Fusion of PET and CT images using wavelet transform

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Abstract

While information about anatomy is available in CT images, information about physiology and metabolism is available in PET images. To integrate both information, the two images are fused. Image fusion methods include simple methods like pixel averaging and sophisticated methods like wavelet transformation. An advantage of using wavelet transformation is that it preserves significant parts of each image. After creating lesions of 10, 8, 6 mm in a NURBS (non-uniform rational B-splines) based cardiac torso (NCAT) phantom, PET images were simulated using SimSET simulator. Attenuation maps of the activity phantom were used as CT images. Each of the PET and CT images was divided into an approximation image and three detailed images by the wavelet transform. The corresponding transformed images generated from the PET and CT images were fused in nine different ways to generate composite images, which were compared to the original images. The basis of comparison is the lesion-to-tissue contrast in the fused image in comparison to the lesion-to-tissue contrast in the original PET and CT images. *Our results* showed that except for one method, the lesion-to-tissue contrast in the fused image was higher than that of the CT images. In the first six methods, the lesion-to-tissue contrast in the fused image was less than the contrast, in the PET image. In the other three methods, the contrast in the fused image was higher than in the PET image. This was true in cases of 10, 8, 6 mm lesions. *In conclusion, we* have show that the approximation image produced a better ultimate image and that the lesion-to-tissue contrast in the fused image was also better than that of the original PET and CT images. This is because the approximation image is comprised of fundamental information of the signal (low frequency) that directly affects the image contrast.

Introduction

Labeled biomolecules with positron emitting nuclides are used as the tracer in positron emission tomography (PET) imaging. The ^{18}F-FDG (Fluorine-18 fluorodesoxyglycose) PET imaging is usually used in oncology because ^{18}F-FDG tracer can demonstrate unnatural metabolism of glucose in tumor cells [1]. While the information about perfusion and metabolism is obtained via PET, computed tomography (CT) scan and magnetic resonance imaging (MRI) provide information about dense and soft tissues [2].

Structure without function is a corpse and function without structure is a ghost [3]. Therefore, both of the PET and CT images are investigated. In the simplest state, visual fusion is used; but due to various slice thickness and patient movement during scanning, this method is difficult, time consuming and inaccurate [4]. In off-line methods, co-registration of images from separate systems is used. Considering the identical positions of the patient in two scans, the irritating cast forming vacuum mattress is used. On the other hand, software fusion, apart from the brain area, is difficult and often unsuccessful because of the patient movement (patient's displacement by himself/herself and the internal non-voluntary movements) [5, 6]. This is while none of the above mentioned problems exists in in-line imaging. Since the patient remains positioned on the same bed for both imaging modalities, temporal and spatial differences between the two sets of images are minimized. Therefore, the cast forming vacuum mattress is not used. In-line PET/CT is an approach that solves the fusion problem through hardware rather than software [7]. After the first phase of imaging, the patient is scanned for the second time lying on the same bed and in the same position; the temporal and local differences between the images are minimized. Therefore, anatomic and physiologic images become conformed to each other properly. Of the advantages of this method, using CT images for attenuation correction and shorter time of the test can be

enumerated [4, 6]. Researchers have shown that the diagnostic accuracy of the obtained images is sufficient and PET-CT fused images are more successful in determining the position, the type and staging of the lesions in comparison to the CT and PET imaging modalities separately [8-11].

Forerunners of nuclear medicine, have uncovered the potential advantages of anatomy/physiology imaging [12]. The fusion of the images is a way of image enhancement that aids the physician to examine the status of an organ in many aspects simultaneously. In in-line imaging, special software is used for the fusion of PET and CT images. From a series of input images, one image (hybrid) is produced and provides the possibility to get the most information out of a data collection, whereas the temporal and local resolution must be ideal, too [13]. Therefore, different images are fused according to the required information, and fusion method depends on the application. For instance, if we intend to display the edges of the fused image clearly, the fusion method is instructed in a way that the information related to the edge of both modalities is reserved [2]. Usually in the image fusion software, the average of the PET images is fused with the CT image [14]. The methods of image fusion include simple and complicated methods. Simple methods include averaging pixels, complicated methods include principal component analysis, and wavelet transform. Since the basis of the wavelet is a form of limited wave (concerning time), the temporal/local information are preserved after transformation. By using the feature of time frequency localization of the wavelet, the possibility of preserving the important coefficients (information) are available for analysis (after transformation). Research studies have demonstrated that the wavelet transform preserves important parts of each image while the fused images are not foggy with less ring-shaped artifacts than the original images [15]. However, a rigorous study of fusion methods for PET-CT and particularly those based on the wavelet transform is lacking.

