The Optimization of Inverse Planning and IMRT

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1. Aperture-based Inverse Planning versus Beamlet-based Inverse Planning

All inverse planning involves weight optimization. Beamlet-based Inverse Planning (BBIP)[5] irradiates complex target volumes with a large number of small beams. The number of small beams or beamlets is often more than one thousand. The optimization process adjusts the weights of these beams to produce a desired dose distribution. Delivery of this large number of small beams is challenging, but many clever techniques have been devised to handle this problem. For example, the delivery step can use tomotherapy with a continuously moving gantry and a fast binary collimator system. Or, fixed gantry angles can be employed with a standard multileaf operating in a Dynamic Multileaf Collimator (DMLC) mode. It is also possible to move the gantry and MLC simultaneously for Intensity Modulated Arc Therapy (IMAT). Some of these approaches can directly model the large number of small beams needed to produce complex dose distributions, but it is also possible to reduce the complexity of the problem with the use of interpreter (also known as sequencer or translator) software that combines the beamlets into a smaller number of larger apertures prior to delivery. Depending on a number of factors like the spacing of the intensity levels used in the reduction process, the final number of apertures often exceeds 100 and can go considerably higher. This large number of fields per patient can extend treatment times to unacceptable levels, and can result in a total number of field changes that exceeds the design capabilities of any multileaf collimator and lead to unnecessary system failures. Taking the example of 20 IMRT patient treatments per day and 100 apertures per patient gives 2000 field changes each day if these patient's are treated on the same accelerator using a step-and-shoot delivery approach.

Aperture-based Inverse Planning (ABIP)[2,3,4] uses a predefined set of apertures for optimization. The number of apertures is typically smaller than 100 for even the most

complex cases. Based on dose constraints for targets and critical structures, weights are determined for these apertures only. It is interesting to point out that the optimization process may discard many of these to give an even smaller final number. It is also important to understand that for this technique to work effectively, selection of the apertures is a critical step for ABIP.

It will be argued here that, no matter which technique is used to deliver the dose, the beamlet-based approach to inverse planning is inefficient. In addition, BBIP creates problems that go beyond the efficiency issue and related to patient safety. These problems can be overcome by selecting the apertures to be used in the planning process prior to the start of the optimization.

2. Problems with Beamlet-based Inverse Planning

There are two major problems with BBIP. First, the very large number of beams that must be considered in the optimization process forces the use of approximate dose calculation schemes. Second, the resulting intensity patterns are usually unnecessarily complex in that there exists within the conformal aperture numerous low intensity elements abutting high intensity beamlets. Researchers have put considerable energy into trying to solve these problems, but the solutions often introduce approximations and compromises that are as troublesome as the problem being addressed. The list that follows identifies some of the compromises and approximations that are characteristic of beamlet-based inverse planning:

Common compromises

a. Monitor units are often unnecessarily high (related to patient total body dose)
b. The number of field segments is typically unnecessarily high (related to MLC wear and tear and increased treatment time)
c. Treatment verification for the typically complex intensity patterns is difficult at best
d. The full capabilities of a standard MLC (collimator rotation and positioning resolution in the direction of leaf movement) are not easily taken advantage of in the delivery process

Approximations

a. Crude dose calculations are commonly used for optimization
b. Intensity patterns are sometimes smoothed to reduce the impact of some of the compromises listed above
c. The handling of MU calculation is often less rigorous than traditional methods and the modeling of extremely small fields can be crude

Suggestions have been made to deal with many of these problems after the optimization is complete. Smoothing the intensity patterns is one example. Another is the use of Monte Carlo calculation of dose distributions coupled with the apertures that are produced by an optimization scheme that has used an approximate calculation technique. The aperture-based method of inverse planning is aimed at solving the problem of complex and approximate intensity patterns from the beginning by considering only a fixed pre-defined set of apertures in the optimization process.

The argument against attacking the problem after the optimization is complete centers on the fact that it is often very hard to achieve particular planning goals, and it is equally difficult to recover from any step that may give a more accurate dose distribution while degrading the quality of the DVHs so that dose constraints are no longer met. This is most evident when trying to satisfy strict protocol dose limits for cooperative group studies. The example given here is based on the RTOG oropharyngeal cancer protocol that is aimed at achieving parotid gland sparing with IMRT. This protocol has challenging dose volume constraints for a complex arrangement of targets with three different dose levels, and critical structures often invaginate or share voxels with the PTVs. Once constraints have been met for this very difficult planning problem, it is not desirable to introduce any changes that might negatively affect the dose volume histograms.

