NSECT Sinogram Sampling Optimization by Normalized Mutual Information

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ABSTRACT

Neutron Stimulated Emission Computed Tomography (NSECT) is an emerging noninvasive imaging technique that measures the distribution of isotopes from biological tissue using fast-neutron inelastic scattering reaction. As a high-energy neutron beam illuminates the sample, the excited nuclei emit gamma rays whose energies are unique to the emitting nuclei. Tomographic images of each element in the spectrum can then be reconstructed to represent the spatial distribution of elements within the sample using a first generation tomographic scan. NSECT's high radiation dose deposition, however, requires a sampling strategy that can yield maximum image quality under a reasonable radiation dose. In this work, we introduce an NSECT sinogram sampling technique based on the Normalized Mutual Information (NMI) of the reconstructed images. By applying the Radon Transform on the ground-truth image obtained from a carbon-based synthetic phantom, different NSECT sinogram configurations were simulated and compared by using the NMI as a similarity measure. The proposed methodology was also applied on NSECT images acquired using MCNP5 Monte Carlo simulations of the same phantom to validate our strategy. Results show that NMI can be used to robustly predict the quality of the reconstructed NSECT images, leading to an optimal NSECT acquisition and a minimal absorbed dose by the patient.

Keywords: Neutron stimulated emission computed tomography, mutual information, MCNP5, radon transform, image reconstruction

1. DESCRIPTION OF PURPOSE

In this study, a novel approach based on Normalized Mutual Information (NMI) is developed to optimize Neutron Stimulated Emission Computed Tomography (NSECT) sampling parameters by using carbon (^{12}C) image reconstructions. Since effective dose and NSECT image quality is directly influenced by the sinogram sampling strategy, it becomes critical that diagnostic NSECT imaging protocol must be optimized to provide maximum image quality under reasonable absorbed dose.

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Medical Imaging 2015: Physics of Medical Imaging, edited by Christoph Hoeschen, Despina Kontos,
Proc. of SPIE Vol. 9412, 94122B · © 2015 SPIE · CCC code: 1605-7422/15/$18 · doi: 10.1117/12.2082496

2. INTRODUCTION

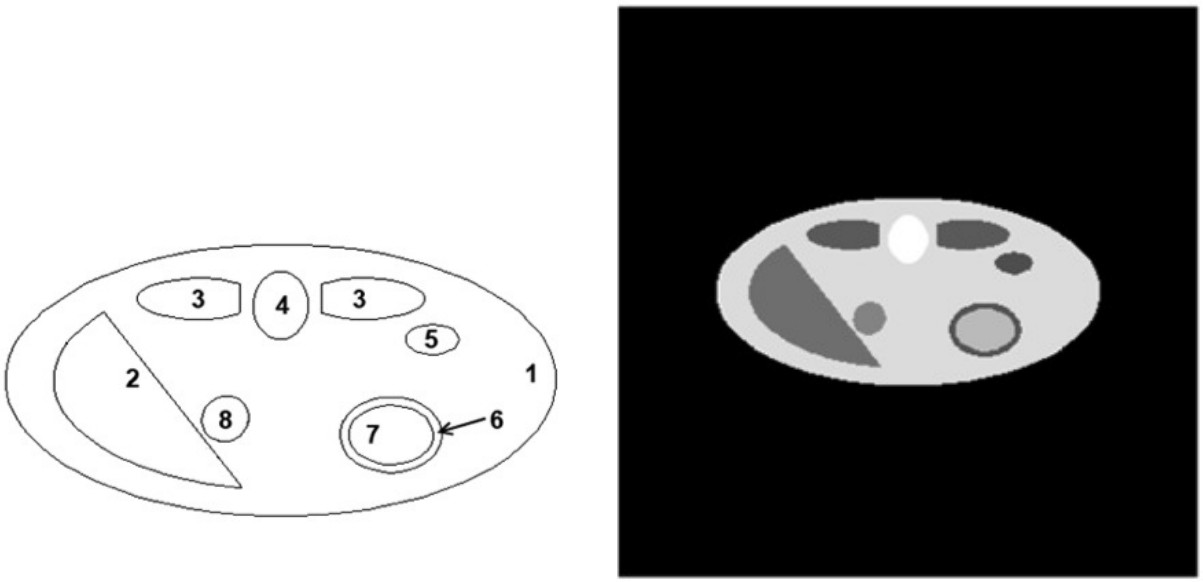
Pathological conditions may alter the isotopic composition of biological tissue due to alterations in the cellular metabolism. Since these alterations precede the morphological changes in the affected tissue, isotope quantification techniques may provide early diagnosis information.

