Practical approach to misalignment correction in a single-circle orbit cone-beam tomography

Marek Karolczak[1], Ulrike Taubenreuther[1],
Klaus Engelke[1], Andreas Lutz[1],
Stefan Schaller[2], Willi Kalender[1]

[1]Institute of Medical Physics, University of Erlangen-Nürnberg, Germany
[2]Siemens AG, Medical Engineering Group, Forchheim, Germany

Abstract

This contribution addresses the reduction of artifacts in cone-beam tomography (CT and SPECT/PET) that are caused by imperfect scanner mechanical alignment (i.e. misalignment). Such artifacts may show up as double contours, split edges, smearing, loss of resolution, change in magnification etc. Misalignment is a problem commonly recognized in SPECT/PET (see for example [12]) whereas in CT its importance has only recently been emphasized with the advent of cone beam geometry [5][9][11], although residual misalignment can be responsible for stair-step artifacts even in single-row helical scanners [7].

In order to improve the quality of reconstructed images it is therefore necessary to take care of misalignment errors, either by proper scanner alignment or by *measuring* the errors in advance and forwarding them to the *reconstruction* algorithm. As high precision mechanical components are very expensive it may be more promising to take the latter approach but the accurate measurement of misalignment parameters still remains a great problem, in particular in the case of high resolution microCT (µCT).

Here we investigated a practical approach: Is it possible to achieve satisfactory artifact reduction by correcting only a few vital misalignment parameters that can be measured easily. We used an modified Feldkamp-based circular scan reconstruction algorithm that we have developed for our µCT cone-beam scanner [1]. This algorithm incorporates corrections for all possible misalignment errors. Misalignment compensation is embedded in the backprojection.

Cone-beam geometry and scanner misalignment

The key components of a cone beam CT scanner are the X-ray source, a two-dimensional X-ray detector and a sample positioner located between them. In µCT typically the tube and detector remain fixed and the object is rotated while in medical CT the object is at rest. However cone beam CT with rotating source and detector has not been realized yet. In SPECT the detector (gamma camera) is equipped with a converging collimator, which focuses at some point behind the object. The detector rotates about the patient along a circular path. For convenience in this contribution we will refer to a CT scanner, but our analysis remains valid for SPECT as well.

In an ideal case the scanner is perfectly aligned, i.e.:

- the straight line between the X-ray focal spot and the center of the detector is normal to the detector surface; this is called the *central ray* that together with central row of the detector defines the *midplane*
- the axis-of-rotation (AOR) is parallel to the detector columns and is projected onto the central column.

There are several reasons why in practice residual misalignments are unavoidable:

- fine adjustment of the scanner requires high precision positioning mechanics, which might be often too expensive to be worth building into the scanner.
- misalignment may result from an unstable X-ray focal spot position, which is usually the case in X-ray tubes with a very small focus size.

There are several degrees of freedom for deviation from the ideal geometry. If we arbitrarily take the *central ray* and the *midplane* as a reference then the misalignment errors can be defined as follows (Fig. 1):

- deviation of the AOR from ideal orientation and position
  - ⇨ *tilt* (inclination) towards the X-ray tube
  - ⇨ *skew* (rotation) around the central ray
  - ⇨ *horizontal transversal* off-center *shift*, i.e. along detector rows
  - ⇨ *horizontal longitudinal shift*, i.e. deviation from the ideal position between the X-ray tube and the detector
- deviation of the X-ray source location from the ideal position
  - ⇨ *vertical shift* from the midplane
  - ⇨ *horizontal transversal shift* from the central ray
  - ⇨ *horizontal longitudinal shift*, i.e. deviation of the X-ray tube ↔ detector distance from the assumed value.

Other possible errors (AOR wobble etc.) are assumed to be negligible or not present at all. For spiral/helical and other more complex acquisition paths more errors have to be appended to the list. For example the direction of object translation (*table feed* in medical CT scanners) may not be parallel to the AOR. The scanned object is then incrementally shifted off-center while being advanced to the next projection position on the spiral path.