The aim of this work was to develop and optimize a wavelet-based fusion method for PET and CT images. To this end, different approaches were implemented and compared to find the best method based on the lesion to tissue contrast enhancement. The contrast of the lesion to the tissue is estimated in the PET and CT images individually, and then they were compared with the lesion to tissue contrast in the fused images. Next, the proposed wavelet fusion method was compared to the simple fusion method used routinely in PET/CT scanners.

Materials and methods

Phantom and image simulator

One method of evaluation and enhancement of medical imaging systems and their mechanisms is using simulation techniques. This is due to the fact that most of the theoretical solutions are practically useless and clinical studies are difficult and expensive in medical imaging studies. Nowadays simulation methods are regarded as an important and essential complement in theoretical discussions and clinical studies [16].

In this study, medical images of a computer patient NURBS-based cardiac torso (NCAT) phantom were made by a method of imaging, which is simulated by SimSET software. The NCAT phantom was provided as a realistic and flexible model of the human anatomy and physiology to be used in nuclear medicine imaging research. The organ models are based on NURBS, non-uniform rational B-splines, as used in computer graphics. NURBS, which defines continuous surfaces, allows the phantom to be defined at any spatial resolution. An important innovation is the extension of NURBS to a fourth dimension; time, to model the cardiac and respiratory motions [16].

All of the organs and skeletal models with the exception of the heart are based on CT scans from the "Visible Human" male data set. The heart is based on gated MRI cardiac scans of a normal patient. The phantom is a hybrid between the realism of pixel-based phantoms and the flexibility of geometry-based phantoms. By fitting NURBS to actual patient data, the phantom is more realistic than those based on solid geometry. In addition, the NURBS primitives give the phantom a mathematical basis allowing the phantom to be very flexible. NURBS surfaces can be altered easily via affine and other transformations to realistically model variations in anatomy and to simulate patient motion [16].

Given a model of the physics of the medical imaging process, medical images of the computerized patient provided by the NCAT can be generated using computational methods. This forms the basis of simulation techniques.

The SimSET simulator is a Monte Carlo's simulation software for emission tomography, which is one of the most powerful specific codes for diagnostic nuclear medicine, and is able to simulate various imaging systems such as single photon emission tomography (SPET) and PET. This software employs the Mont Carlo technique to simulate the physical phases of imaging (producing photon and determining the direction of its primary emission, different photon interactions such as attenuation and scatter with the patient/ collimator/ detector). Each phase of the simulation is done independently and uses the related parameters. The results of different phases are merged to get the ultimate result.

Preparation of phantom

NCAT activity phantom for PET imaging

To produce NCAT phantom, the amount of organs activity must be relatively determined. To determine the relative activity among different organs, we used a normal PET scan. After opening up the image in the MATLAB environment, the activity ratios considering the amount of 100 for left ventricle were right ventricle 75, liver 60, spleen 50, and lungs 10. Then these figures were attributed to the corresponding organs in the NCAT phantom. MATLAB is a program that was originally designed to simplify the implementation of numerical linear algebra routines. MATLAB handles numerical calculations and high-quality graphics, provides a convenient interface to built-in state-of-the-art subroutine libraries, and incorporates a high-level programming language [17].

NCAT attenuation phantom as CT images

The SimSET simulator evaluates the attenuation amount of each organ based on the coefficients of the Zubal phantom. In the last few years, so-called voxel anthropomorphic phantoms, based on CT or MRI, have been created. These phantoms are known as "voxel" since they are made from a set of small volume elements. Once it is created, a phantom may be associated with a Monte Carlo code, for any simulation or application the user requires. At Yale University, in the United States, the Zubal team uses voxel phantoms for Monte Carlo simulations of the internal distribution of radiopharmaceuticals. The size and weight characteristics of Zubal's whole body phantom are reasonably consistent with those of the reference man (ICRP, 1975, 2002) [18].

Since these values are arbitrary, we changed the genuine attenuation map to an attenuating map according to the Zubal coefficients. To this end, we entered the Zubal attenuation coefficients in the activity phantom; consequently, the access to a non-homogenous attenuation map and in accordance to reality in the body organs was obtained.

For producing a lesion in the liver area, first we used a real CT image to determine the contrast of a lesion in the liver to the liver tissue. After opening this image in the MATLAB environment, this contrast was estimated to be about 0.1. The contrast of lesion to tissue in the phantom was considered 0.2, to reach the 0.1 contrast between the lesion and tissue in the CT image. Regarding the formula of contrast, we considered the lesion activity 90 and liver tissue activity 60 where the result for the phantom relative activity was 0.2.

