# Iterative Reconstruction via Preserved Structures Approach for CT Images with Limited Scan Angles

Anush Kolakalur
University of Portsmouth
School of Energy and Electronics
Anglesea Road, Portsmouth
+44(0)2392842396
anush.kolakalur@port.ac.uk

Branislav Vuksanovic
University of Portsmouth
School of Energy and Electronics
Anglesea Road, Portsmouth
+44(0)2392842159
branislav.vuksanovic@port.ac.uk

## ABSTRACT
Iterative image reconstruction techniques for computer tomography (CT) are finite iterations of forward-projections and backward projections. One of the major concerns related to this method is deterioration of the reconstructed images due to various image structure deformations during this procedure. This is usually manifested by blotchy and pixelated appearances of the reconstructed image with the effects becoming more pronounced for low and ultra-low scan angles. This paper proposes a new approach for the reconstruction of CT images ensuring the preservation of structural details and reduced image deterioration and deformation. We call this method iterative reconstruction through preserved structures (IR-PS). The results achieved using proposed IR-PS method are evaluated via RMSE (Root Mean Square Error) measure and SSIM (Structural SIMiliarity) index suggesting improvement in quality of reconstructed images.

## Keywords
Computed tomography, iterative image reconstructions, image degradation, limited scan angle, CT reconstruction

## 1. INTRODUCTION
The computed tomography techniques have seen a significant increase in its use in medicine since its introduction [1,2]. However, this popularity had also led to increased risks due to x-ray radiation exposure by the patients during the procedure [3,4,5]. Radiation effects patients as well as radiologists and the medical professionals who work with CT systems [6]. Because of this, research for reducing radiation dose in the CT systems has been receiving an increased attention by many researchers in the field resulting in the development of numerous strategies to acquire CT image data at clinically accepted dose levels [7]. However, few evidence-based papers claim that the CT image acquisition procedures can compensate for the risks and costs [8–10]. One way of reducing the radiation dose is to reduce projection views or limit the number of scan angles used during the scanning procedure. Alternatively, radiation dose can be reduced by optimising the parameters of the CT systems, such as tube current or voltage, reconstruction thickness etc. [11]

Currently, filter back-projection (FBP) is the most commonly used CT image reconstruction technique, since it is fast and robust for routine radiation doses [12]. FBP works on the assumption that the projection data is noise free. Denoising step is therefore omitted, but the data gets filtered to reduce or enhance other image attributes such as smoothing or enhancing the edges. Later, this is projected back to be reconstructed into an image volume. This technique works well for CT image acquisition at routine radiation doses, but in most situations, at the clinically recommended doses, FBP produces noisy images [13, 14].

Iterative Reconstruction (IR) algorithms were developed as an alternative to the FBP approach. The aim was to produce the image of quality close to quality achieved using the full dose FBP routine when the radiation dose is reduced exceedingly, i.e. under the limited scan angles. IR mainly consist of finite iterations of forward projections and backward projections. These iterations can be carried out either in image domain or in sonogram domain only. Performing the procedure in both, image and sonogram domains has also been implemented and investigated. IR aims to reconstruct images that precisely correspond to the sinogram (measured projection) data. Thus, besides modelling of the imaging system, noise modelling becomes crucial in those procedures [15,16,17,18,19].

IR as a concept has been introduced prior to FBP as an Algebraic Reconstruction Technique (ART) with the aim of solving the CT image reconstruction problem. However, the available computational power was rather limited at that time resulting in ART being replaced by FBP [12,25]. The improved computational power following the advancement of CT systems capabilities, enabled the use of IR. As a result, most of the leading CT vendors have now introduced new and improved IR techniques in their CT imaging systems [26]. Most of technical details related to those algorithms are proprietary and a systematic overview of those methods is not yet available. This is further complicated with the usage of different performance metrics in many of the available comparative studies of those techniques.

