Study on Energy Weighting Imaging Technology in Multispectral CT

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Abstract

The attenuation of X-ray in matter is related to photon energy and material property. The traditional CT imaging technology adopts charge integrating detector, which cannot effectively utilize the photon energy information in imaging. With the ability to distinguish the photon energy, photon counting detector can improve the image quality if appropriate energy weights are chosen according to the attenuation change of matter under different X-ray energies. This paper focuses on the energy weighting imaging method based on the photon counting detector CT. In this paper, various kinds of materials are selected to explore the image-based energy weighting. Imaging experiments show that the energy weighting method can obtain higher contrast-to-noise ratio (CNR) than the conventional photon counting imaging and charge integrating imaging.

Keywords: photon counting detector, energy weight, image domain, signal to noise ratio (SNR)

1 Introduction

By adopting the charge integrating detector, which absorbs the energy of incident photons and converts it into electrical signals, the traditional X-ray CT system generally maps the average X-ray attenuation characteristics of matter. Its imaging principle makes high-energy photons contribute more to the imaging process than the low-energy photons do. Generally, the attenuation coefficient of matter decreases with the increase of X-ray photon energy, and the contrast information provided by the high-energy photon is weak, so the material resolution ability of charge integrating CT under low contrast situation is limited. For example, when the industrial CT is scanning workpieces with similar densities, the image contrast is usually unsatisfying. Similarly, pathological tumors are also difficult to distinguish from normal soft tissue in biomedical CT imaging. The application of multispectral CT technology has changed this situation to some degree. Especially in recent years, with the emergence of photon counting detector, the energy spectrum CT has achieved rapid development. Photon counting detector can identify the energy level of incident photon and then accumulate the photon count in different energy bins. According to this feature, different weights can be assigned to different energies to improve the image SNR\textsuperscript{[1]}. This method can improve the contrast and noise of performance compared with the traditional imaging systems. Currently, the common energy weighting imaging researches mainly include image domain and projection domain methods, energy interval selection, influence of incident spectrum change, analysis of beam hardening effect\textsuperscript{[2-7]}, etc.

The image domain energy weighting technique needs to obtain the contrast and noise information of CT images in each energy region when calculating the weight factor. The reconstructed image reflects the attenuation coefficient of the material, so the image can be used to calculate the weight directly. Then, every image in each energy bin is assigned a weight to obtain the final summed image\textsuperscript{[7]}. This method is not only more accurate in calculating the weighting factor, but also can make the weighted image achieve better SNR.

In this paper, according to the characteristics of image-based weighting, the change of characteristics of different materials’ weighting factors and the influence of weighting on image quality are explored through experiments. The advantages of energy weighting are analyzed compared with the normal photon counting CT and the conventional charge integrating CT.

2 Energy weighting imaging method

Image-based weighting is a method that reconstructs each energy bin and then calculates the weighted sum. Figure 1 is the implementation step of the method. The projected images of each energy region are normalized and individually reconstructed using filtered back projection (FBP). The weighting factors are obtained from CT images of each energy bin, and the reconstructed images are weighted and summed, during which process the weighting factors are calculated by contrast and noise information provided by the images\textsuperscript{[7]}. 
The purpose of weighting imaging is to improve the image quality, therefore, the CNR is used as a measurement in our work. The larger the CNR is, the higher the image contrast and the lower the noise will be. Assuming $i$ is the index of material areas in the image, $\omega$ is the weighting factor, $C$ is the absolute difference in contrast of materials in the image, and $\sigma$ is the standard deviation representing the noise level, then the CNR can be expressed as:

$$\text{CNR} = \frac{\sum_{i=1}^{M} \omega(i) \cdot C_i}{\left( \sum_{i=1}^{M} \omega(i)^2 \cdot \sigma_i^2 \right)^{1/2}}$$

(1)

The optimal weighting factors are achieved when the CNR is maximized, which can be accomplished by computing the derivative of $\omega$ of the above equation:

$$\omega(i) = \frac{J_i}{\sum_{i=1}^{M} J_i}$$

(2)

$$J_i = \frac{C_i}{\sigma_i^2}$$

(3)

$$C_i = |\mu_{c,i} - \mu_{b,i}|$$

(4)

$\mu_c$ and $\mu_b$ represent the attenuation coefficients of the target material and background material, respectively. The noise is determined by the standard deviation of the background area of the CT image. The ROI region can be selected from the CT image to calculate the weighting factor of each energy bin. The weighted image calculation method is as followed:

$$\text{Image} = \sum_{i=1}^{M} \omega_i \cdot (E_i) \cdot \text{Image}_i$$

(5)

The left part of the above formula is the image after energy weighting.

