Study on the material recognition of the region of interest by hyperspectral CT reconstruction methods

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Abstract

The hyperspectral CT system based on photon counting principle can acquire the X-ray absorption spectra of each reconstructed pixel, which makes it possible to analyze the components of the complex samples in the three-dimensional space. In this study, the spectral information of the region of interest (ROI) was reconstructed by line to obtain the absorption spectrum information, so as to identify the material category. In the experiment, a sample containing ten kinds of plastics but does not know the internal structure was adopted for recognition. After hyperspectral CT scan of the sample, four methods were used to obtain the absorption spectra of the ROI, which included filter back projection, filter back projection based on beam-hardening correction, algebraic reconstruction technique, algebraic reconstruction technique based on beam-hardening correction. Experimental results showed that algebraic reconstruction technique based on beam-hardening correction can achieve the highest reconstruction accuracy and filtered back projection algorithm has the fastest computing speed but its accuracy is poor. The reconstruction of X-ray absorption spectra can be used for nondestructive analysis of structure and composition of samples, which has promising prospects in the field of non-destructive testing and biomedical.

Keywords: Multi-mode imaging, Computed tomography (CT), CT reconstruction algorithm, X-ray absorption spectrum (XAS), Beam-hardening correction, Material recognition

1. Introduction

Medical imaging plays an extremely important role in medical diagnosis. Pathological diagnosis is concerned with two aspects of structure and function. The former can help doctors confirm the shape of the lesion, and the latter help doctors determine whether the location is diseased or not [1]. The single-function instrument cannot meet the needs of the current pathological diagnosis in terms of analysis efficiency or cost control in the diagnosis of many difficult miscellaneous diseases, which has led to the rapid development of multi-mode medical imaging technology in recent years [2].

The unique effect of the interaction between X-ray and matter determines that X-ray can be widely used in the field of material identification. After a century-long vigorous development, X-ray has become a powerful tool for analyzing the structure and composition of materials [3]. In structural analysis, computed tomography (CT) and digit radiography (DR) technology has been applied in clinical and can effectively detect the biological structure [4]. In the analysis of components, the development of technologies such as fluorescence analysis, diffraction, electron spectroscopy and absorption fine structure technology has been well developed [5-7]. However, fluorescence analysis, diffraction and electron spectroscopy cannot be applied to organisms, so the absorption fine structure technology has become the key research object in component analysis. The theory of the X-ray absorption fine structure tells us that the absorption spectrum of any substance is unique [8]. Therefore, the spectral CT technology combining structure identification ability of CT technology and components identification ability of X-ray absorption spectrum has become the research focus of multi-mode medical imaging. The spectral CT is also called multi-energy CT. At present, multi-energy CT is only for the identification between 2 or 3 substances, which far from meeting the needs of clinical diagnosis. The main reason is the limited spectral subdivision and the low spectral encoding resolution, the mainstream dual-energy CT can only divide the spectrum into eight bands [9]. In recent years, the rapid development of photon counting X-ray detector makes multi-energy CT...
possible, and X-ray spectral reconstruction algorithm has become a new research hotspots. CdTe detector is a typical photon counting detector, whose energy between each channel is completely separated, and the spectra can be finely divided so as to realize the material identification [10].

In the CT reconstruction algorithm, analytic reconstruction (AR) and iterative reconstruction (IR) is two basic reconstruction algorithms [11], the filtered-back projection (FBP) algorithm is the major AR algorithm and the algebraic reconstruction technology (ART) is the major IR algorithm [12]. The research of this paper is based on a hyperspectral CT system that can subdivide energy spectra. The X-ray of different energy channels was measured by CdTe detector. FBP algorithm and ART algorithm were used for X-ray spectral reconstruction, so as to realize the analysis of the structure and composition of complex materials and achieve the purpose of identifying different substances. The traditional CT algorithm is based on the assumption that the X-ray source is a single energy. In the case of single-energy X-ray, the intensity of X-ray decreases with the thickness of the object in the natural exponential form, and the attenuation coefficients are different constants for different material [13]. However, in practical applications, because a low-energy photon reduces much more than a high-energy photon when penetrating objects, the resulting hardening effect has an effect on the quality of the reconstructed image, resulting in a goblet like wake [14]. In this paper, beam-hardening correction (BHC) was used to correct the effect of hardening effect on the basis of FBP algorithm and ART algorithm, and the advantages and disadvantages of these algorithms in spectral CT reconstruction and material identification were compared.

