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Full range dose Phantom-less Quantitative CT Model for Bone Mineral Density Measurement

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ABSTRACT

This study developed and validated a full-dose-range patient-like phantom calibration algorithm for quantitative computed tomography (QCT) bone mineral density (BMD) measurement. Thoracolumbar CT data and European Spine Phantom scans were retrospectively collected from three CT scanners under 11 common acquisition protocols covering 70-120 kV, 52-260 mAs, and 0-16 mGy CTDI. Qwen2.5-VL was used to automatically extract dose parameters from CT dose reports, and TotalSegmentator was used to segment T11-L2 vertebrae, paraspinal muscle, and subcutaneous fat. Muscle and fat CT values were further filtered using HU thresholds to improve tissue specificity and then used as internal reference tissues to construct synchronous patient-like phantom calibration curves. In ESP validation, predicted BMD showed excellent agreement with reference BMD values, with a Pearson correlation coefficient of r = 0.997 (P < 0.001), mean bias of +0.27 mg/cm³, 95% limits of agreement from -8.78 to +9.32 mg/cm³, MAE of 2.90 mg/cm³, and RMSE of 4.63 mg/cm³. Compared with conventional 120 kVp QCT calibration, which showed an MAE of 14.52 mg/cm³, the proposed method significantly reduced measurement error (P < 0.0001). By using patient-specific internal tissues acquired under the same scan conditions as vertebral bone, this method improves calibration robustness across heterogeneous CT protocols. These findings suggest that the algorithm can provide accurate and stable BMD calibration across diverse dose levels and may support practical phantomless or low-phantom QCT assessment in clinical settings.

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INTRODUCTION

Quantitative computed tomography is an important imaging method for assessing BMD and diagnosing osteoporosis. Conventional QCT calibration usually requires simultaneous scanning of an external phantom under matched acquisition parameters. However, in routine clinical practice, CT protocols vary widely in tube voltage, tube current, and radiation dose, which may introduce calibration bias and limit the practicality of phantom-based QCT. Internal reference tissues such as paraspinal muscle and subcutaneous fat are acquired under the same scanning conditions as vertebral bone and may therefore serve as patient-like calibration references. Recent advances in automated CT segmentation and multimodal large language models also enable efficient extraction of anatomical regions and dose parameters. This study proposes a full-dose-range synchronous patient-like phantom calibration algorithm for QCT BMD measurement across diverse CT protocols.

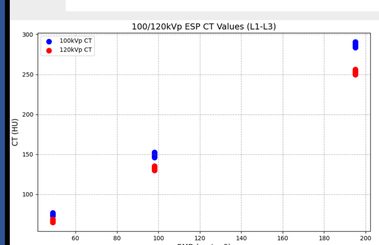
METHODS AND MATERIALS

Retrospective thoracolumbar CT data were collected from three CT scanners, together with repeated European Spine Phantom scans. Eligible scans covered the T11-L2 vertebral levels and had complete dose reports without severe artifacts or spinal lesions.

CTDI values were automatically extracted from dose reports using Qwen2.5-VL. Based on CTDI, tube voltage, and tube current, the data were grouped into 11 common CT acquisition protocols covering a CTDI range of 0-16 mGy.

TotalSegmentator was used to automatically segment T11-L2 vertebrae and extract paraspinal muscle and subcutaneous fat regions of interest. HU-threshold filtering was applied to improve tissue specificity, using -120 to -60 HU for fat and 30 to 80 HU for muscle. Mean CT values of muscle and fat were then calculated.

For each acquisition protocol, ESP training scans were used to fit phantom-based calibration curves. Muscle and fat CT values from patient scans were converted into equivalent reference densities. These internal reference values were then used to construct synchronous patient-like phantom calibration curves. ESP test scans were used to validate the predicted BMD values. Performance was evaluated using Pearson correlation, Bland-Altman analysis, mean absolute error, root mean square error, and comparison with conventional 120 kVp QCT calibration.