Contrast = (lesion activity – liver activity) / (lesion activity + liver activity)

Then, we produced lesions with dimensions of 6, 8, 10 mm. The observation of the Sagital and transverse views of the lesions in the phantom demonstrated that there was no considerable overlap among them.

Both of the PET and CT images were prepared in 256 × 256 size. Some modifications were applied in the MATLAB environment. Then, wavelet analysis of the corresponding PET and CT images (two corresponding specific slices) was applied to transform the PET and CT images into an Approximation section and three Detail sections. Wavelet analysis first starts from the rows and then from the columns [19]. This results in a coarser approximation with four times less pixels and three arrays of details so that the total amount of information is preserved. The analysis was done only in one level because higher levels of analysis decrease the resolution and contrast of the image [15]. The number of samples in each method was five.

By comparing the corresponding pixels in the two images, we applied nine methods of fusion: 1) The Min-Min method: the least amount of the two approximations and the least amount of the corresponding details were used to produce the final image. 2) The Min-Mean method: the least amount of the two approximations and the average amount of the corresponding details were used to produce the image. 3) The Min-Max method: the least amount of the two

Figure 1. Image of the phantom from the Sagital view.

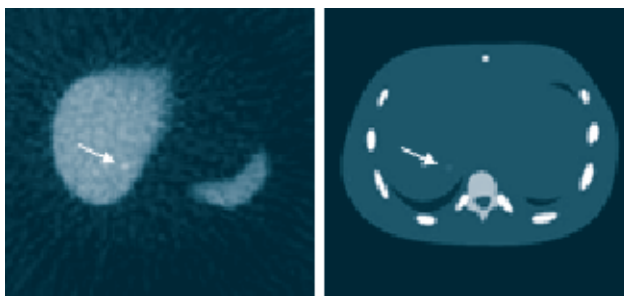**Figure 2.** Images of the phantom from the transverse view.

Figure 3. From left to right: CT image and simulated PET image of the phantom.

approximations and the highest amounts of the corresponding details were used to produce the image. 4) The Mean-Min method: the average amount of the two approximations and the least amount of the corresponding details were used to produce the images. 5) The Mean-Mean method: the average amount of the two approximations and the average amount of the corresponding details were used to produce the ultimate image. 6) The Mean-Max method: the average amount of the two approximations and the highest amounts of the corresponding details were used to produce the ultimate image. 7) The Max-Min method: the highest amounts of the two approximations and the least amount of the corresponding details were used to produce the ultimate image. 8) The Max-Mean method: the highest amounts of the two approximations and the average amount of the corresponding details were used to produce the ultimate image. 9) The Max-Max method: the highest amounts of the two approximations and the highest amounts of the corresponding details were used to produce the ultimate image.

These nine methods were applied to three different lesions with five images.

Results

The contrast of the lesion to tissue in the CT image was 0.1 in all methods. The average contrast of the lesion to tissue in the PET images for the 10, 8, 6 mm lesions were respectively 0.1388, 0.1636, 0.1398 because each lesion in the PET image is observable in some specific slices.

1) The Min-Min method (Table 1)

Table 1. *Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Min-Min method*

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.0997 ± 0.0005	−0.3	−28.2
8 mm lesion	0.0993 ± 0.0009	−0.7	−39.3
6 mm lesion	0.0957 ± 0.004	−4.3	−31.5

The minus sign means that the lesion-to-tissue contrast in the PET-CT image has decreased in comparison to the lesion-to-tissue contrast of the CT and PET images separately. In this method, the contrast of the fused image is consistently less than the contrast in the CT and PET images.

2) The Min-Mean method (Table 2)

Table 2. *Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Min-Mean method*

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1052 ± 0.0045	5.2	−24.2
8 mm lesion	0.1153 ± 0.0119	15.3	−29.5
6 mm lesion	0.1010 ± 0.0033	1	−27.7

In this method, the contrast of the fused image is consistently more than the contrast in the CT image and less than the contrast in the PET image.

3) The Min-Max method (Table 3)

Table 3. *Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Min-Max method*

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1117 ± 0.008	11.7	−19.5
8 mm lesion	0.1310 ± 0.0224	31	−19.9
6 mm lesion	0.1108 ± 0.0015	10.8	−20.7

In this method, the contrast of the fused image is consistently more than the contrast in the CT image and less than the contrast in the PET image.