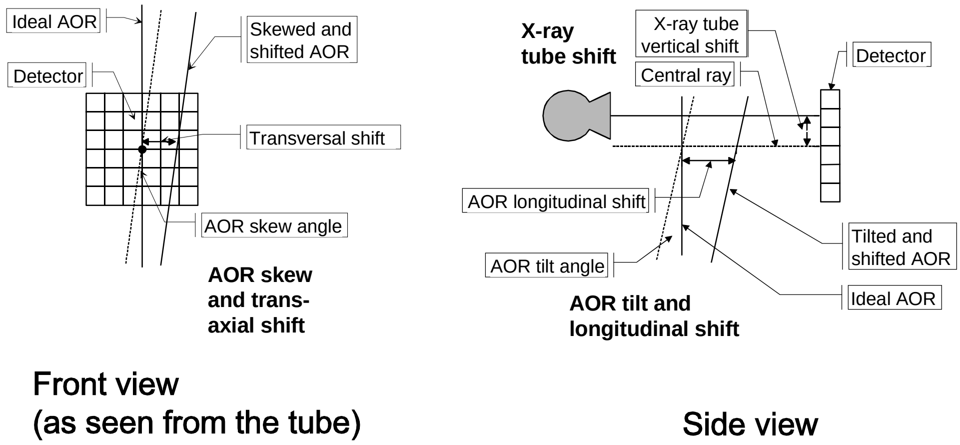

Fig. 1. Definitions of misalignment errors

Reconstruction algorithm with misalignment correction

The original Feldkamp reconstruction algorithm consists of the three main steps:

1) for every detector row and for every projection the projection pixels are independently *weighted* and then *filtered*, with the same one-dimensional filter being applied to each projection row. *Weighting* is done under the assumption that the midplane is perpendicular to the AOR and *filtration* is done along the projection lines *perpendicular* to the AOR. In the case of AOR *skew* weighting and filtration direction do not coincide with detector rows.
2) cone-beam backprojection.

An ideal algorithm incorporating misalignment correction should consist of the following steps:

1) weighting of projections with coefficients corrected for all errors
2) filtration of weighted projections, rotated to correct for the AOR *skew*
3) cone-beam backprojection corrected for tube position and tube ↔ object ↔ detector distances.

In practice such an algorithm has disadvantages. *Before* the entire volume is generated usually single preview slices are reconstructed, in order to select a region of interest for the final volume reconstruction and to possibly interactively tune misalignment correction. In case of the ideal algorithm a complete weighting and filtration of all projections is required to reconstruct even a single preview slice. Thus the reconstruction time would be heavily dominated by the filtration.

Therefore we developed an algorithm with built in misalignment correction where weighting and filtration is done on uncorrected projections. Afterwards the projections can repeatedly be used for backprojections without repeated weighting and filtration. The reconstruction algorithm, which has been described earlier [3][4], uses homogeneous coordinates for the system description and employs an incremental, pixel-driven backprojection.

In the case of a perfectly aligned scanner our algorithm produces results identical to the Feldkamp algorithm otherwise additional artifacts are introduced with our method. However, if AOR *tilt, skew* and *shift* errors are small we expect only a minor additional quality degradation of the final images. In practice they are significantly smaller than those inherent to the *approximate* Feldkamp algorithm.

Influence of misalignment on image quality

Vertical X-ray tube *shift* can be interpreted as if the tube were located on a new, vertically shifted *"midplane"*. As a consequence the sharp slice of the reconstructed volume moves up/down. The quality of reconstructed images is not be affected otherwise.

Horizontal X-ray tube *transversal shift* can be interpreted as if the object were shifted across the field of view and the AOR were *transversally shifted* and the detector slightly rotated. But with proper AOR *shift*-only correction the artifacts would be almost eliminated.

Horizontal X-ray tube *longitudinal shift* changes the object magnification. In the consequence images will be reconstructed "not to scale" and therefore cannot be used for quantitative evaluation of tomograms, but will be otherwise artifact-free.

