EFFECTS OF RADIATION DOSE REDUCTION IN DIGITAL RADIOGRAPHY USING WAVELET-BASED IMAGE PROCESSING

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Abstract – In this paper, we investigated the effect of the use of wavelet transform on dose reduction in computed radiography (CR). The physical properties of the processed CR images were measured using the modulation transfer function (MTF), noise power spectrum (NPS), contrast-to-noise ratio, and peak signal-to-noise ratio. Furthermore, visual evaluation was performed by Scheffe’s pair comparison method. Experimental results showed that sigmoid-type transfer curves for wavelet coefficient weighting adjustment could improve the MTF, and three soft-threshold methods could improve the NPS at all spatial frequency ranges. Moreover, our visual evaluation showed that an approximately 40% reduction in exposure dose might be achieved with the sigmoid-type transfer curve in hip joint radiography.

Keywords: Wavelet transform, Image noise, Radiation dose, Image quality

1. INTRODUCTION

In the clinical implementation of digital radiography, it is imperative to use the appropriate level of radiation for the diagnostic task. It is known that a trade-off exists between noise level and radiation dose. On one hand, a high-dose radiation will lower the noise level but may give excess radiation doses to the patient. On the other hand, a low-dose radiation will lower the signal-to-noise ratio of the image and result in reducing the amount of image information. Thus, it is important to obtain radiological images that provide more diagnostic information at a lower radiation dose. So far, several investigators have reported that wavelet-based image processing techniques are effective in reduction of radiation dose [1-6]. The wavelet transforms can be used to divide an image into several frequency domains. The potential information in each image is retained, and extraction of the image information in each frequency domain is possible. Image noise can be reduced by performing wavelet de-noising technique in the frequency domain. However, to the best of our knowledge, little work has been done to investigate the relations of physical properties of wavelet-processed images and radiation dose reduction. In this work, we investigated the effect of employment of wavelet-based image processing techniques on radiation dose reduction for digital radiography. The physical properties of the wavelet-processed images were measured and evaluated. Furthermore, images of the lumbar spine and hip joint phantoms, obtained from various dose levels in the standard range of X-ray energies, were quantitatively and qualitatively assessed.

2. METHODS AND MATERIALS

2.1 Experiments setup

This study was performed using the CR imaging modality (FCR XG-1, Fuji Photo Film, Tokyo, Japan). The pixel size and the quantization level of the images used were 0.1 mm and 10 bits in type ST-V₆ imaging plate. Radiographs were taken with radiation quality of RQA-5 (HVL=7.1 mm Al, 21 mm Al additional filtration). The image data used in this study consisted of 20 phantom images. The phantom images were evaluated with respect to various physical properties. Furthermore, in order to evaluate the relationship between radiation dose and image quality, radiological examination was carried out using four X-ray images, an anterior-posterior (AP) and oblique (Lauenstein) projection of the hip-joint, an AP and the lateral view of the lumbar on a human body phantom. These four images were taken with four different radiation levels, i.e., 50/100, 64/100, 80/100, and 100/100, as compared to the reference level that is commonly used in clinical radiology practice. The images obtained with the human body phantom and those used for measuring basic physical properties were processed using wavelet transforms.

2.2 Image processing

In the conventional methods using soft-threshold, wavelet basis functions of Haar (Lv4), Daubechies4 (Lv4), and Coiflets4 (Lv4) were adopted for image processing [7]. In addition, a sigmoid-type transfer curve for wavelet coefficient weighting adjustment (sigmoid) together with the use of Daubechies4 (Lv4) was also adopted [8]. The sigmoid filter is used to enhance image contrast: the coefficients with great values and the coefficients of high resolution levels are
heavily weighted. In the wavelet decomposition of level \( j \), the sigmoid-type transfer curves of wavelet coefficient can be expressed as follows:

\[
w_{\text{output}}(m, n) = \alpha \times \left( 1 + \exp \left[ \frac{W_{\text{input}}(m, n) - c}{b} \right] \right)^{-1}, \quad \cdots \quad (1)
\]

where, \( W_{\text{input}}(m, n) \) and \( W_{\text{output}}(m, n) \) represent input and output values, respectively. In this study, the value of \( \alpha \) was computed using equation (2):

\[
\alpha = 2 - \frac{(j - 1)}{N}, \quad \cdots \quad (2)
\]

where, \( N \) represents the maximum decomposition level. Consequently, if decomposition \( j \) becomes smaller, the gradient of the graph obtained from equation (1) get greater. The constant \( c \) was determined using equation (3).

\[
c = d + b \times \ln(a - 1.0), \quad \cdots \quad (3)
\]

where, \( d \) is a constant used to determine inflection point of sigmoid curve, \( b \) represents a constant to determine gradient of sigmoid curve. The values of \( d \) and \( b \) used in this study are 25 and 20, respectively. With regard to \( d \), 25 \% and below noise were controlled [9]. The above-described four filters were applied to the original images.

