Contribution of Algebraic Iterative Reconstruction Algorithm for Joint Space Segmentation Based on Cone Beam Computed Tomography Images

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Abstract. Measurements derived from the joint space segmentation are clinically pertinent to study knee osteoarthritis. Cone beam computed tomography (CBCT) is an emerging low dose imaging method with the potential to be used in a weight bearing position. With a CBCT prototype, we have tested 2 methods of reconstruction: iterative reconstruction (SART) and FDK reconstruction with different intensities and projections number. We used the segmentation of the joint space as a metric to assess the quality of reconstructions. For this aim, we calculated Jaccard (JAC) and Hausdorff indexes (AVD), and thickness measurements 2D and 3D (respectively JS.Th-2D and JS.Th-3D). We have found that the results were more consistent with the SART reconstruction than FDK reconstruction with more stable results whatever the intensities and the projections number. Indeed, JAC indexes were superior to 0.7 at 10 and 15 mA for SART reconstruction and unlike to FDK reconstruction, only 19% values were superiors to 0.7. Moreover, the referent value of JS.Th-3D being 5 mm, the JS.Th-3D results from the SART reconstruction were closer to this value ranging from 4.8 mm to 5.3 mm, whereas, the JS.Th-3D results from the FDK reconstruction were ranging from 4.4 mm to 4.7.

Keywords: Osteoarthritis · Cone beam computed tomography · X-rays · Segmentation · Iterative reconstruction

1   Introduction

Osteoarthritis (OA) is joint disorder that causes pain, stiffness, and decreased mobility and in one of the most disabling disease in developed countries [1]. The disorder is characterized by cartilage loss with as main consequences the narrowing of the joint space width (JSW) [2]. Measuring the JSW on radiographs between the articular cortices of the femur and tibial plateau in a weight bearing position is recommended to assess the structural disease progression [3]. Cartilage thinning and impairment can be also assessed on MRI but high field are necessary to obtain 3D structural information and isotropic voxel [4]. We have developed in a previous study a semi-quantitative method for measuring 3D joint space on high resolution computed tomography images (CT) [5].

New dedicated systems based on cone-beam computed tomography (CBCT) are under development, they have few advantages. The radiation dose is much smaller than conventional CT, it is due to differences in imaging geometry and collimation of X-rays [6]. They are low cost with high compactness and portability comparatively to other technologies [7]. It is possible to reconstruct a 3D volume from two dimensional projections with sub-mm 3D spatial resolution and with isotropic voxel [8]. Flat panel detectors are now large enough to encompass joint for osteo-articular imaging [8]. Finally, they can be used with the patient in the standing position with sufficient fast acquisition [9].

Usually reconstruction method used is based on the Felkamp, David and Kress (FDK) algorithm which is an adaptation of filtered back projection reconstruction for a cone beam acquisition [10]. One strategy to reduce the radiation exposure could be to use iterative reconstruction (IR) methods. At the present time, multiple algebraic methods using iterative methods exist. One of the methods is based on projective ray-by-ray method (ART) [11] and was improved by subset optimization (SART) [12]. This method has been previously tested for 3D cone beam reconstruction [13].

The aim of this study was to test a semi-automated image-processing method to quantify local variations of the JSW in three dimensions using a CBCT prototype. For this aim, we compared 3D images reconstructions at different tube currents, with different numbers of projections and with two different reconstruction methods: FDK or iterative (SART). To test the quality of different images, we used as a benchmark the FDK reconstruction performed at 360°, 720 projections and 15 mA at normal dose.

2   Materiel and Methods

2.1   Experimental Setup

Cone-Beam Computed Tomography Prototype
The cone-Beam Computed Tomography (CBCT) prototype was equipped with a Thales 2630S surgical detector, the source-detector distance was 122 cm, object-detector distance was 15 cm providing a 1560 * 1440 mm volumetric field of view (FOV), the pixel size of the detector was 184 μm. The spot size of the X ray source was 0.6 mm with 30° divergence and operated in pulsed mode with a tube potential fixed at

70 kVp, the effective tube currents were tested at 15 mA, 10 mA and 5 mA with an exposure time of 20 ms. An Aluminum filter of 2 mm was applied. The rotation of motor evolves an orbital range of 360° with a total duration scan of 1 min.

