed before and after filling with calcium carbonate (CaCO_3) powder, allowing assessment of filling efficiency. Subsequently, CT and DXA measurements were conducted, and the

data were compared with those from the RSD RS-113T pelvic phantom. Through this process, the optimal combination of material, infill density, and pattern, yielding CT number and BMD values close to those of the pelvic phantom, was identified and selected for final phantom fabrication.

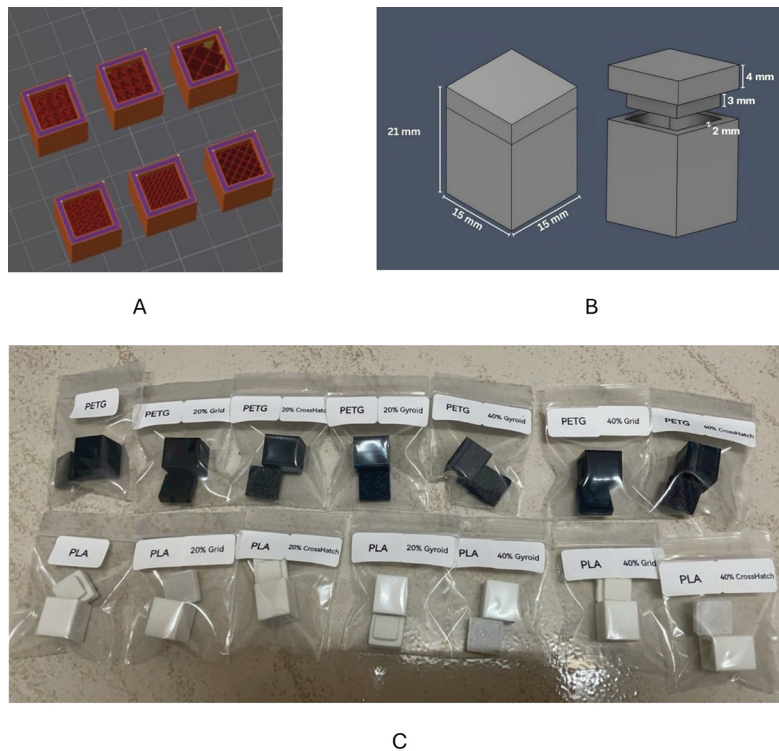


Figure 1. Design and appearance of 3D-printed block samples. A: Block samples printed at infill densities of 20% and 40% using Grid, Cross Hatch, and Gyroid patterns. B: Dimensions of the block sample: 15 mm×15 mm×21 mm. C: PETG and PLA samples printed at infill densities of 0%, 20%, and 40%, with Grid, Cross Hatch, and Gyroid patterns.

Fabrication, characterization, and validation of the lumbar spine phantom

The final lumbar spine phantom was generated by applying threshold-based segmentation to the CT images of the RSD RS-113T pelvic phantom using 3D Slicer software, thereby creating a 3D model that accurately replicated the size and shape of the original phantom. The model was then 3D-printed using the optimized parameters determined from the block sample tests, including the printing material, infill density, and printing pattern. Following fabrication, measurements were performed using both CT (Figure 2)

and DXA. To validate the radiological characteristics of the printed phantom, CT number measurements were taken from three ROIs, one central and two laterals, on CT images of the printed phantom (Figure 3). To evaluate its suitability for bone density quality control applications, the repeatability of five BMD measurements was assessed and compared with that of the GE Lunar iDXA QC phantom (Figure 4). Finally, the measured parameters were statistically compared with those of the reference phantoms to confirm the reliability of the developed 3D-printed phantom.



Figure 2. CT imaging of the developed 3D-printed lumbar spine phantom fabricated from PETG with calcium carbonate (CaCO_3) powder with various material densities. Left: 1.24 gm/cm^3 , Right: 1.27 gm/cm^3 .

