35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Study on Improvement of Signal Detectability Considering Noise Characteristics in Medical X-ray Images

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Abstract—**The purpose of this study is to develop method for improvement of low-contrast signal detectability of general X-ray images used for observing overviews, included noise reduction technique and signal amplification technique, that are difficult to detect in the observing overview. The proposal method consists signal amplification part and noise reduction part. The noise reduction part first identifies and mathematizes the characteristics of the noise attributed to the X-ray imaging system before the subject is imaged. The noise information derived from mathematization is used to remove the noise representing the system noise from the subject image. After noise reduction, all the signals on the subject image with sufficiently reduced noise are amplified by multiplication with an arbitrary coefficient. The feasibility of the proposed method was indicated by three evaluations that were performed vision assessment using the image including the virtual low-contrast signals by four radiological technologists. That of the proposed method was confirmed from results of the evaluations. That of the proposed method was confirmed from results of the evaluations.**

Index Terms—**general X-ray image, signal detectability, noise reduction, observing overview, mathematization.**

I. Introduction

General X-ray imaging is the simplest type of radiation imaging. It has the following advantages: the widest range of application, low cost, and short binding time. It is also less invasive because the radiation exposure dose is much less than that of computed tomography (CT) for the same test. Therefore, it is deemed to be one of the most basic examinations [1-2]. The general X-ray image is frequently used to survey the presence of anomalies through observing an entire area inside the body such as health checks or screening tests rather than observe local area such as bone fracture because general X-ray images are best used for overviews: we can confirm a wide area in the body at a time from a single image. Thus, general X-ray images are still important for overviews even with current developments of advanced diagnostic imaging techniques. Other imaging examinations such as CT or magnetic resonance imaging (MRI) seldom assume the role of the observing overview. However, observing pathological lesions with low contrast, such as tumors, by using general X-ray images is often difficult. These low-contrast signals may be overlooked during interpretation of the radiogram [3-5]. Therefore, in order to efficiently utilize general X-ray imaging or improve diagnostic accuracy, X-ray images should be generated that improve detection of low-contrast signals in possible affected areas. These images are required to both allow the detection of low-contrast signals and provide an observing overview simultaneously because the latter is still important in diagnostic imaging.

This study aims to develop a method for improvement of signal detectability of general X-ray images used for observing overviews, included noise reduction technique and signal amplification technique, that are difficult to detect in the observing overview.

II. Basic cnccept of the method for improvement of signal detectability

First, the proposed method for improvement of signal detectability was required to achieve four goals to realize practical application for medical use.

- Allow both the detection of low-contrast signals and an observing overview simultaneously without the need to change the observation width.
- Establish a noise reduction method with no effect on the signals attributed to humans.
- Establish an adaptive noise reduction method that reflects the noise characteristics of the X-ray imaging system.
- Develop a simple and intuitive method for operators.

Basic concept of the proposal method shown in Figure 1 basically comprises two parts: signal amplification and noise reduction. The noise reduction part first identifies and mathematizes the characteristics of the noise attributed to the X-ray imaging system before the subject is imaged. This information is holistically utilized to decrease the noise representing the system noise. After noise reduction, all the signals on the subject image with sufficiently reduced noise are amplified by multiplication with an arbitrary coefficient. These operations significantly improve the detectability of low-contrast signals.

The noise attributed to the X-ray imaging system can be easily observed from the X-ray image taken without the subject, as shown in Figure 3. Density variation in the image or variation in a gray level represents a noise component because this image accurately reflects the noise generated by the X-ray imaging system. Therefore, ideally, this variation in the whole image should be suppressed accurately and numerically.

First, this study had a different target from that of the general mathematization technique, which targets an input–output relationship (characteristics) of the system or temporal

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978-1-4577-0216-7/13/$26.00 ©2013 IEEE

change in system conditions. This study examined is the space signal distribution. Thus, when (x_i, y_j) denotes a position on the images and $z(i, j)$ is the pixel value of each pixel, this is described as a function of the relationship between the pixel position and pixel value, as shown in

$$z(i, j) = f(x_i, y_j). \qquad (1)$$

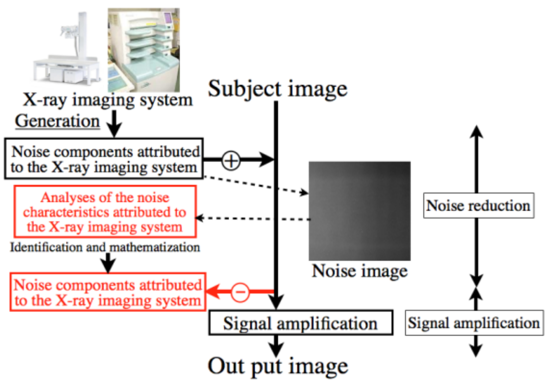

Figure 1. Concept of the proposed method for improving signal detectability. The proposal method consists signal amplification part and noise reduction part. The noise reduction part first identifies and mathematizes the characteristics of the noise attributed to the X-ray imaging system before the subject is imaged. The noise information derived from mathematization is used to remove the noise representing the system noise from the subject image. After noise reduction, all the signals on the subject image with sufficiently reduced noise are amplified by multiplication with an arbitrary coefficient.

