Development of Accurate/Advanced Radiotherapy Treatment Planning and Quality Assurance System (ARTS)*

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Abstract A prototype of accurate/advanced radiotherapy treatment planning and quality assurance system (ARTS) is developed and key technical issues related to the improvement of the treatment accuracy is studied. After a brief introduction to the prototype of ARTS, the advanced development in key technical issues is presented, including image data processing and human body modeling, fast and accurate hybrid dose calculation, multi-objective optimization of inverse planning, intelligent patient positioning, and dose verification.

Key words radiotherapy, treatment planning system, modeling, hybrid dose calculation, inverse planning, positioning, dose verification

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1 Introduction

The objective of radiotherapy is to kill tumour cells to the utmost with effectively protecting the surrounding organs at risk (OAR) and other normal tissues. A high precise treatment planning and quality assurance system can deliver an accurate dose to the tumour site and reduce the dose received by the surrounding normal tissues. So the curative effect and survival quality can be guaranteed. With the improvement of radiotherapy facility, the need of high precise treatment planning system (TPS) and quality assurance system (QAS) is also increased[1]. In the widely-applied radiotherapy systems, some features should be improved[2—9] , for example, in the following aspects: the dose calculation of the actual heterogeneous patients was simulated approximately by using equivalent homogeneous water phantom; the dose calculation engines, i.e. the pencil beam method (PBM), were not really three dimensional (3D); the optimization algorithms of inverse planning, i.e. mostly iterative or simulated annealing algorithms, ignored the multi-objective characteristic of inverse planning and failed to ensure the global optimum solution; the manual positioning was not only error-prone but also time-consuming; conventional

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dose verification was very difficult to obtain real-time dose distribution and could not correct the dose deviation[10—14].

The FDS Team of ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences) and USTC (University of Science and Technology of China), has performed a lot of research work on the scientific and technical issues to develop the accurate/advanced radiotherapy treatment planning and quality assurance system (ARTS)[14, 15]. A prototype of ARTS has been developed. In this paper, after a brief introduction to the prototype of ARTS in Section 2, the advanced development in key technical issues related to the improvement of treatment accuracy is presented in Section 3, including digital human modeling, fast and accurate hybrid dose calculation, multi-objective optimization of inverse planning, real-time positioning, and real-time dose verification. Finally, a brief summary is given in Section 4.

2 Prototype system description

The framework and technical flow chart of the prototype of ARTS is shown in Fig. 1. The features of each key technical process are given in the following sections.

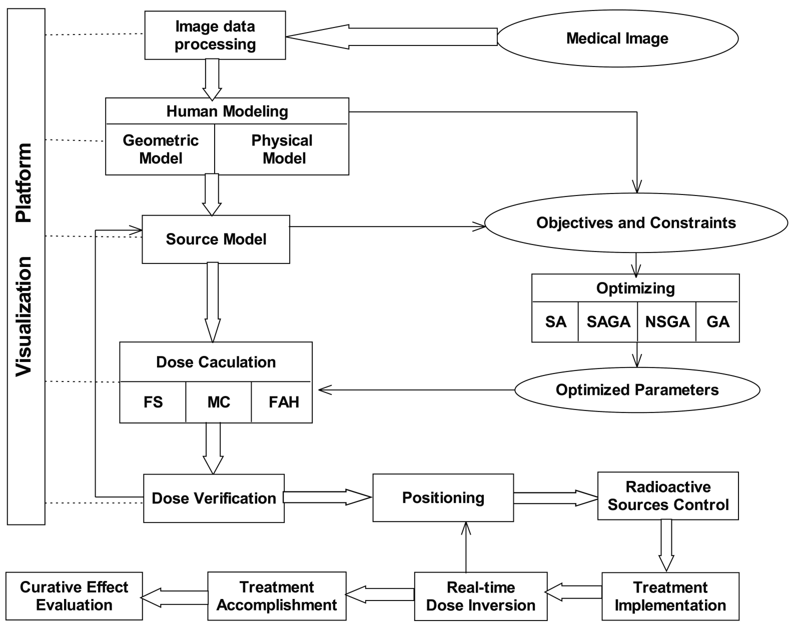

Fig. 1. Framework and technical flow chart of ARTS.

2.1 Information processing and human modeling

ARTS pre-processes various types of medical images such as CT/MRI/PET etc, by registration, fusion, emendation, filtering and enhancement, and then segments the skin boundary, the tumour target and the OAR. Automatic and semi-automatic segmentation methods are applied in ARTS to combine the advantages of computing intelligence and clinical experience[16]. ARTS can three-dimensionally and dynamically visualize the human model, the radioactive source and the dose map, which assist radiation oncologist to analyze the target and region of interest (ROI) for improving the veracity and reliability of diagnosis and treatment[17—20].