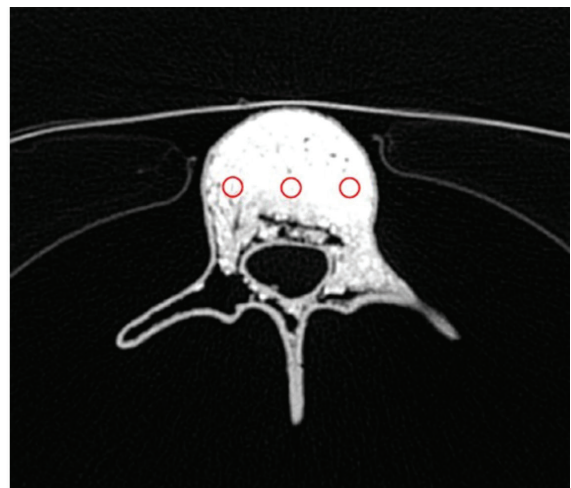
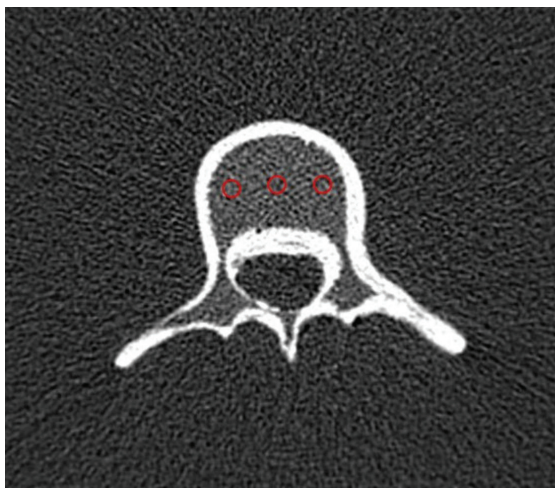


Figure 3. Example of three ROIs, each measuring 7.34 mm^2 , placed at different locations. Left: within vertebral bodies of the RSD RS-113T pelvic phantom, Right: 3D-printed lumbar spine phantom.



Figure 4. GE Lunar iDXA QC phantom used as the reference phantom for BMD validation.

Data analysis

To evaluate the radiological characteristics of the developed 3D-printed lumbar spine phantom in comparison with the RSD RS-113T pelvic phantom, descriptive statistics were calculated and are presented as mean±standard deviation (SD). Agreement between the two phantoms was assessed using Bland-Altman analysis to evaluate systematic bias and the limits of agreement for the measured parameters. All statistical analyses were performed using JASP software (version 0.19.6; JASP Team, Amsterdam, The Netherlands), an open-source statistical analysis package.

To validate the BMD performance of the developed 3D-printed phantom, the coefficient of variation (CV) was calculated from five repeated BMD measurements and compared with the manufacturer's recommended precision criteria ($\leq 2\%$).

Results

Table 1 summarizes the repeatability of CT number and BMD measurements obtained from five repeated scans of the RSD RS-113T pelvic phantom. The phantom exhibited mean CT number and BMD values of 752.94 HU and 1.80 gm/cm² (L1-L5), respectively. These values served as the reference for subsequent Bland-Altman agreement analysis with the developed 3D-printed phantoms. In the first phase of block sample testing, cuboid samples measuring 15×15×21 mm were printed using PETG and PLA filaments with infill densities of 80% and 100%, utilizing Gyroid and Crosshatch infill patterns. DXA measurements revealed that these samples did not generate sufficient signal intensity for reliable BMD calculation, necessitating redesign (Supplementary Table 1).

Table 1. CT number and BMD results obtained from five repeated scans of the RSD RS-113T pelvic phantom.

RSD RS-113T pelvic phantom (Scan number)	CT number (HU)				
	L1	L2	L3	L4	L5
1	733.10	787.40	755.30	793.80	695.50
2	737.92	789.52	761.97	795.41	702.30
3	740.20	785.60	750.80	788.47	703.60
4	736.05	792.44	745.32	789.67	696.30
5	730.60	784.70	751.19	780.50	695.85
Min	730.60	784.70	745.32	780.50	695.50
Max	740.20	792.44	761.97	795.41	703.60
Average	735.57	787.93	752.92	789.57	698.71
SD	3.41	2.79	5.53	5.21	3.50
%CV	0.46	0.35	0.73	0.66	0.50

RSD RS-113T pelvic phantom (Scan number)	BMD (gm/cm ²)				
	L1	L2	L3	L4	L5
1	1.74	1.94	1.88	1.74	1.81
2	1.73	1.91	1.87	1.72	1.80
3	1.75	1.92	1.84	1.73	1.77
4	1.71	1.90	1.82	1.69	1.75
5	1.74	1.93	1.85	1.71	1.80
Min	1.71	1.90	1.82	1.69	1.75
Max	1.75	1.94	1.88	1.74	1.81
Average	1.73	1.92	1.85	1.72	1.79
SD	0.01	0.01	0.02	0.02	0.02
%CV	0.58	0.52	1.08	1.16	1.12