Specimen and Imaging Acquisition

The knee specimen was collected at the Institute of Anatomy Paris Descartes. The collection of these human tissue specimens was conducted according to pertinent protocols established by the Human Ethics Committee at Inserm. Due to this regulation, no data were available regarding the cause of death, previous illnesses, or medical treatments of these individuals. After soft tissue removal, knee specimens were stored at −20 °C. Then, the specimen was scanned in an upright position.

The Experiment Protocols

The reference 3D reconstructions were obtained at 15 mA with an acquisition range angular about 360°, collecting 720 projections and reconstructed with the FDK algorithm. Then, two different strategies were tested with the aim to reduce the dose. For the first strategy, the same parameters were applied with decreasing current: 10 mA and 5 mA. For the second strategy, the number of projections was reduced with a 200° fixed angular range with a few projections varying from 400 to 160 with a reduction of 40 projections for each reconstruction. The scenario was tested with three different current: 15 mA, 10 mA, 5 mA. Two methods of reconstruction were performed FDK and SART algorithms.

2.2 Image Reconstruction

Analytic Reconstruction: Feldkamp-Davis-Kress (FDK)

To accommodate to conical acquisition geometry, filtered back projection analytical reconstruction method has been adapted to the FDK method developed by Feldkamp, Davis and Kress in 1984 [10].

Iterative Reconstruction

The Algebraic Reconstruction Technique (ART) is based on projective method developed by Gabor Herman and coworkers in 1970 [11], minimizing the value "alpha" which is the approximate value reducing the distance between P and [A]. Alpha is calculated by the least square's method:

$$J(\alpha) = \|P - [A].\alpha\|^2 = \sum \left(Pd(\theta p) - Ad(\theta p).\alpha\right)^2 \qquad (1)$$

All projective methods look for the alpha value so to minimize $J(\alpha)$, a convex function, which is noted by:

$$\alpha = \arg \min J(\alpha) \qquad (2)$$

To reduce the salt & pepper noise and to accelerate the convergence process, we used the SART method, derived from the ART algorithm [12].

2.3 Segmentation and Morphometric Measurements

Segmentation of the Knee Joint Space

To evaluate of knee OA progression, we have previously developed a semi-automatic segmentation method for tibio-femoral joint space width (JSW) measurement on computed tomography images [5]. Based on this method, it is possible to measure the thickness on the central slice (JS-Th 2D) and to measure the 3D volume and mean thickness of the JS (JS-Th 3D). We assessed the quality of the segmentation according to the decrease of current and number of projections using as a benchmark the acquisition performed with 720 projections, 360° and 15 mA and reconstructed with the FDK method.

Briefly, the method was applied on frontal views, a Volume of Interest (VOI) corresponding to the medial compartment was manually selected on the central slice. For removing noise, a circular averaging filter within the square matrix of 8 size was used. For extracting bone from soft tissues, a hysteresis threshold method using the quantile of grayscale followed by morphological operations (closing and opening operators) were applied. Finally, the user drew 15 control points in the pertinent region for initialization and the snake model was applied to the entire VOI. Then, the segmentation was expanded 1 cm in front and 1 cm behind in the JS to have 3D results. The process has been applied on MATLAB.

Segmentation Quality Criteria

To evaluate the segmentation, two methods were used 1) the Jaccard Index (JAC) which is a metric based on overlap measurements and 2) Average Hausdorff Distance (AVD) more sensitive to edges and based to distance measurements [14].

- *Jaccard index*

  JAC measures the overlap between two sets of segmented images as the intersection between them divided by their union. In other word, we considered S_t as the JS segmentation of the FKD-15 mA-720 projections as the referent and S_g as the JS segmentation of the tested image:

$$JAC(S_g, S_t) = \frac{|S_g \cap S_t|}{|S_g \cup S_t|} \tag{3}$$

- *Average Hausdorff Distance*

  AVD is a non-linear operator which measures the similarity between 2 geometric shapes. Its finite point sets S_g and S_t is defined by

$$AVD(S_g, S_t) = \max(d(S_g, S_t), d(S_t, S_g)) \tag{4}$$

where $d(S_g, S_t)$ is called the directed Hausdorff distance (HD) and given by

$$d(S_g, S_t) = \frac{1}{N} \sum_{st \in S_t} \min ||S_g - S_t|| \tag{5}$$

where $||S_g - S_t||$ is some norm e.g. Euclidean distance.