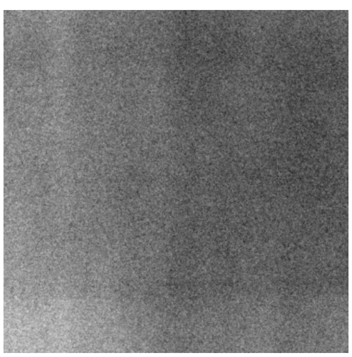

Figure 2. Noise image taken without the subject.

III. Verification of the Noise Image

The noise image includes many types of the noise component attributed to the X-ray imaging system. However, it is difficult to understand the characteristics of each noise component with resolving those noises into each source of generation. In our previous study, we have confirmed that the noise components in the noise image shown in Figure 2 consists position dependent component (stationary component) and position independent component (stochastic component) [6]. Therefore, this study carries out mathematization of the noise image considering each characteristic by spatial frequency range.

A. Low-frequency noise

Figure 3(a) and 3(b) shows the noise image, which are processed using low-pass filter (LPF) at 0.195 cycles/mm with the same X-ray imaging system. In contrast, those images different in dose setting (2 mAs, 20 mAs). A comprehensive variation component is observed in the same position in both noise images. The comprehensive variation component is specific noise attributed to the X-ray imaging such as geometric distribution nonuniformity caused by X-ray tube structure or in-process sensitivity no uniformity of X-ray acceptance surfaces. Thus, the comprehensive variation component have only stationary characteristic.

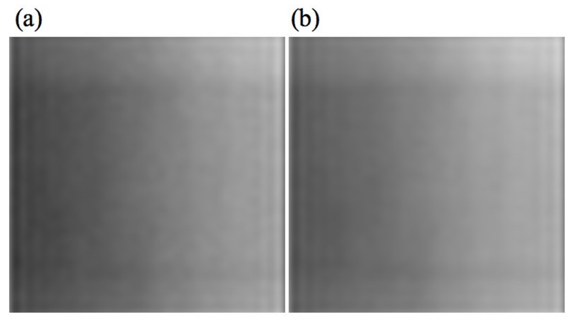

Figure 3. Low-frequency noise image. (a): dose setting at 2 mAs. (b): dose setting at 20 mAs.

B. High-frequency noise

Figure 4(a) and 4(b) shows the noise images, which are iteratively taken with the same X-ray imaging system, and processed using high-pass filter (HPF) at 0.195 cycles/mm. Those noise images are composed chiefly of the component attributed to X-ray emission fluctuation depending on X-ray dose setting. Relationship of between those images is decorrelation. In addition, the density distribution of those noise images is a normal probability distribution. Thus, it is shown that this noise component does not have the stochastic characteristic by advance verifications.

In region in the circle in Figure 4(b), discrete and stippled white noise is confirmed. Those noise components were also confirmed to have temporal repeatability. The generation of those components is related to a no-sensitivity region caused by manufacturing failure or aging degradation of an imaging plate (IP). Therefore, those components are specific noise attributed to the X-ray imaging system. Moreover, those components always appeared in the X-ray images as a white signal. Thus, the discrete components have stationary characteristic. The signal's figure resembles calcification. Hence, those components should be removed positively as they are noise.

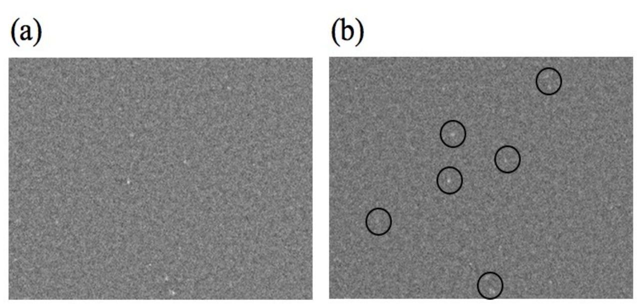

Figure 4. High frequency noise images. Images obtained from the same X-ray imaging system. (b): there are some position dependent noise in the circles.