As a result of the second phase, block samples were redesigned as box-shaped phantoms with lids, maintaining dimensions consistent with the L3 vertebral body. The lids and edges were printed at 100% infill density. Samples were fabricated using PETG and PLA with infill densities of 0%, 20%, and 40%, printed using Grid, Crosshatch, and Gyroid patterns. Samples were weighed before and after filling with CaCO_3 powder to assess filling efficiency. Weight measurements (Supplementary Table 2) confirmed

a significant mass increase following CaCO_3 addition, which correlated with enhanced CT number and BMD signals. In Table 2, CT and DXA measurements showed comparable average CT numbers for PETG and PLA samples containing CaCO_3 . However, the PETG sample printed at 0% infill demonstrated an average BMD of 1.69 gm/cm^2 , closely approximating the RSD RS-113T pelvic phantom's BMD of 1.80 gm/cm^2 . Therefore, PETG was selected as the optimal material for fabricating the lumbar spine phantom.

Table 2. CT number and BMD results from block sample tests conducted in the second phase.

3D printed block % Infill & Pattern	PETG		PLA	
	CT number (HU)	BMD (gm/cm^2)	CT number (HU)	BMD (gm/cm^2)
20% Grid	999.00	1.22	1182.00	0.96
20% Crosshatch	1231.20	1.00	1041.50	0.74
20% Gyroid	1094.90	0.86	955.30	0.72
40% Grid	748.60	0.80	839.50	0.56
40% Crosshatch	961.10	0.75	985.30	0.66
40% Gyroid	860.50	0.67	974.80	0.59
0%	1691.40	1.69	1603.70	0.97

Testing of the 3D-printed lumbar spine phantoms using PETG filaments with densities of 1.24 and 1.27 gm/cm^3 showed that the sample with 1.24 gm/cm^3 density had mean CT number and BMD values of 1061.70 HU and 0.96 gm/cm^2 (L1-L5), respectively. While structurally accurate, this phantom did not

adequately replicate X-ray attenuation compared to the pelvic phantom. In contrast, the phantom printed at 1.27 gm/cm^3 exhibited mean CT number and BMD values of 744.26 HU and 1.58 gm/cm^2 (L1-L5), closely matching the pelvic phantom in both structural and radiological properties (Figure 5).

