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Medical Physics Contribution:

Vector-model-supported approach in prostate plan optimization

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ABSTRACT

Lengthy time consumed in traditional manual plan optimization can limit the use of step-and-shoot intensity-modulated radiotherapy/volumetric-modulated radiotherapy (S&S IMRT/VMAT). A vector model base, retrieving similar radiotherapy cases, was developed with respect to the structural and physiologic features extracted from the Digital Imaging and Communications in Medicine (DICOM) files. Planning parameters were retrieved from the selected similar reference case and applied to the test case to bypass the gradual adjustment of planning parameters. Therefore, the planning time spent on the traditional trial-and-error manual optimization approach in the beginning of optimization could be reduced. Each S&S IMRT/VMAT prostate reference database comprised 100 previously treated cases. Prostate cases were replanned with both traditional optimization and vector-model-supported optimization based on the oncologists' clinical dose prescriptions. A total of 360 plans, which consisted of 30 cases of S&S IMRT, 30 cases of 1-arc VMAT, and 30 cases of 2-arc VMAT plans including first optimization and final optimization with/without vector-model-supported optimization, were compared using the 2-sided t-test and paired Wilcoxon signed rank test, with a significance level of 0.05 and a false discovery rate of less than 0.05. For S&S IMRT, 1-arc VMAT, and 2-arc VMAT prostate plans, there was a significant reduction in the planning time and iteration with vector-model-supported optimization by almost 50%. When the first optimization plans were compared, 2-arc VMAT prostate plans had better plan quality than 1-arc VMAT plans. The volume receiving 35 Gy in the femoral head for 2-arc VMAT plans was reduced with the vector-model-supported optimization compared with the traditional manual optimization approach. Otherwise, the quality of plans from both approaches was comparable. Vector-model-supported optimization was shown to offer much shortened planning time and iteration number without compromising the plan quality.

Introduction

Step-and-shoot intensity-modulated radiotherapy (S&S IMRT) is an external beam radiotherapy treatment modality that can achieve steep dose gradients between the tumor and the nearby healthy tissue by using computer-controlled multileaf collimators (MLCs) to divide a beam into smaller beamlets of varying radiation intensities.[1,2] Volumetric-modulated radiotherapy (VMAT) is a more recent development in IMRT that combines MLC motion with gantry speed and dose rate modulation.[3] Today, VMAT is the preferred treatment for prostate cancer at the Princess Alexandra Hospital, Brisbane, Australia, because of the shorter treatment time and better plan quality. The shorter VMAT treatment time increases patient comfort, decreases the influence of organ motion on the treatment results, and increases the number of patients treated per day on a linear accelerator machine. Additionally, S&S IMRT plan involves just 7 to 9 static beams, whereas VMAT allows 360 degrees of gantry rotation around the patient, which spreads dose in healthy tissues over a larger area and therefore delivers a much lower dose per unit volume of nontarget tissue. Hence, the opinion is that VMAT offers superior plan quality over S&S IMRT.[4] S&S IMRT/VMAT uses inverse planning. It is often time-consuming for the planner to specify suitable dose constraints to the clinical target volume, planning target volume (PTV), and organs at risk (OARs) during optimization, as this is usually carried out by trial and error.

Methods

Vector model solution

Features are characteristics of an object. For example, for computed tomographic (CT) image structures, features can include the height of the PTV, the volume of the PTV, and the shape of the PTV. A vector model is an extraction of all the features from a specific object.[5-7] The similarity between 2 cases can be then found from the direction cosine between 2 vector models.[8] Vector models can be applied on medical images to find their similarity according to different weights of features[9]:

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$$\text{Direction cosine for similarity} = \frac{\sum_{i=1}^{t} X_i Y_i}{\sqrt{\sum_{i=1}^{t} (X_i)^2 \sum_{i=1}^{t} (Y_i)^2}} \qquad (1)$$

where *X* and *Y* are the feature vectors of 2 sample cases, *i* is the item number, and *t* is total items.

The direction cosine has a value of 1 when the 2 vectors are identical, and there is a perfect match between the tested cases. The direction cosine saves more calculation time in the case of an absent feature. However, because different combinations of features can result in the same similarity value, human intervention is still required to filter the cases to determine the best match.

Data collection

This research was a retrospective study in which the S&S IMRT/VMAT plans data were retrieved and used to compare the effectiveness of optimization with vector model and traditional manual optimization. Unique study numbers were used to identify particular cases, and patient identity was not known throughout the study. The human research ethics approvals were obtained from the Hong Kong Polytechnic University and the Princess Alexandra Hospital.

Vector model solution for S&S IMRT/VMAT

To save data storage space and time for matching of medical images, the features of medical images were extracted and encoded as a vector. Because CT images and structure contours were in Digital Imaging and Communications in Medicine (DICOM) format, the features could be extracted using in-house developed Matlab scripts (version 7.10.0, 2010; The MathWorks, Inc., Natick, MA). The feature extraction, similarity calculation, and statistical analysis were all conducted in Matlab version 7.10.0. Features extracted for this study required invariance to scaling, rotation, and translation. This was required so that the program could compare the features despite different organ locations, patient sizes, and patient rotations. Every case underwent feature extraction, and the features were stored in weighted vector format. Different weightings were applied to different features (see Table 1). S&S IMRT/VMAT is more difficult to plan with increasing PTV volume or overlap volume between PTV and OARs. This was the reason why the PTV volume and the overlap volume between PTV and OARs were given the highest weightings. PTV dimension was given the second highest weighting, as it indirectly gives volume information and affects MLC leaf positions surrounding the PTV. Although the OAR volumes and the PTV contour had an impact on the S&S IMRT/VMAT optimization, these parameters had lower priority compared with the PTV volume or the overlap volume. For that reason, the weighting of OAR volumes and the PTV contour features was given the third highest weighting. The rectal gas was a physiologic feature of less importance in S&S IMRT/VMAT optimization. Consequently, the weight of the physiologic feature was significantly smaller in comparison with the structure features. The program proposed a list of top 3 reference cases with highest similarity score, allowing the planner to choose the most appropriate one. If the reference case with the highest similarity score resulted in an optimized plan lacking the required quality, the planner could choose the reference case whose anatomic features had the second highest similarity score if it met all the quality criteria.