3. IMAGE EVALUATION

3.1 Modulation Transfer Function (MTF)

Evaluation of spatial resolution property was performed by measuring the MTFs [10, 11]. The MTFs were measured with an angled-edge method. A tungsten plate (1 mm thickness) was used as an edge device. The direction of the edge was oriented with a small angle (2°–3°). The edge is made of a 100-μm-thick sharp edged tungsten plate and its dimension was 10×10 cm². Images of the edge were acquired with an exposure of 4.63×10⁻⁷ C/kg (50 mAs). After the image of the edge was acquired, the digital image data were transferred to a computer. The edge spread function (ESF) in the direction perpendicular to the edge was then obtained. To reduce the noise in the edge profile, 20 representations of sampled ESF were generated from the region of interest (ROI). The ESFs were then differentiated to obtain the line spread functions and the presampled MTFs were similarly deduced by Fourier transformation. The details of the processing method are given elsewhere [10, 11].

3.2 Noise Power Spectrum (NPS)

NPS measurements were made by exposing the imaging plates to a uniform beam of radiation. For determination of the NPS, the entrance exposure (air kerma) for the images was 4.63×10⁻² C/kg. To remove long-range background trends, a two-dimensional 2nd order polynomial was fitted and subtracted. For the calculation, the central portion of each obtained uniform image was divided into 4 non-overlapping regions, 256×256 in size (80 in total). The NPS was calculated by applying the fast Fourier transform to each ROI and averaging the resulting spectrum estimates. The details of the methodology are reported elsewhere [12, 13].

3.3 Contrast-to-Noise Ratio (CNR)

CNR measurements were made using an acrylic disk on the Burger’s phantom. An ROI with a size of 30×30 pixels was selected at the center of disk and neighbour background. CNR can be calculated by use of the following equation:

\[
\text{CNR} = \frac{m_{\text{BG}} - m_{\text{disk}}}{\sigma_{\text{BG}}}, \quad \cdots \quad (4)
\]

where, \( m_{\text{BG}}, m_{\text{disk}} \) and \( \sigma_{\text{BG}} \) represent the mean of the background, mean of the disk, and standard deviation of background, respectively.

3.4 Peak Signal-to-Noise Ratio (PSNR)

PSNR was obtained from the area covering the entire field of the image using human body phantom. PSNR is given by the squared root of the ratio of the peak value of gray level squared to the mean square error (MSE). PSNR and MSE were obtained using the following equations:

\[
\text{PSNR} = 20 \log_{10}(PV_{\text{max}} / \sqrt{\text{MSE}}) \quad \text{[dB]}, \quad \cdots \quad (5)
\]

\[
\text{MSE} = \frac{1}{M \times M'} \sum_{i=1}^{M} \sum_{j=1}^{M'} (\text{orig\_pixel}_{ij} - \text{comp\_pixel}_{ij})^2, \quad \cdots \quad (6)
\]

where, \( PV_{\text{max}} \) refers to maximum pixel value. The \( M \) and \( M' \) are matrix sizes of the original and processed images, respectively.

3.5 Visual Evaluation

Visual evaluation was conducted by five experienced radiological technologists. The images were displayed on a liquid crystal display (1280×1024 matrix, LCD-1980Xi, Nippon Electric Company, Tokyo, Japan). Statistical significance was tested using Scheffe’s method of paired comparisons. The method of paired comparisons calculates the score of each image by comparative assessment between all possible pairs of images. Comparisons were made by five possible combinations, that is, Haar (Lv4)-processed image, Daubechies4 (Lv4)-processed image, Coiflets4 (Lv4)-processed image, sigmoid filter-processed image, and the original image. Conditions for the visual evaluation, including window level, window width, and display image size were fixed. Each observer independently reviewed the images. Reading time was not limited in this study.
4. RESULTS

4.1 MTF

Figure 1 shows the MTFs for the original image and four images processed by various wavelet transforms. The MTF of sigmoid is superior to the original image at the entire spatial frequency range. In contrast, the MTFs obtained from the three wavelet-based filters are slightly lower than the original one. Among them, Haar basis function shows the highest MTF, followed by Daubechies and Coiflets.