3 Theoretical analysis

According to the weighting imaging model, the relationship between weighting factors and 1) material properties, 2) imaging energy can be studied theoretically. The image-based weighting involves two variables: contrast and noise. Contrast can be simulated by attenuation coefficients of different materials, but it is complicated to calculate the noise of CT images under different materials and energies, which needs reconstruction data under different energies.

Brooks' research on X-ray imaging statistics shows that there is a linear relationship between the SNR of projected images and that of CT images. Therefore, the SNR of reconstructed images can be transformed into the SNR of projected images. So we can analyze the characteristic of weight coefficient from the perspective of projection.
Now consider a simple X-ray imaging model with only two materials (background material and target material). The background material thickness is $L$, its attenuation coefficient is $\mu_b$. The target material thickness is $d$, its attenuation coefficient is $\mu_c$. The signal and noise detected by the detector are respectively expressed as $S_{b,c}(E) = \omega(E) N_{b,c}(E)$ and $\sigma_{b,c}(E) = \omega(E) \sqrt{N_{b,c}(E)}$.

Where $N_{b,c}$ represents the average number of photons passing through the region including the target material, and $\omega$ represents the weight under a certain energy. In the case of the maximum SNR, the weight coefficient can be calculated as $\omega(E) = \frac{1 - \exp(-[\mu_b(E) - \mu_c(E)]d)}{1 + \exp(-[\mu_b(E) - \mu_c(E)]d)}$.

Using the attenuation information of the material, the theoretical value of the weight coefficient can be calculated (figure 2). From the simulation results, two trends of the normalized weight coefficients can be observed. The materials with high densities such as bone and PVC have smaller weights at low energy, and the weight changes are relatively gentle. The weight coefficients of PMMA and soft tissue in low energy region are higher and their changes are more rapid. Based on the above observation, the experiment we design takes bone, soft tissue, water and other materials as the imaging object to analyze the characteristics of weighting factors and their impact on the imaging quality.

### 4 Experimental results

The detector used in our study is an XC-FLITE photon counting detector, featured with cadmium telluride semiconductor material and produced by XCounter. The cadmium telluride crystal thickness is 0.75mm, the number and size of pixels are 1536 x 256, 100 x 100 $\mu$m, respectively. The energy range is 10 to 160kev.

#### 4.1 Schematic design

In terms of energy partition, we choose four energy regions in our imaging experiments. The basic idea of partitioning is to keep the number of photons in each energy region at the same level. The specific experimental conditions are shown in the table:

<table>
<thead>
<tr>
<th>Experiment parameter</th>
<th>parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>tube voltage</td>
<td>60kvp</td>
</tr>
<tr>
<td>tube current</td>
<td>80$\mu$A</td>
</tr>
</tbody>
</table>
Table 2: Energy partition setting

<table>
<thead>
<tr>
<th>Bin1</th>
<th>Bin2</th>
<th>Bin3</th>
<th>Bin4</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.6-28Kev</td>
<td>28-32.5Kev</td>
<td>32.5-41Kev</td>
<td>41-60Kev</td>
</tr>
</tbody>
</table>

MCTP610 model (Shelley Medical Imaging Technologies, London) is selected for the experimental study (figure 3). The background material of the model body is polycarbonate. Six materials are selected as the research objects in this paper, which are bone simulators (SB3), Teflon, HD POLY, Fat, Muscle and Water equivalent epoxy resin.

4.2 Experimental analysis

The analysis of experimental results focuses on the contrast changes of images in different energy bins and the influence of weighting process on the results.

