Constrained optimization for marker-based tumour tracking in VMAT plans

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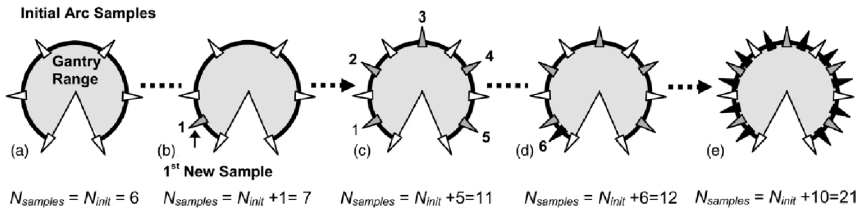
I. Introduction and Impact

This work investigates the incorporation of visibility parameters into the dosimetric optimization of volumetric modulated arc therapy (VMAT) plans using fiducial markers for tracking the tumor. The use of fiducial markers implanted in or at the tumour can be helpful in tumor localization as well as used for real-time tumour tracking during treatment delivery. With the visibility of markers in the beam's eye view (BEV) overlaid by the MLC apertures at each control point defined in the plans, we can use this information in the plan optimization strategy. We hypothesize that treatment plans that ensure a higher chance of successful application of real-time tracking techniques can be produced by incorporating marker visualization objectives in addition to purely dosimetric objectives. Thus, we have investigated an optimization tool (*MonArc*), the precursor to Eclipse's RapidArc, to optimize SBRT VMAT plans using additional marker-based constraints. This approach should produce treatment plans that are suitable for real-time tumour tracking methods to be successfully applied in the clinic.

II. Materials and Methods

- ❑ We investigated this approach on multiple patient disease sites (5 liver, and 5 lung) using a radiotherapy optimization development software (*MonArc* – a precursor to Eclipse RapidArc), where these new visibility constraints could be added to standard dosimetric constraints in the objective function.
- ❑ For all the investigated disease sites, three fiducial markers were implanted inside or around the planning target volume (PTV); and VMAT plans were created for each patient (See Table 1-2 for plan constraints).
- ❑ The VMAT plans were then exported to an inverse planning and optimization tool, *MonArc* developed by Karl Otto [1] , which was used for this custom optimization.
- ❑ *MonArc* utilizes a progressive resolution optimization (PRO) framework similar as found on earlier versions of Varian Eclipse TPS. Figure 1 shows the gantry sampling method used for VMAT.
- ❑ Optimization dose-volume constraints were defined for targets (ITV and PTV) and organs at risk (esophagus, heart, kidneys, lungs etc.).
- ❑ We modified *MonArc* to analyze the multi-leaf collimator (MLC) beam's-eye-view (BEV) at all control points in the gantry arc, while including marker-based visibility constraints of type 'hard' (i.e. requiring 100% visibility of all markers, HC) and 'soft' (i.e. penalizes visibility for one [SC_I] or two markers [SC_{II}] only) in the optimization process. Figure 2A shows the MLC BEV aperture for the different constrained plans in a Liver SBRT patient.
- ❑ *MonArc*-optimized plans were re-imported into Eclipse and patient dose recalculated using AcurosXB (v13.6.23) to ensure dosimetric accuracy.
- ❑ Dose distributions from the constrained plans (HC, SC_I and SC_{II}) were compared to the non-constrained plan (NC) using metrics including conformity index, homogeneity index, mean PTV dose, and doses to organs-at-risk (OAR). [See Table 3-4 for comparison metrics]

III. Optimization method: Direct aperture and progressive resolution (PRO) optimization



- Each iteration of the optimization involves randomly selecting an available gantry sample, then changing either the MU weight or a MLC leaf position for that sample
- MLC positions for the new sample are linearly interpolated from the MLC positions of the adjacent samples
- As new samples are introduced, the sampling frequency increases, thereby improving the modeling accuracy of dynamic MLC and gantry motion.

