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Abstract

CBCT scanners have been widely used in angiography, radiotherapy guidance, mammography and oral maxillofacial imaging. To cut detector size, reduce manufacturing costs and radiation dose while keeping a reasonable FOV, the flat panel detector can be placed off-center horizontally. This scanning configuration extends the FOV effectively. However, each projection is transversely truncated, bringing errors and artifacts in reconstruction. In this paper, a simple but practical method is proposed for this scanning geometry based on truncation compensation and the modified FDK algorithm. Numerical simulations with jaw phantom were conducted to evaluate the accuracy and practicability of the proposed method. A novel CBCT system for maxillofacial imaging is used for clinical test, which is equipped with an off-center small size flat panel detector. Results show that reconstruction accuracy is acceptable for clinical use, and the image quality appears sufficient for specific diagnostic requirements. It provides a novel solution for clinical CBCT system, in order to reduce radiation dose and manufacturing cost.

Full Text

Preamble

A Practical Image Reconstruction and Processing Method for Symmetrically Off-Center Detector CBCT System

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Abstract

CBCT scanners have been widely used in angiography, radiotherapy guidance, mammography, and oral maxillofacial imaging. To reduce detector size, manufacturing costs, and radiation dose while maintaining a reasonable field of view (FOV), the flat panel detector can be placed off-center horizontally. This scanning configuration effectively extends the FOV; however, each projection is transversely truncated, introducing errors and artifacts in reconstruction. This paper proposes a simple but practical method for this scanning geometry based on truncation compensation and a modified FDK algorithm. Numerical simulations with a jaw phantom were conducted to evaluate the accuracy and practicability of the proposed method. A novel CBCT system for maxillofacial imaging equipped with an off-center small-size flat panel detector was used for clinical testing. Results show that reconstruction accuracy is acceptable for clinical use, and image quality appears sufficient for specific diagnostic requirements. This provides a novel solution for clinical CBCT systems to reduce radiation dose and manufacturing cost.

Key words: Cone beam CT, Off-center detector, Image reconstruction, Field of view, Projection truncation, Central artifacts

Introduction

With the rapid development of CT technology, cone beam CT (CBCT) based on volumetric tomography has revolutionized radiation imaging, particularly for angiography, radiotherapy guidance, mammography, and oral maxillofacial imaging. Compared with conventional multi-slice CT (MSCT), CBCT systems offer many significant advantages, such as smaller size, lower radiation dose, and reduced cost. CBCT also shortens examination time and reduces image unsharpness caused by patient translation and distortion due to internal patient movements [1]. Flat panel detectors used in CBCT systems increase X-ray absorption efficiency [2].

However, CBCT systems also have disadvantages. One is low image quality related to noise and contrast resolution because of large amounts of scattered radiation [3]. Another is the limited field of view (FOV), which often causes projection truncation. Generally, FOV dimensions covered by CBCT depend primarily on detector size and shape, beam projection geometry, and beam collimation capability [4]. To reduce manufacturing costs, smaller detectors are always preferred. This paper investigates a novel CBCT scanning geometry that extends FOV width by offsetting the detector position, collimating the beam asymmetrically, and scanning only half the object at each angular position. In this case, projections are transversely truncated, leading to serious truncation artifacts and value errors with traditional reconstruction methods.

In circular orbit CBCT systems, the FDK reconstruction algorithm is widely used due to its simple mathematical formulation, fast computation, and easy implementation [5]. However, traditional FDK requires non-truncated projection data in the horizontal direction; otherwise, it produces serious errors and truncation artifacts. Many attractive algorithms have been suggested over the years for projection truncation problems. Cho et al. [6] proposed pre-weighting and post-weighting FDK algorithms that mitigate truncation artifacts to a certain degree. Zamyatin et al. [7] adapted a similar concept of approximating truncated data by complementary rays for helical CT with off-center detectors. In 2004, Noo et al. [8] reported a two-step Hilbert transform method for parallel-beam and fan-beam reconstruction from transversely truncated projections, building on Zou and Pan's work [9]. Additionally, BPF-type reconstruction algorithms based on PI-lines have been expanded for exact reconstruction within ROI from reduced-scan data containing transverse truncations.

In off-center detector scanning scenarios, BPF reconstruction methods yield good results. Leng et al. [10] applied a BPF algorithm to the fan-beam case with an asymmetric half-size detector. Li et al. [11,12] reported a BPF-type reconstruction algorithm for cone-beam CT systems with reduced-size off-center detectors. Besides FDK and BPF algorithms, algebraic and statistical maximum-likelihood reconstruction algorithms have been used for off-center detector CT reconstruction, handling native truncated cone-beam projection data and improving image quality [13]. However, high computational load remains a major challenge for their clinical use in CBCT imaging.