IR results in reconstructed images of high quality with a slight reduction in the radiation dose [20,21,22,23,24]. Denoising has now been included as one of the major features for many IRs in use today. However, at low and ultra-low scan angles, the main concerns are: a) the pixelated appearances of the structural details (this is sometimes caused by the lack of noise or in other words, over-smoothing of noise), and b) longer computational reconstructing time and high computational power required, especially for full IR [25,26,27]. These pixelated appearances of the visible structural changes occur due to the over-smoothing and filtering of the noise in the iterative noise identification and filtering segments of the IR technique [27,28,29].

The focus of this work is on image reconstructions from low and ultra-low scan angles data. The paper tackles one of the major concerns in the iterative segments of IR schemes - deterioration of the overall reconstructed image due to image structure deformations manifested in blotchy and pixelated appearance, especially pronounced for low and ultra-low scan angles.

A novel IR approach resulting in higher structural similarity indexes is proposed. This scheme integrates an idea of preserving structural details to reduce image deterioration and image structure deformation. Thus, we call this technique iterative reconstruction via preserved structures (IR-PS) method. Results are evaluated using standard measures - Structural Similarity Index (SSIM) and Root Mean Square Error (RMSE).

## 2. MATERIALS AND METHODS

To conduct experiments and test the proposed algorithm, DICOM images were downloaded from an open source website that contained several data sets of human bone structure (https://isbweb.org/data/vsj/).

MATLAB (R2018a) software was used to implement and test the algorithms by reconstructing CT images.

Three techniques tested and compared in this work are: standard FBP reconstruction, IR, and IR-PS algorithms. To assess the performance of the above-mentioned techniques at low and ultra-low scan angles, the scan angles are limited by increasing the projection angle, this, in other words, implies reducing the radiation dose.

## 3. ITERATIVE RECONSTRUCTION via PRESERVED STRUCTURES (IR-PS) TECHNIQUE

### 3.1 FB-PS Stage

The IR-PS technique is implemented in two stages. The first stage is concerned with developing an improved version of FBP scheme, named FBP-PS (filtered back projection via preserved structures) approach. Here, structural maps of FBP reconstructed images were extracted using Canny edge detector. Other detectors such as Roberts or Prewitt can also be used however, in comparison, Canny detects wide range of edges amidst suppressing noise since it uses a multi-stage algorithm [30]. Following this, a concept of pattern recognition from computer vision community is adopted for extracting significant structural details from the edge detecting maps [31]. This approach is explained and illustrated in the rest of this section.

To implement a structural analysis, a 3×3 grid is positioned in the top left corner of the edge detection map and moved through the map in left to right and top to bottom directions. While doing so, for each portion of the map covered by the grid, its center pixel is selected as a 'point of reference' (*por*) and its adjacent values are checked for the same value as *por*. If the adjacent value is not the same as *por*, it is set to zero otherwise it is left unchanged. In grids, where all the adjacent values are different from that of *por* value, this grid is set to zero. In other words, this grid has no structural details to be extracted. In pursuing this process a structural pattern is extracted and this pattern can be considered as the fundamental structure of the image.

Grids of other sizes, 2×2, 4×4 etc. can be used to accomplish this process, with larger grids requiring longer computation. Figure 1 below shows an example of a 3×3 grid being used on a structural map with a *por* = 6. The extracted structure pattern is the shown on the rightmost side of this figure.