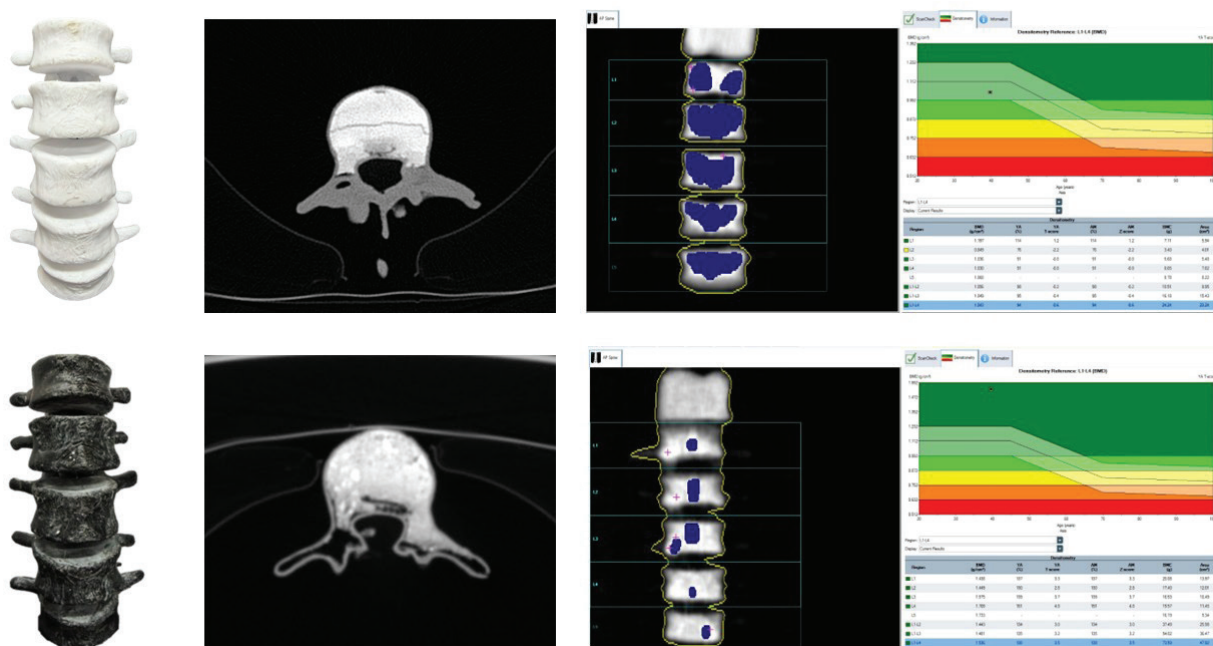


Figure 5. The 3D-printed lumbar spine phantom fabricated using PETG material with calcium carbonate (CaCO_3) powder added to simulate bone mineral content, showing CT and BMD measurements. Top: white indicates a density of 1.24 gm/cm^3 , Bottom: black indicates a density of 1.27 gm/cm^3 .

The repeatability of CT number and BMD measurements, derived from five repeated scans of the 3D-printed lumbar spine phantom fabricated from PETG with CaCO_3 powder added to simulate bone mineral content, is summarized in Tables 3 and 4.

Bland-Altman analysis was performed to evaluate the agreement of CT number and BMD measurements between the developed 3D-printed phantom and the RSD RS-113T pelvic phantom (Figure 6 and Figure 7).

Table 3. Repeatability of CT number measurements obtained from five repeated scans of the 3D-printed lumbar spine phantom fabricated using PETG (white, 1.24 gm/cm^3 , IEMAI, China) and PETG (black, 1.27 gm/cm^3 , eSUN, China) containing calcium carbonate powder to simulate bone mineral content.

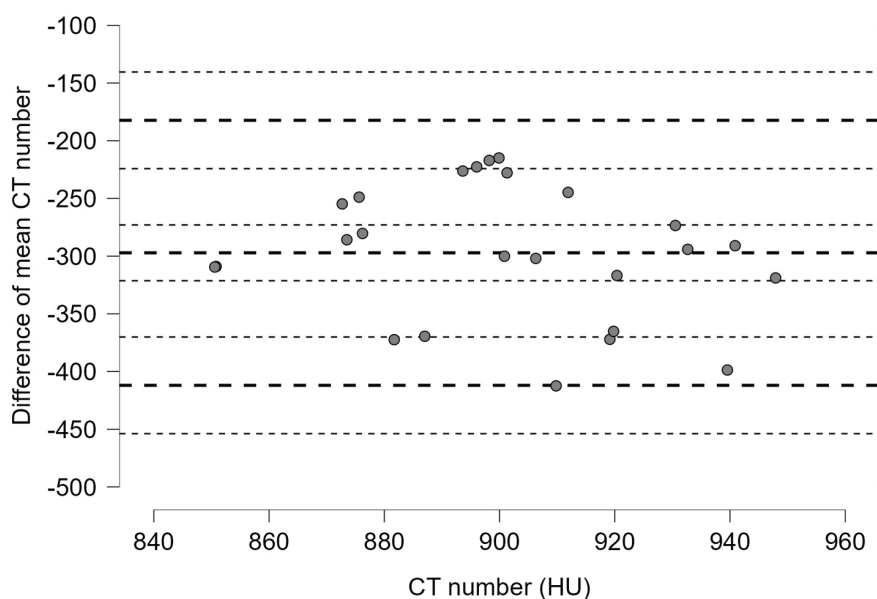
3D-printed PETG “White” filament density = 1.24 gm/cm^3 (Scan Number)	CT number (HU)				
	L1	L2	L3	L4	L5
1	1105.20	1102.40	1138.90	1016.40	1083.00
2	1015.22	1034.29	1079.73	1007.37	1015.86
3	1057.29	1078.80	1050.90	1000.07	1090.36
4	1067.25	1086.37	1107.39	1006.75	1058.12
5	1067.93	1071.75	1116.04	1005.29	1079.83
Min	1015.22	1034.29	1050.90	1000.07	1015.86
Max	1105.20	1102.40	1138.90	1016.40	1090.36
Average	1062.58	1074.72	1098.59	1007.18	1065.43
SD	28.77	22.64	30.45	5.28	27.01
%CV	2.71	2.11	2.77	0.52	2.54