AOR *tilt* moves the object central plane, i.e. the plane being perpendicular to the AOR and containing the tube focus. In case of tilt this plane intersects the detector above/below its central row. As a consequence weighting coefficients for projection pixels are modified. The visible effect of the *tilt* is that slice smearing towards top/bottom of the object will become unsymmetrical.

AOR *skew* has the most severe impact on the image quality in our algorithm, as we filter not only incorrectly weighted projections (weighting coefficients change their values due to the AOR *skew*), but also take slanted rows, instead of rows perpendicular to the AOR. This leads to crosstalk between slices. However, if the *skew* angle is small and if the object structure changes slowly along the AOR then the actually filtered and the required rows do not differ very much.

AOR horizontal *transversal shift* (off center shift) is responsible for double contours in reconstructed images. It can be efficiently eliminated in the backprojection.

AOR *longitudinal shift* – see X-ray tube.

Misalignment measurement

The critical problem for an effective implementation of our algorithm is proper measurement of scanner misalignment. Various procedures have been propose for this purpose [6][8][9]. Some of them take into account all misalignment errors, some are restricted to only a few, assuming others to be negligible. A good overview has been given in [7] along with their own method, in which several equiangular circular projections of a metal sphere phantom are acquired. Two spheres – one below and one above the *midplane* – are mounted away from the AOR. In a superimposed image their shadows form two ellipses – one in the upper and one in the lower half of the image. Scanner misalignment parameters are calculated from the ellipses' positions, orientations, and sizes.

We have evaluated the 'two sphere method' with respect to cone beam µCT using simulations and experiments. We simulated the CT acquisition with known scanner misalignments for cone angles ranging from 5° to 40°. The AOR *skew* error could always be determined with at least 1% accuracy. This was, however, not the case for the AOR *shift.* Accuracy errors in this parameter are linearly dependent on the error in the determination of the center of the spheres. A 1% error in the localization of the sphere center resulted in an AOR *shift* error of 0.4 pixel for a 40° cone angle and of 12 pixel for an 5° cone angle. The other misalignment errors could also determined with sufficient accuracy so that artifacts in the reconstructed images were negligible, apart from the AOR *tilt* error, which cannot be determined with this method at all. In practice even a 1% accuracy error in the detection of the sphere centers will be extremely difficult to achieve due to noise and potential distortions in the detector geometry.

Reconstruction algorithm verification

To evaluate our reconstruction algorithm and its potential to correct for misalignment errors we performed simulations of the numerical *Defrise phantom* and we scanned a physical phantom using typical acquisition parameters (512^2 pixel detector matrix, 2 x 5.7° cone angle, 720 equidistant projections acquired over 360°). The following projection sets were simulated: misalignment-free as a reference, AOR *tilt* of 0.2°, AOR *skew* of 0.75°, AOR transversal *shift* of 20 pixels and a combination of all three errors, i.e. errors equal to the actually measured for the physical Defrise phantom.

The Defrise phantom has been well established as the test object for demonstrating artifacts incurred by approximate reconstruction algorithms. However, it may not optimal for investigating the effect of scanner misalignment. Also it may overemphasize artifacts compared to samples typically investigated with µCT. Other phantoms, more suitable to this task need to be developed

Reconstruction artifacts in simulated Defrise phantom

The slice reconstructed with our algorithm in the case of no misalignment (Fig. 2a) contains characteristic Feldkamp artifacts. In case of a combined AOR misalignment the uncorrected image (Fig. 2.b) is heavily distorted. The image corrected for all three errors (Fig. 2.c) contains only residual artifacts, resulting from (consciously) imperfect handling of weighting/filtration in our algorithm. The sharp part of the image moved down slightly, which results from improper AOR tilt corrections. Slight horizontal streaks originating at the ends of the disks result from the AOR skew error. The AOR shift has been eliminated and leaves no artifacts. We then restricted our misalignment corrections to two errors: AOR skew and transversal shift. The fourth image (Fig. 2.d) shows an image reconstructed without tilt correction. There are no significant differences between the c. and d. images, e.g. traces of the tilt error.

