3D Interpolation Method for CT Images of the Lung

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ABSTRACT

A 3-D image can be reconstructed from numerous CT images of the lung. The procedure reconstructs a solid from multiple cross section images, which are collected during pulsation of the heart. Thus the motion of the heart is a special factor that must be taken into consideration during reconstruction. The lung exhibits a repeating transformation synchronized to the beating of the heart as an elastic body. There are discontinuities among neighboring CT images due to the beating of the heart, if no special techniques are used in taking CT images. The 3-D heart image is reconstructed from numerous CT images in which both the heart and the lung are taken. Although the outline shape of the reconstructed 3-D heart is quite unnatural, the envelope of the 3-D unnatural heart is fit to the shape of the standard heart. The envelopes of the lung in the CT images are calculated after the section images of the best fitting standard heart are located at the same positions of the CT images. Thus the CT images are geometrically transformed to the optimal CT images fitting best to the standard heart. Since correct transformation of images is required, an Area oriented interpolation method proposed by us is used for interpolation of transformed images. An attempt to reconstruct a 3-D lung image by a series of such operations without discontinuity is shown. Additionally, the same geometrical transformation method to the original projection images is proposed as a more advanced method.

Keywords

X-ray CT Image, 3D Reconstruction, Lung, Heartbeat, Geometric Transformation, Area Oriented Interpolation.

1. INTRODUCTION

After the advent of practical use of X-ray CT (X-ray computed tomography) 30 years ago, further improvement in the ability to check and examine precision has been achieved compared with the X-ray film which is merely an image projection. The X-ray CT technique was reborn as a digital X-ray system, DR (Digital radiography) about 20 years ago and introduction of practical image processing system to the medical field began. Moreover, at present, seeking a highly efficient and more precise examination system, the technique development is advancing both in software technique for the more advanced analysis and in hardware technique, such as high-speed X-ray CT technique and the helical scan X-ray CT method.

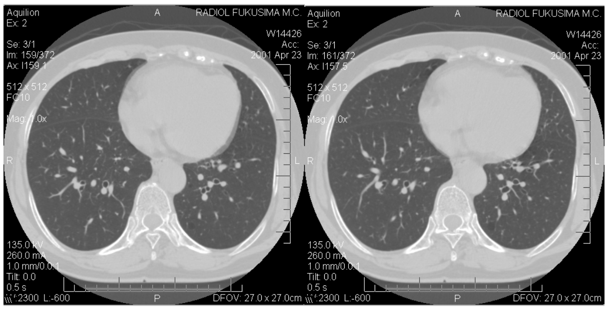
For example, in the helical X-ray CT equipment in Fukushima Medical University, numbers and intervals of the multi-slice CT section images can be set to arbitrary values in the imaging area of 30 cm, for example, 0.5 mm intervals or 3.0 mm intervals.

On the other hand, the more the number of images increases, the longer photography time takes and the more the patient load tends to increase. Also, there appear new problems such as distortion, dimming and aberration which were not problems in the past level of precision.

If these problems are addressed by image processing technique, this new X-ray CT technique should become a more advanced and progressive medical technique.

2. THE X-RAY CT IMAGES OF THE LUNG

Fig. 1 shows parts of X-ray CT images of the lung taken with 0.8 mm interval by the helical X-ray CT equipment in Fukushima Medical University.



(a) (b)

Fig.1 Examples of the X-ray CT images of the lung.

Motion of the beating of the heart is seen as thin shadow like duplex exposure film in Fig.1 (a). The upper and the right side of the photograph are correspond to the front and the left side of the body, respectively.

In this example, the heart and the lung appear together and especially in Fig.1 (a), motion of the beating of the heart is seen as thin shadow like a duplex exposure photograph.
The lung moves as the heart beats because the lung is considered to be an elastic body and the inside boundary of the lung touches the heart.
Bronchi can be seen in inside the lung in Fig.1.

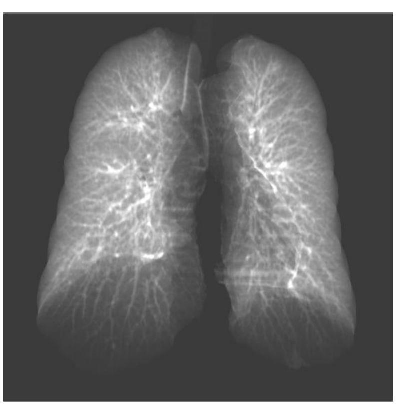


Fig.2 A perspective view of the lung reconstructed from CT images.