3D-printed PETG “Black” filament density = 1.27 gm/cm^3 (Scan number)	CT number (HU)				
	L1	L2	L3	L4	L5
1	767.25	793.42	724.45	758.70	784.44
2	721.07	722.92	706.43	746.79	771.20
3	725.70	748.54	734.28	750.35	776.95
4	763.93	733.84	728.79	754.53	725.05
5	727.01	752.51	719.06	735.04	734.22
Min	721.07	722.92	706.43	735.04	725.05
Max	767.25	793.42	734.28	758.70	784.44
Average	740.99	750.25	722.60	749.08	758.37
SD	20.21	24.03	9.51	8.08	24.01
%CV	2.73	3.20	1.32	1.08	3.17

Table 4. Repeatability of BMD measurements obtained from five repeated scans of the 3D-printed lumbar spine phantom fabricated using PETG (white, 1.24 gm/cm³, IEMAI, China) and PETG (black, 1.27 gm/cm³, eSUN, China) containing calcium carbonate powder to simulate bone mineral content.

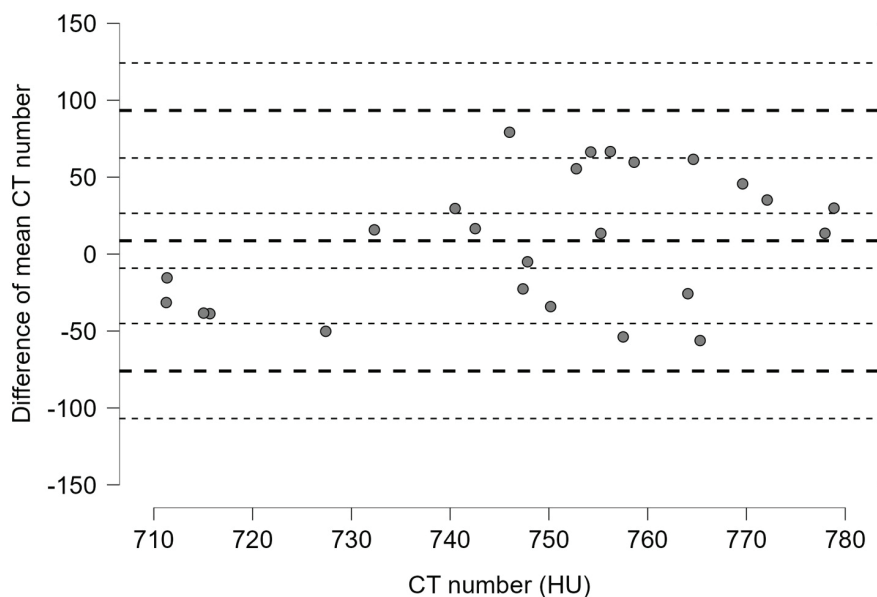
3D-printed PETG “White”		BMD (gm/cm²)				
filament density = 1.24 gm/cm ³						
(Scan Number)	L1	L2	L3	L4	L5	
1	1.20	0.85	1.04	1.03	1.07	
2	1.16	0.69	1.01	0.96	0.87	
3	1.13	0.68	0.93	1.02	0.83	
4	1.14	0.75	1.03	0.93	0.95	
5	1.15	0.75	0.97	0.98	0.89	
Min	1.13	0.68	0.93	0.93	0.83	
Max	1.20	0.85	1.04	1.03	1.07	
Average	1.16	0.74	1.00	0.98	0.92	
SD	0.02	0.06	0.04	0.04	0.08	
%CV	1.72	8.06	4.00	4.08	8.70	