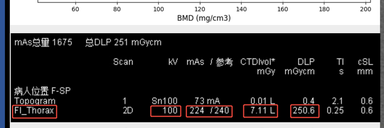


Figure 1. Nonlinear variation of CT values across different tube voltages in ESP.
Figure 2. Example of CT dose report and information to be extracted by Qwen-VL.

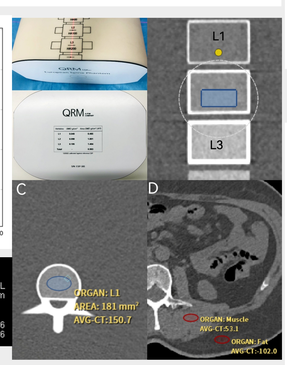


Figure 3. Phantom-less QCT method for measuring BMD on ESP manufactured by QRM.

RESULTS

The final dataset included **12521** CT images with 11 CT acquisition protocols covering 70-120 kV, 52-260 mAs, and 0-16 mGy CTDI. The algorithm was successfully applied across all protocols.

Predicted ESP BMD values showed excellent correlation with reference BMD values, with an overall Pearson correlation coefficient of r = 0.997 (P < 0.001). Bland-Altman analysis demonstrated good agreement, with a mean bias of +0.27 mg/cm³ and 95% limits of agreement from -8.78 to +9.32 mg/cm³.

The overall MAE and RMSE of the proposed method were 2.90 mg/cm³ and 4.63 mg/cm³, respectively. These errors were significantly lower than those of conventional 120 kVp QCT calibration, which showed an overall MAE of 14.52 mg/cm³ (P < 0.0001). The method maintained stable accuracy across both low-dose and high-dose CT protocols.

Group No.	Scanning Parameter	Patient No.	Tube Voltage (kV)	Tube Current (mAs)	CTDIvol (mGy)	DLP (mGy·cm)	Dose Group
1	70 kV, 96 mAs	87	70	104.3 ± 35.4	1.28 ± 1.65	36.0 ± 64.7	[0, 4] mGy
2	80 kV, 152 mAs	253	80	156.3 ± 32.3	2.97 ± 1.09	93.2 ± 40.6	
3	100 kV, 96 mAs	523	100	100.4 ± 26.4	3.65 ± 1.53	121.7 ± 55.1	
4	100 kV, 156 mAs	4381	100	149.2 ± 35.4	5.55 ± 1.38	195.3 ± 62.8	[4, 8] mGy
5	100 kV, 260 mAs	203	100	231.8 ± 51.6	8.78 ± 1.95	359.8 ± 144.5	[8, 12] mGy
6	110 kV, 159 mAs	471	110	160.1 ± 22.3	6.83 ± 1.27	247.9 ± 82.0	[4, 8] mGy
7	110 kV, 218 mAs	167	110	217.9 ± 28.0	9.25 ± 1.66	342.0 ± 120.5	[8, 12] mGy
8	120 kV, 52 mAs	167	120	56.3 ± 12.9	3.73 ± 0.71	134.9 ± 48.6	[0, 4] mGy
9	120 kV, 107 mAs	2718	120	103.9 ± 27.5	6.60 ± 1.40	248.1 ± 82.7	[4, 8] mGy
10	120 kV, 157 mAs	2979	120	154.3 ± 30.1	9.53 ± 1.89	356.2 ± 112.1	[8, 12] mGy
11	120 kV, 221 mAs	622	120	205.2 ± 32.7	12.89 ± 3.53	518.9 ± 215.8	[12, 16] mGy

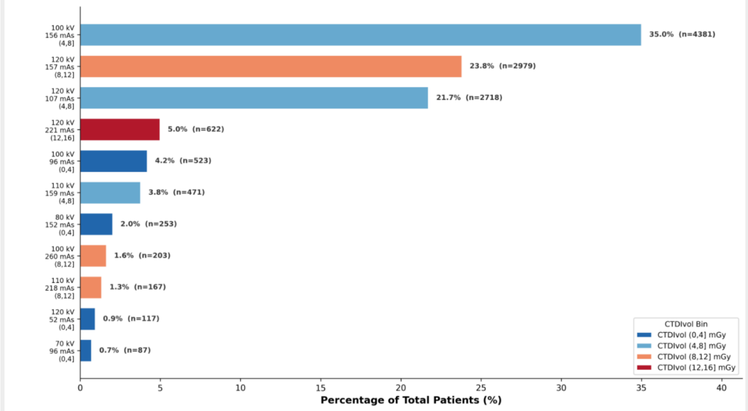


Chart 2. BMD measurement error (mean and standard deviation) on ESP with different scanning parameters..

