Development and Validation of the Suprathreshold Stochastic Resonance-Based Image Processing Method for the Detection of Abdomino-pelvic Tumor on PET/CT Scans

Abstract

Purpose: The detection of abdomino-pelvic tumors embedded in or nearby radioactive urine containing 18F-FDG activity is a challenging task on PET/CT scan. In this study, we propose and validate the suprathreshold stochastic resonance-based image processing method for the detection of these tumors. Methods: The method consists of the addition of noise to the input image, and then thresholding it that creates one frame of intermediate image. One hundred such frames were generated and averaged to get the final image. The method was implemented using MATLAB R2013b on a personal computer. Noisy image was generated using random Poisson variates corresponding to each pixel of the input image. In order to verify the method, 30 sets of pre-diuretic and its corresponding post-diuretic PET/CT scan images (25 tumor images and 5 control images with no tumor) were included. For each sets of pre-diuretic image (input image), 26 images (at threshold values equal to mean counts multiplied by a constant factor ranging from 1.0 to 2.6 with increment step of 0.1) were created and visually inspected, and the image that most closely matched with the gold standard (corresponding post-diuretic image) was selected as the final output image. These images were further evaluated by two nuclear medicine physicians. Results: In 22 out of 25 images, tumor was successfully detected. In five control images, no false positives were reported. Thus, the empirical probability of detection of abdomino-pelvic tumors evaluates to 0.88. Conclusion: The proposed method was able to detect abdomino-pelvic tumors on pre-diuretic PET/CT scan with a high probability of success and no false positives.

Keywords: Abdomo-pelvic tumor, image processing, pelvic PET/CT, suprathreshold stochastic resonance

Introduction

Diagnostic imaging modalities such as ultrasonography, computed tomography, and magnetic resonance imaging can visualize the presence and location of tumors but do not provide its metabolic status and hence, patients are referred for PET/CT scans.

18F-FDG uptake in tumor is more in comparison to normal tissue that makes tumor appear bright on PET/CT scans and thus visually differentiated. Biological elimination of 18F-FDG is mostly through urinary excretion. Hence, urinary bladder contains excreted 18F-FDG, which also appears brighter. Therefore, in most PET/CT scans, the tumor inside or near the urinary bladder can be difficult to visually differentiate. Nuclear medicine physicians are aware of the location of the abnormal mass in abdomino-pelvic area from other diagnostic modalities; therefore, post-diuretic interventions are performed in such patients.

In routine practice, diuretics are administered to flush out the urine containing 18F-FDG, and a post-diuretic PET/CT scan of pelvic region is acquired. Tumor becomes visible (if present) on post-diuretic PET/CT scan.[1-4] However, this technique has a few drawbacks as diuretics causes some potential side effects such as frequent urination lasting for several hours, tiredness, restlessness, muscle cramps, dehydration, nausea, vomiting, skin rash, blurred vision, confusion, headache, increased perspiration (sweating), etc.[5] Apart from this, their use may be contraindicated in some patients,
e.g., in patients with electrolytic abnormalities. Also, post-diuretic studies require a repeat CT scan that gives further additional radiation exposure to patients.

In this study, we propose a suprathreshold stochastic resonance (SSR)-based image processing method for detection of abdomino-pelvic tumor on PET/CT scans. The proposed method is also validated with sample data.

**Methods**

**Stochastic Resonance (SR) and its variant-suprathreshold stochastic resonance**

The concept of stochastic resonance (SR) was first put forward by Benzi *et al.* in 1981.[6] SR is a phenomenon wherein a weak signal gets detected when white noise is added to it. The frequencies in the white noise corresponding to the signal resonate and amplify the original signal and lead to the detection of the signal.

The study of SR in a threshold-based system has received considerable attention. The SSR was first demonstrated in arrays of identical threshold devices in 2000.[7] The most studied model for SSR is the network shown in Figure 1. It consists of *N* identical threshold devices (i.e., single bit quantizers), each operating on a common signal *x* subject to independent additive noise. The overall output *y* is the sum of the *N* noisy binary outputs and is an integer between zero and *N*. The fidelity with which *y* can represent *x* is dependent on noise distribution, the signal distribution, the input signal-to-noise-ratio, *N*, and the threshold level. Performance depends on the conditional distribution of *y* given *x*.