3D-printed PETG “Black”		BMD (gm/cm²)				
filament density = 1.27 gm/cm ³						
(Scan Number)	L1	L2	L3	L4	L5	
1	1.45	1.45	1.60	1.71	1.71	
2	1.39	1.49	1.62	1.67	1.72	
3	1.44	1.41	1.63	1.72	1.72	
4	1.49	1.46	1.53	1.64	1.75	
5	1.44	1.42	1.55	1.79	1.74	
Min	1.39	1.41	1.53	1.64	1.71	
Max	1.49	1.49	1.63	1.79	1.75	
Average	1.44	1.45	1.59	1.71	1.73	
SD	0.03	0.03	0.04	0.05	0.01	
%CV	2.08	2.07	2.52	2.92	0.58	



3D-printed PETG (white) phantom and RSD RS-113T pelvic phantom

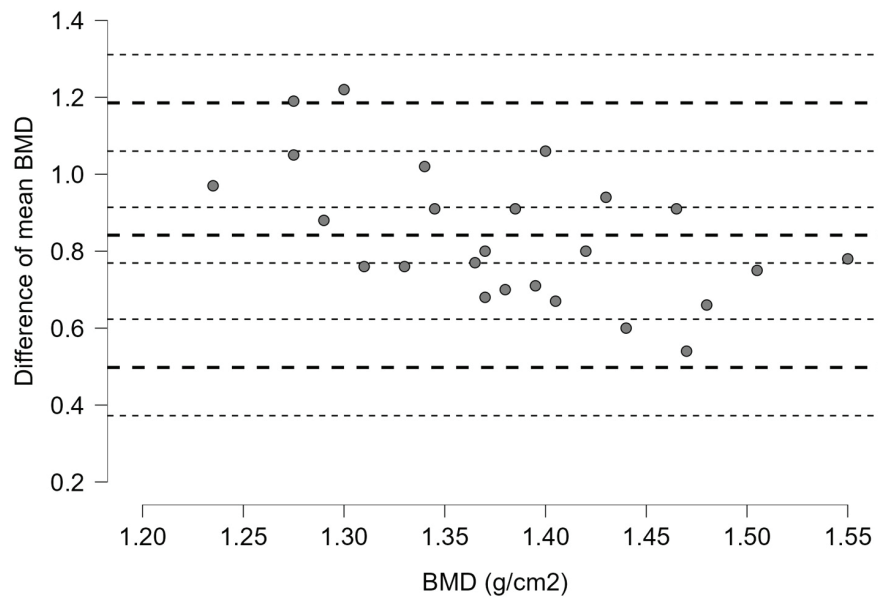
Bias & Limits	Point Value	Lower 95% CI	Upper 95% CI
Mean difference + 1.96 SD	-182.30	-224.20	-140.40
Mean difference	-297.10	-321.30	-273.00
Mean difference - 1.96 SD	-412.00	-453.90	-370.10



3D-printed PETG (black) phantom and RSD RS-113T pelvic phantom

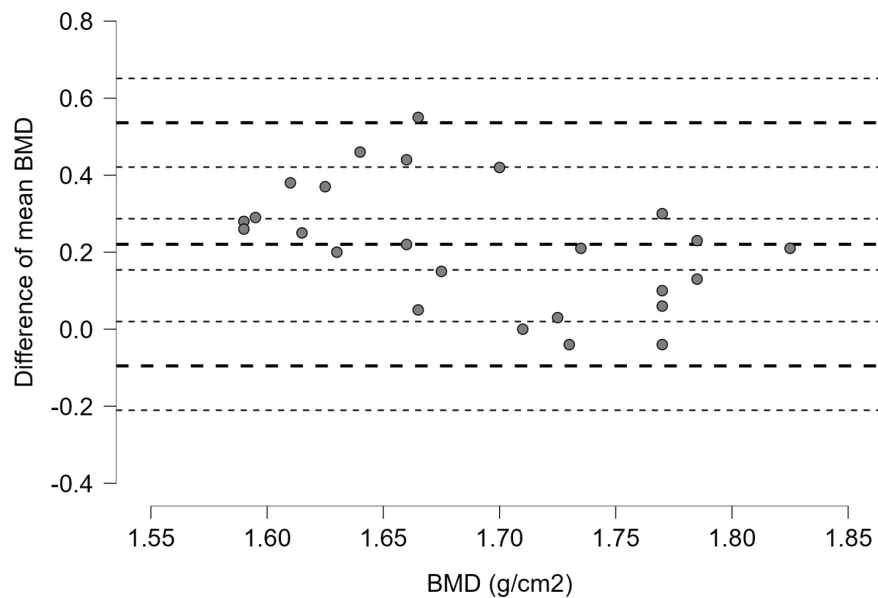
Bias & Limits	Point Value	Lower 95% CI	Upper 95% CI
Mean difference + 1.96 SD	93.32	62.43	124.20
Mean difference	8.65	-9.18	26.48
Mean difference - 1.96 SD	-76.01	-106.90	-45.13

Figure 6. Bland-Altman plots showing the agreement in mean CT numbers. Top: 3D-printed PETG “white” versus RSD RS-113T phantom, Bottom: 3D-printed PETG “black” versus RSD RS-113T phantom.



