Improving Image Quality in Dual Energy CT by Edge-Enhancing Diffusion Denoising

Andreas E. Petropoulos, George F. Vlachopoulos, Spyros G. Skiadopoulos, Anna N. Karahaliou and Lena I. Costaridou

***Abstract*—The aim of this study is to investigate the effect of edge-enhancing diffusion (EED) denoising on the quality of dual energy CT images, derived by varying the weighting of the two spectra (0.1 to 0.9, 0.1 step). The quality of EED denoised weighted images was quantitatively assessed by means of SNR, contrast and CNR measured on ROIs of phantom images corresponding to 14 mg/ml iodine concentration and bone equivalent. The performance of the EED denoising technique was further compared to the performance of median filtering. EED improves significantly the quality of weighted images.**

I. INTRODUCTION

DUAL Energy Computed Tomography (DECT) is one of the evolving fields in radiology. Among the possible applications of DECT, is the ability to enhance contrast of iodinated structures [1]. The basis of DECT is the use of two x-ray spectra of different energies. The linear attenuation coefficient of a material depends on the energy of the spectrum, the density of the material and its atomic number. In the energy range used in radiology, the two main physical processes responsible for the attenuation of radiation through matter are, photoelectric effect and Compton scatter. The cross section per atom for photoelectric effect interaction strongly depends on energy ($1/E^3$) and atomic number (Z^4), while the cross section per atom for Compton scatter interaction depends on atomic number (Z^1). Hence, material differentiation can be achieved by using DECT and especially between materials of high and low atomic number, e.g. iodine, which is used as a contrast agent (Z=53) and soft tissue [1].

Today DECT can be achieved with different technologies; one of them is the dual source CT (DSCT) scanner, which has two x-ray tubes, operating at 80 and 140 kilovoltages. A DECT scanner acquires two projection datasets of different energies. Then, more commonly, low and high kilovoltage images are reconstructed. The low kV images present higher subject contrast, however image noise is higher compared to the 140 kV images. A way to decrease noise at 80 kV is to increase the tube current, but the radiation dose must not exceed the permitted levels. Another way is by combining the 80 kV and 140 kV images, using a linear weighting of the CT value of two spectra, in order to balance the high contrast and high image noise of the 80 kV image with the low image noise of the 140 kV [2]. As the weighting factor of the 80 kV image increases, so does the CT value and contrast in the weighted (fused) image.

Studies have shown that contrast is maximum when the 0.9 and 0.1 weighting of the 80 and 140 kV images, are used, respectively [3]. However, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) have been shown to be higher in images produced with 0.5 or 0.6 weighting factor [2],[4].

The aim of this study is to investigate the effect of edge-enhancing diffusion (EED) denoising on the quality of DECT images derived by varying the weighting of the two spectra (low and high kV images).

II. MATERIAL AND METHODS

A. Dataset and acquisition protocol

In this study the CT scanner used is the Siemens Somatom Definition, which is a dual source and dual energy CT system. The phantom used is a Mini CT QC phantom model 76-430. The disc section consists of a 2.54 cm thick acrylic polymethylmethacrylate (PMMA) disc, with a 15.25 cm diameter containing six large holes of 2.85 cm diameter and four smaller of 1.27 cm diameter. The disc section is attached to a rectangular acrylic bar containing a thin copper wire embedded along a central grove. The four small holes contained four water solutions of Optiray 350 (Ioversol), of concentrations 3.5, 7, 10 and 14 mg/ml. Optiray 350 is a sunstance used as contrast agent in CT scans, one milliliter of it provides 350 mg/ml of organically bound iodine. The phantom also contained materials such as, polyethylene, tissue equivalent of compact bone, polycarbonate, nylon, plastic water and polystyrene (Figure 1). The phantom was scanned with the DSCT in dual energy mode. Dual energy head angio analysis was performed, with tube current-time product values at 213 mAs and 50 mAs, for low and high kV, respectively.

Manuscript received July, 2013.