To retrieve the initial planning parameters of similar prostate S&S IMRT/VMAT cases, structural and physiologic features were compared in a similarity search. The structural features for prostate cancer IMRT planning included the PTV volume (Fig. 1), bladder volume, rectum volume, dimension of the tumor, overlap volume between PTV and OARs, compactness,[10] irregularity,[11] alternative irregularity,[12] and moments of distance from the center for PTV.[10,13,14] The physiologic feature for prostate cancer IMRT planning was the rectal gas that could be extracted as 7 invariant moments.[15] The rectal gas could be quantified by the CT number because the difference in HU between rectal gas and soft tissue was big (rectal gas is approximately –1000 HU and soft tissue is around 0 HU). The rectal gas might affect the shape of the rectum and the PTV. Because the left femoral neck, the right femoral neck, and the body structure were not that distinct in the prostate plan, features from these 3 structures were not considered. From CT images and structures contour DICOM files, the tumor characteristics, OAR characteristics, and their overlap volume were quantified as the following features:

Table 1
Weighting factors of different features

Features	Weight
PTV volume	0.025673941
Bladder volume	0.006418485
Rectal volume	0.006418485
Overlap volume of PTV and rectum	0.025673941
Overlap volume of PTV and bladder	0.025673941
PTV height	0.01283697
PTV width	0.01283697
PTV length	0.01283697
PTV contour compactness	0.006418485
PTV contour irregularity	0.006418485
PTV contour alternative irregularity	0.006418485
PTV contour moment	0.006418485
Seven moments of rectal gas	0.001283697

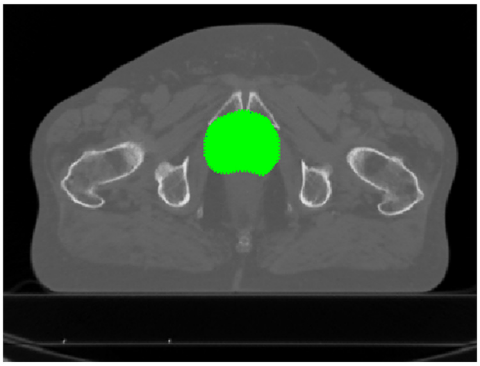

Fig. 1. Example of PTV area extracted from Matlab.

Structural features:

1. volumes (area × height)
   - PTV
   - rectum
   - bladder
   - overlap between PTV and rectum
   - overlap between PTV and bladder
2. dimensions of PTV (PTV slices, major axis, and minor axis)
   - height
   - width
   - length
3. PTV contour
   - compactness
   - irregularity
   - alternative irregularity
   - moments of distance to centroid
4. physiologic feature
   - 7 invariant moments for the rectal gas CT value

Generally, Matlab took a few minutes to extract features. Then, the similarity between a test case and previous S&S IMRT/VMAT patients was calculated using the direction cosine. As some of the previous optimized plans might not have the optimal plan quality, the quality of similar plans was compared, and the most suitable previously optimized plan was selected for reference. Planning parameters were retrieved from the selected reference plan and applied in the test case to save time on the gradual adjustment of planning parameters. The planning optimization was then calculated with an analytical anisotropic algorithm for S&S IMRT plans, and collapsed cone convolution superposition for VMAT plans. The S&S IMRT/VMAT plans needed only few adjustments to meet clinical constraints for the individual case.

To compare the planning time for each optimization approach, the 30 prostate S&S IMRT cases, the 30 prostate 1-arc VMAT cases, and the 30 prostate 2-arc VMAT cases were randomized and replanned using both the traditional manual optimization approach and the vector-model-supported optimization approach as a template for the planning parameters. Planning time was defined as vector model processing time for the test case, optimization time, dose calculation time, and evaluation time.

The 2 sets of previous 101 plans were collected, and transformed vectors were used to establish database references for S&S IMRT and VMAT. A leave-one-out method was used for the S&S IMRT/VMAT reference database (*i.e.*, the original plan of the test case was left out from the reference database and each test case had 100 reference cases). To know the impact of the vector-model-supported optimization, the S&S IMRT/VMAT plans with the first optimization and final optimization were also compared with and without the vector model (Fig. 2).

To study if the proposed optimization approach with the vector model was better than the traditional manual optimization approach, the mean planning time and the plan quality were compared for these 2 optimization approaches. All S&S IMRT cases were replanned using Eclipse treatment planning system (TPS) version 10 (Varian Medical Systems, Palo Alto, CA), and all VMAT cases were replanned using Pinnacle TPS version 9.4 and 9.8 (Philips Radiation Oncology Systems, Fitchburg, WI). One full arc and 2 full arcs were replanned for VMAT plans so the number of control points was the same for both vector model and traditional manual optimizations. The vector model was assessed based on the comparison of planning time, number of itera-