3D-printed PETG (white) phantom and RSD RS-113T pelvic phantom

Bias & Limits	Point Value	Lower 95% CI	Upper 95% CI
Mean difference + 1.96 SD	1.185	1.060	1.311
Mean difference	0.842	0.769	0.914
Mean difference - 1.96 SD	0.498	0.372	0.623



3D-printed PETG (black) phantom and RSD RS-113T pelvic phantom

Bias & Limits	Point Value	Lower 95% CI	Upper 95% CI
Mean difference + 1.96 SD	0.536	0.421	0.651
Mean difference	0.220	0.154	0.287
Mean difference - 1.96 SD	-0.095	-0.210	0.020

Figure 7. Bland-Altman plots showing the agreement in mean BMD values. Top: 3D-printed PETG “white” versus RSD RS-113T phantom, Bottom: 3D-printed PETG “black” versus RSD RS-113T phantom.

For CT number measurements (Figure 6), the developed 3D-printed PETG “white” phantom showed a mean difference of -297.10 HU, with 95% limits of agreement ranging from -412.00 HU to -182.30 HU. In contrast, the developed 3D-printed PETG “black” phantom showed a substantially smaller mean difference of 8.65 HU, with 95% limits of agreement ranging from -76.01 HU to 93.32 HU. Similarly, Bland-Altman analysis of BMD measurements (Figure 7) demonstrated greater agreement between the developed 3D-printed PETG “black” phantom and the standard RSD phantom than between the developed 3D-printed PETG “white” phantom and the standard RSD phantom. The developed 3D-printed PETG “white” phantom showed a mean difference of 0.84 gm/cm², with 95% limits of agreement ranging from 0.50 gm/cm² to 1.18 gm/cm². By comparison, the developed 3D-printed PETG “black” phantom showed

a mean difference of 0.22 gm/cm², with 95% limits of agreement ranging from -0.09 gm/cm² to 0.54 gm/cm². Overall, the developed 3D-printed PETG “black” phantom demonstrated closer agreement with the standard RSD RS-113T pelvic phantom than the “white” phantom, demonstrating smaller systematic bias and narrower limits of agreement for both CT number and BMD measurements.

Finally, developed PETG 3D-printed phantoms were validated using the GE Lunar iDXA QC phantom. In terms of repeatability, the GE Lunar iDXA QC phantom exhibited a coefficient of variation (CV) of less than 2% for BMD measurements (Table 5). The PETG black phantom demonstrated comparable repeatability, with BMD CV values ranging from 0.58% to 2.92%, whereas the PETG white phantom showed consistently higher variability (CV: 1.72%-8.70%).

Table 5. Repeatability of BMD measurements obtained from five repeated scans of GE Lunar iDXA QC phantom.

GE Lunar iDXA QC phantom (Scan Number)	BMD (gm/cm ²)
1	1.501
2	1.501
3	1.500
4	1.501
5	1.502
Min	1.500
Max	1.502
Average	1.501
SD	0.001
%CV	0.047

Discussion

This study focused on developing a 3D-printed lumbar spine phantom for X-ray-based imaging applications. Using FDM 3D printing technology, the phantom required approximately 6 to 9 hours. The average CT number and BMD values of the 3D-printed phantom closely corresponded to those of the RSD RS-113T pelvic phantom. Notably, PETG filament with a density of 1.27 gm/cm³ produced the developed phantoms with mean CT number and BMD values of 744.26 HU and 1.58 gm/cm², respectively, closely matching the pelvic phantom’s values of 752.94 HU and 1.80 gm/cm². This demonstrates the effectiveness of the developed phantoms in simulating both structural and radiological properties. These findings support the feasibility of tuning phantom radiological characteristics through material selection and density control, thereby enabling the fabrication of 3D-printed phantoms that more closely replicate human bone for CT number and DXA measurements.

