CS229 Class Project: Fusion arc treatment planning strategy by adaptive learning cost function based beam selection

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Abstract

Current therapeutic modalities in radiation therapy such as static field IMRT and rotational single-arc VMAT are more oriented to either the plan quality or the delivery efficiency. Recently, fusion arc treatment scheme has been proposed by combining the advantages of two respective modalities. The basic structure is to deliver the dose with rotational arc to maintain the delivery efficiency, while the additional intensity modulations based on static field treatment are inserted to chosen angles to enhance the plan quality. This work presents how to select the regions that need additional intensity modulations, based on adaptive learning cost functions given the beamlet intensity map.

1. Introduction

External beam radiation therapy is the most widely used for treating the tumor patients in these days. Before the actual treatment, how to deliver the dose is planned and optimized, which is called 'treatment planning'. The ultimate objective of the treatment planning is to optimize the beam shapes (fluence-map structures), such that it maximizes the dose to the target, while sparing the dose of radiation to the critical organs.

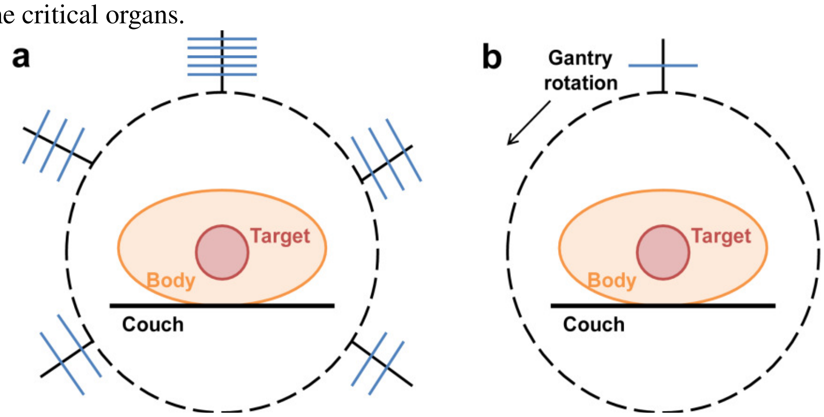


Figure 1 Types of dose delivery in external beam radiation therapy (a) step-and-shoot (static) delivery (b) rotational arc (1-arc) continuous dose delivery

The dose can be delivered to the target volume in two different ways as illustrated in Figure 1, step-and-shoot and rotational arc delivery. Step-and-shoot (static field) treatment[1] delivers the dose in discrete manner at the specific gantry angles, which is used for the intensity modulated radiation therapy (IMRT). On the other hand, rotational arc treatment continuously delivers the dose to the target, which is applied to the volumetric modulated arc therapy (VMAT)[2] with a single arc in most cases. Static field treatment can provide sufficient intensity modulations at appropriate directions, so that it can effectively preserve the critical organs. It, however, sacrifices the delivery efficiency due to the feature of static field treatment, and 5-10 static beams do not own large beam angular frequency to cover the entire angles. VMAT planning guarantees a great deal of delivery efficiency with simple fluence-map structures and their transitions for continuous dose delivery with a single arc. The strict constraint of having a single aperture at each control point, however, does not possess sufficient intensity modulations for some gantry angle directions.

Therefore, to overcome the pitfalls of two therapeutic modalities, we can come up with combining IMRT with VMAT planning, which was newly defined as fusion arc dose delivery[3]. The new treatment scheme basically delivers the dose in continuous fashion, while it can stop and insert additional intensity modulations at selected gantry angles to improve the plan quality at small costs of delivery efficiency. This work presents how to adaptively choose the gantry angles based on the cost function with given information of the resultant fluence-map.

2. Methods

2.1 Fluence-map optimization for single-aperture rotational arc treatment

The basic structure for treatment in this work is the rotational arc treatment with a single aperture. To achieve single-arc treatment, two factors should be considered. First, the fluence-map should be simplified to select one aperture at each control point. If the resultant fluence-map is complicated, it is difficult to take one aperture and maintain the optimized plan quality. Second, the fluence-map transition between two adjacent control points should be sufficiently small such that the dose is continuously delivered with arc treatment. In fact, there is a specific constraint to be met in the transition of the fluence-map structures for continuous arc delivery. Eq.(1) shows the basic model for the fluence-map optimization to reflect two factors,

$$\begin{aligned} &\text{minimize} \;\; \|Dx\|_1 + \sum_{f=1}^{N_f - 1} \{\sum_{u,v} c_f \cdot | x_{u,v,f} - x_{u,v,(f+1)} |\} \\ &\text{subject to} \quad \left\| \sqrt{\lambda_i}\,(A_i x - d_i) \right\|_2 \le \varepsilon_i,\; x \ge 0 \end{aligned} \tag{1}$$

where D is 2D-difference matrix, $x \in \mathbb{R}^n$ is the fluence-map to be optimized (the sub-indices denoted by u,v correspond to the beamlet components of x, while the sub-index f represents the field order ($n = u \cdot v \cdot f$)), $A_i \in \mathbb{R}^{m_i \times n}$ (m_i represents the number of voxels) is the dose matrix, d_i is the dose distribution, λ_i is the importance factor of structure i, and the residue imposed on each structure i is denoted by ε_i. The total-variation (TV) minimization in the first term of the objective is to simplify the fluence-map variations for taking a single segment, while the second term in Eq.(1) increases the fluence-map similarity between two neighboring nodes. The coefficient c_f controls the fluence-map similarity to the total-variation of the fluence-map. In this work, it is set to be 0.1 to both preserve the plan quality and maintain the delivery efficiency.