A. E. Petropoulos is with the Medical Physics Department of University of Patras, Greece (andreaspetropoulos@hotmail.com)

G. F. Vlachopoulos is with the Medical Physics Department of University of Patras, Greece (gvlachop@upatras.gr)

S. G. Skiadopoulos is with the Medical Physics Department of University of Patras, Greece (skiado@upatras.gr)

A. N. Karahaliou is with the Medical Physics Department of University of Patras, Greece (akarahaliou@upatras.gr)

L. I. Costaridou is with the Medical Physics Department of University of Patras, Greece (phone: +302610969111; fax: +302610996113; e-mail: costarid@upatras.gr).

978-1-4799-3163-7/13/$31.00 ©2013 IEEE

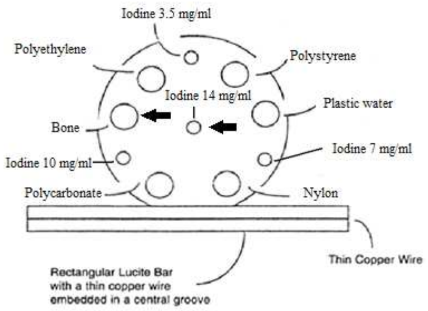

Fig. 1. Sketch of the scanned phantom. The pointed materials were studied.

Low and high kV images, as well as weighted (fused) images were reconstructed. The weighted images are described by the following equation:

$$x = w \cdot x_{low} + (1-w) \cdot x_{high} \tag{1}$$

where w is the *dual energy composition (or weighting factor)*, x denotes the CT value in the weighted image and x_{low} and x_{high} are the CT values of the low and high kV image, respectively [1]. In the current study, weighted images were provided by varying the value of the weighting factor w from 0.1 to 0.9, with 0.1 step.

B. Edge-enhancing diffusion denoising technique

Diffusion is a physical process that equilibrates concentration differences without creating or destroying mass. The equilibration property is expressed by Fick's law:

$$j = -D \cdot \nabla u \tag{2}$$

The equation states that a concentration gradient ∇u causes a flux j which aims to compensate for this gradient. D is the diffusion tensor, which is a positive definite symmetric matrix. The case where j and ∇u are parallel is characterized as isotropic.

The mass preservation statement in diffusion is expressed by the continuity equation:

$$\frac{\partial u}{\partial t} = -div j \tag{3}$$

The diffusion equation is given by substituting j from Fick's law in the continuity equation:

$$\frac{\partial u}{\partial t} = div(D \cdot \nabla u) \tag{4}$$

In image processing u represents the image and concentration differences can be identified as gray value differences.

In case the diffusion tensor is constant over the whole image domain, the diffusion is characterized *homogeneous*, while a space-dependent filtering is called *inhomogeneous*. In addition, diffusion which does not depend on the local properties of the image is called *linear*, otherwise it is called *nonlinear*.

Anisotropic models are introduced in applications where it is desirable to rotate the flux towards the orientation of features of interest. Edge-enhancing and coherence-enhancing diffusion are non linear anisotropic diffusion filtering techniques, introduced by Weickert [5]. Weickert based the diffusion tensor on the structure tensor, which describes structures in the image using first order derivative information.

In this study, an edge-enhancing diffusion (EED) technique was designed to smooth noise, while enhancing edges in 2D axial slice images [6]. Assuming that, μ_1 and μ_2 are the eigenvalues of the eigenvectors V_1 and V_2 of the structure tensor, respectively, the size of the eigenvalue and the eigenvector determine the magnitude and the direction of the gray level fluctuation.

Since the diffusion tensor should reflect the local image structure, it must correspond to the same set of eigenvectors. The eigenvalues of the EED tensor are defined as:

$$\lambda_{e_1} = \begin{cases} 1, & \left(\left|\nabla u_s\right|^2 = 0\right) \\ 1 - e^{\frac{-C}{\left(\left|\nabla u_s\right|^2 / \lambda_e{}^2\right)^4}}, & \left(\left|\nabla u_s\right|^2 > 0\right) \end{cases} \tag{5}$$

$$\lambda_{e_2} = 1$$

where C=3,31488 is a threshold parameter, $\left|\nabla u_s\right|$ is the gradient magnitude of the image at a scale s and λ_e is a contrast parameter, indicating at which contrast the gradient magnitude represents an edge instead of noise. Structures with $\left|\nabla u_s\right| > \lambda_e$ are regarded as edges, for which $\lambda_{e1} \to 0$, hence diffusion is inhibited in this direction, otherwise $\lambda_{e1} \to 1$, and diffusion is not inhibited [5],[6].

