Inverse planning in the age of digital LINACs: station parameter optimized radiation therapy (SPORT)

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Abstract. The last few years have seen a number of technical and clinical advances which give rise to a need for innovations in dose optimization and delivery strategies. Technically, a new generation of digital linac has become available which offers features such as programmable motion between station parameters and high dose-rate Flattening Filter Free (FFF) beams. Current inverse planning methods are designed for traditional machines and cannot accommodate these features of new generation linacs without compromising either dose conformality and/or delivery efficiency. Furthermore, SBRT is becoming increasingly important, which elevates the need for more efficient delivery, improved dose distribution. Here we will give an overview of our recent work in SPORT designed to harness the digital linacs and highlight the essential components of SPORT. We will summarize the pros and cons of traditional beamlet-based optimization (BBO) and direct aperture optimization (DAO) and introduce a new type of algorithm, compressed sensing (CS)-based inverse planning, that is capable of automatically removing the redundant segments during optimization and providing a plan with high deliverability in the presence of a large number of station control points (potentially non-coplanar, non-isocentric, and even multi-isocenters). We show that CS-approach takes the interplay between planning and delivery into account and allows us to balance the dose optimality and delivery efficiency in a controlled way and, providing a viable framework to address various unmet demands of the new generation linacs. A few specific implementation strategies of SPORT in the forms of fixed-gantry and rotational arc delivery are also presented.

1. Introduction
Digital linac with a few other important features has emerged for clinical use. A distinct feature of digital linac is that parameters characterizing radiation delivery such as the gantry angle, collimator angle, couch angle, and dose rate are discretized and can be controlled easily in a programmable fashion. The “fundamental unit” is a “station” point (a “station” can also be called a “node” in CyberKnife™ system). In the emerging digital era of radiation therapy (RT), a treatment will be done through the modulation of station parameters as the delivery is done “station by station”, instead of “beam by beam”. Here we emphasize that a station describes the state of delivery system (including LINAC configurations such as beam energy, aperture shape and weight, gantry/collimator/couch angle). When the auxiliary equipment is stationary, a station is no different from an MLC or jaw-shaped beam. Thus a conventional intensity-modulated beam consists of a collection of stations with the same gantry angle but different MLC segments. Existing radiation therapy scheme does not fully take the digital features of new RT scheme into consideration and how to leverage these new developments to overcome many of the limitations of current RT techniques becomes an urgent issue. Given the fact that the fundamental unit in the new era is “station”, it is fair to say that next-generation of RT will be all about the optimization of station parameters, which we call station parameter optimized radiation therapy (SPORT). VMAT and IMRT are simply two special, and often non-optimal, cases of SPORT. The premise of SPORT is that it will enable us to realize the enormous potential of digital linacs through optimal weighting and spatial distribution of the station points (including non-coplanar, non-isocentric distribution, and even multiple isocenters). In the following, some logistic issues related to SPORT implementation are discussed.

2. Implementation strategies of SPORT
Inverse planning and delivery are generally intertwined. While the station points can be, in principle, distributed arbitrarily in physically realizable parameter space, adding restriction to
limit the size of solution space is often necessary for practical reason. The actual delivery of SPORT can be realized in different ways. To familiarize readers with the novel SPORT scheme, here we describe three categories of SPORT delivery: rotational arc SPORT, fixed-station SPORT, and a combination of the two.

2.1. Rotational arc SPORT

In rotational arc delivery, analogous to VMAT and/or sliding window IMRT beam delivery, radiation is on when going from one station to the next. We have implemented a novel scheme of a rotational arc SPORT and shown that the need for multiple arcs in conventional VMAT can be eliminated through more intelligent distribution of the station points in the same coplanar sampling space. Conventional VMAT\textsuperscript{8-10} such as Varian RapidArc\textsuperscript{TM} discretizes the angular space into equally spaced station points (178 stations) during planning and then optimizes the apertures and weights of the stations. The aperture at an angle in between two stations is obtained through interpolation. This wisdom tacitly ignores the differential need for intensity modulation of different angles. Unless the discretization is infinitely fine (which is computationally prohibitive and avoidably oversamples some angles), the approach is incapable of providing sufficient modulation for some or all directions for many disease sites. As thus, multiple arcs are often required to produce a clinically acceptable treatment plan. In our one-arc SPORT implementation, the angular sampling rate (i.e. the number of stations per unit angle) is modulated according to the need of individual angles for intensity modulation\textsuperscript{7} (see Fig. 1 for a sketch). The essence here is how to identify the need of an individual angle for intensity modulation and provide the necessary intensity modulation for those angles that need it. Obviously, treatment plan for the single arc SPORT can be obtained by a direct optimization of weights and aperture shapes of the station points and their coplanar distribution. Development of such algorithm is to be published elsewhere. In our original study, for the ease of computation, we took a heuristic approach and planned the treatment in an adaptive fashion by starting from a conventional 1-arc VMAT plan with equally spaced stations. The angles that need higher intensity modulation are identified with the help of a “demand metric” defined as:

