Enhancement of positron emission tomography-computed tomography image quality using the principle of stochastic resonance

Anil Kumar Pandey, Sanjay Kumar Sharma, Punit Sharma, Harmandeep Singh, Chetan Patel, Kaushik Sarkar, Rakesh Kumar, Chandra Sekhar Bal

Department of Nuclear Medicine, All India Institute of Medical Sciences, New Delhi, 1Department of Electronics and Communication Engineering, Narula Institute of Technology, Agarpara, Kolkata, West Bengal, India

ABSTRACT

Purpose: Acquisition of higher counts improves visual perception of positron emission tomography-computed tomography (PET-CT) image. Larger radiopharmaceutical doses (implies more radiation dose) are administered to acquire this count in a short time period. However, diagnostic information does not increase after a certain threshold of counts. This study was conducted to develop a post processing method based on principle of “stochastic resonance” to improve visual perception of the PET-CT image having a required threshold counts. Materials and Methods: PET-CT images (JPEG file format) with low, medium, and high counts in the image were included in this study. The image was corrupted with the addition of Poisson noise. The amplitude of the Poisson noise was adjusted by dividing each pixel by a constant 1, 2, 4, 8, 16, and 32. The best amplitude of the noise that gave best images quality was selected based on high value of entropy of the output image, high value of structural similarity index and feature similarity index. Visual perception of the image was evaluated by two nuclear medicine physicians. Results: The variation in structural and feature similarity of the image was not appreciable visually, but statistically images deteriorated as the noise amplitude increases although maintaining structural (above 70%) and feature (above 80%) similarity of input images in all cases. We obtained the best image quality at noise amplitude “4” in which 88% structural and 95% feature similarity of the input images was retained. Conclusion: This method of stochastic resonance can be used to improve the visual perception of the PET-CT image. This can indirectly lead to reduction of radiation dose. Keywords: Image quality, positron emission tomography-computed tomography, Poisson noise, stochastic resonance

INTRODUCTION

In diagnostic nuclear medicine, different radiopharmaceuticals are administered to patients for imaging. These radiopharmaceuticals localize to a specific organ and emit gamma radiation. Since, this gamma radiation is potentially harmful to the body, it is essential that minimum (as low as reasonably achievable [ALARA]) radiopharmaceutical dose be administered. Another important requirement for a diagnostic radioisotope imaging is that the patient remains static during data acquisition. However, this requirement demands injection of relatively larger doses of radiopharmaceuticals, so that good counts are acquired in short acquisition time. It has been observed that after a certain threshold of acquired counts, even if we increase the counts in the image, the diagnostic information remains same; however, the image becomes visually more appealing. As most of the times, radioisotope imaging reports are based on visual analysis; high count image raises observer confidence, while interpreting the scan and is thus preferred. Unfortunately, the extra counts acquired after a certain threshold to obtain more visually appealing images is usually acquired at the cost of additional radiation burden to the patients. Many methods have been previously explored to reduce the administered radiopharmaceutical dose without losing the diagnostic information. These methods ranged from development of newer radiopharmaceuticals, development of image enhancement techniques, newer image reconstruction method, hardware development such as collimators for specific studies, sensitive electronic, time of flight acquisition, etc.

There are reports available in the literature that noise can play a constructive role in detecting weak periodic or aperiodic signals
by a mechanism known as “stochastic resonance.” Stochastic resonance is a statistical phenomenon where when noise is added to the original signal, it increases the probability of detection of the signal amplitude where the resonance occurs. This can be used to visualize the low amplitude signal embedded in noise. A study previously conducted at our center[3] explored the role of stochastic resonance in image enhancement. The authors generated noise based on the image itself and explored many methods to generate this noise such as the bit-slice plane, white random noise (not based on the information in the image) and using Poisson random variable. With all the methods, they showed the possibility of enhancement of the image quality and observed phenomenon of stochastic resonance. Recently, Gonzalez et al.[8] described a noise model to corrupt the image with Poisson noise generated on the basis on the image pixel values. This model of noise generation and its addition to the image for image enhancement have not been explored. If this method is effective, then it can serve as a basis for image processing and thereby indirectly reduce the dose of radiopharmaceutical administered (i.e. radiation burden). Furthermore, the low information density images can be processed by this technique and will make available feature in the image more obvious to the Nuclear Medicine physician. Therefore, in this study, we have investigated the effect of addition of image noise to the positron emission tomography-computed tomography (PET-CT) image itself as an image enhancement technique, once the image has achieved the minimum counts threshold.