2. Experimental

In the experiment, ten kinds of plastics were selected as samples, and the X-ray absorption spectrum data were collected by the X-ray absorption spectrum nondestructive testing device, and the standard spectral database of the samples was established. And then the ten kinds of plastics were packaged as a complex sample. In the absence of an internal structure, the experimenter analyzed the structural information and component information of the complex sample by X-ray spectral reconstruction algorithm.

2.1 X-ray absorption spectrum nondestructive testing device

X-ray absorption spectrum nondestructive testing device based on X-ray absorption and scattering theory, the main parts are the control part and the operation part, as shown in Figure 1. The control part includes three axis servo motion controller produced by Beijing saifan photoelectric, XRB type high voltage power supply produced by Wiseman company and industrial control host. The operation part includes X-ray tube, CdTe detector, translation table, rotation table, light path positioning laser, optical platform, monitor camera, external interlocking travel switch, intelligent temperature controller assembly, display screen and so on. Among them, X-ray tube produced by the Shanghai Keyiwei electronics, model KYW800; CdTe detector produced by the United States Amptek company, model X-123. The operation part is placed in the lead room, so as to avoid radiation leakage, thus protecting the safety of experimenter. High voltage power supply supplies power to the X-ray tube, providing up to 80kV of voltage. The three axis servo platform and the light path positioning laser are used to adjust the space position of the detector and the sample to be measured and to correct the X-ray path.
Figure 1. The schematic diagram of X-ray absorption spectrum nondestructive testing device

2.2 Data acquisition

2.2.1 Standard spectral database of samples

As shown in Table 1, ten plastics are selected as samples to be tested. In order to establish the standard database, the X-ray absorption spectra of the ten kinds of plastics were collected separately. Place the sample on the rotation table and adjust the distance between the center of the rotary table and the radiation source to 490 mm. The distance between the detector and the center of the rotary table is 100 mm. The voltage of the high voltage power supply was set to 60 kV, the tube current was set to 9 μA, and the filament current as 1020 mA. The spectra of each plastic were collected forty times and then averaged as the standard absorption spectrum of the plastic in the database, as shown in Figure 2.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
<th>Molecular formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
<td>(C8H8·C4H6·C3H3N)n</td>
</tr>
<tr>
<td>SG</td>
<td>Silica Gel</td>
<td>mSiO2·nH2O</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet Resin</td>
<td>(C20H30O6)n</td>
</tr>
<tr>
<td>PES</td>
<td>Polyethersulfone resin</td>
<td>(C12H8O3S)n</td>
</tr>
<tr>
<td>POM</td>
<td>Polymethyl methacrylate</td>
<td>(CH2O4)n</td>
</tr>
<tr>
<td>PPR</td>
<td>Polypropylene Random</td>
<td>(C2H4·C3H6)n</td>
</tr>
<tr>
<td>PSU</td>
<td>Polysulfone</td>
<td>(C27H22O4S)n</td>
</tr>
<tr>
<td>PU</td>
<td>Polyurethane</td>
<td>(C10H8N2O2.C6H14O3)n</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
<td>(C2H3Cl)n</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene Fluoride</td>
<td>(C2H2F2)n</td>
</tr>
</tbody>
</table>

Figure 2. The standard absorption spectrum of the plastic in the database
2.2.2 Spectrum CT scan of the complex sample

The detector receives a diameter of 9 mm and has a copper cap with a diameter of 0.8 mm on the detector. The role of the copper cap is to limit the size of the pixel and can weaken the X-ray scattering to make the measurement of the absorption spectrum more accurate, also play the role of alignment. Two light path positioning lasers are used for positioning, one of which points to the horizontal direction and the other points to the vertical direction. The intersection of the two rays is the intersection of the X-ray tube and the detector. In the experiment, the sample placed in the intersection of two lights so that ensure the sample is within the scanning range. The sample maker wrapped the ten samples in a yellow tape, and the experimenter who without knowing the internal structure analyzed the structure and composition information of the complex sample. The system parameters for measuring complex samples were consistent with the system parameters when building the standard spectral database. The CdTe detector was fixed on the translation table, the stroke of the translation table is 160 mm, and the number of steps of the translation table is 41. When the detector moved one step, the sample was rotated 36 times, each rotated by 10 degrees, resulting in 36 sets of projection data. After collecting, 41 multiplied by 36 projection data were obtained.