\begin{equation}
D_M(s) = \sum_{k=0}^{K-1} \left( \sum_{i=0}^{m} \left( |x_i^A(s) - x_i^A(s+k)| + |x_i^B(s) - x_i^B(s+k)| \right) \right) \left( \frac{MU(s) - MU(s+k)}{\alpha(s) - \alpha(s+k)} \right)
\end{equation}

where, \(x_i^A(s)\) and \(x_i^B(s)\) are the i-th MLC leaf positions of banks A and B at the s-th station, MU is the cumulative monitor units, \(\alpha\) is the gantry angle. Intuitively, the metric is the geometric modulation weighted by the segmental MU per gantry angle. The neighbouring 2K stations (K=10 in our study) are used to calculate the demand metric of a point. To boost an angle with a high “demand metric” value, we add a number of stations around the point. The rationale here is that, if the aperture or MU changes a lot at an angle in the original one-arc VMAT, it suggests that more apertures or stations are needed in the vicinity of the angle to meet the angular demand for more intensity modulation. The original and the added stations are then optimized again. A single arc sequence is then constructed for delivery using the TrueBeam\textsuperscript{TM}.

We have applied the technique to a few clinical cases and all demonstrated the success of the proposed scheme. For a clinically complicated head and neck case, for example, we found that the SPORT approach achieves much better target dose uniformity and sparing of right parotid (~20% EUD reduction) as compared to the 2-arc VMAT. The EUDs of the targets and critical structures for different plans reveal the same for other cases. In general, the MUs required for our approach lie between those for 1- and 2-arc VMAT, yet it leads to the best dose distributions.
As compared to the 2-arc VMAT, the single arc SPORT decreases the MUs by 20%-30%, depending on the case. This reduction will not only speed up dose delivery and improve clinical workflow, but also decrease the total-body radiation dose and the risk of secondary cancers\textsuperscript{11-13}. The SPORT plans for these cases have been successfully delivered on a TrueBeam\textsuperscript{TM} Linac.

2.2 Fixed-station delivery
SPORT can also be delivered station by station, much like fixed-gantry IMRT delivery. It is important to note that SPORT is the most general scheme and more conformal and efficiently deliverable dose distribution can be realized. Intuitively, one may consider that SPORT is a scheme with increased angular beam sampling while eliminating dispensable segments of the incident fields. In digital linacs, SPORT delivery is made efficient by (1) removing the redundant segments in the incident beams; (2) concatenating the stations so that they can be delivered in sequence automatically (i.e., auto-field sequencing); and (3) using high dose-rate beams\textsuperscript{5, 6, 14}. The technique, which we termed as DASSIM-RT (dense angularly sampled and sparse intensity modulated radiation therapy) (Fig. 2)\textsuperscript{1}, presents a truly optimal RT scheme with optimal angular sampling (including non-coplanar beams), beam intensity modulation, and possible energy and collimator modulation when going from one gantry angle to another\textsuperscript{15}.

