Alternative methods for evaluation of non-uniformity in nuclear medicine images

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INTRODUCTION

Visual inspection is the prime method in perceiving the existence of non-uniformity in a flood nuclear medicine image(¹). However, for quantitative evaluation mathematical method has been proposed(², ³). Usually the pixels with maximum and minimum counts are determined and the ratio of difference, accepted by sum of the counts, is defined as non-uniformity. This calculation is either performed for the field of view as whole (integral uniformity) or individual parts of the field separately (differential uniformity). In either case, the calculation is merely based on two pixel-values and cannot fully quantify the extent of non-uniformity in the image. Besides, this definition does not distinguish between inherent noise and occasional non-uniformity. This has caused great difficulties in calculation of non-uniformity in low-counts image or large matrix size(⁴, ⁵). In this study, two hypothetical methods for quantitative evaluation of non-uniformity in nuclear medicine images were introduced and examined.

MATERIALS AND METHODS

Statistical analysis

Statistically speaking, pixel counts in a uniform flood image may be considered as a set of random values, since that is due to several physical phenomena involved in the formation of the image. Each phenomenon has its own probability distribution, mainly of Poisson type. Based on the central limit theorem the overall distribution tends toward the Gaussian one. However the main characteristic of Poisson distribution (variance=mean) remains almost valid for the overall distribution.

Keywords: SPECT, quality control, uniformity image, simulation, fast fourier transformation, Kolmogorov-Smirnov test.

Background: Non-uniformity test is the most essential in daily quality control procedures of nuclear medicine equipments. However, the calculation of non-uniformity is hindered due to high level of noise in nuclear medicine data. Non-uniformity may be considered as a type of systematic error while noise is certainly a random error. The present methods of uniformity evaluation are not able to distinguish between systematic and random error and therefore produce incorrect results when noise is significant. In the present study, two hypothetical methods have been tested for evaluation of non-uniformity in nuclear medicine images. Materials and Methods: Using the Monte Carlo method, uniform and non-uniform flood images of different matrix sizes and different counts were generated. The uniformity of the images was calculated using the conventional method and proposed methods. The results were compared with the known non-uniformity data of simulated images. Results: It was observed that the value of integral uniformity never went below the recommended values except in small matrix size of high counts (more than 80 millions counts). The differential uniformity was quite insensitive to the degree of non-uniformity in large matrix size. Matrix size of 64x64 was only found to be suitable for the calculation of differential uniformity. It was observed that in uniform images, a small amount of non-uniformity changes the p-value of Kolmogorov-Smirnov test and noise amplitude of fast fourier transformation (FFT) test significantly while the conventional methods failed to detect the non-uniformity. Conclusion: The conventional methods do not distinguish noise, which is always present in the data and occasional non-uniformity at low count density. In a uniform intact flood image, the difference between maximum and minimum pixel count (the value of integral uniformity) is much more than the recommended values for non-uniformity. After filtration of image, this difference decreases, but remains high. Both proposed methods were more sensitive to the non-uniformity at a much lower count density. Iran. J. Radiat. Res., 2005; 3 (2): 89-94

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According to this assumption, in the absence of non-uniformity, pixel values in a uniform flood image follow a Gaussian distribution of known mean and variance (average pixel count). We further assumed that significant non-uniformity in the image significantly deviate the distribution from Gaussian. Kolmogorov-Smirnov test was examined as a possible mean to measure non-uniformity of flood images.

**Fourier analysis**

A uniform flood image is composed of two components: a constant mean counts in all pixels and noise that randomly and independently changes the pixel values around the mean. Fourier spectrum of such flood image is composed of very high amplitude at zero frequency reflecting the average count and small amplitudes at all other frequencies (reflecting the random noise).

Noise in nuclear medicine is quite a random process; therefore, no frequency component of the noise outweighs. It can be assumed that the frequency amplitudes of the noise are also random variables having a probability distribution (certainly not a Gaussian). We further assumed that significant non-uniformity in a flood image, significantly increases the amplitude of the noise at some related frequencies. In order to verify this hypothesis, the highest frequency amplitude of the noise was compared to the average amplitudes.

**Simulation**

Using the Monte Carlo method, uniform flood images of different matrix size (64×64, 128×128,...,1024×1024) and counts (5, 10, 15,...,200 millions) of Gaussian distribution (P-value>%99) were generated. To simulate the non-uniformity, the following two-dimensional sinusoidal function was used.

\[ NU(i, j) = D \times 0.5 \times (\sin(\frac{n \pi i}{m}) + \sin(\frac{n \pi j}{m})) \]

Where \( m \) is the matrix size, \( i \) and \( j \) are the pixel numbers. The \( n \) in this equation determines the extent of non-uniformity. The values from 11 to 20 were measure to simulate different forms of uniformities. The "D" in this equation reflects the degrees of non-uniformity in the image (representing the integral uniformity in matrix size 64×64 and total counts of 200 millions). The values obtained from this equation, were scaled (multiplied by the average count in the image) and were added to the uniform image\(^5\).