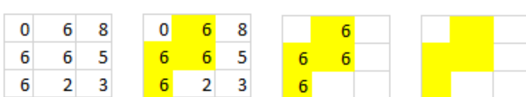

**Figure 1: Structure pattern generation using a 3×3 grid with a *por* = 6**

To avoid overlapping of structure details for edge detection map sizes bigger than grid size the grid can be moved to start at different origins in the structure map, e.g., starting positions of grid at (0,0), (0,1), (1,0) and (1,1) could be applied. This is illustrated in Figure 2, where Figure 2a) shows the initially extracted 6×6 edge map and Figures 2b) – 2e) show the result of generated structure patterns where 3x3 grid is positioned to start at locations (0,0), (0,1), (1,0) and finally (1,1). By labeling the four extracted structure patterns $D_1(x,y)$ to $D_4(x,y)$ for starting position (0,0) to (1,1) respectively, the complete structure pattern is then obtained using:

$$D(x,y) = MAX\{ D_1(x,y), D_2(x,y), D_3(x,y), D_4(x,y)\} \quad (1)$$

The result, complete structure pattern is shown in Figure 2f).

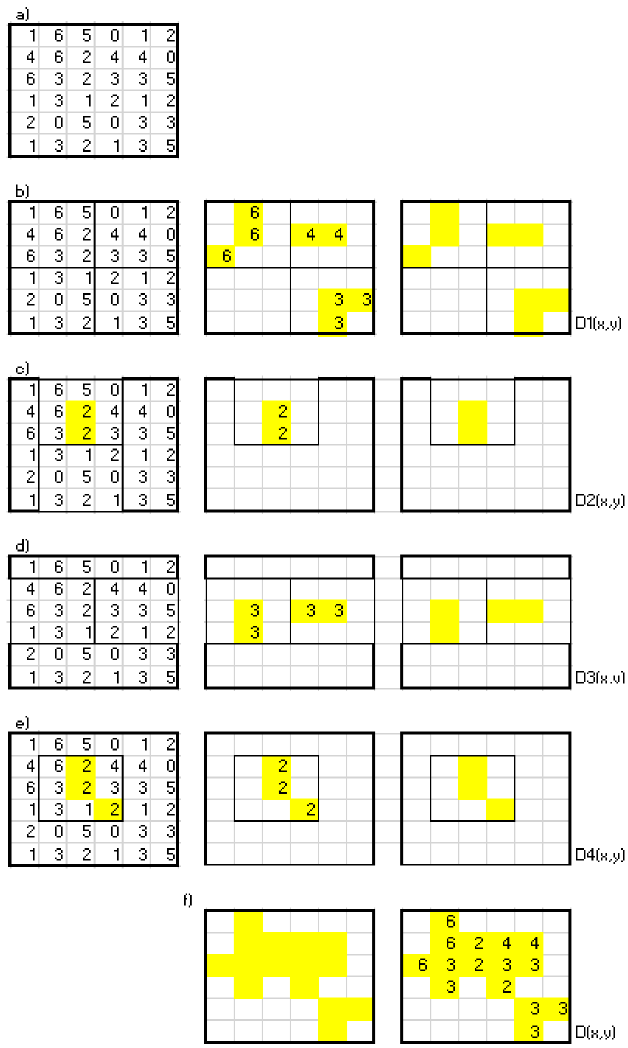


**Figure 2: a) extracted 6×6 edge map, b)-e) structural patterns generated using a 3×3 grid at initial positions (0,0), (0,1), (1,0) and (1,1) f) complete, final structural pattern**

The pixel locations of the developed complete structure pattern are now saved, and the process called overlapping performed. Overlapping leaves the pixel locations of the FBP reconstructed image, corresponding to saved pixel location, unchanged while the other locations are emptied on the FBP reconstructed image. This approach is named filtered back projection via preserved structures (FBP-PS). Obtained results indicate that the FBP-PS has a higher SSIM index and lower RMSE value for limited scan angles.

Flowchart of the FBP-PS algorithm is shown in Figure 3. Here, AT implies ‘After Tuning’ result i.e. result after the overlapping of the complete structure pattern and BT indicates ‘Before Tuning’ i.e. direct FBP reconstructed image.

