

論文の内容の要旨

論文題目 Development of a markerless tumor prediction system using principal component analysis and multi-channel singular spectral analysis with real-time respiratory phase recognition in radiation therapy

(放射線治療におけるリアルタイム呼吸位相認識と主成分分析多チャンネル特異スペクトル解析によるマーカーレス腫瘍動体予測システムの開発)

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This thesis, basically focuses on tracking moving tumors in radiation therapy. The first chapter contains the introduction to the background of this research. Cancer, is increasing yearly in developed countries including Japan. Radiation therapy is one of the widely used treatment modalities. Image guided radiation therapy (IGRT) has played a major role in the precision of radiation therapy especially while tracking moving tumors. Treatment machines are nowadays equipped with x-ray source and its detectors for image guidance which has been an integral part for the simulation, planning, treatment and verification. Confining the radiation to the target and reducing the unnecessary high dose to the healthy tissues still remains a major concern in modern radiation therapy. In the case of moving tumors, the possible reduction of the internal margin becomes absolutely essential. Various strategies have been introduced in order to compensate the tumor motion, beam gating, active or volunteer breath hold, beam tracking, tracking with fiducial or infrared markers etc. Long term breath hold technique lacks the patient comfort and beam gating and beam tracking requires a precise knowledge of the position of the tumor. Gating using infrared or implanted markers have been popular treatment lately where the tumor is irradiated during a certain location. However, there are some disadvantages; a long treatment time due to inefficiency, an uncertainty in the correlation between the target and the marker motion, and invasive procedure for implanted marker. On the other hand, the tumor tracking radiation therapy is currently in applicable phase by means of the development of the image-guidance system. A modern image-guided radiation therapy (IGRT) system has made it possible to monitor the target motion during the external radiation therapy treatment. Most treatment machines are nowadays equipped with one or two kV x-ray source with flat panel detectors with the rotating or fixed gantry and sometimes a

robotic treatment couch for the precise radiation delivery. With such a system, the sight of the tumor location can be adjusted based on the real-time x-ray images.

Even with the real time monitoring there exist a time delay between the beam irradiation and the motion of the target. This is mainly because the adaptive response of a radiotherapy system to a tumor position signal cannot occur instantaneously. Hence the beam cannot follow the target accurately. If the time lag is filled with prediction of tumor position then the treatment beam can eventually follow the target.

Predicting the position of the target in advance is considered as an approach to minimize positioning errors due to time lag in the system. The tumor tracking based on prediction of tumor position or motion using implanted or surface markers has already been introduced. However, the image prediction would be more direct for the lung tumor such that non-rigid deformation occurs due to the significant tumor mobility and elasticity of lung tissue. Also, the predicted image can be used easily to verify the in-treatment accuracy by comparing with planning CT or its digitally reconstructed radiograph. Thus, the image prediction might contribute to the reduction of the internal margin during radiation therapy.

In this research, two different approaches are taken, the first one is the prediction based on principal component analysis (PCA) and multi-channel singular spectral analysis (MSSA). The second approach is the phase recognition based on priorly obtained 4D cone beam CT and the in-treatment images.

In the second chapter, prediction using PCA and MSSA is discussed. PCA or eigen value analysis is a data feature extraction and data representation technique widely used in data analysis and compression. Lung motion model based on PCA has already been reported, which efficiently represents lung motion with few principal components. On the other hand, these models have so far been used only for the image creation, and prediction has not been considered. In this research, as a first approach, a new algorithm is proposed for the prediction of lung motion images. First, a four-dimensional CT (4DCT) image set obtained from a lung cancer patient were examined. The CT image is convenient for the assessment of dynamic image prediction including the information of tumor deformation, however, is not suitable for the real-time prediction because it is currently impossible to acquire the 4DCT images during treatment. Therefore, second, we examined with a kilovolt (kV) fluoroscopic image set, which can be handled in real time. The kV images are the phantom images obtained using a mock tumor, a marker and a linearly driven motion stage phantom. Though this study focuses on markerless tracking, the datas with marker was also obtained for the comparison purpose.

