Normalization of Trabecular Bone Attenuation across kVp Values: A Physics-Based Correction for Opportunistic CT Screening of Osteoporosis

Dvij Sharma[1,2], Sheena Chu[1,2], Aria Salyapongse[1,2], Benjamin Rush[1], Matthew Lee[1], Perry Pickhardt[1,2], John W. Garrett[1,2]

1. *Department of Radiology, University of Wisconsin School of Medicine & Public Health, Madison, WI*
2. *Department of Medical Physics, University of Wisconsin School of Medicine & Public Health, Madison, WI*

Introduction

Opportunistic CT-based osteoporosis screening holds significant promise for population-level early detection, providing volumetric bone mineral density (BMD) assessment at scale. However, its clinical translation has been hindered by a fundamental technical barrier: established diagnostic thresholds are calibrated to 120 kVp, while real-world CT protocols span a broad range of tube potentials. Choice of tube potential significantly impacts Hounsfield Unit (HU) measurement of the same region of interest (ROI), meaning scans acquired outside of 120 kVp cannot be assessed using normative thresholds without CT number correction.

Goal: We developed an explainable, attenuation-based model that can correct trabecular bone attenuation (in HU) for scans at non-standard tube potentials to 120 kVp equivalents for osteoporosis screening. Model performance was evaluated on a large, non-con abdominal CT cohort.

Methods

We simulated polychromatic X-ray spectra (80–140 kV_p) using the SPEKTR tool with TASMICS modeling and appropriate filtration to match clinical CT configurations. Effective linear attenuation coefficients (μ_{eff}) for water and trabecular bone are derived by integrating NIST-tabulated mass attenuation coefficients over these simulated spectra for a given tube potential V. Trabecular attenuation at this potential is then converted into measured linear attenuation coefficient, which is then used to derive 120 kVp-equivalent effective linear attenuation coefficient, and finally 120 kVp-equivalent CT number. We modeled trabecular bone as a volume-weighted mixture of mineralized matrix (cortical bone surrogate) and marrow (adipose-water mixture), using empirical tissue composition data. Finally, L1 trabecular attenuation was extracted using a previously validated, deep-learning-based automated body composition tool that places a standardized ROI within the anterior trabecular space.

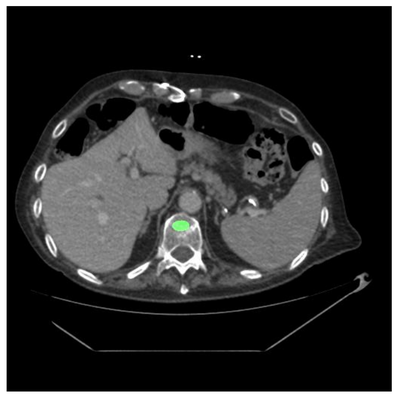
$$\mu_{eff,trab\,(V)} = \frac{\int \mu_{trab}(\varepsilon)\Omega_{(V)}(\varepsilon)d\varepsilon}{\int \Omega_{(V)}(\varepsilon)d\varepsilon}$$

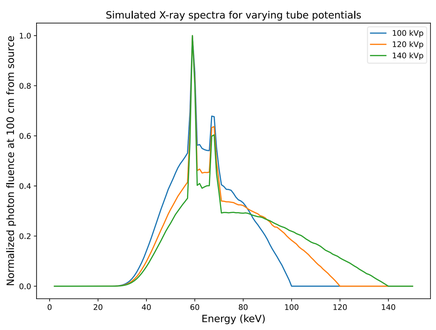
$$\mu_{eff,water(V)} = \frac{\int \mu_{water}(\varepsilon)\Omega_{(V)}(\varepsilon)d\varepsilon}{\int \Omega_{(V)}(\varepsilon)d\varepsilon}$$

$$\mu_{Meas(V)} = \mu_{eff,water(V)} \times \left(\frac{CT\#_{Meas(V)}}{1000} + 1\right)$$

$$\mu_{120eff,trab(V)} = \mu_{Meas(V)} \times \frac{\mu_{trab(120kV)}}{\mu_{trab(V)}}$$

$$CT\#_{120eff(V)} = \frac{(\mu_{120eff,trab(V)} - \mu_{eff,water(120)})}{\mu_{eff,water(120)}} \times 1000\,[HU]$$





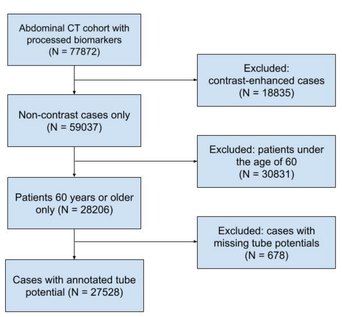


Figure 1: (top-left) simulated spectra at 100,120,140 kVp (top-right) trabecular ROI placed by deep learning tool, shown in green. (bottom-left) derivation of 120 kVp-equivalent CT number correction model (bottom-right) exclusion criteria used for patient cohort selection.