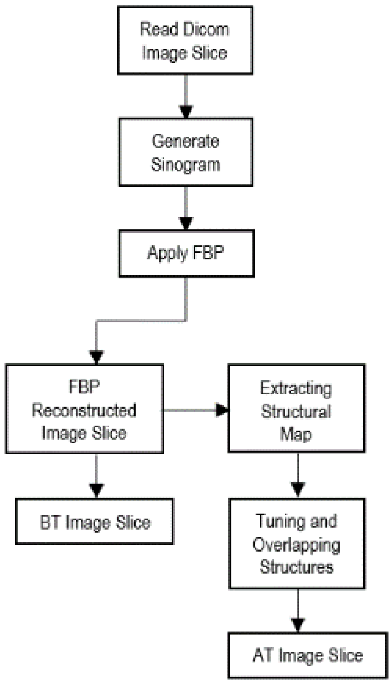


**Figure 3: FBP-PS algorithm flowchart**

## 3.2 IR-PS Stage

The standard IR method uses FBP scheme to establish the initial guess for the image domain iterations. The second stage of the proposed algorithm improves this approach with the idea of using FBP-PS reconstructed image as an initial guess. In addition to that we use the idea of extracting structural patterns in between image domain iterations to preserve structural details and thus reduce the overall image degradation. This scheme is named iterative reconstruction via preserved structures (IR-PS).

Figure 4 shows the IR scheme, with iterations carried out in the image domain. Here, the initial guess from the measured data is filter back-projected using FBP-PS scheme. The initial guess image (FB-PS reconstructed image) is noise filtered. The resultant noise filtered image is then compared with the initial guess image for noise identification. Noise is calculated using PSNR, MSE or SSIM measure. The image identified to contain less noise compared to the other image is considered for extracting structural patterns and is again noise filtered. The structural pattern is then overlapped following the noise filtration process. This iterative process continues until the two resultant images contain the same amount of noise. Here, we use MSE measure for noise identification and perform structural pattern extraction, update and overlap after each fourth iteration. This process helps in preserving the significant structural details.

Currently, IR schemes are based mainly on denoising. In this work, IR-PS technique is presented, where the noise filtering is carried out via a simple combination of a linear and non-linear filters (Wiener and Median filters). A novel structural pattern overlapping idea has been introduced since the principal aim of the work is to preserve structural details and avoid image deformation and subsequent image degradation. Following those initial results of IR-PS technique in preserving image structural details, further work on developing several other methods for noise modelling and suppression can be carried out.