Thickness measurement of the Joint Space
For the quantitative analysis of JS, the software provided by Bruker – CTAn was used. The thickness measurements were measured with the sphere method and applied on the JS segmentation [15]. For this analysis, the output parameters are joint space Thickness 2D (JS.Th-2D) and 3D (JS.Th-3D).

3   Results

The AVD values according to JAC are displayed in Fig. 1 and reconstructed with a various number of projections from 400 to 160. The JAC indexes were found superior to 0.7 in 66% with the SART recontruction and the average AVD value was 0.44 for 15 mA (min-max: 0.33–0.54), 0.77 for 10 mA (min-max: 0,7–0,8) and was 0.56 for 5 mA (min-max: 0,4–0,66). With the FDK reconstruction, the JAC indexes were from 0.07 to 0.9 and only 19% superior to 0.7, AVD values were in average 0.62 for 15 mA (min-max: 0.37–0.84), 0.87 for 10 mA (min-max: 0.6–1.23) and 0.58 for 5 mA (min-max: 0.4–0,66).
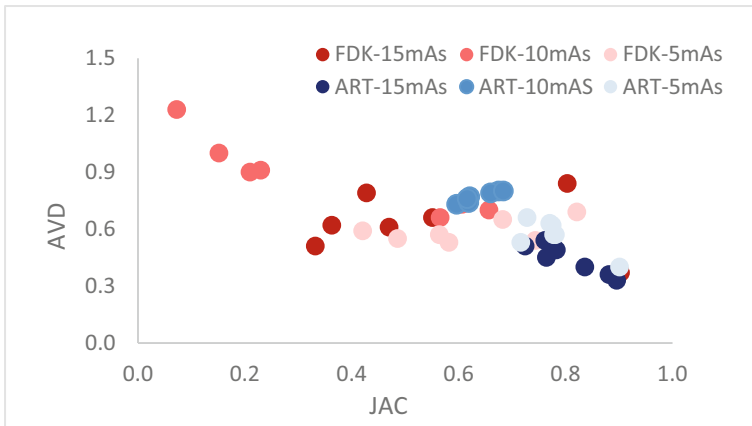
Fig. 1. Average AVD to JAC with a variable projection number from 400 to 160 projections reconstructed by the two methods SART-blue circle and FDK-red circle

For the SART reconstruction, the JAC indexes were more frequently high with low AVD contrary to FDK reconstruction.
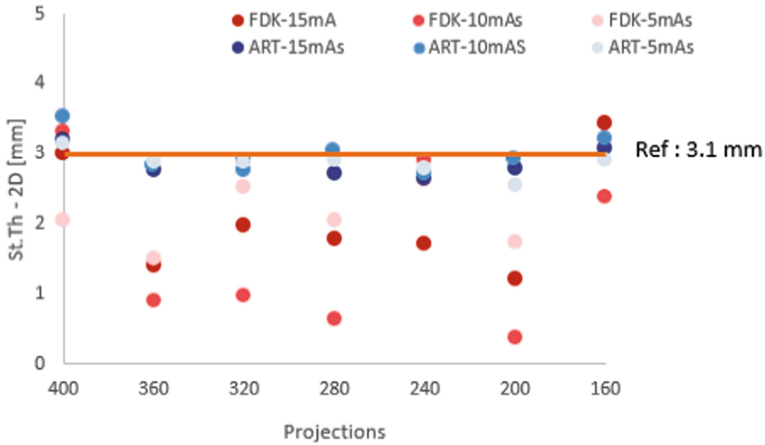
Fig. 2. Joint space thickness measurements based on 2D central frontal images (JS.Th-2D) according to variable projections number from 400 to 160 projections reconstructed by the two methods SART-blue circle and FDK-red circle.