A perspective view of the lung is shown in Fig.2, which is reconstructed from these CT images. The original CT image corresponds to a horizontal section image of the lung in Fig.2.
Bronchi in Fig.1 connect continuously to one another in Fig.2 and it is easy to understand the expanse and the distribution of the bronchi inside the lung.
However, an unnatural bending shape of bronchi can be seen especially near the lower part of the heart. This phenomenon is interpreted as the transformation of the lung caused by the beating of the heart is appeared only in some specific CT images. Also, unnatural horizontal striped shadow patterns can be seen in Fig.2, which seems to correspond to the specific CT images.
Actually, such unnatural transformation, discreteness and shadow might interfere with correct examination, when a doctor examines through X-ray CT images and/or 3D solid images.
Also in case of operation, these factors might cause difficulties in confirmation of the operation position or position relations.
Therefore, the amount of transformation by beating of the heart is detected and the outline shape of the heart is transformed to fit to the shape of the standard heart when still.
Next, the inside of the lung in the CT image plane is transformed proportional to the length from costa to the outline shape of the heart. An area oriented interpolation method [1][2][3] which gives rise to few errors is used for interpolation accompanied with this transformation. A 3D solid image is reconstructed from the interpolated CT images that replace the original CT images.

Outline fitting of the heart

Both the change of the beating of the heart and the transformation of the lung corresponding to the motion of the heart are 3D motions. If the motion, the strength and the order of myocardium and physical properties of the heart and the lung can be known completely, it is a theoretically solvable problem; but this is not a realistic expectation.
Moreover, since the right lung is hardly transformed due to the position of the heart, left side of the body, only the left lung is interpolated in this paper.
The motion and transformation is assumed to be planar motion in each CT image plane because of too much unknown information, where this assumption is a lack of strictness.
Also, the motion of the heart is assumed to be only radial from the central point of the heart in each CT image plane. The radius of the heart in each CT image plane to each specified angle measured under these two assumptions is shown in Fig.3

It is clarified by Fig.3 that in case like a duplex exposure image like Fig.1 (a) the outward radius is at almost maximum radius, while the simple exposure does not always show a stationary minimum condition.
Therefore, the outline shape of the heart to be fitted is set to the inner and the minimum side envelope of each graph in Fig.3.

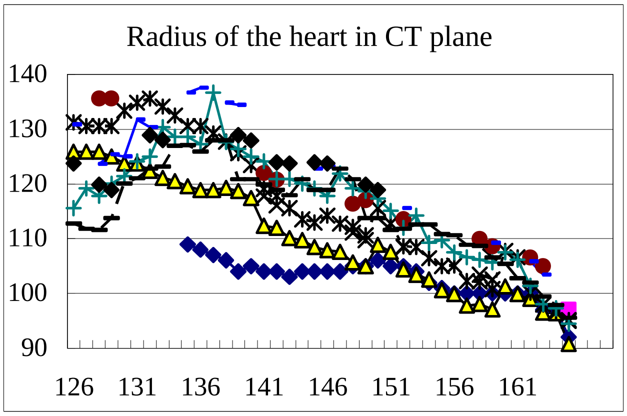


Fig.3 The radius of the heart in pixel unit measured in each direction of clock-wise angle from horizontal line in each CT image, where horizontal axis denotes the CT film number.

Transformation of lung

The transformation of the lung corresponding to the heart beating is three-dimensional, because the lung is an elastic body placed among heart, costa and the diaphragm. However, it is very difficult to detect the change of the three-dimensional transformation of the lung at each pulsation timing of heart beating because existing X-ray CT images have no timing relation between upper and lower images and no synchronization to the heart beating.
Therefore, transformation of the lung is also assumed to be only two-dimensional in each CT plane and compression and extension motion is only in radial direction from the central position of the heart, as the third assumption in the previous paragraph.
This assumption means "Transformation of the lung is only radial from the heart center and amount of transformation is proportional to the distance from the boundary next to the costa toward the direction to the heart center." In the present situation, duplex exposure image is not fixed but transformation of the lung is fixed simply based on this assumption.