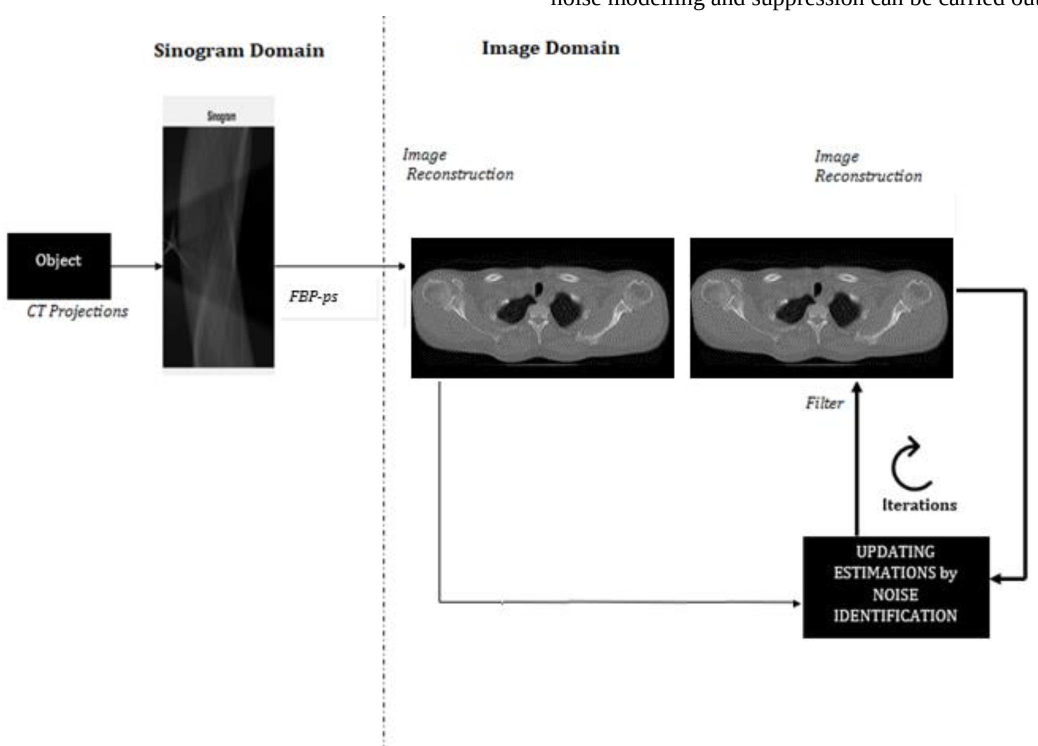


**Figure 4. IR Technique with iterations carried out in Image Domain only**

## 4. RESULTS

Results achieved with the proposed steps - FBP-PS and IR-PS are compared against the results achieved with the standard FBP and IR techniques and presented in Tables 1 and 2. Table 1 shows achieved values of Structural SIMilarity (SSIM) index measure for those four techniques. Different scan angles have been considered, ranging from the full 360 scan angles to very low 33 scan angles. Table 2 contains measured Root-Mean Square Error (RMSE) data for the same scan angles and four techniques implemented and investigated in this work. Improved performance of IR-PS scheme is indicated with the SSIM index values closer to '1' for IR-PS compared to other methods listed in Table 1. At the same time, RMSE values for IR-PS, shown in Table 2 are the lowest compared to other three schemes.

**Table 1. SSIM indexes**

| SCAN ANGLES | FBP | FBP-PS | IR | IR-PS |
|---|---|---|---|---|
| **360** | 0.999437 | 0.9994696 | 0.9994833 | 0.9994691 |
| **180** | 0.997763 | 0.9979911 | 0.998469 | 0.9991202 |
| **120** | 0.9938141 | 0.9943518 | 0.9956198 | 0.9982861 |
| **90** | 0.9897548 | 0.9903242 | 0.9919348 | 0.9976132 |
| **72** | 0.9819777 | 0.9831578 | 0.9860576 | 0.9964959 |
| **60** | 0.9752403 | 0.9766269 | 0.9801684 | 0.9953833 |
| **51** | 0.9889329 | 0.9894478 | 0.9908037 | 0.9960849 |
| **45** | 0.9888619 | 0.9894442 | 0.9911168 | 0.9971819 |
| **40** | 0.9513881 | 0.9537294 | 0.959392 | 0.9891892 |
| **36** | 0.9457578 | 0.947958 | 0.953723 | 0.9864610 |
| **33** | 0.9804637 | 0.9812611 | 0.9835019 | 0.9949537 |

**Table 2. RMSE values**

| SCAN ANGLES | FBP | FBP-PS | IR | IR-PS |
|---|---|---|---|---|
| **360** | 0.0005219 | 0.000505 | 0.0004934 | 0.0005173 |
| **180** | 0.0009011 | 0.0008388 | 0.0007202 | 0.0006299 |
| **120** | 0.0013619 | 0.0012602 | 0.0010634 | 0.0007779 |
| **90** | 0.0015776 | 0.0015068 | 0.0013353 | 0.0008947 |
| **72** | 0.002194 | 0.0020382 | 0.0017413 | 0.0010279 |
| **60** | 0.002544 | 0.0023816 | 0.0020598 | 0.001147 |
| **51** | 0.0015913 | 0.0015214 | 0.0013715 | 0.0010004 |
| **45** | 0.0016224 | 0.0015516 | 0.0013803 | 0.0009273 |
| **40** | 0.003701 | 0.0034474 | 0.0029869 | 0.0015553 |
| **36** | 0.0039193 | 0.0036771 | 0.0032183 | 0.0017018 |
| **33** | 0.0020676 | 0.0019895 | 0.0018041 | 0.0011559 |

Same data is illustrated in Figures 5 a) and b) where bars of different colors represent different image reconstruction techniques.