Clinical application of off-center detector CBCT systems still faces many problems, with one of the most critical being reduction of artifacts caused by small detectors while ensuring correct reconstructed values [14]. This paper investigates off-center detector CBCT scanning geometry and reconstruction methods. Motivated by Cho et al.'s approach [6], we propose a simple but practical solution based on truncation compensation and a modified filtered back-projection (FBP) method. Its feasibility is demonstrated through numerical studies. A novel oral CBCT system with an off-center small-size flat panel detector was designed for maxillofacial imaging, and clinical experiments were conducted.

2.1 System Geometry

In CBCT systems, an X-ray tube and flat panel detector are fixed to a rotating gantry. During rotation, multiple sequential planar projection images of the FOV are acquired as projection data. CBCT systems can theoretically reduce scanning trajectory completeness and still reconstruct using a "short scan" [15]. However, with off-center detector scanning geometry, a full 360° scan is needed to complete the dataset.

As shown in Fig. 1(a), a small off-center detector is placed symmetrically, covering only half of the scanning object at each scanning angle. The scanning plane (O , x, y) is central. S represents the X-ray source, and R is the scan trajectory radius. The flat panel detector width and height are along the a and b axes. Three-dimensional projections from the flat panel detector are represented as p(ϕ, a, b) in Fig. 1(b), where ϕ is the rotation angle. Attenuation projections are represented as f(x, y, z) centered on the origin O of a Cartesian coordinate system. Scanning parameters for simulation and experiment are shown in Table 1 , demonstrating that a smaller detector can achieve a larger transverse FOV, which is useful for cost and dose reduction.

2.2 Reconstruction Method

As shown in Fig. 1(b), projections at each angle view (ϕ) are transversely truncated. This truncation produces a sharp-cut boundary, and its Fourier representation manifests as oscillating ripples and overshoots around the boundary, known as the Gibbs effect. The Gibbs effect and truncation artifacts can be reduced by extrapolating the truncation boundary under continuous and smooth conditions. Various padding methods have been proposed [16–18], but they cause reconstructed CT numbers to deviate from true values or involve overly complex projection estimation processes for commercial application.

In the two-dimensional condition (fan-beam CT scanning), when the detector is off-center, data completeness conditions for exact and stable reconstruction can be satisfied with a full 360° scan [19]. Standard projection data can be obtained by establishing relationships between missing rays and opposite rays. This process is theoretically called exact "rebinning" [20]. In cone-beam reconstruction, circular data acquisition does not yield a complete set of three-dimensional Radon values, thus achieving only approximate reconstruction. A similar padding method can approximately estimate truncated projections from off-center detectors. The missing half of the projections are filled with the nearest opposing rays slice by slice as shown in Eq. (1):

$$\text{pestimate}(\phi, a, b) = p(\phi + \pi \pm 2\beta, -a, b) \quad (1)$$

Then, extrapolated projections are obtained. This estimation is not accurate outside the middle plane; errors increase with cone angle growth, and sudden discontinuities can occur when splicing real and estimated data. The data should be smoothed to avoid artifacts in reconstructed images. Convolution with a Gaussian function is applied to the region of a [$-\Delta$, Δ] in the fixed projection to smoothly link left and right parts. In this study, Δ is set to 12 pixels.

This method provides the closest available data to estimate missing projections. The spliced datasets are filtered while preserving numerical accuracy in the reconstruction volume and perform better than cosine extrapolation, constant extrapolation, linear extrapolation, and other methods. After projection estimation, full-length projection data are obtained. After filtering, only the measured data are used in the back-projection procedure to avoid artifacts induced by inaccurate projection extrapolation. The reconstruction process is summarized as follows.

The projection depends on fan-angle and cone-angle weighted by a pre-weighting factor. Convolution with the ramp-filter gP(a) is applied. Then, pre-weighted and filtered projections are back-projected into the reconstruction volume over the complete 360° angle interval. After filtering, only the measured part (a>0) in the fixed projection is back-projected to form the reconstruction, avoiding artifacts from inaccurate projection extrapolation.

The $1/[U(\phi,x,y)^2]$ term in Eq. (4) is identical to fan-beam back-projection. In the scanning path plane, the missing part is recovered exactly as in FDK. Due to cone angle and data missing, the truncated part cannot be fixed exactly in other planes. There is discontinuity at the boundary between original and estimated projections. Errors are expected to increase away from the middle plane with cone angle growth. Therefore, artifact reduction after reconstruction is needed.

2.3 Central Artifacts Reduction

In reconstructed coronal slices, artifacts appear as a circular region near the rotation center with abnormal intensity variation. Left-right intensity imbalance in central coronal slices is observed. Besides errors in truncated estimation, scatter is another factor causing reconstruction artifacts. In experiments with offset scanning geometry, asymmetric scatter distribution leads to obvious central artifacts, especially around the central axis of the imaging FOV [21]. Accurate scatter estimation and post-processing scatter reduction can decrease central artifacts, but this requires Monte Carlo simulation followed by iterative fitting, which is computationally expensive [22].