2.3 CS-based SPORT inverse planning
CS-based method is an effective way to obtain SPORT or IMRT plan with no redundant intensity modulation. General, a treatment plan is selected from a large pool of physically feasible solutions by optimization of an objective function (OF). BBO\textsuperscript{18, 19} and DAO\textsuperscript{20-22} are two commonly used approaches for inverse planning. DAO attempts to tackle the problem from the delivery aspect by enforcing a pre-chosen (often unjustified) number of segments for each beam and then optimizes the shapes and weights of the apertures. Searching for an optimal solution by using DAO is inherently complicated because of the highly non-convex dependence of the OF on the MLC coordinates and the optimality of final solution is not guaranteed. Furthermore, the optimal number of apertures for a field must be chosen empirically, not by the actual field-specific need. In BBO, on the other hand, the delivery is completely decoupled from optimization and each beamlet is an independent variable - the optimized intensity map is highly complex and entails a large number of segments for delivery, which reduces both delivery efficiency and dosimetric accuracy. Instead of simply smoothing the fluence\textsuperscript{23}, the maps are encouraged to be piece-wise constant by introducing an L-1 total-variation regularization (TVR) in our approach. The maps so obtained will contain sharp transitions, which are
otherwise smoothed if quadratic smoothing is used. The difference between smoothing and TVR can be found in a textbook by Boyd and Vandenberghe. The key to substantially improving the two existing inverse planning methods lies in finding an effective way to seamlessly integrate the machine delivery constraints into the dose optimization process. Instead of directly including the non-convex physical constraints in optimization, we used CS method to accomplish the goal. The technique takes the interplay between planning and delivery into consideration and suppresses the dispensable/redundant intensity modulation of fluence maps naturally. Mathematically, it recasts the conventional DAO defined as

\[
\begin{align*}
\text{Minimize} & \sum_{i} \lambda_{i} (A_{i} x - d_{i})^{T} (A_{i} x - d_{i}) \\
\text{subject to:} & \quad x \geq 0 \quad \text{& is achievable using apertures (aperture constraint)}.
\end{align*}
\]

into

\[
\begin{align*}
\text{Minimize} & \sum_{i} \lambda_{i} (A_{i} x - d_{i})^{T} (A_{i} x - d_{i}) + \sum_{j=1}^{N_{d}} \sum_{f=1}^{N_{f}} \| s_{j, f} - s_{j, f-1} \| \| s_{j, f} - s_{j, f-1} \|
\end{align*}
\]

where, the index \(i\) denotes different organs, \(\lambda_{i}\) is the importance factor, \(A\) is the dose matrix, and \(d_{i}\) is the prescribed dose. In Eq. (2), the aperture constraint is neither linear nor quadratic. The L-1 norm in Eq. (3) is included to reduce the number of signal levels of the intensity maps by encouraging piece-wise continuity, removing the aperture constraint. A feature of the above optimization is that it can be reformulated rigorously as a quadratic programming (QP) problem, and thus efficiently solved using the standard QP. When applied to IMRT, the algorithm can reduce the total MUs for delivery by \(~35\%) while keep the quality of the resultant IMRT plan unchanged! It is also interesting to point out that the CS-based formalism in the FFF domain can be easily formulated to take the inherent shapes of incident beam profiles into account. By introducing an L-1 objective function specific to the known non-flat beam profile characteristics, the method searches for fluencies that are piece-wise constant in a domain defined by the basis function of the non-uniform beams. We demonstrated that optimization of the system provides IMRT fluences that are piece-wise constant in the selected FFF-domain, thus eliminating the inefficiency of dose delivery caused by non-flatness of the incident beams.

2.4 Role of prior geometric and dosimetric knowledge in SPORT optimization

Because of involvement of a large number of variables, a brute-force SPORT optimization can be computationally intractable. Incorporation of partial system knowledge is an effective way to reduce the complexity of the optimization. We have introduced a metric, named beam eye’s view dosimetrics (BEVD), for a priori ranking of the angular space and facilitating the beam orientation optimization in IMRT. The general consideration in constructing the BEVD is that a beam is more preferable if it can deliver more dose to the target without exceeding the dose tolerance of the OARs located on the path of the beam. For computational purpose, a beam portal is divided into a grid of beamlets. Each beamlet crossing the target is assigned the maximum intensity that could be used without exceeding the dose tolerances of the OARs. A forward dose calculation using the “maximum” beam intensity profile is then performed and the score of the given beam direction (indexed by \(f\)) is calculated according to

\[
S_{f} = \frac{1}{N_{v}} \sum_{n=1}^{N_{v}} \left( \frac{d_{v}}{D_{T}^{p}} \right) , \tag{4}
\]

where \(d_{v}\) is the maximum dose delivered to the voxel \(n\) by the beam from the direction indexed by \(f\), \(N_{v}\) is the number of voxels in the target, and \(D_{T}^{p}\) is the target prescription. The BEVD score function goes beyond the simple geometric BEV concept in 3D CRT and captures the main feature of a planner’s judgment about the quality of a beam. The inclusion of a priori BEVD ranking of the angular space should lead to significantly improved convergence and...
computational speed in SPORT configuration optimization. For a given patient, BEVD reveals that some beam directions are better/worse than others in terms of the dose deliverable to the target volume. This has demonstrated, although indirectly, by the interesting work of Rocha et al\textsuperscript{32}, who have developed a BEVD-guided pattern search algorithm for beam placement in IMRT.