MATERIALS AND METHODS

Image selection

Clinical PET-CT images of patients acquired on a dedicated PET-CT scanner (Biograph 2, Siemens, Erlangen, Germany) were included for evaluation. To simulate the routine clinical scenario, low, medium, and high count density images were included in this study. In the algorithm to calculate structural similarity index (SSIM) and feature similarity index (FSIM), entropy as an image quality quantitative index, we converted RGB data into gray scale that is from 0 to 255. At a scale of 0-255, we designated the low count density image as one in which mean pixel counts was <50, medium count density images in which mean pixel counts was from 51 to 150, and high count density image in which mean pixel count image was more than 150. Altogether, images of 15 patients (F-18 fluorodeoxyglucose PET-CT [n = 13] and F-18 fluoride PET-CT [n = 2]) were analyzed.

Image processing

The processing algorithm was implemented using matrix laboratory (matlab) R2013B (The MathWorks, Inc., Natick, Massachusetts, USA). We generated six different Poisson noise matrix (equal in image matrix sizes) having amplitude reduced by the factor 1, 2, 4, 8, 16, and 32 from the original given image. For each image, six noise matrices were added to the image matrix to produce six different resultant output image. For eight sample input images, 48 (8 × 6 = 48) output images were generated. These images were assessed for image quality quantitatively.

Generation of Poisson noise

The matlab function imnoise (‘Poisson’) was used to generate the Poisson noise.[9] The image processing toolbox uses function imnoise to corrupt an image with noise. It generates Poisson noise from the data instead of adding artificial noise to the data. Input pixel values were interpreted as mean of Poisson distributions and then the corresponding output pixel were generated from a Poisson distribution with mean as input pixel values. For accepting or rejecting the generated random number, the imnoise function was based on two criteria. First, where pixels intensities are <50 units, Monte-Carlo Rejection Method have been used.[3] Second, for pixel intensity ≥50, the Poisson probability distribution function becomes very similar to a Gaussian probability distribution function of mean and variance equals to the local pixel intensities.[8]

Quantitative assessment of image quality

Three well-known image quality assessment matrices namely SSIM,[7] FSIM[8] and Entropy[9] were used. SSIM is based on the assumption that human visual perception is highly adapted for extracting structural information from a scene and assesses the image quality based on the degradation of structural information. FSIM is based on the fact that human visual system understands an image mainly according to its low level features. Phase congruency (a measure of the significance of a local structure) is used as the primary feature and image gradient magnitude is the secondary feature in FSIM. SSIM and FSIM index were developed by Wang et al.[7] and Zhang et al.[8] respectively and they have also developed the matlab function to calculate these image quality metric and demonstrated the usefulness of these metric. The respective matlab functions and associated published articles are freely available for download and usage. We have downloaded and used to calculate SSIM and FSIM index. Entropy provides the measure of the information content, a measure of randomness in the image. More the value of entropy more is the randomness, which means more the uncertainty involved with the data of image and more information available in the image. If no uncertainty is associated with the event; no information would be transferred by communicating that the event has occurred.[9]

Qualitative assessment of image quality

Another set of 15 PET-CT images were processed using the six different generated Poisson noise matrix (equal in image matrix sizes) having amplitude reduced by the factor 1, 2, 4, 8, 16, and 32 from the original given image and given to nuclear medicine physician for qualitative evaluation. Two experienced nuclear medicine physicians evaluated the images in consensus. The physician evaluated the PET-CT images on two aspects. First, all images including the original image were randomly arranged and scored based on image quality. The score varied between 1 and 10, with 10 being the best image quality and one being the worst. Second, the reviewers were shown the processed image side by side the original image. The reviewers commented whether the processed images were superior (score 3) or same (score 2) or inferior (score 1) to original “unprocessed image”.
RESULT

Quantitative image quality assessment

The noisy image created using imnoise function was taken as the highest amplitude of the noise. The various grading of amplitude of noise were created by dividing each pixel value by $1, 2, 4, 8, 16,$ and $32$ to have six different amplitudes of noisy images. These were added to the image and the corresponding resultant images were subjected for analysis and the value of entropy, SSIM and FSIM were recorded.

The relationship among the SSIM index and noise amplitude is shown in Figure 1. It clearly demonstrates that SSIM index values increases with the increasing value of noise amplitude and attains a peak and then it starts decreasing. SSIM index attains maximum value at noise amplitude of “4”. At noise amplitude “4”, the SSIM index value is 0.88; meaning that structural similarity after processing the image by this method is 88% with the input image.

The relationship among the FSIM index and noise amplitude is shown in Figure 2. It is clear from the figure that, FSIM initially increases to the maximum value up to the noise amplitude of “4” and then decreases rapidly with further increase in the value of noise amplitude. Still at the value of noise amplitude “4”, the value of FSIM is more than 0.95, that is, after the addition of noise amplitude “4”, the resultant image is 95% similar to the input image as far as this feature is concerned.