Fig 1: Modeling a continuous gantry arc using a progressive static beam angles.

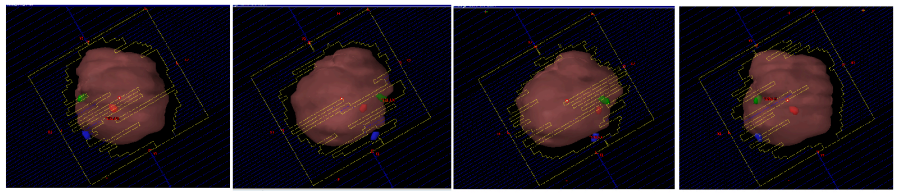
Table 1: Dose-volume and plan constraints for VMAT optimization in lung SBRT patients 1 – 5

Dose constraints			
Targets: Planning Target Volume (PTV); Gross Target Volume (GTV)			
Structures	Min. Dose vol./ Dose	Max. Dose vol./Dose	Fractions/Prescribed Dose
PTV	100%/48Gy	0%/52Gy	4/48Gy
ITV/GTV	100%/48Gy	0%/52Gy	4/48Gy
Relevant organs at risk (OARs): Lung, Esophagus, Heart, Chest wall and Ribs • **Specific plan/optimization constraints**			
OAR (Lung)	• 30% volume receiving < 20Gy		
OAR (Esophagus)	• volume receiving 18.8Gy < 5 cm^3		
OAR (Heart)	• volume receiving 28Gy < 15 cm^3		
OAR (Ribs)	• volume receiving 32Gy < 1 cm^3		
OAR (Chest wall)	• volume receiving 30Gy < 30 cm^3		

Table 2: Dose-volume and plan constraints for VMAT optimization in liver SBRT patients A–E

Dose constraints			
Targets: Planning Target Volume (PTV); Internal Target Volume (ITV)			
Structures	Min. Dose vol./ Dose	Max. Dose vol./Dose	Fractions/Prescribed Dose
PTV	100%/50Gy	0%/52Gy	5/50Gy
ITV	100%/50Gy	0%/52Gy	5/50Gy
Relevant organs at risk (OARs): Kidney, Esophagus, Large Bowel and Heart • **Specific plan/optimization constraints**			
OAR (Kidneys)	• 40% volume to receive maximum 9.0Gy • 50% volume to receive maximum 6.5Gy		
OAR (Esophagus)	• 11% volume to receive maximum 61Gy • 0.2% volume to receive maximum 70Gy		
OAR (Large Bowel)	• 50% volume to receive maximum 32Gy		
OAR (Heart)	• 50% volume to receive maximum 30Gy		

IV. Results



I. Non-Constrained (NC) plan aperture | II. Hard-Constrained (HC) plan aperture | III. Soft-Constrained (SC_I) plan aperture | IV. Soft-Constrained (SC_{II}) plan aperture

Fig 2A. Example MLC beams'-eye-view (BEV) aperture shapes at a specific control point in 'visually constrained' *MonArc* plans – with the three markers either fully blocked(I), fully visible (II) and partially visible (III-IV) – for an example Liver SBRT patient B.

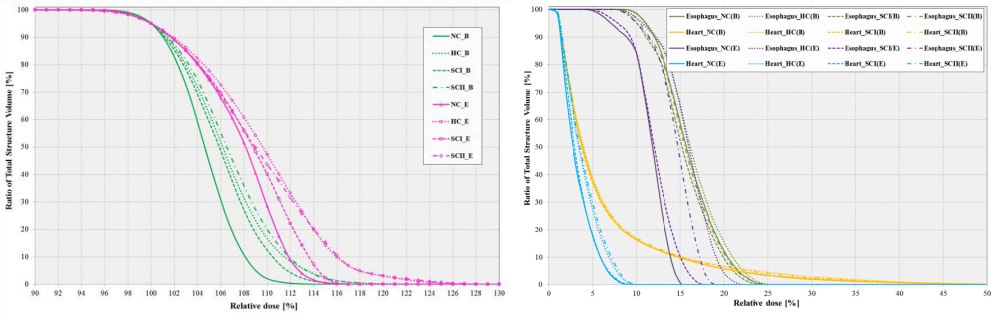


Fig 2B: DVH comparison [zoomed-in] for (a) PTV and (b) OARs (esophagus and heart) between *MonArc*-based non-constrained (NC), soft-constrained (SC_I and SC_{II}) and hard-constrained (HC) VMAT plans on two Liver SBRT patients B and E.