The model of SSR shown in Figure 1 has been used in this study. In present case, the signal is the intensity value of the pixel in image that can be represented by *f*(*x*, *y*). There were one hundred identical threshold values (*N* = 100, all operated on mean pixel intensity value multiplied by a *constant factor*), each operating on a common signal *f*(*x*, *y*) subject to independent additive noise. The output image *g*(*x*, *y*) is the binary image that is the averaged output of the image obtained after thresholding.

Considering the image to be a set of random variables, the noisy image frames were generated using random variates from a Poisson distribution *P*(λ), where λ = the corresponding pixel value in the pre-diuretic PET/CT scan image.

The one-dimensional model shown in Figure 1 was extended for the image to two dimensional.

**The proposed method**

The method consists of following seven steps.

1. Read a pre-diuretic PET/CT image, convert it into a gray-scale image, and then convert the gray-scale image data into double,

   Denote a pre-diuretic PET/CT image = *f*(*x*, *y*)

2. Generate a noisy image whose size is equal to a pre-diuretic PET/CT image. As follows:

   The pixel value of the new image = *P*(λ), the Poisson variate, where λ = the corresponding pixel value of pre-diuretic PET/CT image, since the mean rate of arrival of photons at this image point is the observed intensity,

   Denote, noisy image = η(*x*, *y*)

3. Add the pre-diuretic PET/CT image and noisy image,

   *g*(*x*, *y*) = *f*(*x*, *y*) + η(*x*, *y*)

   And store *g*(*x*, *y*).

4. Calculate the mean counts in the image *g*(*x*, *y*), multiply this mean count with the *constant factor* ranging from 1.0 to 2.6, and consider the resulting value as threshold. Apply this threshold value on the image *g*(*x*, *y*). This image will be the first frame of the output image, denoted by *I*$_1$.

5. Repeat the steps 2-4, one hundred times, i.e., generate *I*$_2$, *I*$_3$, *I*$_4$,..., *I*$_{100}$.

6. Sum all the one hundred images generated in step 5 as,

   $I = \sum_{i=1}^{100} I_i$, where sum is done pixel wise,

   Divide the image matrix *I* by 100,

   Label the resultant image as the final SSR-processed pre-diuretic PET/CT image.

7. Save the final SSR-processed pre-diuretic PET/CT image for the further analysis.

The method was implemented using MATLAB R2013b (The Math Works, Inc. 3 Apple Hill Drive Natick, MA 01760-2098) on a personal computer. A total of 30 sets of pre- and their corresponding post-diuretic PET/CT
images (total 60 images) of 30 individual patients who had undergone PET/CT scans for suspected abdominopelvic tumors were used in the study. Out of these 30 sets of images, 5 sets of images in which no tumor was visible on post-diuretic images were taken as the control. The post-diuretic images were taken as the gold standard to compare the corresponding SSR-processed pre-diuretic PET/CT image.

During initial experimentation, we found the threshold value greater than mean counts that visualize the embedded tumor and also a different threshold for every input image. Therefore, we decided to vary the constant factor (to be multiplied with mean counts that result in threshold value) for input images from 1.0 to 2.6 incremented with each step by 0.1.

For each pre-diuretic PET/CT image, 17 SSR-processed pre-diuretic PET/CT images were created and inspected for the visualization of tumor, and the SSR-processed pre-diuretic PET/CT image that most closely matched with the gold standard (post-diuretic scan) was selected. In this way, 510 (17 × 30 = 510) SSR-processed pre-diuretic PET/CT images were reviewed. The SSR-processed pre-diuretic PET/CT images were further evaluated by two nuclear medicine physicians. Although the goal of the processing method was only to detect the tumor on the pre-diuretic image, the image review criteria also included commenting upon various other image quality attributes that formed areas to the further research regarding improvements that can be made in the image quality. The criteria for evaluating the images were:

Figure 2: Constant factor for each image set a threshold value for images (by image number). There is no unique threshold value. In fact, it is the constant factor multiplied to mean count that resulted in a threshold value.