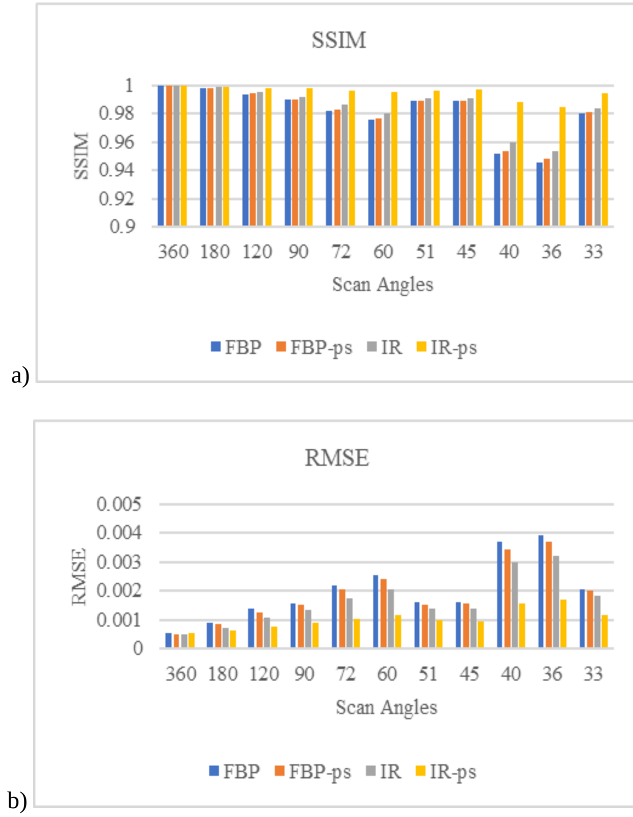


**Figure 5. a) SSIM and b) RMSE values for different reconstruction schemes and different scan angles**

Figure 6 shows a digital phantom image reconstructed using four schemes with 72 scan angles while the Figure 7 shows the same phantom reconstructed using IR-PS scheme for low scan angles (40, 36 and 33).