- **Homogeneity index** = $\frac{\text{Maximum isodose in target}}{\text{reference isodose}}$
- **Conformity index** = $\frac{\text{Reference isodose volume}}{\text{target volume}}$

Table 3: Quality metrics for optimized VMAT plans on lung SBRT patients (A–E), where soft constrained plans for one and two markers were averaged, and compared to hard- and non-constrained plans. [CI = conformity index; HI = homogeneity index; MU = monitor units].

Metrics per patient	1	2	3	4	5
Non-constrained plan i.e. NC					
Average Index, (CI+HI)/2	1.172	1.215	1.181	1.224	1.143
$D_{99\%}$ >= 90% of Rx	96.9%	95.7%	92.0%	92.4%	93.8%
V20Gy < 30% (Lungs)	2.10%	1.64%	3.37%	5.02%	12.13%
V28Gy < 15cc (Heart)	0.42	0.00	0.00	0.00	14.12
V32Gy < 1cc (Ribs)	0.56	5.28	10.15	1.62	13.08
MU	1180.8	1384.9	1786.4	1473.2	1507.5
Soft-constrained plan on one marker i.e. SC_I = (SC1 + SC2 + SC3)/3					
Average Index, (CI+HI)/2	1.204	1.300	1.166	1.267	1.156
$D_{99\%}$ >= 90% of Rx	96.9%	96.2%	94.2%	94.3%	93.9%
V20Gy < 30% (Lungs)	2.18%	1.78%	3.53%	5.96%	12.89%
V28Gy < 15cc (Heart)	0.29	0.00	0.00	0.00	13.06
V32Gy < 1cc (Ribs)	0.56	5.94	10.74	3.69	12.09
MU	1155.8	1106.8	1081.6	1043.6	1183.5
Soft-constrained plan on two markers i.e. SC_{II} = (SC12 + SC13 + SC23)/3					
Average Index, (CI+HI)/2	1.203	1.330	1.167	1.304	1.172
$D_{99\%}$ >= 90% of Rx	96.8%	96.0%	94.4%	94.3%	92.8%
V20Gy < 30% (Lungs)	1.99	1.80	3.62	5.18	12.93
V28Gy < 15cc (Heart)	0.37	0.00	0.00	0.00	14.01
V32Gy < 1cc (Ribs)	0.58	6.02	11.20	6.78	12.51
MU	1138.0	1065.3	1008.1	1002.1	1151.0
Hard-constrained plan on all three markers i.e. HC ≡ SC_{III} = SC123					
Average Index, (CI+HI)/2	1.201	1.354	1.278	1.305	1.195
$D_{99\%}$ >= 90% of Rx	96.4%	95.7%	91.2%	94.9%	92.1%
V20Gy < 30% (Lungs)	2.10%	1.81%	3.84%	5.94%	13.16%
V28Gy < 15cc (Heart)	0.31	0.00	0.00	0.00	13.39
V32Gy < 1cc (Ribs)	0.56	6.19	11.87	5.36	13.98
MU	1159.7	1036.5	1041.3	965.4	1107.8

Table 4: Quality metrics for optimized VMAT plans on liver SBRT patients (A–E), where soft constrained plans for one and two markers were averaged, and compared to hard- and non-constrained plans. [CI = conformity index; HI = homogeneity index; MU = monitor units].

