Title:
Fast Imaging Processing applied to Respiratory Gated Radiotherapy Using 4D CT

Authors:
Po-Jyun He, fcf08239527@gmail.com, National Chung Cheng University
Jyun-Syuan Huang, gs1458@gmail.com, National Chung Cheng University
Hong-Tzong Yau, imehty@ccu.edu.tw, National Chung Cheng University

Introduction:
In this research, we develop a respiratory gated radiotherapy system by fast image processing for solving the tumor position uncertainty problem that is caused by human chest expansion due to breathing. Traditional radiotherapy can only predict the tumor position by indirect external information that is inaccurate. This system uses internal marker of diaphragm contour extracted from X-ray fluoroscopy and can simulate the radiotherapy based on 4D CT data and the dynamic 3D model generated by the DICOM-RT information. We can show by 3D simulation and 4D animation that the radioactive treatment is on only when the diaphragm is within the active range that links directly to the accessible tumor positions.

In this study, through the Marching Squares algorithm, the user can extract diaphragm contour at the instant, and generate the radiation projection range by movement of the diaphragm contours at different times. Finally, using FAST algorithm allows us to determine whether the diaphragm contour extracted from the visual X-ray image is in the radioactive range. We can use the Marching Cubes algorithm to reconstruct the 3D model of tumor extracted by adaptive region growing from the 4D CT images. More information such as the bone, the skin model, the liver and the heart, can be extracted from DICOM-RT for simulating the complete radiotherapy.

Related work:
According to the statistics of Taiwan's Ministry of Health and Welfare, cancer remained the top of ten major death causes from 2013 to 2015. Among different cancers in Taiwan, lung cancer and liver cancer are ranked the first and the second. To deal with cancer, there are three common treatment methods including surgery, radiation therapy and chemotherapy. According to different position and spreading speed of the cancer tumor, the doctor will choose a suitable treatment method or a combination of different methods. In general, surgery is used to treat the tumor that grows slowly and has not spread into surrounding tissues, radiation therapy to treat the tumor that grows quickly and spreads into surrounding tissues, and chemotherapy to treat the tumor around the human body.

For radiation therapy of lung cancer or liver cancer, the doctor plans the treatment process from the computer tomography image of the patient before the therapy, but patient respiration causes the cancer tumor to move from place to place during the radiation therapy, so the doctor needs to use a respiratory gated radiation process to control and improve the treatment effectiveness. Currently, there are two major respiratory gated radiation approaches. The first one is to use the respiratory breathing percentage to assess the tumor position. The second uses a marker placed on the patient's chest to predict the position of the tumor. Both methods are indirect methods and are not accurate in determining tumor positions. Therefore, in this work we develop a new respiratory gated radiation

system assisted by 4D CT medical imaging and real-time respiratory tracking using diaphragm detection. The real-time tracking process, combined with 4D CT data, can more effectively determine the tumor position during the radiation therapy. Using the Marching Cubes algorithm, we can segment organs and tumor from the 4D CT. The doctor not only can plan the radiation therapy but also can simulate the radiation process in 4D (3D plus time) before the therapy.

Main Idea:

The purpose of this research work is to do the respiratory gated radiotherapy based on direct fast image processing. It combines the 4D CT and the DICOM-RT data to calculate the radioactive range; it also performs the simulation of radiotherapy for pre-surgery planning and education training. There are two major parts in the research that includes setting the radioactive range and the real-time respiratory tracking. The proposed process flow is shown in Figure 1.
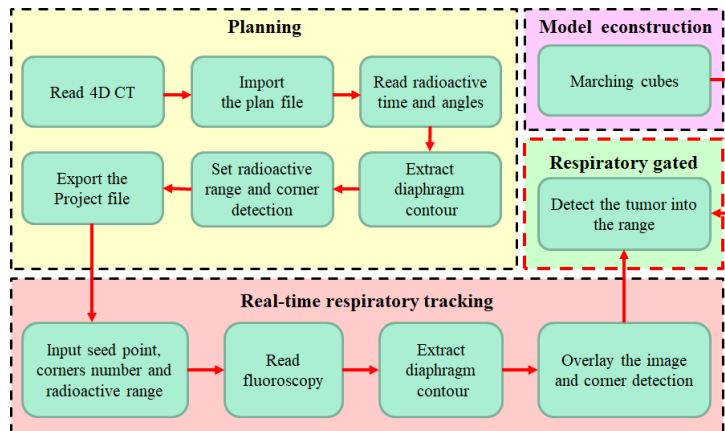
Fig. 1: The proposed system.