ARTS can automatically reconstruct the human models with 3D geometrical (anatomic structure and position attribute) and physical (elemental composition and density) information for various dose calculation methods based on clinical needs. For example, ATRS can convert the series CT-images into the inputs for the 3D Monte Carlo simulation with MCNP or EGS. To accelerate the dose calculation based on a 3D Monte Carlo method, several voxel-uniting methods, i.e. simple uniting, depth-first uniting and cube-first uniting methods are developed to unite small voxels into coarse cells in the Monte Carlo model[21, 22].

2.2 Dose calculation

To meet the various demands on speed and precision (forward treatment planning, inverse planning optimization and treatment planning verification), the Fast and Simple (FS) dose calculation, the Monte Carlo (MC) dose calculation and the Fast and Accurate Hybrid (FAH) dose calculation methods are studied[23—26]. The FS dose calculation methods include Regular Beam Model (RBM)[27] and Finite Size Pencil Beam (FSPB)[28]. The improved RBM with the tissue heterogeneity correction can obtain the dose distribution in human bodies irradiated by regular beam fields[29] based on measured database. With the Monte Carlo simulation database, FSPB can obtain the dose distribution with irregular beam fields by dividing the irregular field into regular beamlets[30]. Both RBM and FSPB are used in forward determination and inverse planning optimization. The accurate dose calculation results can be achieved by Monte Carlo codes, such as EGS and MCNP. To improve the calculation speed, a Monte Carlo-Analytical hybrid dose calculation method is developed, which will be introduced in Section 3.

2.3 Planning optimization

Inverse planning is a multi-objective optimization problem. Although radiotherapy has been applied to the treatment of tumours for almost a century, the multi-objective characteristic of inverse planning has not been fully recognized until recent years[31]. At present, most of inverse planning systems handle multiple objectives in terms of an aggregating function by combining the individual objective values into a single utility value before optimizing. This method is acceptable for convex multi-objective optimization problem, but it is not always the case. Thus it cannot guarantee to obtain the optimum solution.

Multi-objective optimization of inverse planning is one of the key steps to ensure the accuracy of radiotherapy. According to its multi-objective characteristic, Genetic Algorithm (GA), fast and elitist Non-dominated Sorting Genetic Algorithm (NSGA-II), Simulated Annealing (SA) and hybrid method of SA and GA (SAGA) are developed for multi-objective optimization of inverse planning[32, 33]. Objective functions based on dose distribution and hybrid dose-volume are developed to optimize energy, beam orientation, size, location and the other field parameters. Moreover, the attempt to use prior information of variables in optimization can enhance the algorithm's efficiency[34, 35].

2.4 Patient positioning

Fractionation therapy is commonly used in radiotherapy and the procedure usually lasts several weeks, so the accuracy of patient positioning may affect the radiotherapy precision greatly. At present, positioning error and organ motion are the main obstacles for the improvement of radiotherapy precision[36]. Crossing laser aiming technique is widely used in most hospitals to assist manual positioning, but time-consuming and inaccurate. Advanced positioning methods, such as electronic portal imaging device (EPID), are used to assist patient positioning in advanced hospitals, but very expensive and hard to be widely applied.

According to stereo vision and photogrammetric techniques, positioning method based on binocular vision is proposed. Firstly, two cameras are calibrated with a special target; secondly, images of the patient surface from various directions are taken by calibrated cameras, then the surface is reconstructed and the coordinates of reference points are calculated; thirdly, the positioning system is used to adjust the patient to the planned position by coordinate error between the real-time and reference position[37].

Considering the patient's body may change size during the treatment process, a calculation method of positioning error is proposed based on the dynamic template matching technique, which is an improvement to the former fixed template matching method to correct positioning error. This technique can not only improve the positioning precision, but also eliminate the influence brought by body change[38, 39].

2.5 Planning verification

The dose verification function of treatment planning system is one of the most important parts in radiotherapy to verify whether the dose at treatment location is the same as the treatment planning. Emulated human phantom, ion chamber, thermoluminescence dosimeter (TLD), semiconductive ion chamber and films are applied to perform the absolute dose verification in order to ensure that the accurate dose is delivered to the tumour site[40]. The MC particle transport simulation method can be also used in the dose verification.

3 Advanced development

3.1 Digital human modeling

The digital human model can reflect the 3D anatomical structures of the human body which normally goes through the four development stages: visual human, physical human, biological human and intellectual human. They can be defined as stylized model, tomographic model and hybrid model[41, 42]. FDS Team is developing the digital physical human model and establishing a series of tomographic and hybrid models to Chinese digital human for radiotherapy as well as for radiation protection.

Based on a series of Chinese image data sets at different genders and ages, organs and tissues are segmented firstly, and then specific identification numbers are assigned to correlate their physical properties, i.e. elemental compositions and density derived from CT numbers. Absorbed dose in various irradiation conditions can be calculated by Monte Carlo method[43].

With the boundary representation (BREP) method, the first Chinese hybrid computational model constructed by Nonuniform Rational B-Spline (NURBS) and Polygonal Mesh is able to be adjusted to fit the characteristics of various individuals and to be applied as the model foundation for 4D (3D-spatial and 1D-timing) accurate radiotherapy in the future[44].