4.2.1 Multiple energy bin weighting factor

In order to evaluate the weight changes of each material under different energies, the material contrast is analyzed, firstly. It can be seen from the reconstructed images of different energy regions shown in figure 4 that the contrast in the high energy region is relatively low, while the noise is relatively weak. Figure 5(a) is the quantitative analysis of the contrast of each material.
Figure 5: (a) The contrast of materials in different energy bin, (b): The optimal photon energy weighting factors calculated for variety of materials

Under the above conditions, the weighting factors of materials in each energy region are calculated, and the curves of the weighting factors are shown in figure 5(b). From the low energy region to the high energy region, the weight values gradually decrease, and different materials show different changing trends. The weights of low density materials such as tissue and water are higher in low energy range. And they change faster with energy, too. The simulated materials present two trends in general, which are consistent with the theoretical analysis results. Therefore, the selected materials can be divided into high density and low density (or high atomic number and low atomic number) categories. In energy weighting, different weights should be selected for the two types of materials. Finally, two weighted reconstructed images can be obtained.

4.2.2 Comparison of different imaging methods

In order to verify the advantages of energy weighting, different imaging methods are compared experimentally, including energy weighting CT imaging with both high atomic number and low atomic number objects, photon counting CT imaging and charge integrating CT imaging. In the process of energy weighting, weights are selected individually for two kinds of materials with different atomic numbers. The experimental conditions of charge integrating CT are consistent with those of photon counting CT.

The reconstruction results of different imaging methods are shown in figure 6. Due to the high absorption coefficient of bone and other high atomic number materials, their contrast values are relatively good in all the four imaging methods. On the other hand, the imaging results of tissue and water are very different among these imaging techniques. Their contrast values are enhanced successively according to the order as charge integrating CT, photon counting CT and energy weighting CT. The quantitative analysis of the CNR of each material is consistent with the observation results from the image.

Figure 6: Reconstruction results: (a) charge integrating, (b) ordinary photon counting, (c) high atomic number material weighting imaging, (d) low atomic number material weighting imaging

The quantitative analysis of the experimental results shows that the energy weighting imaging can balance the contrast and noise of the image, hence improve the CNR (figure 7).
To evaluate this improvement, we compute the ratios between the CNR values of different imaging methods. CNR of the charge integrating CT image is taken as the reference, namely the denominator. CNR values of the ordinary photon counting image, energy weighting image and charge integrating image are used as the numerator of the ratios, respectively (see equation 9 for calculation method). All the resulting ratios are shown in table 3.

\[ \text{CNR}_{\text{ratio}}(i) = \frac{\text{CNR}(i)}{\text{CNR}_{\text{integrating}}} \]  

In the formula above index i stands for three imaging types: integrating, counting and image-based weighting. It can be seen that the CNRs of materials with low atomic number, such as tissue and water, are significantly increased when imaging weighting is applied.

<table>
<thead>
<tr>
<th>SB3</th>
<th>TEFLON</th>
<th>HD POLY</th>
<th>FAT</th>
<th>TISSUE</th>
<th>WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrating CT</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Counting CT</td>
<td>1.13</td>
<td>1.17</td>
<td>1.18</td>
<td>1.21</td>
<td>1.33</td>
</tr>
<tr>
<td>Image-based weighting CT</td>
<td>1.32</td>
<td>1.36</td>
<td>1.37</td>
<td>1.40</td>
<td>1.91</td>
</tr>
</tbody>
</table>

5 Conclusion

In CT imaging, the improvement of CNR can make the structures that are visually similar in the case of low contrast easier to distinguish. Therefore, the purpose and advantage of energy weighting imaging is to improve the image CNR. The computation of weighting factor is based on the maximization of CNR. This paper first analyzes the characteristics of the weighting factor. Then, it indicates the calculated weighting factors of different materials are the same as those obtained by theoretical simulation. Subsequent analysis of CT images shows that CNR in image-based energy weighting imaging is significantly improved compared with that in charge integrating imaging and ordinary photon counting imaging.

Projection-based weighting imaging method can calculate the weighting factor from the theory, and only one FBP reconstruction is needed after the energy weighting process. Therefore, compared with the image-based method, it is faster and requires no manual selection of ROI region to calculate the weight. The weight estimation based on the characteristics of the material and the photon energy is beneficial to the in-depth analysis of the energy weighting imaging process. Our next step is to study the projection-based weighting imaging technique.

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