4) The Mean-Min method (Table 4)

Table 4. *Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Mean-Min method*

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1335 ± 0.0138	33.5	−3.8
8 mm lesion	0.1530 ± 0.0208	53	−6.5
6 mm lesion	0.1321 ± 0.0147	32.1	−5.5

In this method, the contrast of the fused image is consistently more than the contrast in the CT image and less than the contrast in the PET image.

5) The Mean-Mean method (Table 5)

Table 5. *Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Mean-Mean method*

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1295 ± 0.0134	29.5	−6.7
8 mm lesion	0.1477 ± 0.0194	47.7	−9.7
6 mm lesion	0.1296 ± 0.0148	29.6	−7.3

In this method, the contrast of the fused image is consistently more than the contrast in the CT image and less than the contrast in the PET image.

6) The Mean-Max method (Table 6)

Table 6. *Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Mean-Max method*

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1345 ± 0.0132	34.5	−3.1
8 mm lesion	0.565 ± 0.0224	56.5	−4.3
6 mm lesion	0.1355 ± 0.0142	35.5	−3.1

In this method, the contrast of the fused image is consistently more than the contrast in the CT image and less than the contrast in the PET image.

7) The Max-Min method (Table 7)

Table 7. Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Max-Min method

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1442 ± 0.018	44.2	3.9
8 mm lesion	0.1714 ± 0.027	71.4	4.8
6 mm lesion	0.1450 ± 0.0185	45	3.7

In this method, the contrast of the fused image is consistently more than the contrast in the CT and PET images.

8) The Max-Mean method (Table 8)

Table 8. Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Max-Mean method

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1423 ± 0.0173	42.3	2.5
8 mm lesion	0.1682 ± 0.0259	68.2	2.8
6 mm lesion	0.1442 ± 0.0184	44.2	3.1

In this method, the contrast of the fused image is consistently more than the contrast in the CT and PET images.

9) The Max-Max method (Table 9)

Table 9. Lesion-to-tissue contrast in the PET-CT image and its comparison to the CT and PET images using the Max-Max method

	PET-CT contrast	Increase or decrease relative to the CT contrast (%)	Increase or decrease relative to the PET contrast (%)
10 mm lesion	0.1454 ± 0.0169	45.4	4.7
8 mm lesion	0.1704 ± 0.0246	70.4	4.2
6 mm lesion	0.1464 ± 0.0019	46.4	4.7

In this method, the contrast of the fused image is consistently more than the contrast in the CT and PET images.

In the following graphs, the numbers 1 to 9 stand for nine different methods of fusion and are in order of Min-Min (1), Min-Mean (2), Min-Max (3), Mean-Min (4), Mean-Mean (5), Mean-Max (6), Max-Min (7), Max-Mean (8), Max-Max (9).

Finally, we compared our results with the results of simple fusion method. In the simple fusion, PET and CT images were fused using the following formula:

$$PET\text{-}CT\ image = 50\%\ PET + 50\%\ CT$$

In this method, the lesion-to-tissue contrast in the fused image is about 8.7% less than the lesion-to-tissue contrast in the PET image for the 10 mm lesion. In addition, this decrease happens for the other two lesions.

Discussion

With the availability of multisource data in many fields, such as medical imaging, data fusion has emerged as a new and promising research area [19, 20]. Many of the researchers in the field of image fusion believe that wavelet transform is a useful method for image fusion [21, 22].

The goal of image fusion is to make an image whose information content is more than what is found in each of the separate images. In this research, the goal of different fusion methods was to increase the lesion-to-tissue contrast in the fused image in comparison to the lesion-to-tissue contrast in the PET and CT images separately.

As seen in diagrams 1, 2, 3, except for the first method, for the other methods the lesion-to-tissue contrast in the fused image is more than the lesion-to-tissue contrast in the CT image. This is true for all three 10, 8, 6mm lesions.