We basically used equi-spaced 60 control points for the plan optimization with 6 degree angular distant. The resultant fluence-map acquired by Eq.(1) can still have a couple of different intensities. In most control points, only one aperture is taken, while it is assumed that two apertures are taken in certain directions that need additional intensity modulations. The next subsequent section will specify how to choose the directions, where additional static field treatment is beneficial for improving the plan quality.

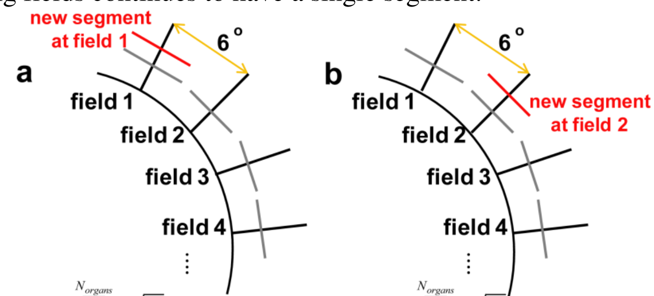
2.2 Fluence-map optimization for single-aperture rotational arc treatment

In order to acquire the actual fluence-map, the solution acquired by Eq.(1) should pass through additional process, called 'leaf-sequencing'. The resultant fluence-map is classified into different intensity levels, finally being split into different apertures. In most gantry angles, it takes only one aperture for single-arc dose delivery, while this work suggests having additional segment in certain directions.

The directions that need additional segment can be obtained from the adaptive learning approach with the solution acquired by Eq.(1). With that approach, it is important to see which directions are contributing to improving the plan quality. This can be measured by summation of the data fidelity terms in Eq.(1), $\sum_{i=1}^{N} \| \sqrt{\lambda_i}\,(A_i x - d_i) \|_2$. If the residue decreases, the plan quality is considered to be enhanced. More specifically, we measure the cost function defined in Eq.(2)

$$\text{minimize} \;\; c(x_{new,k}) = \sum_{i=1}^{N} \| \sqrt{\lambda_i}\,(A_i x_{new,k} - d_i) \|_2 \tag{2}$$

where $x_{new,k}$ is the fluence-map having an extra segment at *k-th* static field, and $c(x_{new,k})$ is a cost function with the fluence-map. For instance, $x_{new,1}$ represents that the extra segment is only added to the first static field, while the remaining static fields have a single aperture. This is well described in Figure 2, where it has two cost function values when adding an extra segment to the first and the second static field. If the certain directions have lower costs, then it would be interpreted that the directions can get profits by adding the additional segment. It selects the 6 static fields that correspond to the 6 lowest cost function values. The reason that it chooses the 6 locations is to balance between the plan quality and the delivery efficiency. For those 6 locations, the extra segment is inserted, whereas the remaining fields continues to have a single segment.



$$c_{new1} = \sum_{i=1}^{N_{organs}} \| \sqrt{\lambda_i} \cdot (A_i x_{new1} - d_i) \|_2, \quad c_{new2} = \sum_{i=1}^{N_{organs}} \| \sqrt{\lambda_i} \cdot (A_i x_{new2} - d_i) \|_2$$

Figure 2 Cost function values when the extra segment is only added to (a) the first static field, and (b) the second static field

2.3 Evaluations

To validate the proposed algorithm, the prostate data was applied with the beamlet size 18x16 (5mm beamlet resolution). The CT images obtained for the treatment is down-sampled twice for plan optimization. The planning target volume (PTV) is located at the center of body, corresponding to the location of prostate, while the critical organs to be preserved are set to be bladder, rectum, and femoral heads close to the target volume. At the initial step, the fluence-map is optimized with 60 static fields by Eq.(1). The single segment is taken in most static field locations, while the 6 locations chosen from the adaptive beam angle selection method have two segments assigned. The remaining control points are filled with linear interpolations on two adjacent fluence-map structures, such that the entire control points are deployed with 2 degree angular distant. The fluence-map optimization based on the TV minimization is performed by a large-scale L1-solver, called TFOCS[4]. This study compares the two separate plans: proposed fusion arc treatment plan and conventional VMAT plan.