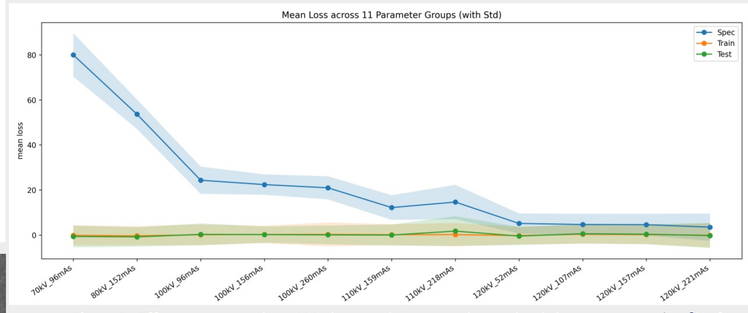
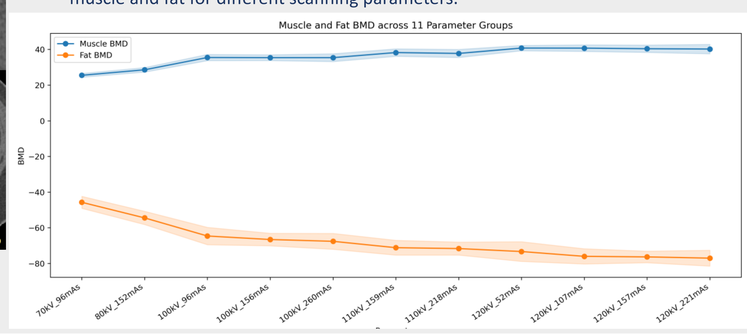


Chart 3. Effective equivalent HA density (mean and standard deviation, mg/cm³) of muscle and fat for different scanning parameters.



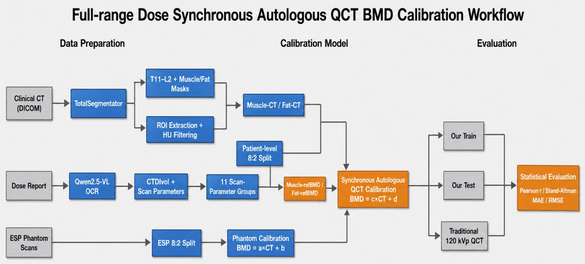
DISCUSSION

The proposed calibration method addresses a key limitation of conventional QCT: dependence on external phantom scanning under matched acquisition conditions. By using paraspinal muscle and subcutaneous fat as internal reference tissues, the method reflects patient-specific scanning conditions and reduces calibration bias caused by protocol variation.

Automatic segmentation with TotalSegmentator enabled stable extraction of vertebral and soft-tissue regions, while Qwen2.5-VL supported efficient dose parameter extraction from CT dose reports. Together, these components allowed the construction of a full-dose-range calibration framework suitable for heterogeneous clinical CT protocols.

The strong correlation, low bias, and reduced error compared with conventional 120 kVp calibration suggest that this approach may improve the practicality of QCT BMD assessment, especially in opportunistic screening or low-dose CT settings. Limitations include the single-center retrospective design, use of three CT scanners only, and validation primarily based on ESP phantom data. Further multicenter and prospective clinical validation is needed.

Figure 4. Workflow of full range dose phantom-less QCT.



CONCLUSIONS

A full-dose-range synchronous patient-like phantom QCT calibration algorithm was developed and validated. By combining automated internal tissue segmentation with dose-aware calibration, the method achieved accurate and stable BMD estimation across diverse CT acquisition protocols. This approach reduces reliance on external phantom scanning and has potential clinical value for practical phantomless or low-phantom QCT BMD measurement.

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