A coherence-enhancing diffusion (CED) technique [5] was not considered in the current study, since CED is designed to enhance line-like textures. Furthermore, since the images in this study do not present line-like textures, a CED technique is not applied.

The parameters of the EED algorithm were set as suggested in state-of-the-art literature [6]. Specifically, the standard descretization scheme was chosen, the time step size was set at 0.15, while scale s was set at 1. The number of iterations and λ_e were experimentally set at 12 and 0.0025, respectively.

C. Quantitative evaluation

The acquired CT DICOM original weighted images were converted to PNG images. The mean and standard deviation (σ) pixel CT values were measured at circular regions of interest (ROIs) of the same size corresponding to two materials, 14 mg/ml iodine concentration and bone equivalent material, as well as to PMMA part of the phantom disc, considered as background. The signal-to-noise ratio (SNR), contrast and contrast-to-noise ratio (CNR) were calculated using the following formulas, respectively:

$$SNR = \frac{mean\,value_{material}}{\sigma_{material}} \tag{6}$$

$$Contrast = mean\,value_{material} - mean\,value_{background} \tag{7}$$

$$CNR = \frac{mean\,value_{material} - mean\,value_{background}}{\sigma_{background}} \tag{8}$$

EED denoising filtering was applied on the original weighted images. The quality of the processed images was also assessed by means of SNR, contrast and CNR measured on the same ROIs corresponding to iodine solution, bone and background.

Finally, the performance of EED denoising was compared to the performance of median filtering (applied on the original weighted image), by calculating SNR, Contrast and CNR indices on the same ROIs (iodine solution, bone and background).

III. RESULTS

Figures 2-4 illustrate the differentiation of SNR, Contrast and CNR measured on original, median filtered and EED filtered weighted images, with respect to the weighting factor *w* of the two spectra. Results are provided for the two materials studied (iodine solution and bone).

As observed in Figure 2, the optimal SNR value for original and EED filtered weighted images is achieved with the 0.5 weighting factor, for both materials considered. The optimal SNR value for median filtered weighted images is differentiated with respect to the material depicted, being 0.8 for iodine and 0.4 for bone.

As observed in Figure 3, iodine and bone contrast on original, median filtered and EED filtered weighted images is linearly increased as the weighting factor is increased. Contrast remains constant on original and processed (median and EED filtered) weighted images, for all values of the weighting factor considered in the current study. The highest contrast value is achieved with 0.8 and 0.9 weighting factors for both materials.

The optimal CNR value for original weighted images is achieved with a weighting factor of 0.7 for both materials, while the corresponding optimal CNR value for median and EED filtered weighted images is achieved employing a weighting factor of 0.8 and 0.7, for iodine and bone, respectively (Figure 4).

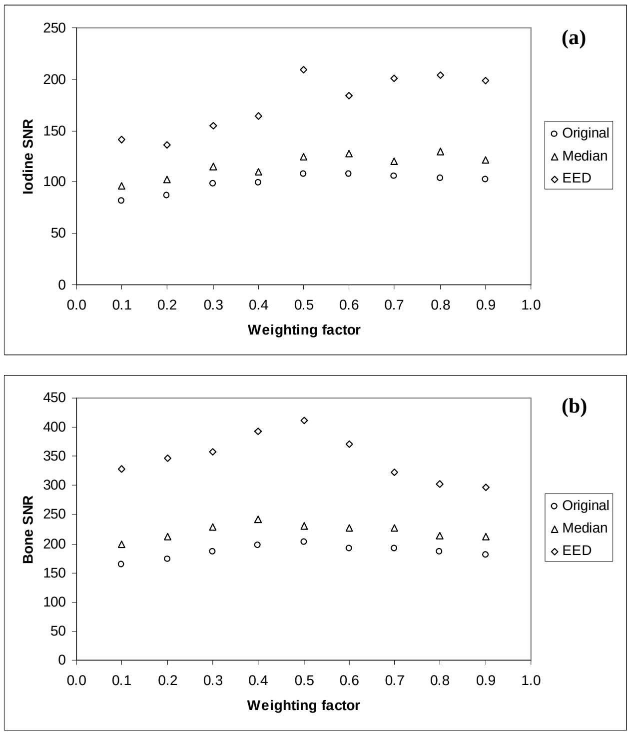

Fig. 2. SNR of the original, median filtered and EED filtered weighted images for (a) iodine solution and (b) bone, for all the weighted images studied.