3D printing offers several advantages, including the ability to fabricate complex anatomical geometries,

tune internal density, and produce customized phantoms through a relatively straightforward manufacturing process. These capabilities make 3D printing particularly well suited for designing imaging phantoms for radiological testing. Supporting this approach, previous studies have demonstrated the feasibility of using 3D-printed phantoms for quality assurance and performance evaluation in CT,¹⁵ and X-ray radiography by carefully tailoring material composition¹⁶ and internal structure to achieve clinically relevant attenuation, CT number values,¹⁷ and BMD ranges.^{18,19}

Based on the findings from the first phase of block sample testing, cuboid samples (15×15×21 mm) were fabricated using PETG and PLA filaments at infill densities of 80% and 100%, employing Gyroid and Crosshatch infill patterns. DXA measurements demonstrated that these samples produced insufficient signal intensity for reliable BMD quantification. This was attributed to the relatively low density of the filament materials, which limited DXA’s ability to detect and measure bone-equivalent signals. Therefore, the sample designs were modified to include CaCO₃

powder with an infill density of 0% to increase X-ray absorption and improve BMD detectability. The results showed that PETG- and PLA-based samples containing CaCO_3 exhibited comparable mean CT numbers; however, the PETG sample fabricated with 0% infill achieved an average BMD of 1.69 gm/cm^2 (Table 2), closely approximating the pelvic phantom's BMD of 1.80 gm/cm^2 . These findings are consistent with previous research by Badiuk *et al.*,²⁰ who reported that adding CaCO_3 and strontium carbonate into resin increased CT numbers up to approximately 1000-1500 HU for bone modeling. While Badiuk's study employed resin-based printing, this work utilized PETG filament. Although PETG is more expensive and more challenging to print than PLA, its superior mechanical strength and flexibility justified its selection, with a 0% infill density chosen for the fabrication of the 3D-printed phantom.

Limitations

This study has several limitations. Firstly, the amount of CaCO_3 powder incorporated during the 3D printing process could not be precisely controlled, which may have introduced variability in phantom composition and imaging properties. Secondly, the absence of surrounding soft tissue-equivalent materials may have affected CT attenuation and BMD accuracy. In addition, the two phantoms were scanned under different conditions; the RSD RS-113T phantom includes a soft tissue-equivalent surround, whereas the 3D-printed lumbar spine phantom was scanned in air. Given the influence of beam hardening, scatter, and attenuation from surrounding materials, these differences may have introduced systematic bias. Future work should incorporate soft tissue-equivalent materials or housing to better simulate clinical conditions and enable more direct comparison with anthropomorphic phantoms. Further development should also explore composite bone-mimicking filaments and alternative printing technologies to improve spatial resolution, material uniformity, and phantom homogeneity. Finally, further optimization and cross-vendor evaluation across different DXA systems are warranted to establish its broader applicability.

Conclusion

This study developed and validated a 3D-printed lumbar spine phantom using PETG filament (density 1.27 gm/cm^3) containing CaCO_3 powder. The phantom demonstrated radiological characteristics comparable to those of the commercial RSD RS-113T pelvic phantom and provided reliable BMD measurements when evaluated using the GE Lunar iDXA QC phantom, supporting its potential as an alternative phantom for DXA quality assurance and research applications. Further optimization and multicenter, cross-vendor validation across different DXA systems are warranted to establish its broader applicability.

Ethical approval

Ethical approval was not required for this study, as no human subjects were involved and no human data were collected.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

Availability of data

Data required for this study may be made available by the author(s) upon reasonable request.

CRediT authorship contribution statement

Thunyarat Chusin: conceptualization, review and edit, supervision; **Pakaphorn Kongfun:** methodology, data collection, data analysis; **Suchanya Chanapim:** methodology, data collection, data analysis; **Suphichaya Thanashappokin:** methodology, data collection, data analysis; **Thanyawee Pengpan:** conceptualization, review and edit, supervision; **Kingkarn Aphiwatthanasumet:** conceptualization, methodology, original draft, review and edit, supervision. All authors jointly discussed the results and approved the final version of the manuscript.

Generative AI and AI-assisted use

Not applicable

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