2.5 Delivery efficiency of fixed station SPORT
The delivery time is described by Eq. (1). For a given SPORT configuration, CS-based fluence optimization will find the irreducible fluence maps, which means that further sparsification of the maps will deteriorate the resultant dose distribution. As exemplified in References 25, 27, the MU can be reduced by 30%-63\%, depending on the complexity of the case and the characteristics of the beams (i.e., FFF or flattened beams). In general, the total MLC travel time (the last term in Eq. (1)) is also reduced significantly when the dispensable MLC segments are eliminated. As a result, the delivery time will be reduced greatly as a result of intensity sparsification (the 2\textsuperscript{nd} and 3\textsuperscript{rd} terms in Eq. (1) are generally small compared to the other two terms). The Eq. (1) should include the contributions resulted from the couch motion when non-coplanar points are included in the SPORT treatment.

3. Summary
The emergence of digital linac calls for new strategies for treatment plan optimization and delivery. The concept and implementation of SPORT has been summarized. In general, existing 3D conformal RT (CRT), IMRT and VMAT represent special cases of SPORT. SPORT has a number of unique features and makes it possible to maximally utilize the technical capacity of digital linac. In rotational arc SPORT, for example, it completely eliminates the need for 2 or more arcs, yet providing dose distributions with unprecedented conformity and normal tissue sparing. On a more fundamental level, the benefit of SPORT stems from the better definition of search space and explicit incorporation of parameters characterizing the station points in inverse planning. SPORT enlarges the solution space through improved angular and intensity sampling of the stations\textsuperscript{1}. As has indicated in numerous studies, conformal dose distribution is essential to the improved treatment outcome and better patient care. Therefore, the SPORT formalism and tools should have a measurable clinical impact resulting in improved patient care in the future.

Acknowledgement: The work was partially supported by grants from NIH (1R01 CA133474, 1R21 CA153587 and 1K99 166186).