Major advantages of aperture-based inverse planning are that the reduced number of total fields used in the optimization allows the use of a precise calculation algorithm from the beginning so that no adjustments have to be made after the fact, and the superposition of just a few apertures per conformal aperture makes the intensity patterns simplifier.

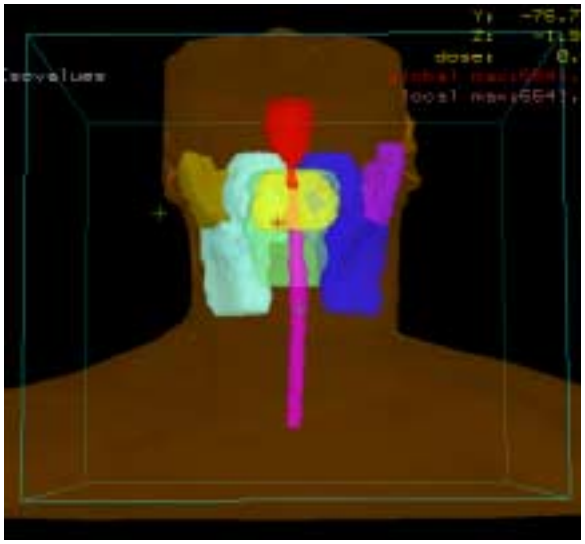
3. How are the ABIP field segments designed?

It is easy to understand the rules for establishing aperture shapes if the analogy of placing partial transmission blocks over critical structures is used. These partial transmission blocks serve to bend isodose lines around these regions. Of course, partial transmission blocks are not convenient to use and an MLC equivalent is needed. An MLC can mimic a partial transmission block through the use of three field segments. This procedure can be visualized by considering the beam's-eye view of a large target with the spinal cord running vertically through its center. This is the general geometry of the example that follows. In order to achieve the effect of placing a partial transmission block over the spinal cord, the following segments are used: First, a conformal segment that encompasses the entire target including the portion of the spinal cord that overlaps the target is defined. Second, a field segment that conforms to the target but stops short of including the spinal cord is established. Third, a field segment that covers the remaining portion of the target without including the spinal cord is established. Proper weighting of these targets will produce the equivalent of a partial transmission block with any desired transmission that is limited by the ability of the multileaf to absorb radiation. If there are numerous targets receiving different doses (classic boost arrangement) and more than

one critical normal tissue, finding the weights of a very large number of segments requires inverse optimization software. This software is often mistakenly referred to as weight optimization software.[1,6] It is in fact the same software routinely used for any inverse planning.

4. Example of a complex head and neck case

As an example of the comparison of BBIP and ABIP, a single case of a patient with oropharyngeal cancer is presented. This case was treated under the dose constraints as



described in the Radiation Therapy Oncology Group (RTOG) protocol H-0022. The complete details of this protocol are given at the RTOG we site (www.rtog.org). This case is illustrated above as a 3-dimensional view of the targets and the patient's anatomy.

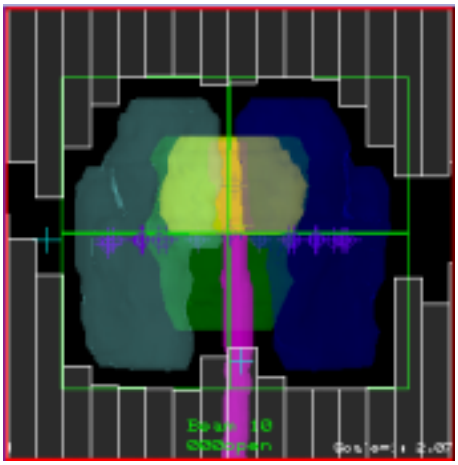
There are three different dose levels for this case. The area of gross tumor is shown as a PTV in yellow. The prescription for this PTV is 66 Gy treated in 30 fractions. Surrounding the PTV for the gross tumor is a region of subclinical disease at high risk that has a prescription dose of 60 Gy to be treated in the same 30 fractions. This PTV is shown in green. The neck nodes on this patient's left are also considered to be at high risk an are to receive a dose of 60 Gy. This PTV is shown in blue and is to be treated simultaneously with the other volumes. The final target is for the nodes on the right side that have a prescription dose of 54 Gy. These nodes are shown in teal and are also treated in 30 fractions.