3. AREA ORIENTED INTERPOLATON

In digital image processing, more advanced information can sometimes be gotten by synthesizing a different image or by comparing numerous images with one another. Each image is generally registered by Affine transformation, i.e., transformation operation such as parallel motion, rotation, expansion and reduction. Each pixel value of the Affine transformed image is re-calculated through interpolation, because the position of the sampling point after Affine transformation is different from the original point in general. The Affine transformed values are used to be given by the traditional interpolation method such as the nearest neighborhood interpolation method, the bi-linear interpolation method and the cubic convolution interpolation method.

One-dimensional analysis of digital data

An example in which an analog function $f(x)$ is sampled or quantized to digital data $f(x_i)$ is considered.
In case of voltage measurement, the value $f(x_i)$ denotes the instantaneous value of the sampling time x_i, where time for sampling dx_i is sufficiently short compared to the sampling interval $x_{i+1}- x_i$.
On the other hand in case of image data, the value $f(x_i)$ denotes integral or average value of the section represented by x_i with section width $dx_i = x_{i+1}- x_i$.

$$f(x_i) = (F(x_i + dx_i/2) - F(x_i - dx_i/2)) / dx_i \qquad (1)$$

In Eq. (1) F(x) denotes integration of $f(x)$.

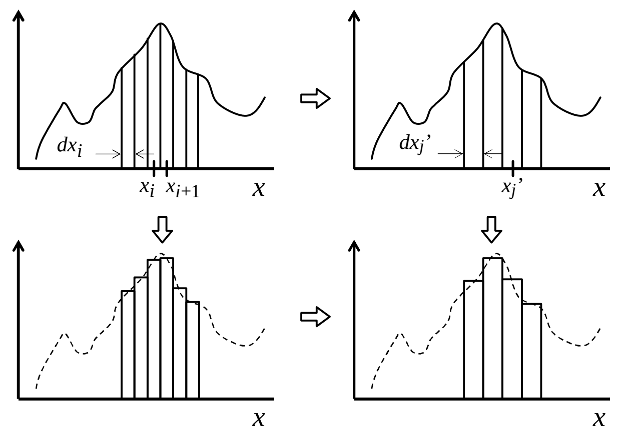


Fig.4 The sampling value of image data denotes integral or average value of the sampling section.

In case of Affine transformation, the represented points are re-sampled, and x_i and dx_i are changed to x'_j and dx'_j, where $dx'_j = x'_{j+1} - x'_j$.

$$f(x'_j) = (\mathrm{F}(x'_j + dx'_j/2) - \mathrm{F}(x'_j - dx'_j/2))/dx'_j \qquad (2)$$

Usually as there are only discrete image data $f(x_i)$, integration function $\mathrm{F}(x)$ is of course unknown.

Eq. (2) is integrated in a general Affine transformation case where boundary of x'_j+- $dx'_j/2$ of transformed pixel x'_j are in the region of x_n and x_m of the original pixel x_i, respectively.

$$\begin{aligned} f(x'_j)dx'_j &= \mathrm{F}(x'_j + dx'_j/2) - \mathrm{F}(x_n - dx_i/2) + \mathrm{F}(x_{n-1} + dx_i/2) \\ &\quad - \mathrm{F}(x_{m+1} - dx_i/2) + \mathrm{F}(x_m + dx_i/2) - \mathrm{F}(x'_j - dx'_j/2) \\ &= \mathrm{F}(x'_j + dx'_j/2) - \mathrm{F}(x_n - dx_i/2) + f(x_{n-1})dx_i + \quad \sim \\ &\quad + f(x_{m+1})dx_i + \mathrm{F}(x_m + dx_i/2) - \mathrm{F}(x'_j - dx'_j/2) \\ x_n - dx_i/2 &<= x'_j + dx'_j/2 <= x_n + dx_i/2 \\ x_m - dx_i/2 &<= x'_j - dx'_j/2 <= x_m + dx_i/2 \end{aligned} \qquad (3)$$

The unknown integration in Eq. (3) can be replaced by the trapezoidal formula in numerical integration.