References
1. Li R, Xing L. Bridging the gap between IMRT and VMAT: dense angularly sampled and sparse intensity modulated radiation therapy. Med Phys. 2011;38: 4912-4919.
2. Wang L, Kielar KN, Mok E, Hsu A, Dieterich S, Xing L. An end-to-end examination of geometric accuracy of IGRT using a new digital accelerator equipped with onboard imaging system. Phys Med Biol. 2012;57: 757-769.
3. Fahimian B, Yu V, Xing L, Horst K, Hristov D. Trajectory Modulated Prone Breast Irradiation: A LINAC-based Technique Combining Intensity Modulated Delivery and the Motion of the Couch. Int J Radiat Oncol Biol Phys. 2013: submitted.
4. Xing L, Philips M, Orton C. DASSIM-RT is likely to become the method of choice over conventional IMRT and VMAT for delivery of highly conformal radiotherapy. Med Phys. 2013;40: 020601-020603.
5. Cho W, Bush K, Mok E, Xing L, Suh T-S. Development of a fast and feasible spectrum modeling technique for flattening filter free beams. Medical Physics. 2013;40: in press.
6. Cho W, Kielar KN, Mok E, et al. Multisource modeling of flattening filter free (FFF) beam and the optimization of model parameters. Medical Physics. 2011;38: 1931-1942.
7. Li R, Xing L. An adaptive planning strategy for station parameter optimized radiation therapy (SPORT): Segmentally boosted VMAT. Med Phys. 2013;40: 050701.
8. Yu CX. Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomosurgery. Phys Med Biol. 1995;40: 1435-1449.
9. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. Med Phys. 2008;35: 310-317.
10. Crooks SM, Wu X, Takita C, Matzich M, Xing L. Aperture modulated arc therapy. Phys Med Biol. 2003;48: 1333-1344.
11. Hall EJ. Intensity-modulated radiation therapy, protons, and the risk of second cancers. Int J Radiat Oncol Biol Phys. 2006;65: 1-7.
12. Hardcastle N, Metcalfe P, Ceylan A, Williams MJ. Multileaf collimator end leaf leakage: implications for wide-field IMRT. Phys Med Biol. 2007;52: N493-504.
13. Williams PO, Hounsell AR. X-ray leakage considerations for IMRT. Br J Radiol. 2001;74: 98-100.
14. Georg D, Knoos T, McClean B. Current status and future perspective of flattening filter free photon beams. Med Phys. 2011;38: 1280-1293.
15. Zhang P, Happensett L, Yang Y, Yamada Y, Mageras G, Hunt M. Optimization of collimator trajectory in volumetric modulated arc therapy: development and evaluation for paraspin SBRT. International journal of radiation oncology, biology, physics. 2010;77: 591-599.
16. Zhu L, Lee L, Ma Y, Ye Y, Mazzeo R, Xing L. Using total-variation regularization for intensity modulated radiation therapy inverse planning with field-specific numbers of segments. Phys Med Biol. 2008;53: 6653-6672.
17. Zhu L, Xing L. Search for IMRT inverse plans with piecewise constant fluence maps using compressed sensing techniques. Med Phys. 2009;36: 1895-1905.
18. Bortfeld T. Optimized planning using physical objectives and constraints. Seminars in Radiation Oncology. 1999;9: 20-34.
19. Xing L, Wu Y, Yang Y, Boyer AL. Physics of intensity modulated radiation therapy In: Mundt AJ, Roeske JC, editors. Intensity Modulated Radiation Therapy: A Clinical Perspective. Hamilton & London: BC Decker Inc., 2005:20-52.
20. Shepard DM, Earl MA, Li XA, Naqvi S, Yu C. Direct aperture optimization: a turnkey solution for step-and-shoot IMRT. Med Phys. 2002;29: 1007-1018.
21. Bednarz G, Michalski D, Houser C, et al. The use of mixed-integer programming for inverse treatment planning with pre-defined field segments. Phys Med Biol. 2002;47: 2235-2245.
22. Cotrutz C, Xing L. Segment-Based Dose Optimization Using a Genetic Algorithm. Physics in Medicine & Biology. 2003;48: 2987-2998.
23. Matuszak MM, Larsen EW, Fraass BA. Reduction of IMRT beam complexity through the use of beam modulation penalties in the objective function. Med Phys. 2007;34: 507-520.
24. Boyd S, Vandenberghe L. Convex Optimization. New York: Cambridge Univ Press, 2004.
25. Zhu L, Choi K, Boyd S, Xing L. Total-Variation Regularization Based Inverse Planning for Volumetric Modulated Arc Therapy. Med Phys. 2009;36: submitted
26. Zhu L, Lee L, Ma Y, Ye Y, Mazzeo R, Xing L. Using total-variation regularization for intensity modulated radiation therapy inverse planning with field-specific numbers of segments. Phys Med Biol. 2008;53: 6653-6672.
27. Kim T, Zhu L, Suh TS, Geneser S, Meng B, Xing L. Inverse planning for IMRT with nonuniform beam profiles using total-variation regularization (TVR). Med Phys. 2011;38: 57-66.
28. Wang L, Mok E, Xing L. Pros and Cons of Flattening Filter Free IMRT: A Comparison with Conventional IMRT with Flattened Beams. Med. Phys. 2010;37: 3375.
29. Pugachev A, Xing L. Pseudo beam'-eye-view as applied to beam orientation selection in intensity-modulated radiation therapy. Int J Radiat Oncol Biol Phys. 2001;51: 1361-1370.
30. Pugachev A, Xing L. Incorporating prior knowledge into beam orientation optimization. Int J Radiat Oncol Biol Phys. 2002;54: 1565-1574.
31. Schreibmann E, Xing L. Dose-volume based ranking of incident beam direction and its utility in facilitating IMRT beam placement. Int J Radiat Oncol Biol Phys. 2005;63: 584-593.
32. Rocha H, Dias JM, Ferreira BC, Lopes MC. Beam angle optimization for intensity-modulated radiation therapy using a guided pattern search method. Phys Med Biol. 2013;58: 2939-2953.