JS Thickness (JS.Th-2D) results according to the variable projections number are displayed in Fig. 2. The JS.Th 2D reference value was 3.1 mm. The average JS.Th-2D of SART recontruction was 2.8 for 15 mA (min-max: 2.6–3.2), was 3 for 10 mA (min-max: 2.7–3.5) and was 2.9 for 5 mA (min-max: 2.5–3.1). Whereas the average AVD values of FDK reconstruction was 2.1 for 15 mA (min-max: 1.2–3.4), was 1.6 for 10 mA (min-max: 0.4–1.6) and was 2.2 for 5 mA (min-max: 1.5–3.1).

JS.Th-2Ds derived from the SART reconstruction were closer to the referent value. Whereas, the JS.Th-2Ds derived of the FDK reconstruction were underestimated with large discrepancies (Fig. 2).
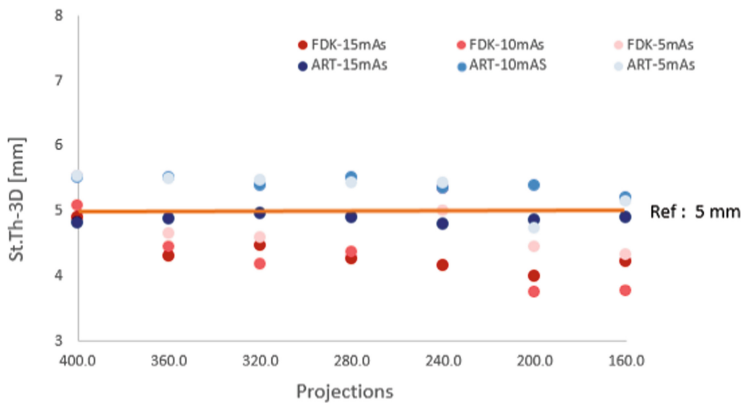
Fig. 3. Joint Space thickness based on 3D volume of the joint space (JS.Th-3D) according to variable projections number from 400 to 160 projections reconstructed with the two methods SART-blue circle and FDK-red circle.

The referent value of JS.Th-3D was 5 mm, the JS.Th-3D derived from the SART reconstruction were closer to the referent value and ranging from 4.8 mm to 5.3 mm. Whereas, the JS.Th-3D derived from the FDK reconstruction were ranging from 4.4 to 4.7 mm with large discrepancies in comparison to segmented images from SART reconstruction.

4   Discussion

CBCT is an emerging technique for diagnosis and follow up of osteo-articular diseases with the advantage to be performed in a weight bearing position contrary to clinical CT [9]. The segmentation of the JS is clinically pertinent for diagnosis and following of knee osteoarthritis and must be performed in weight bearing knee position. Usually, joint space thickness measurements are performed on radiographs with as main drawback to be a 2D measurement. 3D imaging is an interesting approach, but low dose acquisitions are necessary, which can be potentially bring by cone beam CT imaging. With a CBCT prototype, we have tested classical FDK reconstruction and iterative reconstruction as SART with various intensities and various numbers of projections with as main objective to reduce the dose as much as possible. For this aim, we have used as a benchmark the FDK reconstruction performed at 360°, 720 projections and 15 mA.

A semi-automatic method previously developed in our group was used and correlated with cartilage thickness [5]. The segmentation process is considered as a great importance in medical imaging [14] and used in the present study as a marker of image quality. The segmentation quality is classically assessed by the JAC and AVD. The JAC index is sensitive to both the delineation of the boundary (contour) and the size (the volume of the segmented object). The AVD which is HD averaged over all points is more stable and less sensitive to outliers than HD, this metric has a special interest where the boundary delimitation is important.

We have found that the JAC indexes were higher and AVD were lower with the SART reconstruction even with a low intensity and number of projections contrary to the FDK reconstruction where the results of the JS segmentation were very discrepant from one reconstruction to another.

In the same way, the JS.Th-2D and JS.Th-3D obtained from SART reconstruction were closer to the reference measurement obtained at 720 projections, 360°, 15 mA with FDK reconstruction. On the contrary segmentation results from the FDK reconstruction were underestimated and scattered.

5   Conclusion

It is possible to reduce the dose delivery to patients by reducing either the intensity or the number of projections with iterative reconstruction such as SART method while having sufficient image quality to allow segmentation of the joint space.

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