Improvement in robustness and delivery efficiency of intensity-modulated proton therapy using single-field optimization with energy absorber

1. Statement of Innovation/Impact

Compared to passively scattering proton therapy, intensity modulated proton therapy (IMPT) treatment plans created by multi-field optimization (MFO) is capable of creating highly modulated dose distributions because it simultaneously optimizes spots from all fields. However, since each proton beam in an MFO plan delivers doses with large in-field dose gradients, the delivered dose distribution is highly sensitive to setup and proton range uncertainties.

In contrast, the single-field optimization (SFO) approach optimizes each field individually and creates a uniform dose distribution from each beam. Therefore, SFO plans are usually more robust to uncertainties than MFO plans. SFO plans are also more clinically desired because of their much lighter work load for patient QA. On the other hand, however, it is often difficult for SFO plans to achieve clinically acceptable normal tissue sparing due to its limited modulations.

Energy absorbers have been used in proton therapy beams in order to reduce spot size (thus penumbra margin) and to shift the range of the proton beam for desired penetration. With smaller spots, better normal tissue sparing can be obtained without sacrificing target coverage. In addition, since the proton beam is shifted to higher energies with energy absorber, fewer energy layers are required to form the spread-out Bragg Peak owing to the wider Bragg Peaks at higher energies. Thus, delivery of the proton beams becomes more efficient.

In this work, we make use of energy absorbers to create SFO treatment plans (EA-SFO). With energy absorbers, SFO with 2 fields can create treatment plans that are clinically

![Figure 1. Banded DVHs of selected structures from the 3-field MFO plan and the 2-field EA-SFO plan of a typical patient. The solid curve represents the nominal plan. The shaded bands are bounded by the highest and lowest dose plans; they represent the range of DVH variations that could occur under uncertainties. The nominal plan of 2-field EA-SFO achieved target coverage that is close to 3-field MFO. The 2-field EA-SFO plan shows narrower bands in the target DVHs, indicating improved plan robustness.](image)
acceptable and are close to the quality of 3-field MFO plans. Compared to the MFO approach, we found the benefits of EA-SFO to be threefold:
   a) EA-SFO improves the plan robustness to setup and range uncertainties;
   b) EA-SFO reduces the number of energy layers by 46% thus improves delivery efficiency;
   c) EA-SFO significantly reduces the time required for patient QA.

2. Major results
   All the nominal IMPT plans and the perturbed plans were generated in the Eclipse treatment planning system. The EA-SFO plans have all achieved clinically acceptable quality. Figure 1 shows banded-DVH curves of a typical patient, in which the width of the bands corresponds to the robustness of the plan of the structure. In terms of dosimetric indices, the EA-SFO plans yielded an average band width reduction of 38.5% in the targets as well as a slight reduction in OARs, as can be seen from figure 2. As we expected, the EA-SFO plans also resulted in an average reduction of 46% in the number of energy layers (table 1). Based on these results, we conclude that EA-SFO provides improved plan robustness and delivery efficiency, although the plan optimality might be slightly compromised.

![Figure 1](image1.png)

![Figure 2](image2.png)

Figure 2. Average dosimetric measures from the 3-field MFO plans and the 2-field EA-SFO plans of the four patients. Each column corresponds to the nominal plan; the positive and negative ends of the error bars correspond to, respectively, the highest dose and lowest dose plans. Therefore, the size of the error bars indicates the magnitude of plan sensitivity to uncertainties. Generally, the 2-field EA-SFO plans show smaller error bars than the 3-field MFO plans, indicating a superior robustness of the 2-field SFO plans to 3-field MFO plans.

Table 1. Number of energy layers required by each beam for the 3-field MFO and 2-field EA-SFO plans.

<table>
<thead>
<tr>
<th></th>
<th>Patient #1</th>
<th>Patient #2</th>
<th>Patient #3</th>
<th>Patient #4</th>
<th>average of total</th>
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<tbody>
<tr>
<td>3-field MFO</td>
<td>61, 62, 64</td>
<td>55, 59, 47</td>
<td>53, 58, 54</td>
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<tr>
<td>2-field EA-SFO</td>
<td>49, 47</td>
<td>42, 45</td>
<td>46, 47</td>
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<tr>
<td>reduction</td>
<td>46%</td>
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