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Quantitative Cone-Beam CT of Bone Mineral Density Using Model-Based Reconstruction

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Abstract

Purpose: We develop and validate a model-based framework for artifact correction and image reconstruction to enable application of Cone-Beam CT (CBCT) in quantitative assessment of bone mineral density (BMD). Compared to conventional quantitative CT, this approach does not require a BMD calibration phantom in the field-of-view during an object scan.

Methods: The quantitative CBCT (qCBCT) imaging framework combined fast Monte Carlo (MC) scatter estimation, accurate models of detector response, and polyenergetic Poisson likelihood (PolyPL, Elbakri *et al* 2003). The underlying object model assumed that the tissues were ideal mixtures of water and calcium carbonate (CaCO₃). Accuracy and reproducibility of qCBCT was evaluated in benchtop test-retest studies emulating a compact extremity CBCT system (axis-detector distance=56 cm, 90 kVp x-ray beam, ~16 mGy central dose). Various arrangements of Ca inserts (50–500 mg/mL) were placed in water cylinders of ~11 cm to ~15 cm diameter and scanned at multiple positions inside the field-of-view for a total of 20 configurations. In addition, a cadaveric ankle was imaged in five configurations (with and without Ca inserts and water bath). Coefficient of variation (CV) of BMD values across different experimental configurations was used to assess reproducibility under varying imaging conditions. The performance of the model-based qCBCT framework (MC + PolyPL) was compared to FDK with water beam hardening correction and MC scatter correction.

Results: The PolyPL framework achieved accuracy of 20 mg/mL or better across all insert densities and experimental configurations. By comparison, the accuracy of the FDK-based BMD estimates deteriorated with higher mineralization, resulting in ~120 mg/mL error for a 500 mg/mL Ca insert. Additionally, the model-based approach mitigated residual streaks that were present in FDK reconstructions. The CV of both methods was ~15% at 50 mg/mL Ca and less than ~8% for higher density inserts, where the PolyPL framework achieved 20–25% lower CV than the FDK-based approach.

Conclusion: Accurate and reproducible BMD measurements can be achieved in extremity CBCT, supporting clinical applications in quantitative monitoring of fracture risk, osteoporosis treatment, and early osteoarthritis.

Keywords

bone mineral density; cone-beam CT; model-based iterative reconstruction; extremities imaging

1. INTRODUCTION

Bone mineral density (BMD) is an important biomarker in osteoporosis(OP) and in a variety of other conditions that lead to bone loss and elevated fracture risk (e.g. as a sequel to radiotherapy). Volumetric measurements of BMD using quantitative CT (qCT) are becoming increasingly prevalent in clinical practice [1]. Typical implementations of qCT involve scanning the patient with a hydroxyapatite (HA) calibration phantom placed in the field-of-view (FOV). The HA phantom is used to convert the reconstructed CT numbers to BMD. Accurate BMD measurements require high uniformity of CT numbers (i.e. the same material should have the same CT number independently of the location in the volume), which necessitates careful management of artifacts due to scatter and beam hardening.

Dedicated extremity cone-beam CT (CBCT) [2] provides novel capabilities for orthopedic imaging, such as volumetric evaluation of weight-bearing joints and enhanced spatial resolution compared to conventional CT [3]. The latter may enable new applications in in-vivo assessment of bone microstructure [4], where the performance of extremity CBCT will likely benefit from the recent introduction of systems based on CMOS x-ray detectors [5].

To achieve comprehensive assessment of bone health, high-resolution imaging capabilities of extremity CBCT must be augmented by accurate BMD measurements. We investigate quantitative performance of a previously developed comprehensive CBCT artifact correction framework [6] combined with polyenergetic model-based reconstruction (PolyPL) [7]. PolyPL implicitly models the object in terms of base material densities, obviating the need for BMD calibration phantom in the FOV. The performance of this “phantomless” quantitative CBCT (qCBCT) is assessed in benchtop studies in terms of accuracy and test-retest reproducibility.

2. METHODS

2.1 Polyenergetic Poisson likelihood (PolyPL) with ideal mixture model

We adopt a polyenergetic Poisson likelihood objective introduced in [7] (smoothness penalty omitted for clarity):

$$-L(\rho) = \sum_{i=1}^N h_i \left(\int I_i(E) \exp \left(\sum_k^K -m_k(E) \sum_j^P a_{ij} \rho_j f_k(\rho_j) \right) dE \right) \quad (1)$$

The objective assumes $k=1 \dots K$ base materials; $h_i(t) = -y_i \log(t) + t$ is the negative-log-likelihood, Y_i is the transmission measurement in pixel i ; $I_i(E)$ is the source spectrum for measurement i ; m_k is the energy-dependent mass attenuation for material k ; and a_{ij} is an element of the projection matrix for voxel j and measurement i .