Set radioactive range

At first, the user needs to read 4D CT, then reads the DICOM-RT and obtains the radioactive time and radioactive angles, and re-slices the corresponding 4D CT to the corresponding angle, and finally, sets the seed point and uses the marching squares algorithm to get the diaphragm contour. This method is repeated to process other CT images until the two upper and lower diaphragm contours are obtained. The user can use these two diaphragm contours to define the radioactive range and detect the corners of the radioactive range. The software will then export the project file with the position of seed, the position of radioactive range and corner number.

Real-time respiratory tracking

The software reads the project file to get the position of seed, the position of radioactive range, and reads the fluoroscopy (monitoring X-rays during radiotherapy), and then uses the seed point to get diaphragm from fluoroscopy in real-time. Finally, the software compares the diaphragm with the radioactive range to determine if the diaphragm is in the radioactive range or not. If it is within the range, the radiation projection is turned on to project at the targeted tumor. The main idea of this work is that the monitoring X-ray image is used to detect and create the real-time diaphragm and compared with the radioactive range obtained by 4D CT. This method is a direct tracking method compared with the traditional indirect methods using external tracking schemes. In the following sections, we will describe the methods in more detail.

The process flow and result of diaphragm segmentation

At first for data preparation, the user needs to read and re-slice the CT data at the specified angle. For the resliced CT image, a seed point and a threshold value are set. Because the diaphragm is between the lung and the liver, and the HU number of lung is -500 and HU of liver is between 40 and 60. So the initial threshold is set at 0 and the initial seed point is located inside the lung area. This setting helps to extract the diaphragm because it properly segments the area between the liver and the lung. The result is shown in Figure 2 (left).

We can reconstruct a 3D model of diaphragm from many diaphragm contours, and use error analysis to determine if the result of segmentation is good. The error calculation is between two models: one is reference model, and the other is compared model. The distance of each point on the compared model to all points on the reference model is calculated, and then the color map of the deviations is shown in Figure 2 (right).
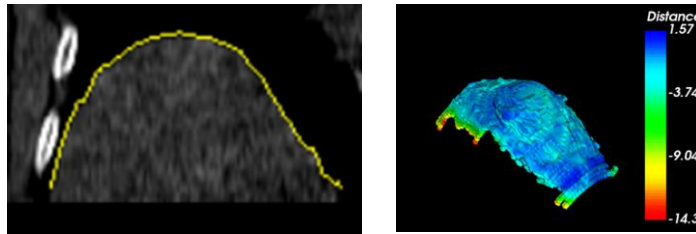

Fig. 2: (Left) Result of diaphragm segmentation. (Right) Error analysis.

Set radioactive range

We can get the treatment time from DICOM-RT, therefore we can extract two upper and lower diaphragms from the CT data corresponding to the respective treatment time covering the radiation projection. Then we can obtain a designated range from those diaphragms. The next is to make sure that during the radiation treatment, the radiation beam is turned on only when the diaphragm from the X-ray fluoroscopy is within the designated range.