The model's efficacy was evaluated using a retrospective cohort of 28,206 non-contrast abdominal CT scans from patients over 60 years of age. In this case, age thresholding was performed to curate a patient cohort most at risk of osteoporosis. We performed a population-level analysis by stratifying the cohort by tube potential (100, 120, and 140 kVp) and comparing distributions before and after applying the physics-based correction factor. Finally, we also benchmarked our model against a recently developed linear regression-based correction model.

Results

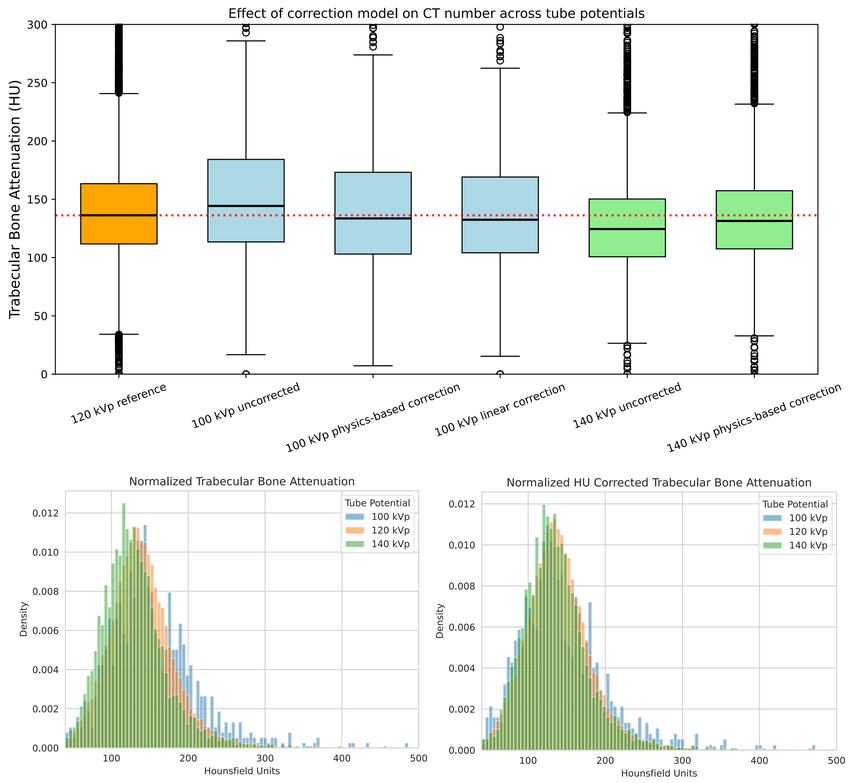


Figure 2: (top) boxplots and (bottom) histograms of HU distributions before and after correction model is applied.

The boxplot in *Figure 2* shows that after applying the correction factor, the 100 kVp CT number distribution is shifted down to a lower median HU, while the 140 kVp CT number distribution is shifted up to a higher median HU (both towards the 120 kVp distribution). The histograms further confirm that for both the 100 kVp and 140 kVp distributions, applying the correction model greatly increases overlap with the 120 kVp distribution. Additionally, in the case of the 100 kVp distribution, the boxplot shows that our physics-based correction model performs as well, if not slightly better, than a currently published linear correction model. Statistical analyses showed that our model eliminated significant distributional differences between corrected 100 kVp and baseline 120 kVp distributions.