The image prediction algorithm consists of four steps, (i) input image acquisition (ii) principal component calculation using PCA (iii) prediction using MSSA and (iv) image reformation

using PCA. The basic summary of the prediction algorithm is the extraction of pattern using PCA and the prediction by MSSA using the pattern and the present data.

The result obtained for the image prediction in case of patient showed a successful prediction of tumor deformation and motion. The prediction time for the region of interest (roi) was reduced up to 0.12 sec with the cross correlation between the original and the predicted image being more than 0.99 in average. Similar to the patient images, for the case of linearly driven phantom, the prediction was successful in both the cases using the roi as tumor with the marker and tumor without the marker. In both the cases, the prediction accuracy or the correlation coefficient was more than 0.99. The purpose of using the images with the marker was to verify that the algorithm irrespective of marker can predict the motion of the tumor accurately.

The third chapter, includes the phase recognition algorithm. This approach was specifically designed for the Elekta Synergy system a rotating gantry system in the University of Tokyo Hospital and is completely based on the requirement of the medical physicists and oncologists in the hospital. The basic algorithm consists of four parts, (i) acquisition of pre-4DCBCT which is a part of a regular pre-treatment procedures in the hospital. (ii) second step is the reprojection of pre-4DCBCT images to acquire the template images for the ten phases. The first and the second step is performed prior to the treatment starts in the hospital. (iii) the third step is the acquisition of in-treatment projection images. This is also a regular procedure during the treatment in University Hospital. The acquisition of in-treatment images is possible using projection streaming client system provided by the Elekta Synergy. (iv) The fourth and the final step is the matching between the template projected images and the in-treatment images at the same angle. The phase with the highest cross correlation coefficient value is the predicted phase. For our offline analysis, the verification is performed by the angular data obtained by the Amsterdam Shroud technique in the hospital. In case of online, the real-time phase data can be acquired by using the Anzai belt system or other phase recognition methods.

The phase recognition algorithm was performed in the one dimensional respiratory phantom, four dimensional dynamic phantom and the number of patient datas. The patient datas are also classified as the patient treated with the conventional FF (flattening filter) beams with the treatment time of up to 4 min and the FFF (flattening filter free) beams. FFF treatment beams with breath-hold has been recently introduced in University Hospital using Elekta Synergy System, reducing the treatment time from conventional 4 mins to 90 secs (6 MV photon beams).

In all the cases (phantom or patient), the results of template matching between the templates projected images and the in-treatment projection images at more than 94 percent of the angles has shown the phase exactly or closer (± 1 phase) to the actual phase. In less than 6 percent cases, the actual phase is several phase different and lacks the possibility to be the same. As it is a rotational treatment, even in the cases where the tumor is temporarily masked by the high density

structures such as bone and spinal cord the prediction or the phase recognition has been accurate. Initially the quality of images in FFF beams were a major concern however, the results in case of FFF treatment beams indicate not much distortion compared to the traditional FF beams.

The fourth chapter consists of the general discussion and the future prospect of this current research. The general discussion parts includes the explanation about the risk and benefits of the use of diagnostic kV imaging. The transition of this research from PCA/MSSA based to the phase recognition using prior 4D-CBCT. It also explains how different template matching procedures such as mutual information and structure similarity index (SSIM) were used for verification along with the cross correlation coefficient. One of the major part of this chapter is the phase recognition based on planning CT i.e. the 4DCT which is acquired days prior to the treatment. The result indicated that for the planning CT case, the phase recognition result is almost similar to the 4D-CBCT case. However, the use of 4D-CBCT will have higher impact and accuracy as it is acquired on the same day and same position. The chapter concludes with a general summary and future prospects.

This thesis consists of two appendix section, one includes the minor principal component calculation and the other one is the time lag experiment which shows the time lag for the projection streaming client system to display the real-time images.