A total number of 2640 realizations of flood images were simulated which represented 6 matrix size, 40 counts, and 11 degree of non-uniformity. For each image the integral uniformity, differential uniformity, Kolmogorov-Smirnov statistics (P-value, critical value, criterion), and the ratio of maximum noise amplitude to the average amplitude of noise were calculated. A software package in visual BASIC 6.0 was developed to perform all the necessary operations. The results were saved in binary format and later processed using Microsoft Excel software. All the above-mentioned procedures were repeated 5 times based on the report of Tenhunen and colleagues in 1998\(^6\).

**RESULTS**

**Integral uniformity**

Simulation study showed that the value of this parameter besides the uniformity was exponentially dependent on total counts and matrix size. In large matrix size, the count dependency is very high due to poor statistics and high noise level. In a uniform image of 1024×1024- matrix size even at total count of 200 million, the value of this parameter does not go below 13%. Only in a uniform image of 64×64- matrix size, the value may go below 1% if the total count is more than 80 millions. Figure 1 shows the value of integral uniformity for matrix 64×64 with 20-200 million counts.

Based on this simulation study, the preferable matrix sizes for calculation of integral uniformity is 64×64 and minimum counts required was 80 millions. Increasing the count up to 200 millions just improve the results by less than 0.3%. No significant differences were observed in behavior of this parameter in simulation study and real phantom study. In figure 2 the comparison of integral uniformity for different matrix sizes with 20-200 million counts are shown.
**Evaluation of non-uniformity in nuclear medicine images**

**Differential uniformity**

The values of this parameter are always less than the values of integral uniformity in similar conditions. However, it becomes quite insensitive to the degree of non-uniformity in large matrix size. Only matrix size of 64×64 is suitable for calculation of differential uniformity. No significant differences were observed in the behavior of this parameter in simulation study and real phantom study.

**Kolmogorov-Smirnov test**

The uniform simulated image had perfect Gaussian distribution (p-value >0.97). It was observed that in such condition a small amount of non-uniformity changes the p-value significantly specially in small matrix size where 0.3% non-uniformity at counts of more than 100 millions makes the p-values almost zero. However is big matrix size the sensitivity to non-uniformity decreases but...
remains acceptable if the total count is more than 100 millions. Figure 3 shows the value of Kolmogorov-Smirnov test for matrix 64×64 with 20-200 million counts.

In real phantom study, it was not possible to get uniform image of acceptable Gaussian distribution. The p-value for the 64×64-matrix size was 0.82 to 0.95. The p-value for 128×128-matrix size was 0.67 to 0.86. For the bigger matrix size the p-value was quite negligible. This implies that the count distribution in nuclear medicine flood image is not exactly Gaussian. As mentioned earlier, the test was quite sensitive to the non-uniformity in the simulated study. The failure in real images was probably due to significant non-uniformity in the apparently uniform image.

**FFT test**

This parameter has the opposite behavior compared to the other. In small matrix size at all counts, it can reflect the non-uniformity irrespective to the degrees of non-uniformity.
At larger matrix size the absolute value of this parameter increases and it can reflect the degree of non-uniformity if it is not high. In simulated images, this parameter could perfectly reflect the non-uniformity even at very low counts.

In real studies this parameter was significantly count dependent. In figures 4 and 5 the value of fast fourier transformation for matrix 64×64 and 1024×1024 with 20-200 million counts are illustrated. In figure 6 fast fourier transformation for different matrix size with 20-200 million counts are compared.

**DISCUSSION**

The present method of uniformity calculation does not distinguish between
noise, which is always present in the data, and occasional uncertainty. The standard procedure requires the image to be filtered before calculation in order to minimize the noise\textsuperscript{(2, 3)}. However, the recommended filter does not remove the noise perfectly. Our simulation study showed that the filter drops the standard deviation of noise to 0.375 of initial values irrespective to the matrix size and average count. Similarly, integral and differential uniformities fall to almost the same level on the average (0.372±0.022 of initial values in our simulations).

Based on the simulation results, it is almost impossible to reach the recommended value of 1\% for uniformity in matrix size bigger than 64×64 due to random variation. Practically all QC software calculates the uniformity in 64×64 matrix though physicists usually acquire image of larger matrix size in seeking better resolution\textsuperscript{(7)}.

It should also be considered that the filter has a similar effect on non-uniformity. Filtration lowers the noise level and at the same time lowers the amplitude of non-uniformity. In other words, the suggested filter lowers the non-uniformity significantly and the calculated value is always less than the real value of non-uniformity.

A simple protocol for flood imaging is to put a point source in front of collimator at a distance longer than 5 times the crystal diameter. In such condition, the count density in the periphery of the image is almost 1\% less than the center, hence 1\% inherent non-uniformity\textsuperscript{(8)}. In double and three head cameras where it is not usually possible to put the source at large distances, curvature correction is required before calculation that causes increasing this type of error.

From the statistics, both integral and differential uniformities are simply the range of the count distribution. These parameters are calculated from the two most apart values and do not reflect anything in between. A nuclear medicine image may have up to one million pixels. Range is the simplest and most primitive measure of dispersion with very limited application.

Noise creates statistical variation (random error) in a flood image but non-uniformity does not have statistical nature and may be considered as a type of systemic error. A good method for evaluation of non-uniformity should not be sensitive to the statistical variation.

In conclusion, two methods used in this study were found potentially useful for evaluation of non-uniformity in flood images. Both methods were successful in detecting the non-uniformity at a much lower count density.

REFERENCES