![MTF Graph](image)

**Fig. 1 MTFs of Original, Haar, Daubechies, Coiflets, and sigmoid filter.**

4.2 NPS

Figure 2 shows the NPS values. The NPS values of the sigmoid have pronounced increase as compared with that of the original image. In contrast, the NPS values of soft-threshold method have noticeable decrease. It is noted that the NPS profile of Haar function fluctuates. As illustrated in Fig 2, the NPS values for sigmoid-processed images show the highest rank, followed by original, Haar, Daubechies, and Coiflets.

![NPS Graph](image)

**Fig. 2 NPSs of Original, Haar, Daubechies, Coiflets, and sigmoid filter.**

4.3 CNR

Figure 3(a) illustrates the CNRs obtained with acrylic disk images. Figure 3(b) and (c) depicts an example of the processed images including the original one and the corresponding disk profiles obtained from the central portion of the images. The CNR values of soft-threshold are superior to the original image. However, the CNR value of sigmoid shows slightly lower compared to that of the original image. As shown in Fig 3(b), the sigmoid image is similar to original image in shape, although it has the smallest CNR values. Haar image generated blocking artifacts. Furthermore, Daubechies and Coiflets images show considerable blur. In addition, as shown in Fig. 3(c), the contrast of sigmoid image increases as compared to that of any other image.

4.4 PSNR

Figure 4 shows the relationship between the radiation dose ratio and the PSNRs. The PSNRs in Fig. 4(a), (b), (c) and (d) were obtained from hip joint (antero-posterior), hip joint (Lauenstein), lumbar (antero-posterior) and lumbar (lateral), respectively. Note that the PSNRs of three soft-threshold methods have not much changed. They show the similar results, even if the portions examined are different. However, the PSNR of the sigmoid-processed image shows noticeable decrease. The PSNR of sigmoid tends to decrease slightly with the reduction of exposure dose. However, the PSNRs of the soft-threshold methods show insignificant change.

4.5 Visual Evaluation

Figure 5 illustrates visual evaluation results using Scheffe’s method of paired comparisons. In the case of hip joint radiographs, sigmoid provides excellent results compared to other images up to 80/100 radiation dose ratio. When radiation dose ratio is 64/100, sigmoid is superior to other images. However, sigmoid shows unsatisfactory result when radiation dose rate is 50/100 radiation dose ratio. In the case of lumbar radiographs, as a whole, sigmoid does not provide satisfactory results compared to other images. In other words, sigmoid filter is not effective for lumbar radiographs.
Fig. 3 CNRs of Original, Haar, Daubechies, Coiflets, and sigmoid filter.
(a) CNR values of original and processed images.
(b) Images of acrylic disk.
(c) Disk profiles of original and processed images.

Fig. 4 PSNRs of Haar, Daubechies, Coiflets, and sigmoid filter in Hip Joint AP, Hip Joint Lauenstein, Lumbar AP, and Lumbar Lateral.
Fig. 5 Visual evaluation of Haar, Daubechies, Coiflets, and Sigmoid filter in Hip Joint AP, Hip Joint Lauenstein, Lumbar AP, and Lumbar Lateral.
We observed that the four adopted wavelet filter have considerable differences in physical properties measurement. In the NPS measurement, noise characteristics were improved by using soft-threshold methods. However, as a sacrifice for noise reduction, blur effect generally appears on acrylic disk images. These results suggest that soft-threshold methods were not adequate for clinical application in its current form. Furthermore, images processed by Haar basis function show blocking artifacts. The reason might be attributed to the use of low scale levels. Thus, it may result in fluctuation in NPS profile of Haar function. On the contrary, the use of sigmoid method can improve spatial resolution and image contrast as shown in Fig. 3(b) and (c), although noise becomes more obvious compared to the three soft-threshold methods.

In digital radiographic systems, generally, a trade-off exists between image resolution and noise characteristics. An image may only be superior in one image quality characteristic while being inferior to another in the other characteristic. A visual evaluation was performed in addition to the investigation of physical characteristics. Our evaluation results show that the use of sigmoid method can visually improve image quality. Therefore, sigmoid filter is superior to soft-threshold methods and comparable to the original image in hip joint radiography, when a reduction of approximately 40% in exposure dose was made.

However, the use of sigmoid filter for lumbar radiography is limited because of the increase of noise level. So, in order to overcome this difficulty, we plan to apply filter based on a sigmoid-type transfer curve to high noise level images, such as lumbar radiography.

6. CONCLUSION

In this study, we investigated the effect of the use of wavelet transform on dose reduction in CR. The physical properties of the processed CR images were measured and compared. In the investigation of physical properties, the experimental results confirmed that the soft-threshold method can significantly reduce noise level and sigmoid method can effectively improve resolution characteristic. Moreover, our visual evaluation showed that an approximately 40% reduction in exposure dose might be achieved with the sigmoid-type in hip joint radiography.
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