The plan quality of two plans is assessed by various criteria. The dose volume histogram (DVH) curves, which accumulate the dose volume matching the amount of dose of radiation, and dose distributions are used to see the dose sparing to the critical organs. To evaluate the dose conformity to the target, the conformation number (CN)[5] is used as defined in Eq.(3).

$$Conformation\ Number(CN) = \frac{V_{\tau,ref}}{V_\tau} \cdot \frac{V_{\tau,ref}}{V_{ref}} \tag{3}$$

where V_τ is the volume of PTV, $V_{\tau,ref}$ represents the target volume receiving the dose greater than or equal to the reference dose, and V_{ref} is the total volume receiving the dose greater than or equal to the reference dose. The first term is required to be equal to or greater than 95% (0.95), while the second term is recommended to be large enough to assure the secure and safe dose delivery to the target. The delivery efficiency is quantified by the estimated dose delivery time with reference to two pulications[2,6].

3. Results and Discussions

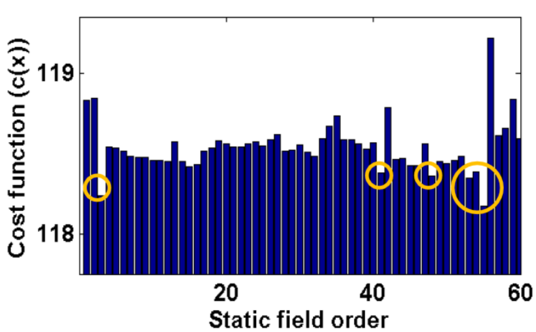


Figure 3 Cost function values at which extra segment is sequentially added to 60 static fields

Figure 3 shows the cost function values of 60 static fields when the extra segment is sequentially added to a static field. As stated, 6 static field locations corresponding to the 6 lowest cost function values have two segments, which are 13, 41, 48, 53, 54, and 55th static fields. The remaining static fields have a single segment assigned, and single-arc based planning is executed by linear interpolation.

Figure 4 (a) and (b) reveals the dose volume histogram and dose distributions, which implies the dose sparing to the critical structures in two plans acquired by our proposed fusion arc and conventional VMAT schemes. The proposed treatment scheme has slightly better dose sparing in femoral heads and rectum structures than that of conventional VMAT plan. The improvement is explicitly illustrated in the dose distributions, where the dose sparing to the femoral heads enhances through the addition of apertures to appropriate directions according to the adaptive learning cost function values.

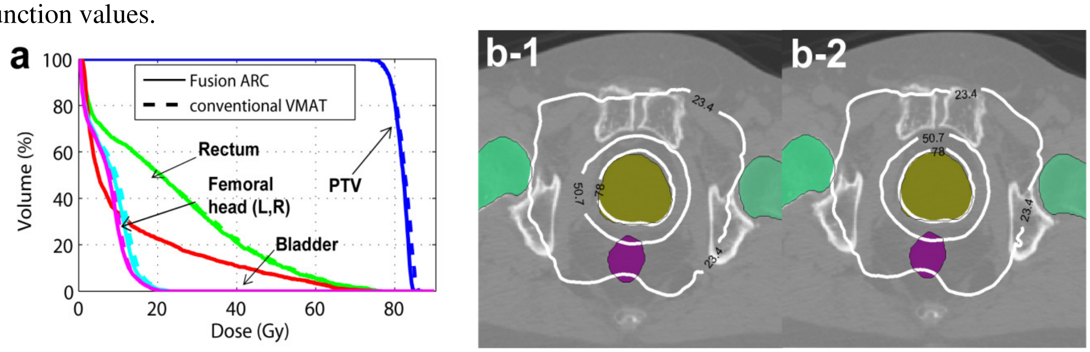


Figure 4 Comparing fusion arc and VMAT (1-arc) plans in (a) DVHs and (b) dose distributions of the proposed plan (b-1), and conventional VMAT (b-2) (iso-dose lines are corresponding to 30,65, and 100% of the prescribed dose

The additional segments newly assigned to 6 static fields also affect the dose conformity to the target. The proposed plan yields greater conformation number (CN) than the conventional VMAT plan, as specified in Table 1. CN acquired by single-arc VMAT planning is about 0.82, while our proposed plan produces about 0.84. It demonstrates that our proposed fusion arc planning strategy can contribute to improving the plan quality in terms of the dose sparing to the critical organs and dose conformity to the target. The enhancement in dose the plan quality, however, should accompany the sacrifice in the delivery efficiency, relative to single-arc VMAT plan, which is listed in Table 1. The expense in the delivery efficiency is not significant compared with the plan done by the step-and-shoot dose delivery only, which is about 3-5 min.

	Fusion arc	VMAT (1 arc)
CN	0.8236	0.8388
T (s)	61.83 s	76.57 s

Table 1 Dose conformity to the target by CN and estimated dose delivery time of two different plans

4. Conclusion

This work presents fusion arc treatment planning strategy. It inserts additional segments to a certain static fields, where single-arc based treatment planning is basically applied. The angles that need the additional segments assigned are determined by the adaptive learning cost function values, based on the resultant fluence-map. The proposed planning scheme overcomes the drawbacks of the conventional single-arc VMAT planning, and improves the plan quality in terms of the dose sparing to the critical organs and dose conformity to the target.

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