NSECT is an emerging imaging modality that allows for isotope quantification from biological tissue based on the neutron-nucleus inelastic scattering reaction.[1] After neutron interaction, the excited nuclei emit gamma rays whose energies are unique to the emitting nuclei. A tomographic reconstruction feature-based on first generation tomography scan can be performed by projecting a collimated neutron beam across the sample and recording the gamma photons whose energies identify the elements of interest.

NSECT offers an alternative technique to isotope quantification from histological analysis, which requires an invasive biopsy procedure for tissue analysis, and to nuclear medicine techniques such as Positron Emission Tomography (PET) and Single Photon Emission Tomography (SPECT), which are based on the interaction between the radiation emitted by an administered radioactive tracer in the patient and the biological tissue. In contrast, the NSECT technique can directly measure the naturally occurring isotope compositions present in the patient.

Successful applications of this new technique are the evaluation of the hepatic hemochromatosis,[2] breast microcalcification development,[3] and the detection of breast[4] and renal cancer.[5] While in CT a continuous X-ray beam is applied, as the source rotates from 0 to 180 or 360 degrees[6] generating a highly sampled sinogram, in NSECT such highly sampled sinogram is not practical given clinical concerns over radiation dose.[7]

This work describes a technique to perform the NSECT sinogram sampling based on the NMI between a ground-truth image, which represents the known chemical composition of the irradiated media, and the expected tomographic images reconstructed from different sinogram samplings of the ground-truth image. Monte Carlo (MC) simulations of NSECT acquisitions[8] were performed to validate our NSECT sinogram sampling technique.



(a) (b)

Figure 1. (a) Layout of the organs reconstructed by the tomographic image composed by: (1) soft tissue, (2) liver, (3) kidneys, (4) spine, (5) spleen, (6) stomach wall, (7) stomach content, and (8) gallbladder. (b) Ground-truth image from ^{1}2C concentration.

3. METHODS

For two images A and B, mutual information (MI) can be defined as:

$$I(A,B) = H(B) - H(B|A), \tag{1}$$

where $H(B)$ is the Shannon entropy of image B, computed as the probability distribution of the gray values. $H(B|A)$ describes the conditional entropy, based on the probability of observing intensity b in image B given that the corresponding pixel in A has intensity a. In other words, MI represents the amount by which the uncertainty about B decreases when A is given; that is, the amount of information A contains about B. Because A and B can be interchanged, $I(A,B)$ is also the amount of information B contains about A. In image registration applications, images are geometrically aligned in such a manner that MI is maximal.[9]

Studholme *et al.*[10] argued that any image similarity measure should be invariant to changes in the size of the overlap region through the course of registration. Hence the normalized mutual information (NMI) has been proposed as an alternative:

$$Y(A,B) = \frac{H(A) + H(B)}{H(A,B)} \tag{2}$$

where $H(A)$ and $H(B)$ are the marginal image entropies and $H(A,B)$, the joint image entropy. The higher the value of $Y(A,B)$, the more similar the images are with respect to the regions of overlap, i.e., the marginal entropies have been maximized and the joint entropy is minimized.