C. Mathematization

The noise image is formulated by the characteristics of the noise components as following equation:

$$z(i\,,j) = k + g(x_i, y_j) + \varepsilon(x_i, y_j) + \mu, \qquad (2)$$

where $z(i, j)$ is the pixel value of each pixel, k is a direct current component, $g(x_i, y_j)$ is a low-frequency stationary component, $\varepsilon(x_i, y_j)$ is a high-frequency stationary component and μ is high-frequency stochastic component.

IV. Detail of the Method for Improvement of Signal Detectability

In this paper, noise reduction method for components that can be judged clearly to be specific to the X-ray imaging system is added in the proposed method indicated in the basic concept term in this paper. The proposed method targets stationary components. However, the model for the high-frequency stationary noise is not directly used to noise reduction because this noise component is discrete components. Therefore, this paper proposes way to high-frequency stationary noise reduction directly using noise image processed using the HPF. Figure 5 shows detail of the method for improvement of signal detectability considering handling of the high-frequency stationary noise. First, subtraction processing is performed on a subject image to remove low-frequency stationary noise using the original noise image generated from the mathematical noise model. Here, for reduction of the low-frequently noise, the mixed model, which is mixed Fourier series with adjustably cycle and polynomial equation. The polynomial equation is used to identify aperiodic components in the low-frequency noise. The Furrier series is used to identify periodic like components. The image after subtraction processing is copied as many times as necessary. The second processing subtracts high-frequency noise images prepared beforehand by multiple shooting from the copied image. The stochastic noise component is dominant component in the high-frequency noise in both of the noise image and the subject image. Therefore, averaging processing inhibits variation of the high-frequency stochastic noise associated with subtraction processing. The pixel value in averaged image is multiplied by the coefficient to create a signal amplification image.

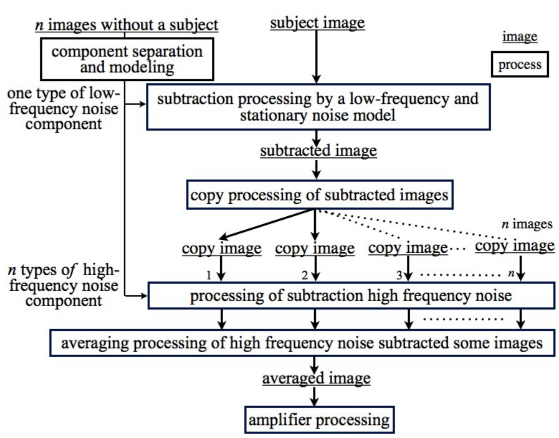

Figure 5. Proposed signal detectability improvement method.

V. Evaluation for Proposal Method

In order to indicate the feasibility of the proposed method, three evaluations were performed using the image including the low-contrast signals:

1) Is the low-frequency stationary noise removed?

2) Is the high-frequency stationary noise removed?

3) Are the low-contrast signal detectability and medical practicality improved?

A. Evaluation method

In order to perform evaluations 1 and 2, two types of images were prepared. The first image included a thin high-absorbent material object. This image can be used to evaluate the reduction in noise components because it is a simple construction. The second image included a plastic material object with a bar pattern construction. This image was used to evaluate the reduction in noise components in the complex structural image. With regard to the evaluation images used for evaluations 1 and 2, the proposed method only reduced the noise in the processed images. For evaluation, four radiological technologists visually assessed the condition of the low- and high-frequency stationary noise components using a visual analog scale (VAS) with a 100-mm length for both the original and processed images.

In order to perform evaluation 3, the biological image was prepared. This image shows a fish with a simulated tumor as the low-contrast signal. The purpose of this image was to evaluate the improvement of the low-contrast signal detectability by the proposed amplification method because this image simulates the images for observing overviews. Therefore, the observation width of this image was set to 900; this setting is equivalent that used for observation overview. The images for evaluation 3 were processed by the proposed method with four-time amplification processing. The compared images are not only the original image for the observing overview but also the image after amplification processing and smoothing with a 3 × 3 window, the image with the amplification processing but without the noise reduction process and the image with a narrow observation width as conceivable similar processed image. For evaluation, four radiological technologists visually assessed the improvement of low-contrast signal detectability and practicality in the medical field using the VAS with a 100 mm length. A hearing investigation of the same content was also performed.

B. Evaluation results and discussion

The image included the plastic material object with a bar pattern construction shown in Figure 6(a) and 6(b); it is an example for evaluation 1. Figure 6(a) shows the original image without process, and Figure 6(b) shows the processed image. As shown in Figure 6(b), the disappearance of gradual variation component in and out structural object (Figure 6(a)) was confirmed.