Metrics per patient	A	B	C	D	E
Non-constrained plan i.e. NC					
Average Index, (CI+HI)/2	1.168	1.088	1.097	1.180	1.064
PTV dose, D_{mean}	106.9%	104.6%	103.5%	106.9%	107.4%
$D_{0.5cc}$ < 32Gy (esophagus)	17.09	9.99	3.34	4.21	7.21
D_{30cc} < 30Gy (heart)	11.55	8.30	1.18	1.21	2.75
$D_{0.5cc}$ < 32Gy (large bowel)	21.78	3.30	37.10	13.19	2.73
MU	1122.4	1451.7	938.9	1036.6	1124.9
Soft-constrained plan on one marker i.e. SC_I = (SC1 + SC2 + SC3)/3					
Average Index, (CI+HI)/2	1.320	1.150	1.239	1.138	1.146
PTV dose, D_{mean}	111.9%	105.9%	106.4%	105.9%	108.5%
$D_{0.5cc}$ < 32Gy (esophagus)	17.20	10.14	4.13	4.49	8.11
D_{30cc} < 30Gy (heart)	13.42	8.15	1.25	1.37	2.98
$D_{0.5cc}$ < 32Gy (large bowel)	20.89	3.59	44.25	16.41	3.04
MU	772.2	1421.8	808.9	797.6	1010.4
Soft-constrained plan on two markers i.e. SC_{II} = (SC12 + SC13 + SC23)/3					
Average Index, (CI+HI)/2	1.405	1.171	1.256	1.149	1.209
PTV dose, D_{mean}	112.2%	106.3%	107.8%	105.7%	108.6%
$D_{0.5cc}$ < 32Gy (esophagus)	17.68	10.29	4.37	4.51	9.10
D_{30cc} < 30Gy (heart)	17.01	8.42	1.29	1.43	3.12
$D_{0.5cc}$ < 32Gy (large bowel)	21.17	3.76	47.50	17.32	3.19
MU	783.1	1397.4	780.7	771.4	966.4
Hard-constrained plan on all three markers i.e. HC ≡ SC_{III} = SC123					
Average Index, (CI+HI)/2	1.448	1.178	1.290	1.199	1.302
PTV dose, D_{mean}	114.8%	106.3%	111.8%	107.4%	109.4%
$D_{0.5cc}$ < 32Gy (esophagus)	17.21	10.62	4.49	4.87	10.02
D_{30cc} < 30Gy (heart)	17.73	8.97	1.34	1.62	3.21
$D_{0.5cc}$ < 32Gy (large bowel)	20.49	3.82	50.71	18.07	3.27
MU	767.6	1357.8	769.7	745.1	954.3

V. Summary and Conclusion

- Liver patients: Using the average index, there was a 7.1% difference for SC_I, 10.6% for SC_{II} and 14.6% for HC plans respectively, compared to NC plans for the liver patients. NC produced the best target conformity and the least OAR doses for the entire set.
- Lung patients: Using the average index, there was a 2.7% difference for SC_I, 4.1% for SC_{II} and 6.7% for HC plans respectively. NC produced the best target conformity and the least OAR doses for the entire dataset, followed by the SC_I, SC_{II} and HC plans.
- The SC_I plans produced slightly better OAR dose-quality results compared to the SC_{II} plans, while the HC plan produced the worst. Finally, OAR dose metrics for the five lung and liver patients show that all plans consistently met the clinical dose objectives. However, some lung SC_I plans outperformed the NC plan, exposing the heart OAR to up to 50% less dose relative to the reference NC plan.
- In conclusion, we demonstrated that visibility constraints can be incorporated into the optimization together with dosimetric objectives to produce treatment plans satisfying both types of clinical objectives. This approach can help real-time tracking using VMAT.

Acknowledgements

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Reference(s)

[1] Karl Otto, "Volumetric modulated arc therapy: IMRT in a single gantry arc", Medical Physics 35 (1), January 2008

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