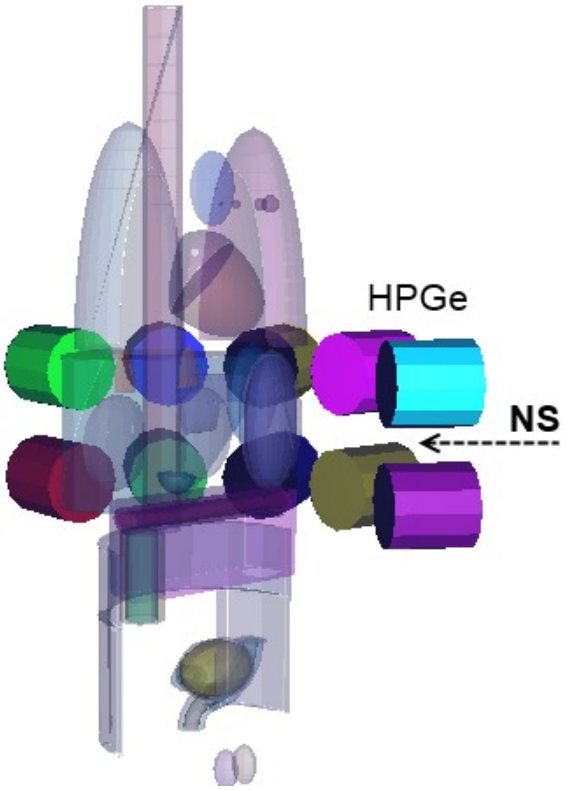


Figure 2. Arrangement of 10 high purity germanium (HPGe) detectors in two semi circles with 22 cm radii mounted around the anatomical phantom (NS: 5 MeV neutron source).

Here, we will use the NMI to evaluate the similarity between the ground-truth image and the reconstructed images with different sinogram settings. A male MIRD phantom[11] was used to mimic the human torso and

was used to generate a ground-truth image from a transverse cross-section. Pixel intensities from ground-truth image represent the chemical composition based on the concentration of the isotope of interest across the irradiated tissue. Here, only the isotope ^{12}C is evaluated (Figure 1).

Setup	Projection width (cm)	Overlap between projections (cm)
1	2.0	1.0
2	1.0	0.5

Table 1. Spatial projection sampling parameters evaluated on a tomographic acquisition. Both setups were acquired with a rotational increment of 5 degrees.

The ground-truth image was reconstructed was initially reconstructed by varying the following sinogram sampling parameters used in an NSECT scan: angular and linear projection offset, projection width, and spacing between adjacent projections. Among several combinations of parameters, two sinogram settings of interest were selected and shown in Table 1. NMI was calculated between the ground-truth image and the reconstructed images for each sinogram configuration by performing the Radon Transform (RT) on the ground-truth image obtained from ^{12}C.

In addition, MC simulations of a first generation NSECT scan were also performed. An acquisition system composed of 10 high purity germanium (HPGe) detectors was arranged in two semi circles with 22 cm radii mounted around the anatomical phantom as shown in Figure 2. Each semi circle contained 5 detectors, angled 30 degrees from each other on the x-axis. There is a 4 cm gap between the two rows of detectors where the collimated 5 MeV neutron source (NS) is projected. Such neutron energy was chosen in order to stimulate the ^{12}C isotope. The HPGe detectors are cylindrically shaped with 10 cm diameter and 10 cm height. The same sinogram settings were used to reconstruct tomographic images based on the ^{12}C concentration across the organs in the phantom. The correspondence between the ground-truth image and the MC reconstruction was also evaluated by NMI computation.

Setup	NMI from MC-based reconstruction	NMI from RT-based reconstruction
1	1.56	1.54
2	1.60	1.58

Table 2. NMI evaluation based on different sinogram samplings.

4. RESULTS

The similarity of the reconstructed images from both methods was compared against the ground-truth image from ^{12}C concentration. Table 2 shows that the level of agreement between techniques is about 1% for both setups of sinogram sampling. The tomographic reconstructions are shown in Figure 3.

5. CONCLUSIONS

The reconstruction method based on Radon Transform was able to reproduce the majority of the details of the NSECT image, as the quality of the reconstructions matched those of MC with the same parameters. Given a ground-truth image, the sinogram sampling process can be optimized by maximizing the correspondence using the MNI measure, yielding sampling settings to achieve a low dose delivery through a reduced number of neutron beam projections.

The proposed methodology is fully based on reference images which hold information about the element location and concentration. In a real medical imaging framework, it will be necessary to provide both anatomy and chemical composition based on information from a group of patients. This dataset also must provide the dose deposition delivered to a standard phantom during the scanning for each sinogram sampling setting. As demonstrated, when the NMI evaluation is associated with the dose delivery, it becomes a cost function for decision making, relating the desired quality of reconstruction based on level of similarity with dose deposition.