The critical structures are the parotid glands on the right and left sides shown in brown and purple, and the brain stem and spinal cord shown in red and purple. Nine equally spaced gantry angles starting with an anterior field are used for this treatment. A detailed description of the dose prescription is given in the table below.

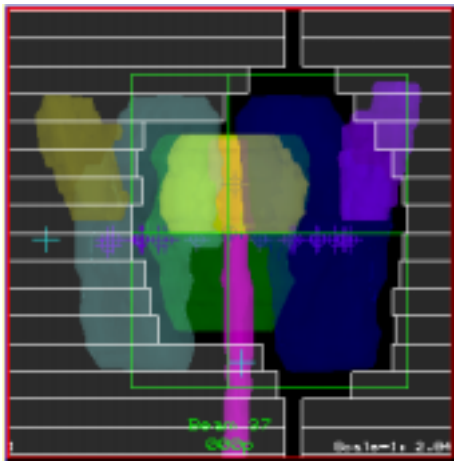
Region Defined by Contour	**Prescribed Dose (Gy) for 95% Coverage of Target Volume or Max Dose for Critical Structure (Gy)**
Gross Tumor plus Lymph Node Metastasis	66.0 (No more than 20% of volume to receive >72.6, and no more than 1% to receive <61.4)
Subclinical Disease at High Risk	60.0 (No more than 20% of volume to receive >66.0, and no more than 1% to receive <55.8)
Subclinical Disease	54.0 (No more than 20% of volume to receive >59.4, and no more than 1% to receive <50.2)
Brainstem	54.0
Spinal Cord	45.0
Mandible	70.0
Unspecified Tissue Outside the Targets	72.6
Parotid Glands	1) Mean dose to either parotid <26 2) At least 50% of either parotid gland will receive <30 3) At least 20 cc of the combined volume of both parotid glands will receive < 20

Using this oropharynx cancer case as an example, the following rules are used to define the apertures. Approximate numbers for the apertures or segments are given at each step in the process, and some field outlines are included to illustrate the process.

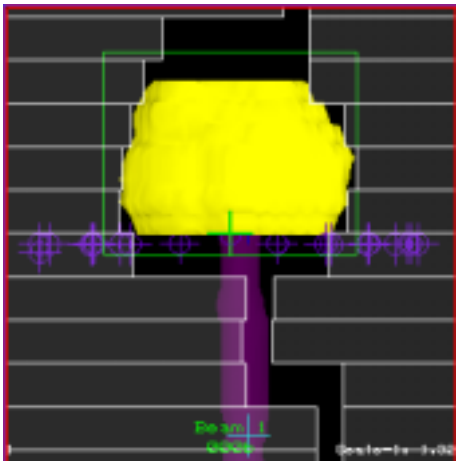
(1) For each gantry angle, establish a field segment that conforms to the beam's-eye view (BEV) of all targets (54, 60 and 66 Gy levels) combined. This gives a total of 9 segments when nine different gantry angles are used. Rotate the MLC to obtain the best fit.



(2) Repeat process by defining segments that conform to the BEV of the combined 60 and 66 Gy targets, but exclude the portion that receives the lowest prescribed dose. This gives an additional 9 segments.