3. Data processing methods

The first step of the data processing is to add the reading value of each channel of the spectrum measured by the detector as its gray value to reconstruct the image. And then find the area covered by each material in the image, the coordinate information of the region is used as the input to reconstruct the hyperspectral. Finally, the correlation test is used to realize the material identification.

3.1 Image reconstruction

In the process of image reconstruction, the absorption spectrum values of all channels were added as the gray values and then obtained projection data. The projection data was used as input and the FBP was used to reconstruct the complex sample section image, as shown in Figure 3(a).

![Image](Figure 3. Information of position from the reconstructed image (a) reconstructed image (b) internal structure of sample)

According to the reconstructed image, the internal structure information of the object can be obtained and provides coordinate information for the spectral reconstruction. As can be seen from Figure 3, the section of the complex sample is represented by ten circles with the same diameter, and the ten circles are numbered to get the location information of each circle, as shown in table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
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<td>X axis</td>
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<td>16</td>
<td>24</td>
<td>10</td>
<td>17</td>
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<td>Y axis</td>
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<td>31</td>
<td>13</td>
<td>18</td>
<td>22</td>
<td>27</td>
<td>7</td>
<td>11</td>
<td>17</td>
</tr>
</tbody>
</table>
3.2 Spectral reconstruction and material identification

For each channel of the absorption spectrum, the absorption spectrum of the target position can be obtained by taking the number of channels as abscissa and the gray value of the target position by reconstructing as ordinate. As shown in Figure 4, the absorption coefficients corresponding to each channel can be obtained from the reconstructed image of the corresponding channel when the pixel M is reconstructed.

The relation between the number of channels and the energy of X-ray was obtained by least square method:

\[ E = K(c + A) \]  

(1)

where, \( E \) is energy of X-ray, \( c \) is the number of channels, and \( K \) and \( A \) are coefficients \(^{[15]}\). After fitting by the measured value, \( K=200.7639 \), \( A=-0.3561 \). In the spectral reconstruction, four kinds of reconstruction algorithms were adopted: filtered-back projection (FBP), algebraic reconstruction technique (ART), filtered-back projection with hardening correction (FBP-HC) and the algebraic reconstruction technique with hardening correction (ART-HC), and the constructed spectra were normalized to Maximum-Minimum Standard.

FBP processes the projection data at first and then does the back projection reconstruction:

\[ f(x, y) = \int_{-\infty}^{+\infty} p(t, \theta) \ast h_{S-L}(t) \, d\theta \]  

(2)

where, \( f \) is the density function to be solved, \( p \) is the projection data at step \( t \) and angle \( \theta \). The S-L filter was used here:

\[ h_{S-L}(nT) = -\frac{2}{\pi^2T^2(4n^2-1)} \]  

(3)

Iterative reconstruction constructs the spectrum by solving the equations by ART, which are iterated over several times until the criterion is required. The process of ART can be divided into seven steps:

a) Initialize the unknown image vector:

\[ \hat{X}_j = \hat{X}_j^{(0)}, \quad (j = 1, 2, 3, ..., N) \]  

(4)

b) Calculate the equation i, that is, the estimated projection value of ray i:

\[ p_i^* = \sum_{j=1}^{N} W_{ij} X_j^{(0)} \]  

(5)

c) Calculate the error, that is, correction artifact:

\[ \Delta_i = p_i - p_i^* \]  

(6)

d) Calculate the corrected values of the first pixel j:
\[ V_i = \frac{(p_i - p_i^*)}{N_i} * \omega_i \]  

(7)

where \( N_i \) is the total number of pixels which the ray \( i \) passing through.

e) Calculate the corrected vectors of the first pixel \( j \):

\[ X_j = X_j^{(0)} + V_j \]  

(8)

f) Insert the previous corrected vectors into the next equation, and repeat step b) to step e), so that all the rays of all the images in the loop are completed, which means that a round of iteration has been completed.

g) The iteration results of last round as the initial value, and repeat step b) to step e) can get to the results of \( K \) round. If the results meet the requirement of convergence, that is, there is a positive integer \( K \) for a given very small positive \( \epsilon \), so that when \( k > K \), there is:

\[ |X_j^{(k)} - X_j^{(k-1)}| < \epsilon, \quad (j = 1, 2, 3, ..., N) \]  

(9)

In order to eliminate the effect result by the hardening effect on the reconstruction results, a simple exponential decay fitting method was adopted [13]:

\[ I = I_0 e^{-\mu x^\alpha} \]  

(10)

where, \( I_0 \) is the intensity of the ray passing through the object, \( I \) is the ray intensity after the object, \( \mu \) is the linear attenuation coefficient, \( x \) is the thickness of object, \( n \) is the hardening correction factor. When \( n \) takes different values, the degree of hardening correction is different, and the effect of the reconstructed image is different.