The objective is solved for the unknown vector of voxel densities, denoted as p . The crucial feature of PolyPL is the tissue fraction function $f_k(p)$, which links the density of a voxel to the (mass) fraction of base material k in the voxel. Unlike previous methods proposed for beam hardening correction [8], [9], the estimation problem does not require a binary segmentation of voxels into one single material, but rather supports a continuous mixture of base materials with respect to total density.

In this study, we derived the tissue fraction function from the ideal mixture model, which applies to immiscible collections of materials such as cortical bone and water. The model assumes that volumes are additive. Fig. 1 shows $f_k(p)$ for two base materials used in this work, water (f_w) and calcium carbonate (CaCO_3 , abbreviated here by f_{ca}). The tissue fraction functions were obtained by a least square fit of pure densities (p_w, p_{ca}) in the ideal mixture model to specifications of Gammex Ca tissue characterization inserts (Gammex, USA). The results of the fit were smoothed to ensure that $f_k(p)$ was continuous up to 1st derivative, as required by the separable paraboloidal surrogate algorithm used to optimize (Eq. 1).

The framework of Eq. 1 can be extended to more materials, including metal implants. The transition to a metal-water or metal bone mixture in such an object model can either be based solely on voxel density, or may involve utilizing knowledge of implant location in the reconstructed field of view, obtained e.g. using 3D-2D registration from prior knowledge of the shape of the metal component[10].

2.2 Model-based qCBCT artifact correction and reconstruction framework.

The framework combined PolyPL or analytical Feldkamp reconstruction (FDK) with scatter estimation using a fast Monte Carlo (MC) model of x-ray propagation [6] applied to the reconstructed volume. Whenever FDK algorithm was used, the projection data was first processed with water beam hardening correction (linearization) based on precomputed tables of transmission signal vs. water line integral [6]. The reconstruction algorithms and the MC simulator utilized TASMICS/Spektr models [11] of x-ray spectra tuned to match Aluminum transmission measurements on the experimental setup. Energy-dependent detector response was simulated based on linear cascaded systems.

The accelerated MC scatter simulation involved tracking of very low number of photons (10^5 photons/projection) followed by kernel denoising [10]. This approach yielded simulations times of <5 sec/projection. MC scatter estimates were subtracted from measured projections to yield a corrected dataset.

The framework was initialized by generating a baseline reconstruction using five alternating iterations of water-corrected-FDK (voxel size of 0.4 mm, ramp filter with cutoff at Nyquist frequency) and Monte Carlo (MC) scatter correction. The attenuation values from FDK (μ) were converted to total density (ρ) by interpolating from a table of total density and attenuation values given by:

$$\mu = \frac{\int \left[\left(\frac{\mu}{\rho} \right)_W \rho f_w(\rho) + \left(\frac{\mu}{\rho} \right)_{Ca} \rho f_{Ca}(\rho) \right] q D dE}{\int q D dE} \quad (2)$$

where q is the source spectra and D is the energy-dependent detector gain. The density map was used to initialize PolyPL. 100 iterations of PolyPL were performed with additional MC scatter estimation every 25 iterations. Voxel size was 0.4 mm; quadratic penalty with penalty strength $\beta=10^6$ was used.

2.3 Experimental validation.

Experimental studies were performed on a flat-panel detector (Varex 4030, Varex, USA) testbench emulating an extremity CBCT system. The source-axis distance was 41 cm, and the source-detector distance was 56 cm. CBCT data were acquired using tube current of 90 kV and 0.2 mAs / frame. The x-ray beam was filtered with 2 mm Al and 2.5 mm Cu. The scan involved 720 projections over 360°. The resulting CTDI central dose was ~16 mGy. Pixel size was 0.388 mm.

The first experiment investigated accuracy and reproducibility of BMD obtained using the proposed “phantomless” qCBCT. High degree of reproducibility is required for any quantitative imaging metric intended for use in longitudinal or population studies. The validation presented here is thus an essential first step for translation of qCBCT to clinical applications in BMD measurements.

Fig. 2A summarizes the imaging configurations. Gammex Ca inserts ranging from 50–500 mg/Ml were positioned in various arrangements in two water cylinders of different diameter (11.7 cm and 15.6 cm). Each phantom arrangement was scanned 4 times in different positions within the field of view (FOV, Fig. 2B) yielding 20 configurations to assess test-retest reproducibility.