Figure 3: Histogram of the constant factors. Constant factor “2” has maximum frequency.

Figure 4: Constant factors and its effect on the visualization of tumor. (a) Tumor is embedded in bladder urine, (b) tumor is not visible till constant factor 1.6, (c) tumor and bladder are visible at constant factor 1.7, (d) after raising constant factor more, i.e., 1.8, bladder is better suppressed in comparison to (c), (e) After further raising constant factor, tumor is visualized. (f) Afterwards tumor is disappeared or very faintly few dots are visible.

Figure 5: Pre-diuretic image, its SSR-processed image using the proposed method, and post-diuretic image. Tumor detected in the SSR-processed pre-diuretic image at the position corresponding to the tumor present in the post-diuretic image is shown.
pre-diuretic images detected the tumor in accordance with their gold standard post-diuretic images, and out of 25 pre-diuretic PET/CT tumor images, the proposed method detected tumor on 22 pre-diuretic PET/CT images (empirical probability for the detection of tumor is therefore equal to 0.88). In all five control pre-diuretic PET/CT images, no false-positive result was reported. The tumor on the SSR-processed pre-diuretic PET/CT got visualized at the constant factor that ranged from 1.2 to 2.2 [Table 1]. Table 1 lists the value of the constant factor for each 30 pre-diuretic images. Image numbers 26-30 are the control images in which there were no tumors present in their corresponding post-diuretic image.

It is obvious from Table 1 and Figure 2 that there is no unique threshold value. In fact, it is the constant factor multiplied to the mean count that resulted in the threshold value and this threshold value at which tumor becomes visible in the output image is a function of input image data itself. Figure 2 represents graphically how the threshold value varied with the pre-diuretic PET/CT image. The histogram of the constant factors shows that the maximum number of images in which the SSR-processed pre-diuretic image was in accordance with their gold standard in the range 1.6-2 [Figure 3].

Results

Out of total 30 pre-diuretic PET/CT images (including both 25 tumor image and 5 control images), 27 SSR-processed pre-diuretic images detected the tumor in accordance with their gold standard post-diuretic images, and out of 25 pre-diuretic PET/CT tumor images, the proposed method detected tumor on 22 pre-diuretic PET/CT images (empirical probability for the detection of tumor is therefore equal to 0.88). In all five control pre-diuretic PET/CT images, no false-positive result was reported.

The tumor on the SSR-processed pre-diuretic PET/CT got visualized at the constant factor that ranged from 1.2 to 2.2 [Table 1]. Table 1 lists the value of the constant factor for each 30 pre-diuretic images. Image numbers 26-30 are the control images in which there were no tumors present in their corresponding post-diuretic image.

Figure 6: Tumor nearby the bladder visualized in the SSR-processed image. Set of two image (1st row and 2nd row). Representative images (pre-diuretic, its SSR processed and post-diuretic) showing the detected tumor in concordance with POST-DIURETIC

Figure 7: Another two sets of PET/CT image in which the presence of the tumor was detected by the proposed method

a. the tumor is visible on the pre-diuretic-processed image,
b. tumor delineation on the pre-diuretic-processed image,
c. heterogeneity in the tumor comparable to the post-diuretic image, and
d. image contrast on the pre-diuretic-processed image.

The nuclear medicine physicians were provided three images namely the pre-diuretic image, its SSR-processed pre-diuretic image, and its corresponding post-diuretic image. Their responses were recorded and analyzed.