The magnified image included a high-absorbent material object shown in Figure 7(a) and 7(b); it is an example for evaluations 2. Figure 7(a) shows the original image, and Figure 7(b) shows the processed image. The circled regions in the original image include the high-frequency stationary noise components. As shown in Figure 7(b), the disappearance of high-frequency stationary noise included original image (Figure 7(a)) was confirmed.

According to results of the VAS of the degree of noise perception in evaluation 1 and 2, the VAS value in the each processed image decreased considerably compared to that in the original image. Therefore, the stationary noise components were accurately removed.

The fish image with the embedded simulated tumor was an example for evaluation 3. Figure 8(a) shows the image for the observing overview, and Figure 8(b) shows the image after the proposed method was applied. When both images are compared, the processed image clearly shows the simulated tumor, which is difficult to see in the observing overview without changing the observation width.

Finally, the VAS results for practicality in the medical field were indicated by comprehensive reviews of both the detectability of the simulated tumor and the condition of the surrounding tissue or clarity of the bone structure. The VAS value of the processed image was higher than that of the original image for the observing overview. On the other hand, VAS values of the processed image and the image with a narrow observation width applied were about the same. However, narrow observation width processing is seldom used for the observing overview because of the medical restrictions. Therefore, the image with the proposed method applied is the most practical as a medical image used for the observing overview. Regarding the other images, the hearing investigation revealed that the condition of the white-out bone in the image is not practical.

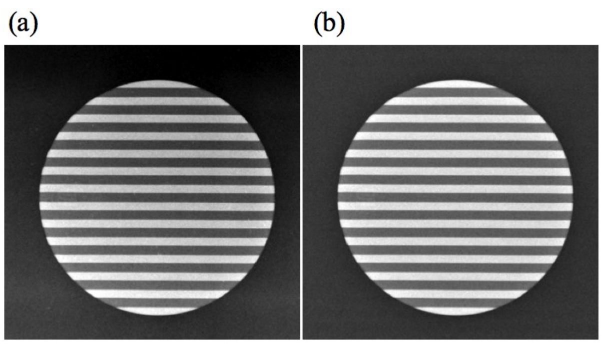

Figure 6. Image included a plastic material object with a bar pattern. (a) original image and (b) processed image.

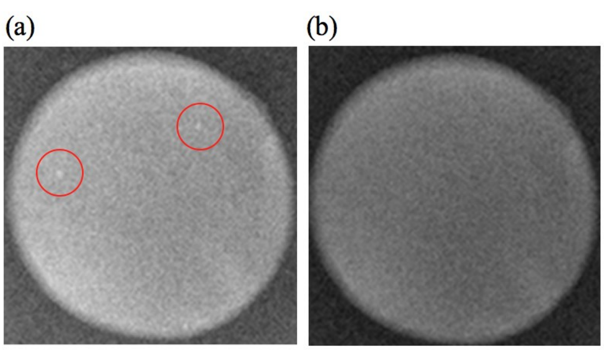

Figure 7. Magnified image of the high-absorbent material object. (a) original image and (b) processed image.

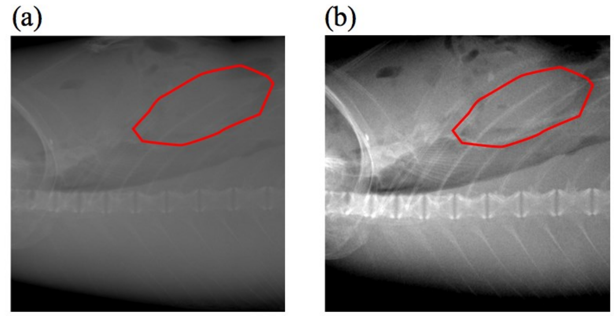

Figure 8. Appearance of the simulated tumor.(a) Original image and (b) processed image.The simulated tumor is in the ellipse region.

VI. Discussion

Methods for two-dimensional image processing have been studied in many fields. Those studies targeted noise reduction, signal detection or pattern recognition, and so on. In addition, many advanced techniques such as adaptive processing or learning processing have been developed [7]. In this study, the proposed method for improving signal detectability is a combination of subtraction processing and averaging processing. Processing of general X-ray images for observing overviews should consider medical constraints such as an unchanging observation width and medical practicality as the highest priorities. A previous study that proposed processing targeting of images has not confirmed that the observation width was unchanged. The concept of observing an entire object while enhancing signals has high novelty. In order to incorporate the processing into an actual system in a medical environment, real-time processing is recommended. The proposed method has high practicality because it can fulfill this condition.

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