The relationship among the Entropy and noise amplitude is shown in Figure 3. For all the eight images, the entropy of the processed image was more than that of the entropy of the input image even at the lowest value of noise amplitude. As the noise amplitude increases the value of the entropy increased for the entire image up to the noise amplitude of “4”. However, in some cases it increased while in few cases, it decreased. All the images showed similar characteristics.

In our study, the addition of noise improved the image quality on quantitative analysis. We found that the amplitude of the noise to be added has a great role to play. The optimum amount of noise, which will definitely improve the image, depends on the value of the count density available in the image. Higher count density images improved with the addition of the low amplitude noise and lower count density images improved with high amplitude noise. The output images retained structure and feature similarity of the input image.

The eight sample images that have maximum value of difference in entropy before and after processing, SSIM and FSIM are shown in Table 1. From Table 1, it is clear that the entropy of the resultant images was more than the original in seven out of eight images and SSIM and FSIM was above 0.84 in all eight images. This means that the noise matrix having amplitude value “4” is optimum because it improves the information content and simultaneously retains the structure and feature of the original image. These images are not only visually more appealing, but also do not deteriorate the original information of the image. It increases the information density content of all images without sacrificing the original structure in the input image. The value of SSIM, FSIM confirms the fact. The value of entropy confirms the information content has increased.
Qualitative image quality assessment

The scores of the original and processed PET-CT images are shown in Table 2. The scores of the different processed images were not much different. An important observation was that there was no deterioration in the image quality after addition of noise. The highest scores were seen for processed image 1 in Figure 4 and processed image 2 in Figure 5, even better than original images. The scores of the different processed images are shown in Table 3. All images had a score of 2 or more, thereby implying that the quality of images was either superior or same as that of the original image. The highest mean score was 2.6 (median score 3) for the processed image 1.

DISCUSSION

Given the possible long-term harmful effects of radiation, the minimum radiopharmaceutical dose (ALARA) should be administered to each patient. Diagnostic information does not improve after the acquisition of a certain threshold of counts; however, image becomes visually more appealing as counts in the image increases, and therefore is more preferred. The acquisition of extra count requires administration of higher radiopharmaceutical doses. This study was conducted to develop a postprocessing method to improve the visual perception of the image having required threshold counts. This will help in reduction of radiopharmaceutical dose as well as radiation dose to the patient. This will also reduce the public exposure because patient becomes unsealed source of radiation after administration of radiopharmaceuticals.

The image information is conveyed by a finite number of photons, these photons follows Poisson distribution in time and space and results in image graininess. Hence, it is important to guard against false alarms (spurious visual pattern that may arise from the random character of the photon distribution and not from the original content of radionuclide itself). The only way to guard against the false alarms is to increase the per pixel count in the images. In this study, we have increased the count per pixel in the PET-CT image by mathematical processing (adding Poisson noise corrupted image to the image itself). Since the two data sets happen to come from the same distribution function, the numerical value at any sample point would resonant (influence the intensity value of that pixel). It is obvious that this technique is different from multiplying each pixel value by a constant since there would be no such single constant common to all the sample points. The value by which each pixel is changed is derived from the inherent attribute of the underlying population. This technique was called “stochastic resonance” since it was taken from both stochastic process (Poisson process) and numerical resonance (under algebraic manipulation). The present technique is based on Stochastic resonance as we are utilizing the principle of stochastic resonance in which we are adding generated noise based on image data to the image itself. In this study, we found that the amplitude of noise has a major role to play. As the amplitude of noise increases, the image improves and after a certain threshold, the image starts deteriorating. In this respect, our result is similar to that reported by other investigators working on the principle of stochastic resonance. They also have observed that the amplitude of the noise is very important and they have adjusted this parameter in such a way that it improves signal to noise ratio. In the process of stochastic resonance the signal gets enhanced when noise was added to it, because resonance occurs at the matching frequency of noise and signal. Input pixel value are taken as mean of Poisson distribution for the noise to be generated. The generated noise pixel value will be comparable to the input pixel value and after addition to the input pixel value; some of the pixel value, which was already above the threshold may attain maximum intensity. And the pixel values, which were below the threshold, may cross the threshold. Since the gray scale value ranges from 0 to 255, so, with the addition of high amplitude noise, the maximum number of pixel may attain counts equal to 255, resulting in low information and the number of gray level in the input image will be reduced (low value of entropy). Similarly,
if the input image has good counts statistics then it will require the addition of low amplitude noise for better image quality.

Qinghua et al. [11] has shown an image enhancement method using stochastic resonance in sonar image processing. Their stochastic resonance model is based on overdamped motion of a Brownian particle in a bistable potential in the presence of noise and periodic forcing. They have shown an image of a rectangle imbedded in the very high noise and recovered that rectangle by adding Gaussian white noise. Similar model have been used by

---

**Figure 4:** An original low count positron emission tomography-computed tomography image along with six processed images with their mean score given by nuclear medicine physician, amplitude of noise added, structural similarity index, feature similarity index and entropy. Based on clinical judgment processed 1 image scored maximum and was superior than original.