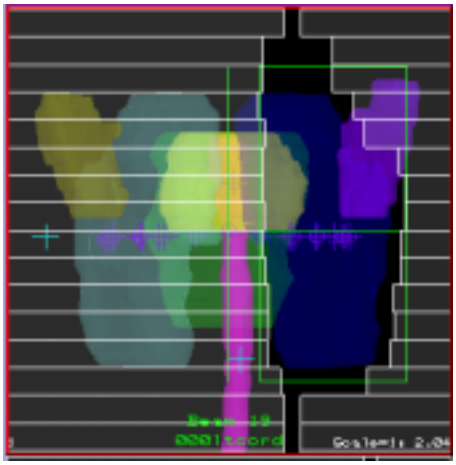


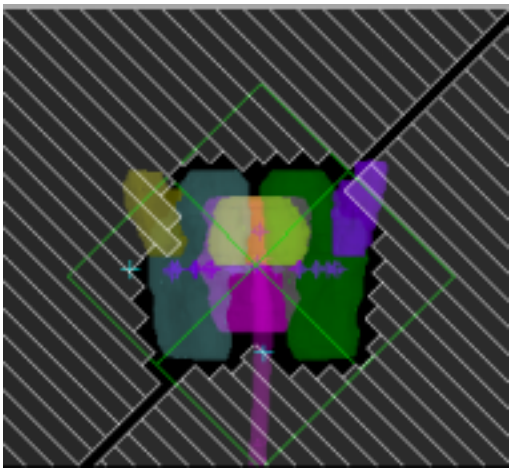
(3) For each gantry angle, define field segments that conform to the BEV of the boost volume with the highest prescription dose of 66 Gy. This gives 9 more segments.



(4) For each selected critical structure lying in the path of the conformal beam for the combined targets, construct field segments that conform to the combined targets but fully shielded the critical structure. This was done for the spinal cord plus brain stem, and for one parotid gland (right side) for the examples shown here. In some

situations this step may require more than one additional segment per critical structure and is repeated for each gantry angle. Approximately 27 additional segment were needed for this step.

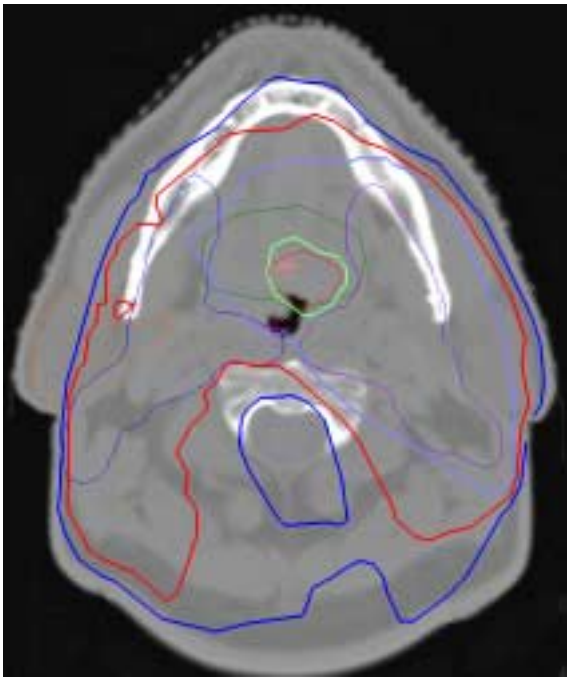




(5) Repeat step (4) for the 60 and 66 Gy targets combined. This gives an additional 27 segments.

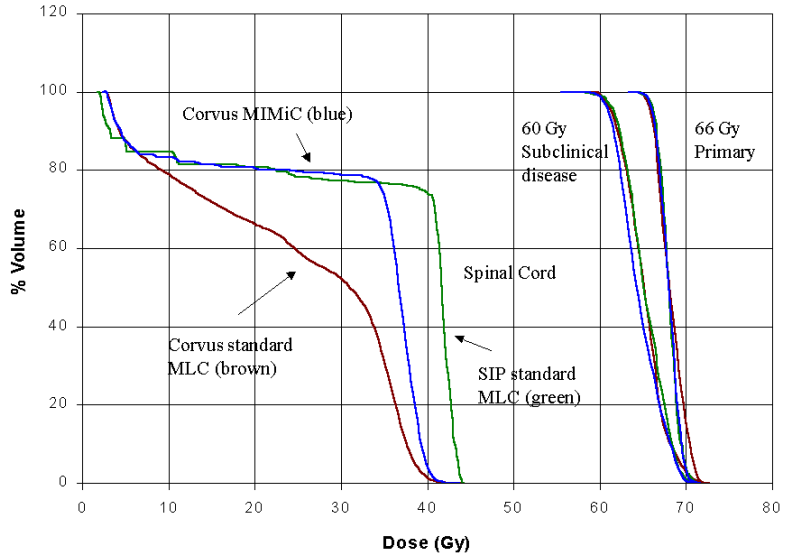
(6) For the complete target and again for each gantry angle, add extra segments to adjust for the dose inhomogeneity that results from shielding critical structures that do not run the length of the target. This gives approximately 18 extra segments.