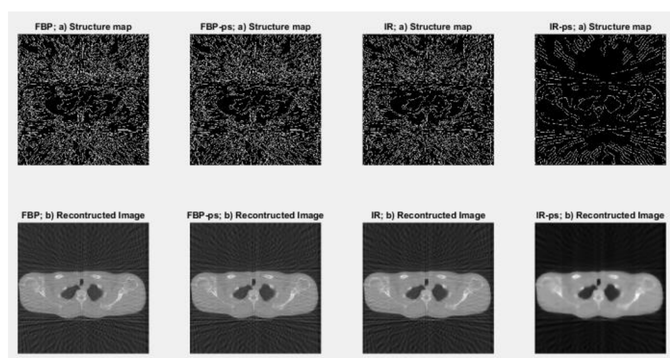


**Figure 6. Digital phantom reconstructed using FBP, FBP-PS, IR and IR-PS schemes**

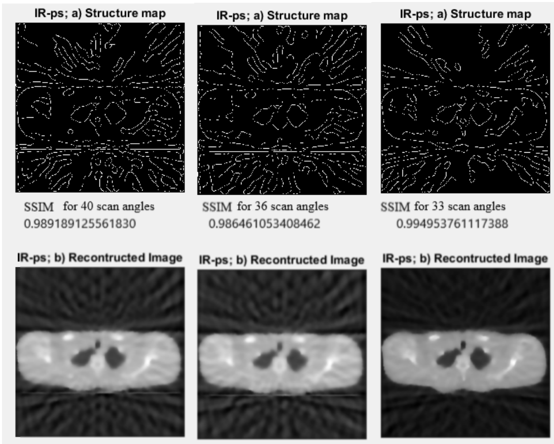


**Figure 7. Digital phantom reconstructed using IR-PS scheme for different scan angles**

## 5. CONCLUSIONS

This paper proposes a novel method to reduce overall image degradation introduced when IR technique is applied to CT images. This is achieved by preserving significant structural details present in the medical image, thus the method is named IR-PS. The idea relies on using edge detection map for suppressing the majority of noise present in the image and can be considered to be a relatively novel concept in this field. The SSIM indexes achieved with this method are very close to '1' and the measured RMSE are low indicating low reconstruction errors when compared to original FBP image. Although a simple noise filtering (combination of a linear and non-linear filtering) is used for the IR-PS schemes, most of the noise was suppressed by the extraction of structural pattern and overlapping concept.

In the Further work will be carried out on CT image datasets instead of digital phantoms, with electronic noise from the CT systems representing a challenge to be tackled using the proposed IR-PS scheme. This might be achieved by applying noise modelling along with the structure-preserving concept.

## 6. REFERENCES

[1] Xu J, Mahesh M, Tsui BM (2009) Is iterative reconstruction ready for MDCT? J Am Coll Radiol 6:274–276

[2] Brenner DJ, Hall EJ (2007) Computed tomography—an increasing source of radiation exposure. N Engl J Med 357:2277–2284

[3] Smith-Bindman R (2010) Is computed tomography safe? N Engl J Med 363:1–4

[4] Hall EJ, Brenner DJ (2008) Cancer risks from diagnostic radiology. Br J Radiol 81:362–378

[5] Smith-Bindman R, Miglioretti DL, Johnson E et al (2012) Use of diagnostic imaging studies and associated radiation exposure for patients enrolled in large integrated health care systems, 19962010. JAMA 307:2400–2409

[6] Bogdanich W (2011) Radiation Boom. The New York Times. Available via http://topics.nytimes.com/top/news/us/series/radiation_boom/index.html.

[7] Lee TY, Chhem RK (2010) Impact of new technologies on dose reduction in CT. Eur J Radiol 76:28–35

[8] Hentel KD, Sharma R, Wladyka C, Min RJ (2011) Appropriate use of CT in the emergency department. Emerg Med 1:6–13

[9] Macias CG, Sahouria JJ (2011) The appropriate use of CT: quality improvement and clinical decision-making in pediatric emergency medicine. Pediatr Radiol 41(Suppl 2):498–504

[10] Taylor AJ, Cerqueira M, Hodgson JM et al (2010) ACCF/SCCT/ ACR/AHA/ASE/ASNC/NASCI/SCAI/SCMR 2010 Appropriate Use Criteria for Cardiac Computed Tomography. A Report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, the Society of Cardiovascular Computed Tomography, the American College of Radiology, the American Heart Association, the American Society of Echocardiography, the American Society of Nuclear Cardiology, the North American Society for Cardiovascular Imaging, the Society for Cardiovascular Angiography and Interventions, and the Society for Cardiovascular Magnetic Resonance. Circulation 122: e525-e555

[11] Kerl JM, Bauer RW, Maurer TB et al (2011) Dose levels at coronary CT angiography—a comparison of dual-energy, dual source, and 16-slice CT. Eur Radiol 21:530–537

[12] Fleischmann D, Boas FE (2011) Computed tomography—old ideas and new technology. Eur Radiol 21:510–517

[13] Pan X, Sidky EY, Vannier M (2009) Why do commercial CT scanners still employ traditional, filtered back-projection for image reconstruction? Inverse Prob 25:1230009