$$\begin{aligned} &\mathrm{F}(x'_j + dx'_j/2) - \mathrm{F}(x_n - dx_i/2) \\ &\qquad = f(x_n)((x'_j + dx'_j/2) - (x_n - dx_i/2))/dx_i \\ &\mathrm{F}(x_m + dx_i/2) - \mathrm{F}(x'_j - dx'_j/2) \\ &\qquad = f(x_m)((x_m + dx_i/2) - (x'_j - dx'_j/2))/dx_i \end{aligned} \qquad (4)$$

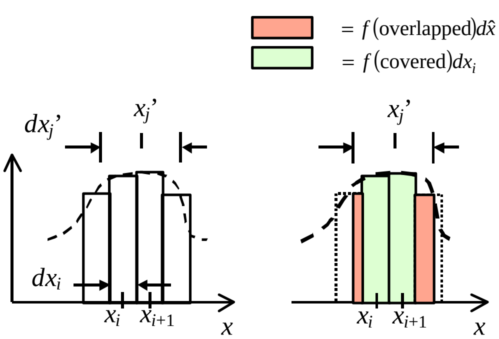


Fig.5 The interpolated value in one-dimensional AOI is calculated as weighted summation with weight function of sampling width of overlapped area.

Finally newly re-sampled values can be obtained by Eq. (5).

$$\begin{aligned} f(x'_j)dx'_j &= f(x_n)((x'_j + dx'_j/2) - (x_n - dx_i/2))/dx_i \\ &\quad + f(x_{n-1})dx_i + \quad \sim \quad + f(x_{m+1})dx_i \\ &\quad + f(x_m)((x_m + dx_i/2) - (x'_j - dx'_j/2))/dx_i \end{aligned} \qquad (5)$$

The interpolation method calculated by Eq. (5) is called by Area Oriented Interpolation (AOI) method.

Although traditional interpolation methods give good results, they correspond to the case in which dx_i is negligibly small compared to sampling interval x_{i+1}- x_i mentioned above and their points of view are fundamentally different from Eq. (2). Clear differences between Eq. (5) and the traditional interpolations occur in two cases; when positions of re-sampled points are very close to peak values, maximum or minimum, and in a binning process.

Two-dimensional interpolation method for image data

The one-dimensional interpolation method of Eq. (5) is easily extended to a two-dimensional interpolation method:

1) Get coordinates of the four corners belonging to the re-sampling point projected on the original image plane.
2) Calculate overlapped areas of re-sampling pixels on the original image plane and center of gravity of the overlapped areas. Each overlapped area A_i of overlapped pixels on the original image plane is calculated, where ith pixel value of the original image is f_i
3) Calculate values of re-sampled pixels, where the value of the re-sampled pixel is given by the equation (sum of $\mathrm{A}_i f_i$)/(sum of A_i).

The pixel value $f(x_n)$ at the center of gravity of the overlapped pixel area on the original image is adopted by the three traditional interpolations mentioned above, and we named these as Area oriented interpolation; AOI, Area oriented bi-linear interpolation; AOI-Linear, and Area oriented cubic convolution interpolation; AOI-Cubic, respectively.

Effectiveness and applications of AOIs

Each traditional interpolation method has a characteristic, merit and demerit; although computation is very easy, distortion is conspicuous in the nearest neighborhood interpolation method, the bi-linear interpolation method gives smooth but dimmed image while the cubic convolution interpolation method gives high-contrasted and clear image with plenty of computation amount.

Comparing differences between AOIs and the traditional methods through a simulation of sample images, only a slight difference can be seen at a glance and each AOI keeps characteristics of the original interpolation method. In the differential images between transformed images and the original image, subtle changes in contrast can be seen in the traditional interpolation methods, while the difference can be hardly seen in AOIs, especially in AOI-Cubic.

Also in detailed analysis, roughness and chapping can be seen in boundary part of the changing picture and subtly changing texture in the traditional method but hardly seen in AOIs.

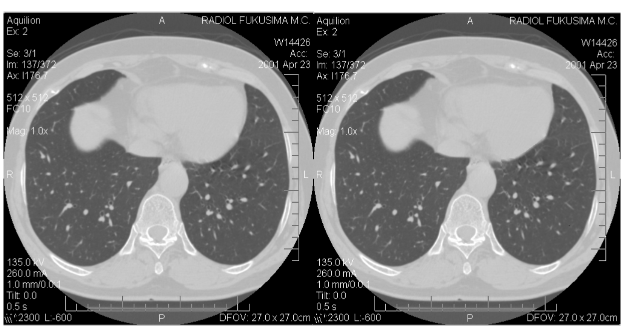
One dimensional AOI described in section 3 is very useful for spectrum analysis, facsimile data correction and so on.