In the first six methods, the contrast in the fused image is consistently less than the contrast in the PET image, whereas in three other methods the contrast in the fused image is more than the contrast in the PET image. This holds true for
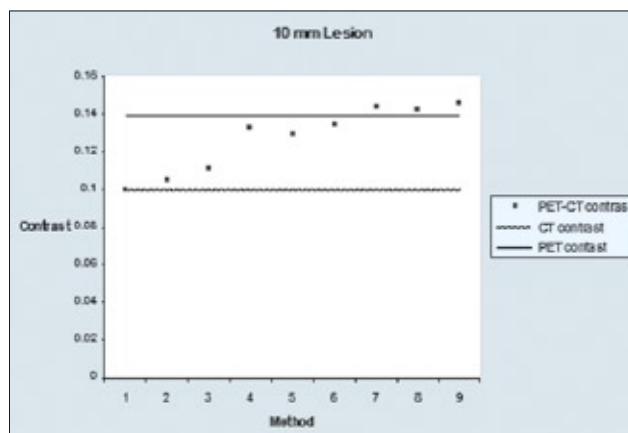

Diagram 1. Comparison of lesion-to-tissue contrast in 9 different fusion methods to the lesion-to-tissue contrast in the CT and PET images for the 10 mm lesion.
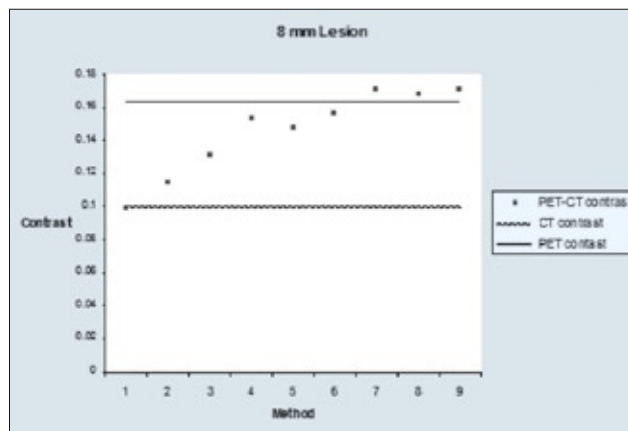

Diagram 2. Comparison of lesion-to-tissue contrast in 9 different fusion methods with the lesion-to-tissue contrast in the CT and PET images for the 8mm lesion.

Diagram 3. Comparison of lesion-to-tissue contrast in 9 different fusion methods with the lesion-to-tissue contrast in the CT and PET images for the 6mm lesion.
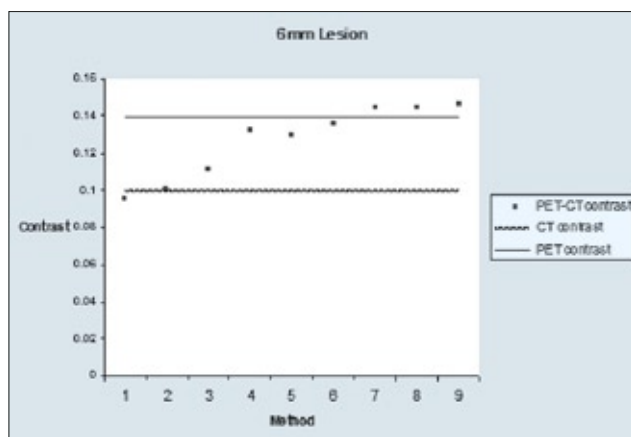
all three lesions. Consequently, in the methods that the effect of the approximation section is maximized (last three methods), the lesion-to-tissue contrast in the fused image is more than the lesion-to-tissue contrast in the CT and PET images.

There is no meaningful difference among the three methods in which the effect of approximation is the maximum amount. However, the difference of these three methods with the first six methods is meaningful. This is because the approximation section is comprised of general information of the signal (low frequency); the effect of this part in the fused image is more and the less important information is lost. On the contrary, the effect of this part in the fused image is less when using the first six methods and thus more information that is general is lost.

The loss of trivial information (high frequency) would not have any considerable effects on the lesion-to-tissue contrast in the fused images. Due to the fact that noise in nuclear medicine imaging is usually of high frequency content, the decrease of the effect of the detail sections in the fused image leads to decrease of the noise in the images.

For the 10 mm lesion, in the three methods that the effect of the approximation section is maximized, the lesion-to-tissue contrast in the fused image is about 3.7% more than the lesion-to-tissue contrast in the PET images. On the other hand, using the simple fusion method, the lesion-to-tissue contrast in the fused image is about 8.7% less than the lesion-to-tissue contrast in the PET images. Therefore, the difference between the two results is meaningful and our method generates superior results.

In conclusion, while there are different ways that the information contained in the CT and PET images can be combined to generate a superior image, the best method for PET and CT image fusion is wavelet fusion. For best performance, the Max-Min, Max-Mean, or Max-Max combination of the wavelet transform coefficients of the two images should be used. The lesion to tissue contrast in the combined image generated by the proposed wavelet fusion method is superior to that of the simple fusion method (averaging of the two

images). As such, wavelet fusion is the method of choice for every day practice.

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