Figure 8: A false negative result in which tumor was present, but it was not detected by the proposed SSR method

Figure 9: Control image and the SSR-processed image showing that no false positive result is produced by the proposed method

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Figure 4 shows how the proposed method transforms the input pre-diuretic PET/CT image when the constant factor
Pandey et al.: SSR-based image processing method

in five control images. The principle of SR has been used in many areas such as general photographic image processing including the medical imaging, signal detection, and medicine.[8-14] SSR has already been used in image processing.[15] However, none of the above cited studies has addressed the issue of the detection of abdomino-pelvic tumor on whole body PET/CT images. In this way, the current study explores a new possibility. The detection of tumor in the pre-diuretic images has not been addressed using the digital image processing method earlier, and hence the result of current study cannot be compared to other methods.

The output result of the proposed method was found to be dependent on the constant factor multiplied with the mean count (threshold value) changes. Figure 5 shows the input pre-diuretic PET/CT image, its SSR-processed, and its corresponding post-diuretic image. Figure 4 and Figure 5 visually demonstrate that the proposed method was successful in making the tumor visible on the pre-diuretic PET/CT image.

The result of evaluation of SSR-processed pre-diuretic PET/CT images by the two nuclear medicine physicians is given in Table 2. Both physicians detected the presence of tumor in 22 PET/CT images out of 25 PET/CT images having tumor present in the post-diuretic image. Besides this, they found good contrast between tumor and background in 17 images, average contrast in 4 images, and poor contrast in 1 image. Tumor delineation was good in 16 images, and in 6 images the size of the tumor was over estimated. In five control images, no false positive results were noted; however, in three images they have noticed the enhanced bladder wall.

Tumor uptake was made visible by the proposed method [Figure 6] and [Figure 7] that can be confirmed with the post-diuretic image. Figure 8 shows a false negative result. Tumor was present as can be seen in the post-diuretic image; however, it was not detected by the proposed method. None of the constant factor in the selected range of 1.0-2.6 was helpful in the visualization of tumor. Figure 9 shows a control image of the patient having no tumor in post-diuretic pelvic PET/CT scan. The processed pre-diuretic PET/CT image by the proposed method has the similar information, i.e., no tumor detected (no false-positive).

Discussion

In this study, we proposed and validated an image processing method based on the principle of SSR that helps in the detection of abdomino-pelvic tumors on whole body PET/CT scans.

The empirical probability of detection of tumor using this method computes to 0.88 on a sample of size 25 tumor images, and no false positive results were observed in five control images. The principle of SR has been used in many areas such as general photographic image processing including the medical imaging, signal detection, and medicine.[8-14] SSR has already been used in image processing.[15] However, none of the above cited studies has addressed the issue of the detection of abdomino-pelvic tumor on whole body PET/CT images. In this way, the current study explores a new possibility. The detection of tumor in the pre-diuretic images has not been addressed using the digital image processing method earlier, and hence the result of current study cannot be compared to other methods.

The output result of the proposed method was found to be dependent on the constant factor multiplied with the mean count, i.e., the threshold value. In this respect, the result of current study is in agreement of the other authors working on the principle of SSR.[6]

The proposed method succeeds in the detection of the tumor on pre-diuretics PET/CT scans images, though the image quality is below that expected by nuclear medicine physicians. This is so because the method produces a binary image. The goal of the study was only the detection of tumor if present, in the pre-diuretic PET/CT image. Nuclear medicine physicians would also look for the heterogeneity of the tumor, delineation of the tumor, and overall contrast between the tumor and another structure as present in the post-diuretic image (gold standard). This as a value addition will be the next goal and the work will be continued further.

The present study focused on demonstrating the use of SSR technique and chose the best threshold by trial and error. Automatic selection of the appropriate threshold would be necessary to make the technique practically usable. This would require further experimentation, and another study needs to be conducted in future to pursue this goal. This method can also be used to visualize the structure that might be embedded in high background activity, or a structure that might be rather close to