It is not necessary to mention about usefulness of AOIs to all kind of two-dimensional image data transformation.

In case of three-dimensional surface image, such as texture on the wire frame model or the polygon model, the relationship between the original textured image and the transformed projection image should be clarified by the perspective projection transformation. After that, AOI gives a smooth and realistic view in the same process with two-dimensional AOI.

For three-dimensional image like reconstructed inner model of the human body from CT images, the center of gravity position and volume of the overlapped voxel is used instead of area in AOIs. The transformed value is calculated from summation of each brightness at the center of gravity weighted by each overlapped voxel volume. After the same treatment as the two-dimensional image, the three-dimensional image is transformed by AOIs theoretically and adequate precision is expected.

4. CT IMAGE OF THE LUNG AFTER TRANSFORMATION



(a) (b)

Fig.6 An example of the transformed lung CT image. (a) and (b) are before and after transformation, respectively.

An example of the lung CT image transformed by this method is shown in Fig.6.

The left side heart, the right in the figure, becomes small and the lung becomes big after transformation.

Heartbeat to the back is very strong in the left side of the heart in Fig. 6 (a) and the influence appears as strong oppression transformation on the left side lung near the back, while this unnatural oppression disappears in Fig.6 (b) after transformation by AOI-Cubic method to the assumption position of the still state heart.

No unnatural bends can be seen in Fig.7, a 3-D image reconstructed from the transformed CT images.

Fig.7 A perspective view of the lung reconstructed from the transformed CT images.

5. INTERPOLATION WITHIN PROJECTION IMAGES

Although the shapes of the bronchi have been interpolated in the transformation result in the previous paragraph, the duplex exposure structure which is accompanied by the heartbeat as in Fig. 1 (a) has not yet been removed.

When producing CT images, projection images from each direction are taken in all directions (Radon transform). The duplex exposure structure is understood as a so-called partial volume effect which is caused by size dependences of the heart on direction due to the heartbeat at this time.

Since it is easy to separate the edges of the heart from other edges in the projection image, the outline of the heart is extracted from the projection image first. Then, the shape of the heart, consistent in all directions with no partial volume effects in the projection images, is found and transformed. Next, the lung projection image in each direction is interpolated based on the outline of the heart in the same way as in section 2; each part’s distance from the costa is transformed in proportion to the ratio of the length between the costa and the heart transformed before and after. After that, each CT image can be produced by inverse Radon transform from the projection images.

Both the outline of the heart and the shapes of bronchi should be automatically interpolated in the CT images.

6. REMAINING PROBLEMS AND FUTURE WORK

Since it is difficult to obtain the original projection (Radon transformed) images, the new more advanced interpolation method has not been completed yet. The proof and the effectiveness of this interpolation may be shown in the future.

Transformation of the lung accompanied by heartbeat is essentially three-dimensional as described in section 2. As the heart expands, the lung is compressed in the radial direction and is extended spherically around the heart at the same time. This extension transformation is not limited in the CT image plane but appears in the upper and/or the lower CT image plane.

In addition, quantification of these transformations is not only difficult at present but also impossible theoretically without synchronization with heartbeat.

A duplex exposure image can possibly quantify the extension transformation within a CT image. When the heart image is taken twice, the lung image is considered to be taken twice simultaneously and the exposure amount is considered to be proportional. If the whole image can be analyzed by the duplex exposure function, it is theoretically possible to analyze the quantity and the direction of the transformation at each point inside the lung.

Regrettably, it was difficult to detect a duplex exposure function in the CT image this time and the above contents could not be confirmed and will be examined in a forthcoming case study.

7. ACKNOWLEDGEMENT

We thank to Dr. Hiroshi Moriya, an associate professor of Fukushima Medical University very much for the provision of X-ray CT images and useful advice from the medical standpoint.

This study is funded by the Ministry of Land, Infrastructure and Transport, Japan as the project “The mutual cooperation among prefectural universities and so on in Tohoku region” promoted by Tohoku Development and Research Center, Japan.

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