[14] Nelson RC, Feuerlein S, Boll DT (2011) New iterative reconstruction techniques for cardiovascular computed tomography: how do they work, and what are the advantages and disadvantages? J Cardiovasc Comput Tomogr 5:286–292

[15] Funama Y, Taguchi K, Utsunomiya D et al (2011) Combination of a low-tube-voltage technique with hybrid iterative reconstruction (iDose) algorithm at coronary computed tomographic angiography. J Comput Assist Tomogr 35:480–485

[16] Gervaise A, Osemont B, Lecocq S et al (2012) CT image quality improvement using adaptive iterative dose reduction with wide volume acquisition on 320-detector CT. Eur Radiol 22:295–301

[17] Korn A, Fenchel M, Bender B et al (2011) Iterative reconstruction in head CT: image quality of routine and low-dose protocols in comparison with standard filtered back-projection. AJNR Am J Neuroradiol 33:218–224

[18] Prakash P, Kalra MK, Digumarthy SR et al (2010) Radiation dose reduction with chest computed tomography using adaptive statistical iterative reconstruction technique: initial experience. J Comput Assist Tomogr 34:40–45

[19] Winklehner A, Karlo C, Puippe G et al (2011) Raw data-based iterative reconstruction in body CTA: evaluation of radiation dose saving potential. Eur Radiol 21:2521–2526

[20] Sato J, Akahane M, Inano S et al (2011) Effect of radiation dose and adaptive statistical iterative reconstruction on the image quality of pulmonary computed tomography. Jpn J Radiol 30:146–153

[21] Moscariello A, Takx RA, Schoepf UJ et al (2011) Coronary CT angiography: image quality, diagnostic accuracy, and potential for radiation dose reduction using a novel iterative

image reconstruction technique-comparison with traditional filtered back projection. Eur Radiol 21:2130–2138

[22] Singh S, Kalra MK, Gilman MD et al (2011) Adaptive statistical iterative reconstruction technique for radiation dose reduction in chest CT: a pilot study. Radiology 259:565–573

[23] Pontana F, Duhamel A, Pagniez J et al (2011) Chest computed tomography using iterative reconstruction vs filtered back projection (part 2): image quality of low-dose CT examinations in 80 patients. Eur Radiol 21:636–643

[24] Leipsic J, Labounty TM, Heilbron B et al (2010) Estimated radiation dose reduction using adaptive statistical iterative reconstruction in coronary CT angiography: the ERASIR study. AJR Am J Roentgenol 195:655–660

[25] Yanagawa M, Honda O, Kikuyama A et al (2012) Pulmonary nodules: Effect of adaptive statistical iterative reconstruction (ASIR) technique on the performance of a computer-aided detection (CAD) system-Comparison of performance between different-dose CT scans. Eur J Radiol 81:2877–2886

[26] Nelson RC, Feuerlein S, Boll DT (2011) New iterative reconstruction techniques for cardiovascular computed tomography: how do they work, and what are the advantages and disadvantages? J Cardiovasc Comput Tomogr 5:286–292

[27] Singh S, Kalra MK, Hsieh J et al (2010) Abdominal CT: comparison of adaptive statistical iterative and filtered back projection reconstruction techniques. Radiology 257:373–383

[28] Singh S, Kalra MK, Gilman MD et al (2011) Adaptive statistical iterative reconstruction technique for radiation dose reduction in chest CT: a pilot study. Radiology 259:565–573

[29] Prakash P, Kalra MK, Ackman JB et al (2010) Diffuse lung disease: CT of the chest with adaptive statistical iterative reconstruction technique. Radiology 256:261–269

[30] Canny J. A computational approach to edge detection. IEEE Transactions on pattern analysis and machine intelligence. 1986 Nov (6):679-98.

[31] Liu GH, Li ZY, Zhang L, Xu Y. Image retrieval based on micro-structure descriptor. Pattern Recognition. 2011 Sep 1;44(9):2123-3