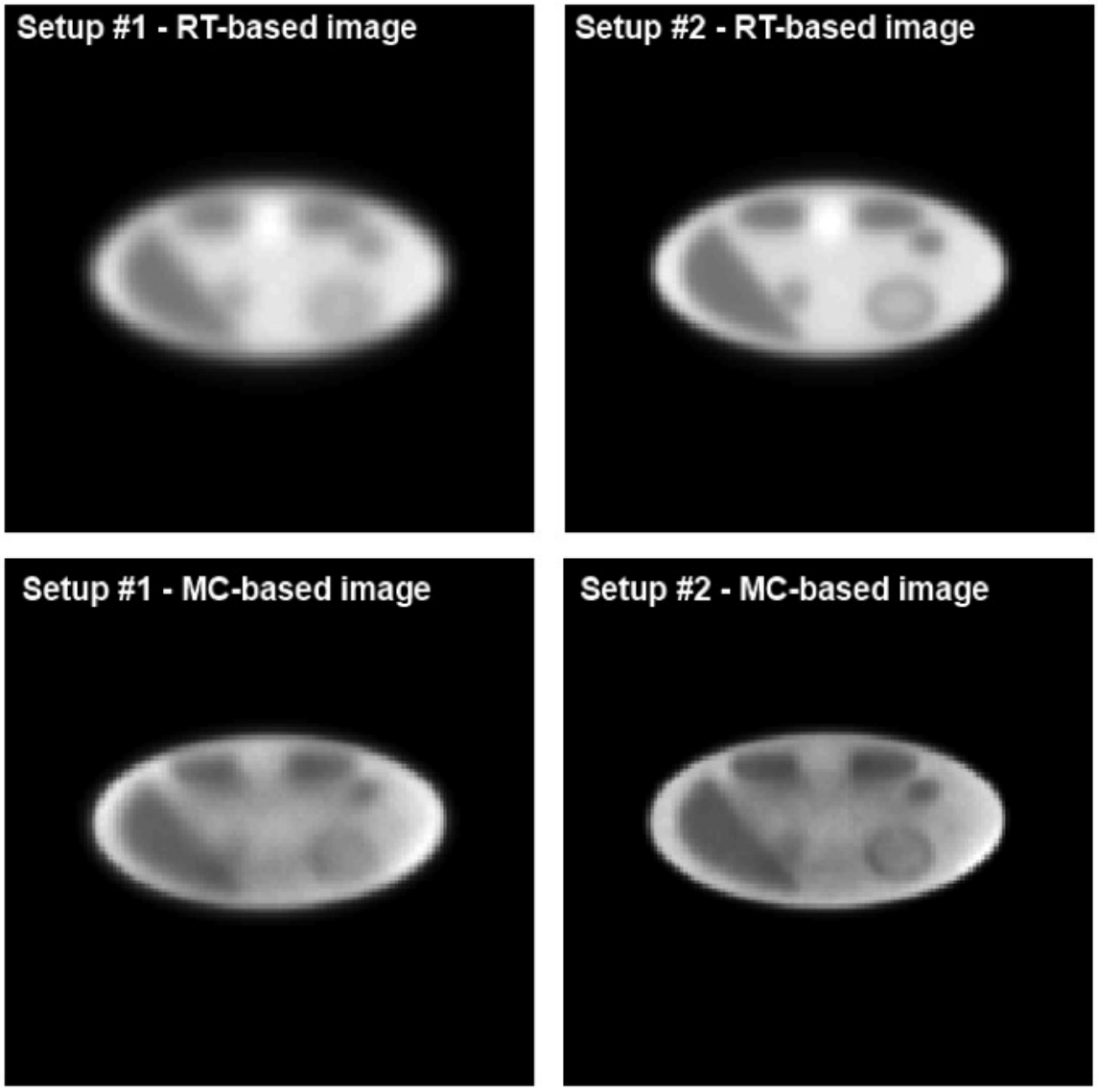


Figure 3. Tomographic images according to setups of sinogram samplings 1 and 2 for RT and MC image reconstructions.

To the best of our knowledge, this is the first methodology that employs the NMI measure to optimize NSECT acquisition strategies. This technique has the potential to relate the desired quality of reconstruction with tissue dose deposition.

6. ACKNOWLEDGMENTS

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), grant number 2010/04206-4.

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