Extract the contour of diaphragm from X-ray fluoroscopy

The diaphragm needs to be extracted from the X-ray fluoroscopy in real time. We first use the Otsu algorithm [2] to convert the image to binary (black and white) image. The Marching Squares algorithm is then used to segment the diaphragm between the lung and the liver. The initial threshold value for the Otsu algorithm only needs to be set once in the beginning. The rest of the marching Squares algorithm is highly efficient and it only takes 0.004 second each time. Our calculation of the diaphragm in real time can match well with the 30 FPS of the X-ray fluoroscopy. Figure 3 shows the result of diaphragm segmentation from X-ray fluoroscopy in real time.

Fig. 3: Result of diaphragm segmentation at X-ray.

Corner detection

To detect whether the diaphragm is inside the radioactive range, we need to have a faster scheme by detecting the feature points or corners of the diaphragm. Here we use FAST algorithm [4] which is very efficient for such task. After setting the radioactive range, the corner points will be found. During the respiratory tracking, the software will check the number of corner points to see if it is the same with the pre-planned number and use that to determine whether the diaphragm is in the radioactive range or not.

Real-time respiratory tracking

We export the project file with the corner number, position information of radioactive range and seed point. The user uses the software of real-time respiratory tracking to read the project file, and then it can do the real-time respiratory tracking. The result of tracking is shown in Figure 4 left (The green range is radioactive range from the pre-plan; the red line is the contour of diaphragm from real-time segmentation). The software will combine the diaphragm and the radioactive range to determine whether it is in the radioactive range. If the diaphragm is in the radioactive range, the radioactive range will become yellow. Such result is shown in Figure 4 right.
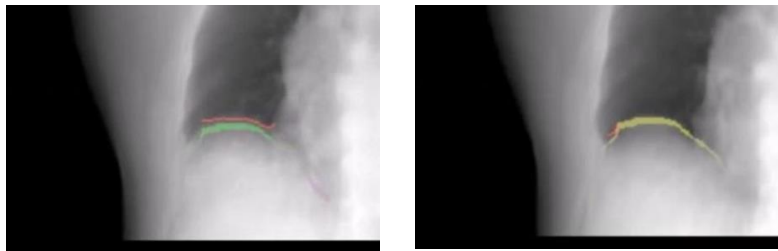

Fig. 4: (Left) Out of radioactive range. (Right) In the radioactive range.

All of the above procedures rely on using X-ray fluoroscopy to do the respiratory gated radiotherapy. Because the speed of taking fluoroscopy is 30 pieces per second, the process time of software needs to meet the requirements. In this work, we utilize the FAST algorithm, together with the Marching Squares algorithm, to extract the contour of diaphragm. The result is very acceptable with the high efficiency of the algorithm and the computation speed.

Reconstruct 4D CT

4D CT is achieved by the addition of the time scale to traditional 3D CT. If we reconstruct a 4D CT model, we can use it to create animation of the chest expansion and the corresponding organ and tumor movement. The 3D and 4D solid models can be constructed by the Marching Cubes algorithm using the CT data. We can combine the radioactive angles from DICOM-RT to simulate radiotherapy. We also can reconstruct the lung, the liver and the heart models from DICOM-RT to be included in the radiotherapy simulation. The simulation can be used for the treatment planning and verification. It links the 3D tumor movement range that corresponds to the radioactive range of the diaphragm. We can use the simulation to verify the treatment planning and also use it to provide training to young resident doctors.

The tumor model, bone model and skin model are reconstructed from 4D CT, and we use red, white and milky white to display them. The result is shown Figure 5 left. The liver model and lung model are reconstructed from DICOM-RT, and we use dark red and pink for display. The transparent green line is the radiation line. The result is shown in Figure 5 right.
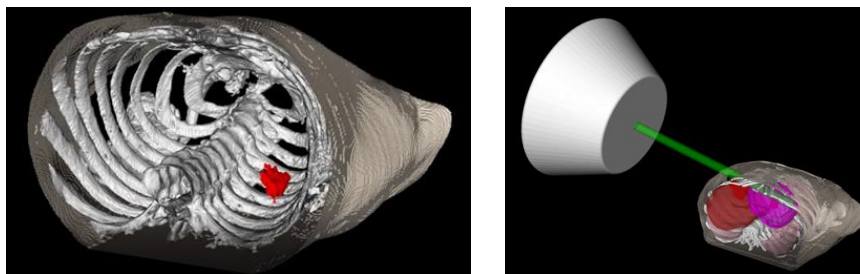
Fig. 5: (Left) Display of tumor, bone and skin model. (Right) Radiotherapy simulation.