3.2 Hybrid dose calculation

The analytic method has the advantages of high speed and acceptable precision in homogeneous regions, but large error exists in inhomogeneous regions. MC simulation can achieve high precision dose calculation results for all regions, but time-consuming. One of the key aspects of dose calculation is to develop fast and accurate hybrid dose engine with advantages of the above two methods by applying various dose calculation methods in different regions. In this study, the region requiring high precision dose calculation result is named “high precision region (HPR)”, simulated by the MC method. As the particles coming from the exterior may affect the dose distribution in “HPR”, the transition region between the “HPR” and the other regions calculated by analytic method for high speed (“fast speed region (FSR)”) should be determined carefully.

Both the Modified Dose Spread Array (MDSA) method[45] and the secondary electron range (SER) method are used to determine the transition region. The idea of the MDSA method is to carve homogeneous regions into voxels, using the MC method (assumed photons only interact with one voxel) to simulate particle transport, and then obtain the spatial distribution of energy deposited by electrons, positrons and photons that spread from the site of the primary photon interaction voxel. Here, the energy deposition is used to determine the transition region between the “HPR” and “FSR”. When interaction voxel is out of the radiation field, the SER method based on secondry electron range is applied to determine the transition region. The fast and accurate hybrid dose engine couples advantages of analytic and MC methods, which is developed to achieve the optimum between speed and precision in all region[46].

3.3 Multi-objective inverse planning optimization

The multi-objective optimization of intensity maps for each beam, beam angles, number of beams and the optimum leaf sequencing of Multi-Leaf Collimator (MLC) are developed for the Intensity Modulated Radiation Therapy (IMRT) in ARTS based on the multi-objective algorithm, the objective function of inverse planning and the FSPB.

The conventional and modern optimization algorithms are combined to optimize intensity maps for each beam: firstly the population of the multi-objective optimization algorithm is initialized by using the conventional gradient method; secondly the Pareto-front solutions for doctor’s selection are obtained by multi-objective optimization algorithm. The optimization of beam angles and number of beams is time-consuming and complex, because the solution space is very large and each beam needs to optimize the intensity maps. In ARTS, the NSGA-II is used for beam automatic selection, and the intensity maps are optimized with Conjugate Gradient method.

The leaf sequencing algorithms of multi-leaf collimation are applied to guarantee that output dose rates of every point in field can be modulated according to optimum intensity. A lot of leaf sequencing algorithms of multi-leaf collimator in the step and shoot mode have been developed[47—50], but they cannot always be optimal for all input intensity matrices. In ARTS, several advanced algorithms are integrated to select the optimum algorithm. The optimum algorithm is selected according to the principle of minimizing the total number of monitor units (TNMU) and the number of segments (NS). The optimum leaf sequencing that satisfies the hardware constraints to control the multi-leaf collimator by the MLC prescription preparation system (MLCPPS) is chosen to get the planned dose distribution[51].

3.4 Video-based patient positioning

Surface mark commonly applied in clinic to assist positioning is not only inaccurate but also easy to be erased. A positioning method without surface mark is developed. Before treatment, the images of the patient are taken by cameras, and then the 3D image of the patient's body surface is reconstructed as the template image. In the following treatment, the template image is projected on the patient's real-time image, and the correlation ratios of corresponding area are calculated to evaluate the positioning error, and then the treatment bed is adjusted to realize high-precise positioning[52].

Issues involved treating the breast or abdomen tumour need to be solved, as the tumour's position will change along with the organ motion. So a non-touch breath gate-controlling method is developed to forecast the tumour's position by real-time detecting the contour of the breast and abdomen, and to control the accelerator to irradiate the tumour site when the tumour's position is in the range with tolerable error, eliminating the error caused by the patient's breaths or organ motion.

By combining the above positioning methods, a video positioning system is proposed, which consists of the positioning module based on binocular vision, the module based on contour matching and the breath gate-controlling module. These modules supplement each other to ensure the precision of positioning[53].

3.5 Real-time dose verification

Dose inversion for planning verification is to obtain the internal dose information by using the external dose information, including real-time dose verification and energy spectrum reconstruction. The real-time dose verification provides not only the function of the traditional dose verification but also the error to help the accelerator head to readjustment. For real-time dose verification in photon radiotherapy, the primary ray reconstruction method is applied in the patient 3D dose distribution reconstruction by practical measurement and convolution principle with 2D dose distribution on the exit plane and CT images[54—56]. For energy spectrum reconstruction, the nonlinear programming method is developed to realize the photon and electron energy spectrum reconstruction effectively[57—61].

4 Summary

The radiotherapy is a very complex process related to various scientific and technical issues, and any minimal errors may lead to deficient dose to tumour and over dose to normal tissues, which may result in serious tumour complications. Aiming at achieving accurate radiotherapy, the project of ARTS was launched. A series of key technical issues related to accurate radiotherapy are studied, including human medical image data processing and human body modeling, dose calculation, planning optimization, patient positioning, dose verification, etc. The key issues related to the heavy particle treatment, brachytherapy etc are also underway.

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