The recognition process used correlation test method. The reconstructed spectral \( A \) was compared with the corresponding spectral \( B \) in the standard database. When the correlation coefficient is the minimum, the nearest the two spectrum is, the material in the region is determined to be the kind of plastic.

\[ \text{dist}(A, B) = \sqrt{\sum_{i=1}^{n} |A_i - B_i|^2} \]  

(11)

4. Results and discussion

4.1 Optimum parameters of hardening correction

In eq. (10), when the correction parameter \( n \) takes different values, it means that the degree of hardening correction is different and the effect of reconstruction is also different. The core parameter \( n \) in the exponential fitting method is related to the voltage of X-ray tube and the material composition of sample under test. For this complex sample, the optimal parameters \( n \) was determined by the effect of image reconstruction. As shown in Figure 5, when \( 0 < n < 1 \), the effect of reconstruction is blurred because the corrected direction deviates from the actual value. When \( n = 1 \), that is, without hardening correction, the effect of reconstructing the image is normal. With the increasing of \( n \), the effect of reconstruction in \( n=1.2 \) is obviously better than the without hardening correction. When \( n>1.5 \), the image is over corrected.

Figure 5. Different reconstructed images when adopt different hardening correction factors
4.2 Comparison of spectral reconstruction algorithms

Four spectra were obtained by reconstructing the spectrum of SG (a substance in the complex sample) through four algorithms, as shown in Figure 6. Compared with the actual spectrum (curve SG), the reconstructed results are similar to the curve SG. The reconstructed spectra after hardening correction are closer to the actual value relative to those without hardening correction. The correlation test was used to analyze the accuracy of different algorithms in material identification, and the average time needed to reconstruct a spectrum was recorded, as shown in Table 3. The FBP algorithm has a shortest reconstruction time, but the accuracy of the reconstruction results is the worst. The ART algorithm has a high accuracy, but the reconstruction is time-consuming. The introduction of the hardening correction algorithm will increase the reconstruction time, but the accuracy of the reconstruction results can be greatly improved.

![Figure 6. The spectrums of SG in database and reconstructed by four reconstruction algorithms](image)

Table 3. Comparison of reconstruction accuracy and reconstruction time of four algorithms

<table>
<thead>
<tr>
<th>algorithms</th>
<th>FBP</th>
<th>FBP-HC</th>
<th>ART</th>
<th>ART-HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>50%</td>
<td>80%</td>
<td>80%</td>
<td>100%</td>
</tr>
<tr>
<td>Reconstruction time</td>
<td>2094</td>
<td>2310</td>
<td>8272</td>
<td>8757</td>
</tr>
</tbody>
</table>

5. Conclusions

A complex sample that unknown internal structure and component was used as experimental sample in this study and the projection data containing multiple spectral channel information were obtained by spectral CT scanning of the complex sample. The structure of the sample was analyzed by CT reconstruction of the projection data, and the position coordinate information of the region of interest (ROI) was obtained. The spectral reconstruction was carried out according to the projection spectrum data and the location coordinate information of the ROI. The reconstructed spectral and standard spectral databases were used for correlation tests to determine component information of the complex sample. By comparing FBP and ART algorithms of spectral CT, and considering the influence of hardening effect in the algorithm, the recognition accuracy of ART was higher, but its operation speed was slow, the operation of FBP was speed, but the recognition accuracy was relatively low. From the experimental results, the ART-HC algorithm can effectively identify the components of the sample. The study can effectively analyze the structural and component of an object under the premise of no damage to the object, which has a good prospect in biomedical and nondestructive testing.
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References

11. Hartmann, Ulrich; Seume, JoergR. Combining ART and FBP for improved fidelity of tomographic BOS[J]. Measurement Science and Technology, 2016, 27(9):097001