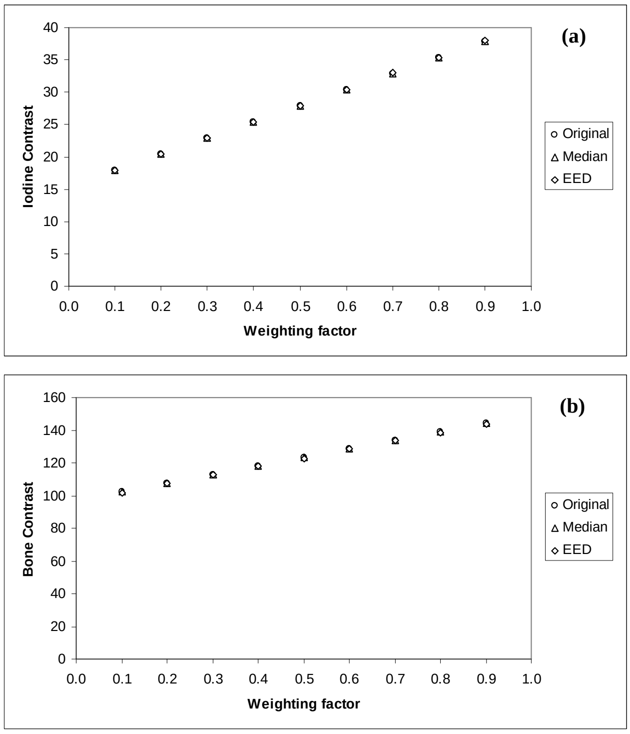

Fig. 3. Contrast of the original, median filtered and EED filtered weighted images for (a) iodine solution and (b) bone, for all the weighted images studied.

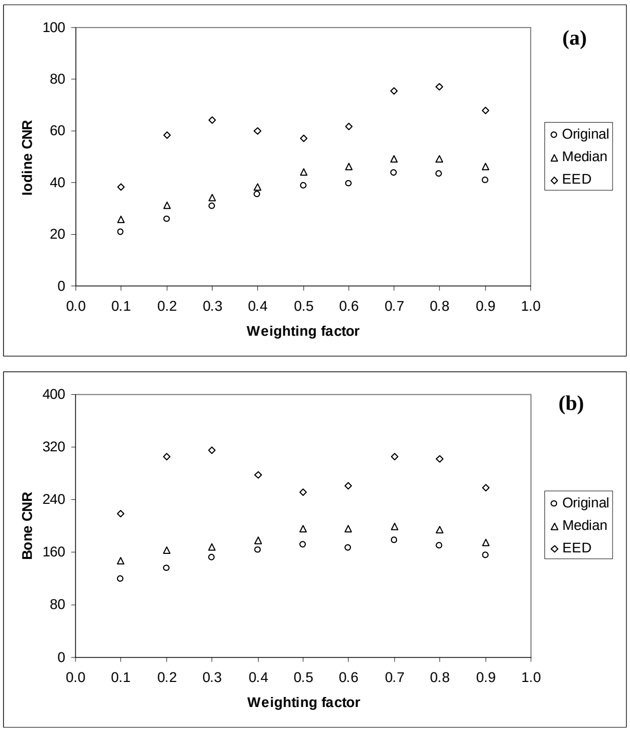

Fig. 4. CNR of the original, median filtered and EED filtered weighted images for (a) iodine solution and (b) bone, for all the weighted images studied.