**Figure 5:** An original high count positron emission tomography-computed tomography image along with six processed images with their mean score given by nuclear medicine physician, amplitude of noise added, structural similarity index, feature similarity index and entropy. Based on clinical judgment processed 2 image scored maximum and was superior than original.
other authors\(^[12]\) in the enhancement of computed tomography and magnetic resonance images. Simonotto \( et \ al.\)^\([13]\) have also shown an image enhancement technique using stochastic resonance. They had added Gaussian noise with zero mean and standard deviation equal to the pixel value in the image for improving image quality.

In this study, we have added Poisson noise corrupted image to the image data. Here, it adds Poisson random variable (noise pixel value) proportional to the pixel value to every pixel value, and increases maxima and minima point both proportional to the pixel value in the image data, so the each pixel values are scaled by random number as if the patient had activity and the time period of data acquisition would have more. This study was conducted on patient PET-CT images and is unique in this regard. Processing by this method improves the image quality of both low as well as high count images. We found that processing by this method does not alter the image quality much. Although it may not improve the image quality for visual analysis, there is definitely no deterioration of image quality.

We have not included phantom images in this study. In phantom study, it is possible to embed weak signal in noise and enhancement of that weak signal also needs to be verified with this technique. However, our objective was to make the information available in the image more obvious to the Nuclear Medicine physician reporting the PET-CT. Detection of weak signal embedded in the noise have been shown by using stochastic resonance model as bistable potential well and adding white noise Gaussian noise with mean zero.\(^[11,12]\)

In this study, it has been investigated on the PET-CT images where generally we have good counts images, even though in this study, we have selected only those images where the reader confidence was low at the time of reporting the scan. Our future plan is to apply the same technique on very low count density images such as I-131 whole body imaging or 131 I-metaiodobenzylguanidine imaging, etc., where low count is the norm.

**CONCLUSION**

This method of stochastic resonance can be used to improve the visual perception of the PET-CT image. This can indirectly lead to reduction of radiation dose.

**REFERENCES**

1. Rose A. Vision Human and Electronics, the Visual Process. New York, London: Plenum Press; 1974. p. 1-28.
2. Wiesenfeld K, Moss F. Stochastic resonance and the benefits of noise: From ice ages to crayfish and SQUIDs. Nature 1995;373:33-6.
3. Pandey AK. Image processing in nuclear medicine: Role of filters and stochastic resonance. Ph. D Thesis. New Delhi: All India Institute of Nuclear Medicine; 2000.
4. Gonzalez RF, Woods RE, Eddins SL. Image restoration and reconstruction. Digital Image Processing Using MATLAB. New Delhi: Tata McGraw Hill Education Pvt. Ltd.; 2011. p. 163-231.
5. Press WH, Teukolsky SA, Vetterling WT, Flannery BP. Numerical Recipes in C, Random Numbers. 2nd ed. New Delhi: Cambridge University Press; 1992.
6. Mathews J, Walker RL. Mathematical Methods of Physics. 2nd ed. Reading, MA: Addison Wesley; 1971.
7. Zhang L, Mou X, Zhang D. FSIM: A feature similarity index for image quality assessment. IEEE Trans Image Process 2004;13:600-12.
8. Zhang L, Mou X, Zhang D. FSIM: A feature similarity index for image quality assessment. IEEE Trans Image Process 2011;20:2378-86.
9. Gonzalez RF, Woods RE, Eddins SL. Image compression. Digital Image Processing using MATLAB Low Price ed. New Delhi: Pearson Education; 2005.
10. Adair RK. Didactic discussion of stochastic resonance effects and weak signals. Bioelectromagnetics 1996;17:242-5.
11. Qinghua YE, Huang H, Zhang C. Image enhancement using stochastic resonance. Available from: http://www/image2003.com available as on 16 Feb 2014.
12. Rallabandi VP, Roy PK. Stochastic resonance-based tomographic transform for computed tomographic image enhancement of brain lesions. J Comput Assist Tomogr 2008;32:966-74.
13. Simonotto E, Riani M, Scife C, Roberts M, Twitty J, Moss F. Visual perception of stochastic resonance. Phys Rev Lett 1997;78:10.

How to cite this article: Pandey AK, Sharma SK, Sharma P, Singh H, Patel C, Sarkar K, et al. Enhancement of positron emission tomography-computed tomography image quality using the principle of stochastic resonance. Indian J Nucl Med 2014;29:235-40.

Source of Support: Nil. Conflict of Interest: None declared.