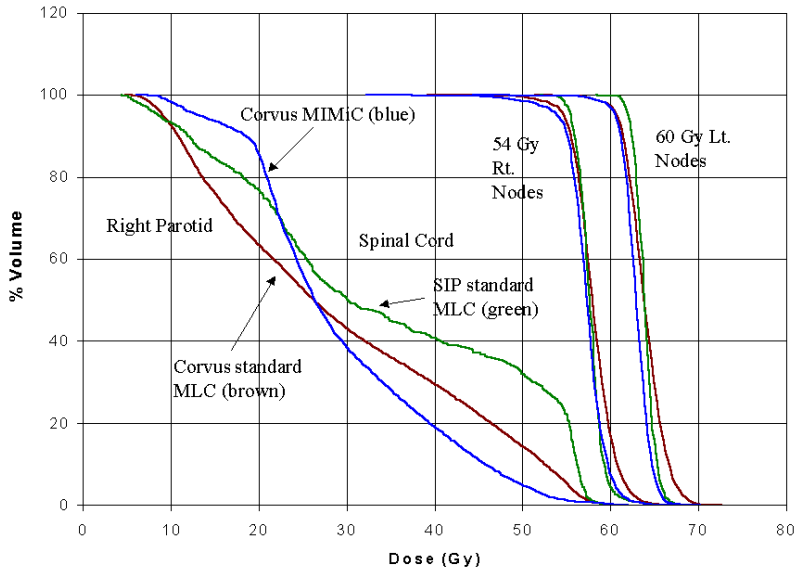
Some additional segments have been added to solve this particular planning problem. These segments serve to balance the high-dose streaking that can occur at the cross-



sectional position of the highest dose boost, or at the low-dose region that occurs as a result of shadowing the parotids to bend isodose curves around these critical structures. The figure above shows the dose distribution obtained with the ABIP planning method for a single transverse section through the patient at the level of the gross tumor.

In this example, as per the RTOG protocol, only the parotid on the patient's right side is protected. The dose distribution is highly conformal and meets all the constraints of the RTOG protocol. The PTV for the gross tumor is shown in red surrounded by the light green 66 Gy isodose line. A region of subclinical disease at high risk surrounds the gross tumor PTV and is shown in green. This PTV has a prescription dose of 60 Gy. The left neck nodes also are to receive a prescribed dose of 60 Gy.





The PTV for this volume is shown touching the central green PTV on the left and extending laterally around the spinal canal. The light blue isodose line is 60 Gy and surrounds most of these two 60 Gy volumes. The PTV for the right neck nodes is shown in blue. Its prescription dose is 54 Gy. The red 54 Gy isodose line is shown surrounding this volume as well as all of the higher dose volumes. Notice also the blue 45 Gy line shows a hole that surrounds the spinal cord. The DVHs for this plan are shown in the two figures above.

These figures compare three different IMRT approaches. The aperture-based inverse planning method is shown in green in the two figures, and is coded as SIP. There are two beamlet-based inverse planning techniques shown in these figures. They both use the NOMOS CORVUS planning, but differ in terms of the delivery technique employed. The red curves are for dose delivery with a standard multileaf collimator system and the blue curves couple the planning with the MIMiC binary collimator.

The top figure includes DVHs for the spinal cord and two of the four PTVs. One set of curves in this figure is for the PTV of the region of gross tumor (with a prescription dose of 66 Gy and shown in yellow in the first figure in this document), and the other is for the region of subclinical disease that surrounds this region (prescription dose of 60 Gy and shown in green in the first figure). Notice that there is very little difference for the three inverse planning/dose delivery methods.