Analysis was performed on 5.2 mm³ regions of interest (ROIs) at the center of the Ca inserts. qCBCT accuracy was measured as the absolute value of difference in mean density values between the Gammex datasheet Ca concentration and the reconstructed value within the ROI. The coefficient of variation (CV, σ/μ) was used to gauge the reproducibility between imaging configurations.

The second study assessed reproducibility in realistic anatomy using a cadaveric ankle. Five imaging configurations, emulating variability in patient anatomy and positioning, were obtained by placing Ca inserts (20–400 mg/mL) and water containers alongside the ankle (Fig. 2C). A set of rigidly registered 7.6 mm³ bone ROIs was used to measure CV across the various imaging configurations.

3. RESULTS AND BREAKTHROUGH WORK

Fig. 3 shows reconstructions of the various water cylinder configurations obtained with water-corrected FDK (the baseline reconstruction of Sec. 2.2) and PolyPL. Overall, excellent

scatter correction has been achieved, as evidenced by high uniformity of the water background. Since water-corrected FDK does not account for beam hardening in bone, residual streaks are present in FDK reconstruction, but greatly mitigated in PolyPL.

BMD values measured in each insert in all repeat scans are shown Fig. 4A. PolyPL yields improved agreement with nominal Ca concentrations and less spread of BMD values across all configurations. Accuracy of BMD values (mean across all configurations) is further analyzed in Fig. 4(B). The accuracy of PolyPL is better than 20 mg/mL for all Ca concentrations, whereas FDK shows increasing error with increasing nominal BMD (up to about 120 mg/mL error at 500 mg/mL). Analysis of reproducibility in terms of CV is shown in Fig. 4(C). The CV for both PolyPL and FDK is better than 15% for all BMD inserts. However, PolyPL CV is comparable to that of FDK for BMD<100, and is typically 0.7–0.8 that of the FDK at BMD 100 mg/mL. We note that the bias present in FDK reconstructions could be somewhat reduced by application of a BMD calibration phantom in the FOV instead of using the approximate Eq. (3). PolyPL, on the other hand, achieves better accuracy and reproducibility than FDK without any in-scan calibration.

Fig. 5 shows the cadaveric ankle, with overlays of mean BMD and CV over all repeats in different imaging configurations. The CV is typically better than 20%, confirming the reproducibility of qCBCT BMD measurements in this realistic setup. As shown in Fig. 5E, the CV of ankle ROIs is typically better in PolyPL than in water-corrected FDK. In cortical bone ROIs, a 50% reduction in CV can be observed from PolyPL.

4. CONCLUSIONS

The proposed combination of MC-based scatter correction and PolyPL yielded accurate and reproducible CBCT measurements across a broad range of imaging conditions. The reproducibility of reconstructions obtained with water-corrected FDK and MC scatter estimation was also acceptable, indicating that the MC scatter model plays a significant role in providing the desired robustness to changes in object and imaging configuration. PolyPL delivers improved artifact correction, reconstruction accuracy, and reproducibility compared to FDK. Furthermore, PolyPL enables “phantomless” qCBCT measurements, greatly simplifying the imaging workflow.

CBCT has traditionally been considered to provide poor quantification because of significant scatter and detector nonuniformity. This study shows that appropriate algorithmic corrections based on a detailed system model can yield sufficient quantitative accuracy and reproducibility to support CBCT applications as biomarker of bone mineralization. Ongoing studies include application of PolyPL to high resolution reconstructions. We are also investigating BMD accuracy in the presence of metal hardware using PolyPL guided by approximate knowledge of metal location obtained through deformable 3D-2D registration of a prior implant model.

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Figure 1.

PolyPL object model $f_k(p)$ water and CaCO_3 fractions as a function of voxel density

Figure 2.
(A) Phantom configurations for the water cylinder study.(B) Experimental setup for the water cylinder study.(C) Scan configurations for the cadaver ankle study.

Figure 3.
Representative water cylinder reconstructions obtained using water-corrected FDK and PolyPL for various imaging configurations.

Figure 4.

(A) BMD measurements for all Ca inserts and all water cylinder scans. (B) Accuracy (mean across all repeated experiments) with respect to nominal Ca concentration. (C) Coefficient of variation of BMD values, indicating test retest reproducibility between the various imaging configurations.

Figure 5.

(A)-(D) Cadaveric ankle density map as reconstructed with polyPL with BMD overlay in (A) (C) and CV overlay in (B)(D). (E) Coefficient of variation for 8 registered ankle ROIs.