Image post-processing in the reconstructed volume is practical for reducing central artifacts. Here we use bicubic interpolation in the central area. The selected central area in each transaxial plane is replaced by bicubic interpolation data and smoothed by a 3D Gaussian filter, reducing central artifacts to a certain extent. In oral imaging, central artifacts have little impact on diagnosis since we focus on teeth and jaw; thus, simple processing is sufficient for clinical application.

3.1 Simulation

To provide a stringent and realistic test for the proposed method, a mathematical 3D jaw phantom with varying contrast levels was used for simulation studies, evaluating reconstruction performance and displaying important structures in the jaw region with minimal simple geometrical objects [23]. Three molars were replaced with high-density crowns to observe metal artifact influence. Projections were obtained by a flat panel detector. In each scan, the total number of projection views was 360 over a full 360° circle around the jaw phantom. The reconstructed volume size was 512$×512×$512. Scanning geometry was the same as Fig. 1.

Different slices were reconstructed using conventional FDK method from full-size detector CBCT scanning and the proposed method from half-size detector

CBCT scanning. All images are shown in the same gray scale of [0.5, 3]. Results demonstrate that the proposed method can reconstruct volume images for off-center half-size detector CBCT systems and avoid truncation artifacts. There is no severe reconstruction difference between full-size FDK method and the proposed method. However, streak artifacts are more severe in the presence of high-contrast objects.

Reconstructed gray-scale profiles of transaxial slices are shown in Fig. 4, indicating that density deviations from full-length detector data and off-center detector data are similar in reconstructed results. The proposed method can save detector size and reconstruct the object correctly.

For quantitative comparison, we use NMSD (Normalized Root Mean Squared Distance) as an evaluation standard, defined as Eq. (6). The average NMSD is 0.92$\times10^{-4}$ for different slices with full-size detector and 1.13$\times10^{-4}$ for the proposed method with half-size detector. The reconstructed value is more accurate than other extrapolation methods and acceptable for clinical application, especially in dental imaging and IGRT.

3.2 Experimental

Using a high-contrast FORBILD jaw phantom, objects can be accurately reconstructed by the proposed method from a half-size detector. However, clinical scanning objects are far more complicated than phantoms. Therefore, we conducted experiments with clinical oral scanning data on a novel experimental CBCT system designed for maxillofacial imaging with a 13 cm$\times 13cm flat panel detector. By off-centering the detector, the FOV achieves 15cm\times$8 cm and covers the maxillofacial region. In experiments, the X-ray tube operated at 100 kVp and 3 mA. Total projection number was 360. Rotation and data acquisition took about 20 s per scan. Reconstructed transaxial and sagittal planes are shown in Fig. 5. The proposed method can reconstruct fine detailed high-contrast structures from off-center detector CBCT systems and remove truncation artifacts.

In general, image quality and reconstruction accuracy meet clinical requirements, especially for oral and maxillofacial imaging. As shown in Figs. 5 and 6, image quality is acceptable due to truncation artifact removal. There is a trade-off between signal-to-noise ratio (SNR) and projection amount. Compared with full-size detector configuration, SNR is impacted because projection data are reduced by half, and streak artifacts are more severe with high-contrast objects. This can be reduced by image processing methods after reconstruction. Considering dose and cost reduction, this approach is practical and useful.

4 Discussion

This method is demonstrated through clinical study. Future enhancements will likely focus on improving image quality and reducing noise disturbance. New reconstruction algorithms will emphasize dose benefits and high image quality, such as algebraic reconstruction techniques and statistical reconstruction algorithms. In CBCT systems, poor soft tissue contrast is another challenge, and scattered radiation is a significant factor reducing contrast.

5 Conclusion

This paper introduces a novel circular CBCT scanning configuration with off-center detector that effectively reduces detector size, saves manufacturing cost and radiation dose, and extends transverse FOV. A processing method based on truncation compensation and modified FDK-type algorithm is proposed. Its effectiveness is demonstrated by numerical simulation and experiment. Reconstruction accuracy is acceptable for clinical use, and image quality is sufficient for specific diagnostic requirements. The method also offers high computational efficiency and easy implementation for commercial application. Using GPU acceleration, the volume can be reconstructed from raw projection data in half a minute. Central artifacts are reduced by image processing after reconstruction without impacting diagnosis. However, using this scanning geometry degrades SNR of reconstructed images due to reduced detector size. In the future, noise reduction methods will be studied to improve image quality.

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Note: Figure translations are in progress. See original paper for figures.