TABLE I
% INCREASE OF SNR ON DENOISED WEIGHTED IMAGES AS COMPARED TO ORIGINAL ONES, FOR THE IODINE SOLUTION AND BONE.

weighting factor	*Iodine*		*Bone*	
	Median	***EED***	***Median***	***EED***
0.1	17.6	73.2	20.7	99.6
0.2	17.7	56.5	21.5	99.1
0.3	17.6	58.0	23.3	93.3
0.4	10.9	65.6	22.3	98.4
0.5	15.1	93.5	14.2	103.2
0.6	17.5	69.9	18.3	93.2
0.7	13.5	89.9	18.1	67.8
0.8	24.7	95.8	15.3	62.9
0.9	18.3	93.9	17.4	64.5

TABLE II
% INCREASE OF CNR ON DENOISED WEIGHTED IMAGES AS COMPARED TO ORIGINAL ONES, FOR THE IODINE SOUTION AND BONE.

weighting factor	*Iodine*		*Bone*	
	Median	***EED***	***Median***	***EED***
0.1	23.0	82.3	23.0	82.7
0.2	20.4	125.4	20.6	125.4
0.3	10.2	107.7	10.1	107.3
0.4	8.7	70.2	8.6	70.0
0.5	14.3	47.0	14.3	47.0
0.6	17.4	56.5	17.2	56.4
0.7	11.9	71.5	11.9	71.2
0.8	13.5	77.0	13.5	77.2
0.9	13.1	66.9	13.1	66.6

Table I provides the % increase of SNR on denoised weighted images (by means of median and EED filtering) as compared to original ones, for iodine solution and bone. The average % increase of SNR index on the denoised weighted images as compared to the original ones is 18.0 (range: 10.9-24.7) for the median filtering technique and 82.1 (range: 56.5-103.2) for the EED filtering technique.

Table II provides the % increase of CNR on denoised weighted images (by means of median and EED filtering) as compared to original ones, for iodine solution and bone. The average % increase of the CNR index on the denoised weighted images, as compared to the original ones, is 14.7 (range: 8.6-23.0) for the median technique and 78.2 (range: 47.0-125.4) for the EED filtering techniques.

IV. DISCUSSION AND CONCLUSIONS

The current study focused on investigating the effect of a EED denoising technique on the quality of DECT images. DECT weighted images were provided by varying the value of the weighting factor *w* from 0.1 to 0.9, with 0.1 step. The quality of denoised images was quantitatively assessed employing contrast, CNR and SNR image quality metrics measured on ROIs corresponding to 14 mg/ml iodine concentration and bone equivalent. The performance of EED filtering was further compared to the performance of median filtering.

The EED filtering technique improved significantly the quality of DECT images for all weighting factors of the two spectra (low and high kV images) studied. In addition, the EED filtering demonstrated an increased performance as compared to the median filtering.

While the current study has to be enhanced considering testing on clinical datasets and non-linear weighting of the two spectra, results suggested the potential of EED denoising in improving quality of DECT images.

ACKNOWLEDGMENT

The authors would like to thank the staff of the Radiology Department of Olympion General Hospital, Patras, Greece.

REFERENCES

[1] T. R. C. Johnson, C. Fink, S. O. Schönberg, M.F. Reiser, *Dual Energy CT in Clinical Practice*. New York: Springer-Verlag. 2011.

[2] J. Paul, *et al.*, "Image fusion in dual energy computed tomography for detection of various anatomic structures: Effect on contrast enhancement, contrast-to-noise ratio, signal-to-noise ratio and image quality", *Eur J Radiol*, vol. 80, no. 2, pp. 612-619, 2011.

[3] C. Thomas, D. Ketelsen, I. Tsiflikas, *et al.*, "Dual-energy computed tomography: Is there a penalty in image quality and radiation dose compared with single-energy computed tomography?", *J Comput Assist Tomogr*, vol. 34, no. 2, pp. 309-315, Mar/Apr. 2010.

[4] F. F. Behrendt, B. Schmidt, C. Plumhans, *et al.*, "Image fusion in dual energy computed tomography: effect on contrast enhancement, signal-to-noise ratio and image quality in computed tomography angiography", *Invest Radiol*, vol. 44, no. 1, pp. 1-6, Jan. 2009.

[5] J. Weickert, "Anisotropic Diffusion in Image Processing", B. G. Teubner: Stuttgart, 2008.

[6] A. M. Mendrik, E-J. Vonken, A. Rutten, *et al.*, "Noise reduction in computed tomography scans using 3-D anisotropic hybrid diffusion with continuous switch", *IEEE Trans Med Imaging*, vol. 28, no. 10, pp. 1585-1594, Oct. 2009.