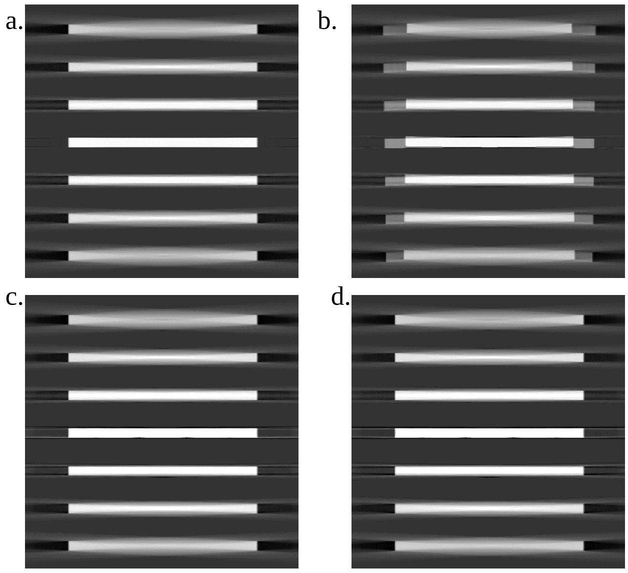

Fig. 2. Sagittal slices reconstructed from simulated projections: a – ideal case (no misalignment), b – AOR *tilt*, *skew* and *shift* uncorrected, c – all three corrected, d – AOR *skew* and *shift* corrected only (e.g. no *tilt* correction)

Images of a physical (scanned) Defrise phantom

Reconstructed images of the physical phantom demonstrate the influence of misalignment errors on the image quality in a measured phantom. It is clear that in the real case all seven misalignment errors are present. The uncorrected image is heavily distorted. However, the image corrected for AOR *shift*, *skew* and *tilt*, e.g. assuming other four errors to be negligible (as actually determined by the dual-ellipse method), contains only residual artifacts. Furthermore, the image with AOR *shift* and *skew* correction only (e.g. not *tilt* correction) does not look qualitatively worse. Hence the influence of the *tilt* error is negligible.

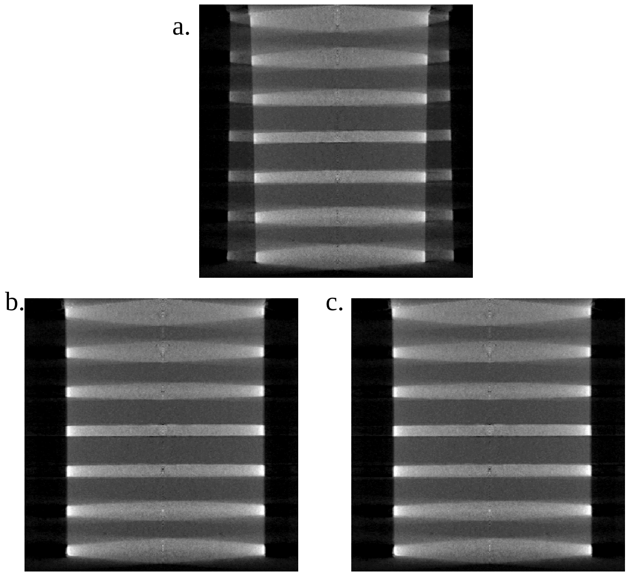

Fig. 3. Sagittal slices reconstructed from measured projections: a – uncorrected misalignment, b – AOR *skew*, *shift* and *tilt* corrected, c – AOR *skew* and *shift* corrected (no *tilt* correction)

Conclusions

This paper concerns the problem of scanner mechanical misalignment in cone-beam tomography. We have defined seven misalignment errors which may be present in a real-world scanner and analyzed their influence on the reconstructed image quality. We then proposed an effective approximate implementation of a Feldkamp-based reconstruction algorithm capable of correcting for all misalignment errors. In the algorithm a practical approach is used, with weighting and filtration performed on uncorrected projections and misalignment correction built into backprojection. The concept of storing weighted and filtered projections to be later used in backprojection proved to be advantageous in terms of saving processing time.