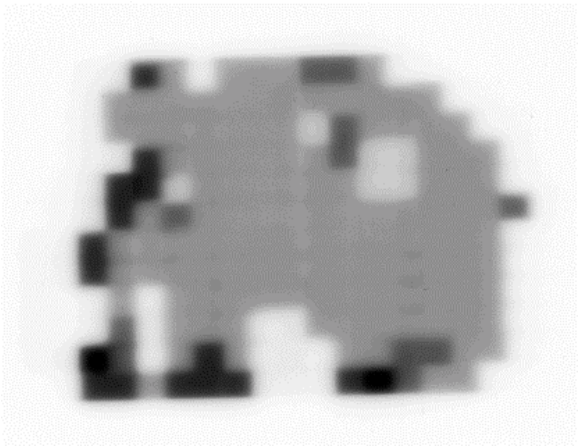
The second figure showing DVHs includes curves for the right parotid and the nodal regions on the patient's right and left side. All planning/delivery methods meet the dose constraints (30 Gy or less to 50% of the volume of the PTV) for the single parotid shown. Notice that the ABIP method gives the highest dose to 50% of the volume. Balanced against this is the very sharp shoulder that is evident for the low-dose region of the right neck nodes that receive a prescribed dose of 54 Gy. The tradeoff is due to the fact that the parotid on the right side pushes up against and shares some voxels with the 54 Gy PTV. Again, for this figure, the DVHs are similar and meet protocol constraints.

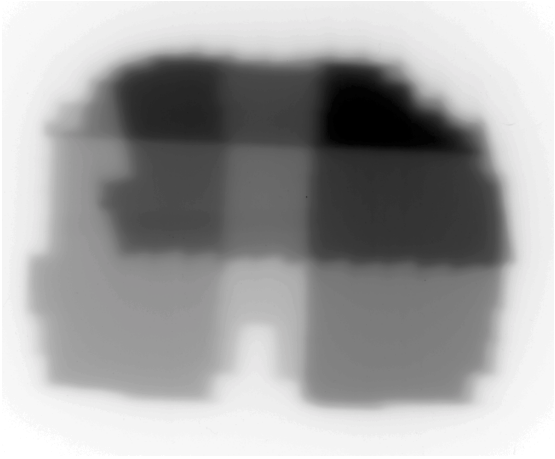
The figures that follow show the intensity patterns for the CORVUS inverse planning method used together with a standard MLC on the left and the ABIP method on the right. A total of 35 segments were needed to create the pattern on the left with an Elekta collimator, and 5 segments were needed when the same collimator was used for the aperture-based method. Thus, a factor of 7 decrease was found for this single case and the zero degree gantry angle. (It is interesting to point out that the total number of apertures needed to solve this planning problem using 9 different gantry angles was 44)

Averaging the results for two nine-field cases (the one shown here and another similar case), this factor of 7 decrease for one gantry direction of one case changed

slightly to an overall decrease of about a factor of 6 for the total of 18 different gantry angles for the two cases.

Again for two cases, the monitor units were compared and showed a large improvement for the ABIP method. There was a factor of 8 decrease in monitor units for the ABIP method compared to the CORVUS planning approach coupled with MIMiC dose delivery. Compared to the use of a standard MLC together with the CORVUS system, the monitor units for the ABIP method was reduced by a factor of 3.





5. What is the Bottom Line?

The ABIP method for inverse planning can significantly reduce both the number of segments and monitor units used for IMRT. This is accomplished without loss of dose coverage for the targets and sparing of nearby critical structures.

The large decrease in the number of apertures directly translates to reduced wear and tear on the multileaf collimator system, and the significantly lower monitors units impacts directly on patient total body dose. The intensity pattern for the ABIP method is simple and offers the opportunity to use standard port filming techniques for treatment verification. That is, the intensity pattern shown above for the anterior treatment field can be compared to the first two figures in this document and clearly illustrates the correspondence between the summation of all the targets and the baseline density that conforms to these targets. This is the single aperture that can be used to verify positioning of the figure through the port filming process. A similar conformal field does not emerge form the intensity pattern for the beamlet-based delivery method shown in the figure on the left. Verification of the entire intensity pattern for the ABIP method can be achieved by using the now standard method of

placing a film in front of the patient at the level of the block tray to monitor dose delivery at each separate gantry angle.

The simplicity of the ABIP intensity pattern throws into question the need for any dynamic dose delivery method for IMRT, and argues strongly for targeting future research efforts toward developing simpler techniques for this important new treatment modality.

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