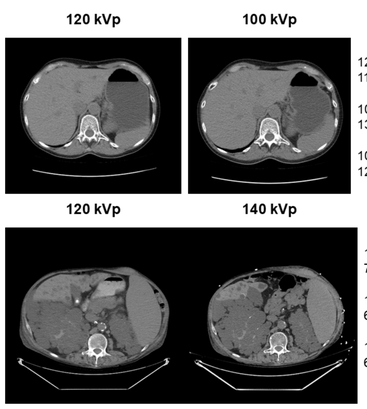
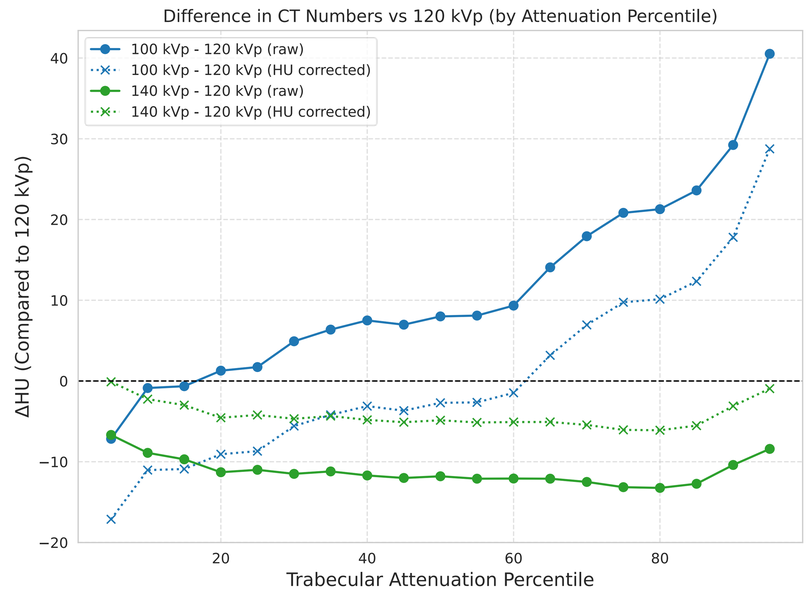


Figure 4: Sample pair of 120 kVp and 100 kVp scans acquired 26 days apart (top) and pair of 120 kVp and 140 kVp scans acquired 20 days apart (bottom).

Δ indicates the absolute difference between the 100/140 kVp measurement and the 120 kVp measurement in HU, with the correction model reducing Δ substantially. Apart from being used at population-level this figure indicates how the correction model can also faithfully harmonize CT number at the individual patient, allowing for osteoporosis screening regardless of tube potential.



%ile	120 kVp reference [HU]	100 kVp without correction [HU]	100 kVp corrected [HU]	140 kVp without correction [HU]	140 kVp corrected [HU]
25	111.7	113.4	103.0	100.7	107.5
50	136.3	144.3	133.6	124.5	131.4
75	163.4	184.2	173.1	150.3	157.3

Tube potential [kVp]	MAPE without correction (%)	Corrected MAPE (%)	Percentage reduction in MAPE (%)
25	111.7	113.4	103.0
50	136.3	144.3	133.6
75	163.4	184.2	173.1

Figure 3: (top) Trabecular attenuation percentiles against CT number with 120 kVp reference subtracted out. (center) Tables of CT number at 1st, 2nd , 3rd quartile before and after correction, and (bottom) associated mean absolute percentage errors (MAPE) pre and post correction.

Figure 3 shows that the 140 kVp distribution has a smaller difference in CT number with the 120 kVp distribution across all trabecular attenuation percentiles post-correction. Specifically, ΔHU is reduced from 11.0 HU to 4.2 HU at the 25th percentile, from 11.8 HU to 4.9 HU at the 50th percentile, and from 13.1 HU to 6.1 HU at the 75th percentile. Using this data, MAPE between the 140 kVp and 120 kVp distributions is reduced by 58.4% post-correction. While the 100 kVp distribution is also brought closer to the 120 kVp reference post-correction, this relationship is more variable across percentiles. The conversion model appears to over-correct at low trabecular attenuation, but beyond around the first quartile, performs better at reducing ΔHU. At the 25th percentile, ΔHU is increased from 1.7 HU to 8.7 HU, but at the 50th and 75th percentiles, ΔHU is reduced from 8.0 HU to 2.7 HU and from 20.8 HU to 9.7 HU respectively (MAPE reduction of 22.0% post-correction).

Discussion

- Our correction model was effective in harmonizing distributions of scans performed at 100 kVp or 140 kVp versus scans performed at 120 kVp, and could successfully convert trabecular bone CT number at a non-standard tube potential into a 120 kVp-equivalent CT number.
- Clinically, this may allow opportunistic osteoporosis screening for a wider range of patients, including larger patients requiring 140 kVp scans or patients requiring low dose protocols (including thin / pediatric patients).
- Unlike previous data-driven corrections, our method can be easily implemented for any tube potential using publicly available NIST-tabulated data, with correction factors being derived from first principles rather than big data.
- Since our method uses generalizable X-ray spectra, it can be more easily integrated into modalities such as photon-counting CT, intraoperative CT, and PET/CT.
- Our model uses tunable parameters that can be used for different patient anatomy.

Conclusions and Future Work

- We present a physics-based model that can effectively convert trabecular attenuation in HU at non-standard potentials into 120 kVp-equivalents for opportunistic osteoporosis screening.
- Our study used energy-integrating detectors; further work may wish to explore model efficacy on photon-counting detectors.
- Model should also be tested on diverse patient demographics using multi-institutional cohorts (federated learning).

Acknowledgements

Special thanks to the Departments of Radiology and Medical Physics, and the Center for High Value Imaging, at UW-Madison.