Semi-automatic adaptive region growing

For segmentation of tumors, we use the adaptive region growing methods [1,3]. The advantage of this semi-automatic method is that the user just need to set a seed point and the software will calculate the center of gravity and use it as the seed point for the next slice. The software will repeat the same process until the segmentation is finished. The result of tumor segmentation is shown in Figure 6; the result of 3D tumor model is shown in Figure 7.
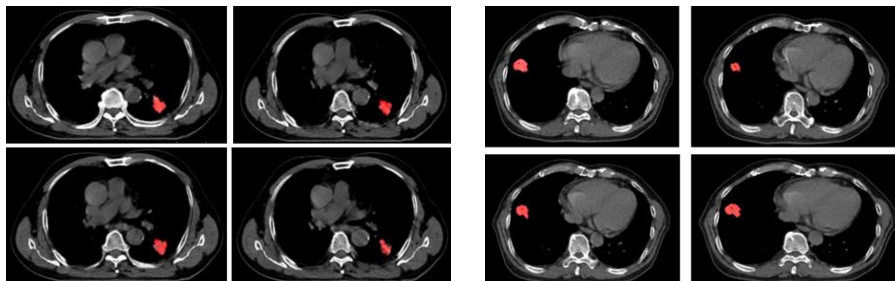

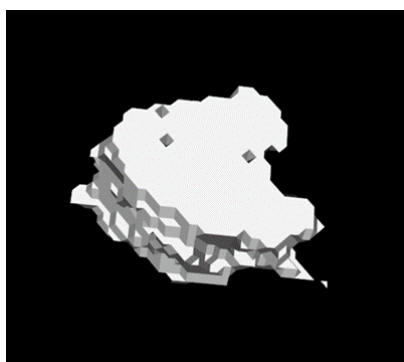Fig. 6: Tumor segmentation.

Fig. 7: Tumor model.

Conclusion:

In this research, we develop a respiratory gated radiotherapy system for treating lung or liver tumor that tends to move their positions due to breathing during the radiotherapy. Instead of indirect external marker, this system uses internal marker of diaphragm contour extracted from X-ray fluoroscopy to predict the tumor positions. In addition, the system can simulate the radiotherapy based on 4D CT data and the dynamic 3D models generated by the DICOM-RT information. We can

show by 3D simulation and 4D animation that the radioactive treatment is turned on only when the diaphragm is within the active range that links directly to the accessible tumor positions. The research methods extensively utilize image processing algorithms and schemes including image segmentation, corner detection and 3D model reconstruction. It uses Marching Squares algorithm and adaptive region growing algorithm on image segmentation; it uses FAST algorithm on corner detection and it uses Marching Cubes on 3D model reconstruction.

This research work improves the problem of external marker uncertainty because the external marker cannot produce the accurate positions of moving tumor due to breathing. Because we use internal marker by fluoroscopy to obtain the information of tumor and organs, we can get better result than using external marker, hence it can reduce the treatment mistake of projecting radiation at healthy organs but not tumors. We reconstruct models from 4D CT, and we use those models to simulate the motion of the tumor and organs. User can easily know their position information at each respiratory state. The treatment information and radiation projection angles are also extracted from the DICOOM-RT. We combine the 3D models and radioactive angles to generate a radiotherapy simulation in which we can show that the radiation projects at the tumor only when the diaphragm is within the radioactive range that the user sets. This, will in turn link to the X-ray fluoroscopy image during the real radiotherapy in real time.

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