| Image set no. | Constant factor multiplied to mean counts | Image set no. | Constant factor multiplied to mean counts | Image set no. | Constant factor multiplied to mean counts |
|---------------|------------------------------------------|---------------|------------------------------------------|---------------|------------------------------------------|
| 1             | 1.8                                      | 11            | 1.9                                      | 21            | 1.6                                      |
| 2             | 1.9                                      | 12            | 2.2                                      | 22            | 2.0                                      |
| 3             | 1.8                                      | 13            | 2.0                                      | 23            | 1.9                                      |
| 4             | 1.7                                      | 14            | 2.0                                      | 24            | 1.8                                      |
| 5             | 1.4                                      | 15            | 2.1                                      | 25            | 1.8                                      |
| 6             | 1.3                                      | 16            | 1.7                                      | 26 control image | 1.9          |
| 7             | 1.2                                      | 17            | 1.6                                      | 27 control image | 1.6          |
| 8             | 1.4                                      | 18            | 2.0                                      | 28 control image | 1.6          |
| 9             | 2.0                                      | 19            | 1.6                                      | 29 control image | 1.9          |
| 10            | 1.9                                      | 20            | 1.5                                      | 30 control image | 2.1          |

Thirty pre-diuretic PET/CT images and the constant factor multiplied to the mean counts (threshold value) are shown. These constant factors resulted in the SSR-processed pre-diuretic PET/CT image that most closely matched with their gold standard.
In cases wherein due to any reason diuretics cannot be administered, the method even in its present form can be utilized to experiment with various thresholds and choose appropriate visualization.

**Conclusion**

The proposed method was able to detect abdomino-pelvic tumors on pre-diuretic PET/CT scan with a high empirical probability of success and with no false positives. This method can also be used to visualize the structure that might be embedded in high background activity, or a structure that might be rather close to another high uptake organ. In cases wherein due to any reason diuretics cannot be administered, the method even in its present form can be utilized to experiment with various thresholds and choose appropriate visualization.

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**Conflicts of interest**

There are no conflicts of interest

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| Image set | Tumor detected | Heterogeneity | Contrast | Delineation |
|-----------|---------------|---------------|----------|-------------|
| 1         | Yes           | Not Reflected | Good     | Good        |
| 2         | Yes           | Not Reflected | Poor     | Over-estimated the area |
| 3         | Yes           | Reflected     | Average  | Mild over estimation (Bladder wall added) |
| 4         | Yes           | Reflected     | Average  | Good        |
| 5         | Yes           | Reflected     | Good     | Mild overestimation |
| 6         | Yes           | Cannot commented due to change in UB shape in post-diuretic view | Good | Good but bladder wall shown |
| 7         | Yes           | Cannot commented | Good     | Good but over estimation due to bladder wall added |
| 8         | Yes           | Reflected     | Good     | Over estimation |
| 9         | Yes           | Reflected     | Average  | Good concordance |
| 10        | Yes           | Bad           | Good     | Extreme overestimation |
| 11        | Yes           | Reflected     | Average  | Mild overestimation |
| 12        | Yes           | Reflected     | Good     | Good but bladder wall seen |
| 13        | No            | –             | –        | –           |
| 14        | Yes           | Bad           | Good     | Good        |
| 15        | Yes           | Not reflected | Good     | Good        |
| 16        | Yes           | Not reflected | Good     | Good        |
| 17        | Yes           | Not reflected | Good     | Good        |
| 18        | Yes           | Not reflected | Good     | Good        |
| 19        | Yes           | Reflected     | Good     | Good but bladder activity seen |
| 20        | Yes           | Not Reflected | Good     | Good        |
| 21        | Yes           | Reflected     | Good     | Good        |
| 22        | Yes           | Reflected     | Good     | Good        |
| 23        | No            | –             | –        | –           |
| 24        | No            | –             | –        | –           |
| 25        | Yes           | Bad           | Good     | Good        |
| 26        | No            | –             | –        | –           |
| 27        | No            | –             | –        | –           |
| 28        | No            | –             | –        | –           |
| 29        | No            | –             | –        | –           |
| 30        | No            | –             | –        | –           |

Control images

The result of evaluation of SSR-processed pre-diuretic PET/CT images by two nuclear medicine physicians is shown. From Image set 1-25 had tumors, and Image set 26-30 were the control images in which there were no tumors.
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