The problem o reliable measurement of all misalignment errors in a given scanner remains unsolved, especially for high resolution µCT scanners with small cone angles. Existing procedures did not prove to be robust enough to provide satisfactory results. Therefore we restricted misalignment correction to two main errors (AOR *shift* and *skew*) to obtain good quality tomograms. We showed that in a practical case artifacts caused by misalignment are therewith significantly reduced. However, the algorithm still preserves its potential to correct for all errors, should they be known for a given scanner.

The algorithm has been validated on simulated and physical Defrise phantom. Real data were acquired on a µCT scanner, whose misalignment had been measured. Images reconstructed with the proposed algorithm do not suffer from significant additional (apart from Feldkamp-specific) artifacts.

References

1. **K. Engelke, M. Karolczak, A. Lutz, U. Seibert (Taubenreuther), S. Schaller, W. Kalender,** *Mikro-CT. Technologie und Applikationen zur Erfassung von Knochenarchitektur,* Der Radiologe, No. 39, pp. 203-212, 1999
2. L. A. Feldkamp, . C. Davis, J. W. Kress, *Practical cone-beam algorithm*, J. Opt. Soc. Am., A/Vol. 1, No. 6, pp. 612-619, June 1984
3. **S. Schaller, M. Karolczak, K. Engelke**, K. Wiesent, *Implementation of a fast cone-beam backprojection algorithm for µCT using homogeneous coordinates,* Radiology, November 1998, (RSNA Congress, 1998)
4. **M. Karolczak, S. Schaller, K. Engelke, A. Lutz, U. Seibert (Taubenreuther),** K. Wiesent, **W. Kalender**, *Implementation of a cone-beam reconstruction algorithm for the single-circle source orbit with embedded misalignment correction using homogeneous coordinates*, submitted to Medical Physics
5. F. Noo, S. Schaller, R. Clackdoyle, T. A. White, T. J. Roney, *Image Reconstruction from Misaligned Truncated Helical Cone-beam Data,* IEEE Conference Record of the 1999 Nuclear Science Symposium and Medical Imaging Conference, Seattle, USA, 1999
6. A. V. Bronnikov, *Virtual alignment of x-ray cone-beam tomography system using two calibration aperture measurements,* Optical Engineering, Vol. 38(2), pp. 381-386, 1999
7. J. Hsieh, *Three-Dimensional Artifact Induced by Projection Weighting and Misalignment*, IEEE Transactions on Medical Imaging, Vol. 18, No. 4, pp. 364-368, April 1999
8. F. Noo, R. Clackdoyle, C. Mennessier, T. A. White, T. J. Roney, *An analytic method based on identification of ellipse parameters for scanner calibration in cone-beam tomography,* Physics in Medicine and Biology, 2000
9. **U. Taubenreuther**, *Correction and Calibration Methods for Cone-Beam MicroCT*, PhD Thesis, University of Erlangen, 2001
10. A. Rougée, C. Picard, C. Ponchut, Y. Trousset, *Geometrical calibration of x-ray imaging chains for three-dimensional reconstruction,* Computerized Medical Imaging and Graphics, Vol. 17(4/5), pp. 295-300, 1993
11. T. A. White, T. J. Roney, R. J. Pink, F. Noo, R. Clackdoyle, M. Smith, W. F. Jones, *Comparison of fan- and cone-beam imaging capabilities on a portable x-ray imaging system. In: Developments in X-ray tomography II, Ulrich Bonse,* Proceedings of SPIE, Vol. 3772, pp. 138-146, 1999
12. G. T. Gullberg, B. M. W. Tsui, C. R. Crawford, J. G. Ballard, J. T. Hagius, *Estimation of geometrical parameters and collimator evaluation for cone-beam tomography,* Medical Physics, Vol. 17(2), pp. 264-272, 1990