Is There a Clinical Benefit with a Smooth Compensator Design Compared to a Plunged Compensator Design for Passive Scattered Protons?

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Purpose/Objectives

The purpose of this study was to investigate the potential dosimetric and milling time benefits of smooth compensators

Learning Objectives:
1) Understand the purpose of a compensator in passive scattered protons
2) Outline the uncertainties with plunged-depth compensators
3) Investigate the potential benefits of using smooth compensators

Introduction

Proton therapy has the ability to deposit the maximum dose per beam in the target at a defined depth with its Bragg Peak. [1] This gives protons the ability to preserve healthy tissues distal to the target. The distal dose conformality is aided by a wax or acrylic compensator for passively scattered proton therapy.[2, 3]

The most common manufacturing design for compensators is a "plunged" technique. The plunged technique mills the compensator through a series of points, one-by-one to a specific depth with a drill bit of a specified diameter, usually 2-5mm, and taper angle, usually 2-3 degrees. A high resolution design is optimal, but the thickness of the drill bit degrades the degree of resolution of the compensator design and resultant dose distribution on the distal end of the target.[6, 7] In addition, this technique can be very time consuming because the compensator design is very complicated and involves hundreds of plunge points. Clinical effectiveness and patient start times can be affected by the time requirements of the plunge technique.

Alternatively, a "smooth" compensator design is available in the TPS. The plunged-depth points must be converted into a three dimensional wireframe surface so that the compensator can be milled with a smooth surface. There are a few limitations one must consider before clinical implementation of smooth compensators. Access to conversion software that can convert the TPS output into a readable format by the CNC Mill and an engineer with knowledge about how to setup the CNC Mill with the correct tools to mill the smooth compensator is needed for this technique. The smooth compensator design marginalizes steep depth gradients, reduces the distal dose resolution issues related to the drill bit size, and eliminates drill bit tapering issues in the TPS algorithm.

Methods and Materials

Five patients from five different clinical sites, prostate, lung, liver, brain, and CSI, were selected for this study. The patients were randomly selected within each site in order to give the study a broad analysis and distribution of various anatomical sites.

Four smooth compensator plans were designed and compared to the original plunged depth plan. The "Smooth Base" plan is a copy of the original plunged depth plan with the same parameters, but the compensator milling design was changed to smooth. The three additional smooth compensator plans were Double Smear (DS), PTV +1cm, and Manual Edits (ME). The DS plan had doubled the calculated smear value with all other parameters unchanged. The PTV +1cm plan added an additional 1cm to the PTV which was used for the compensator design only. The ME plan was individually assessed and the treatment planner made manual adjustments to the compensator to increase the dose to the areas of the CTV lacking coverage. The plans made sure to have the minimum amount of PTV coverage as the original plunged depth plan in order for the plans to be comparable.

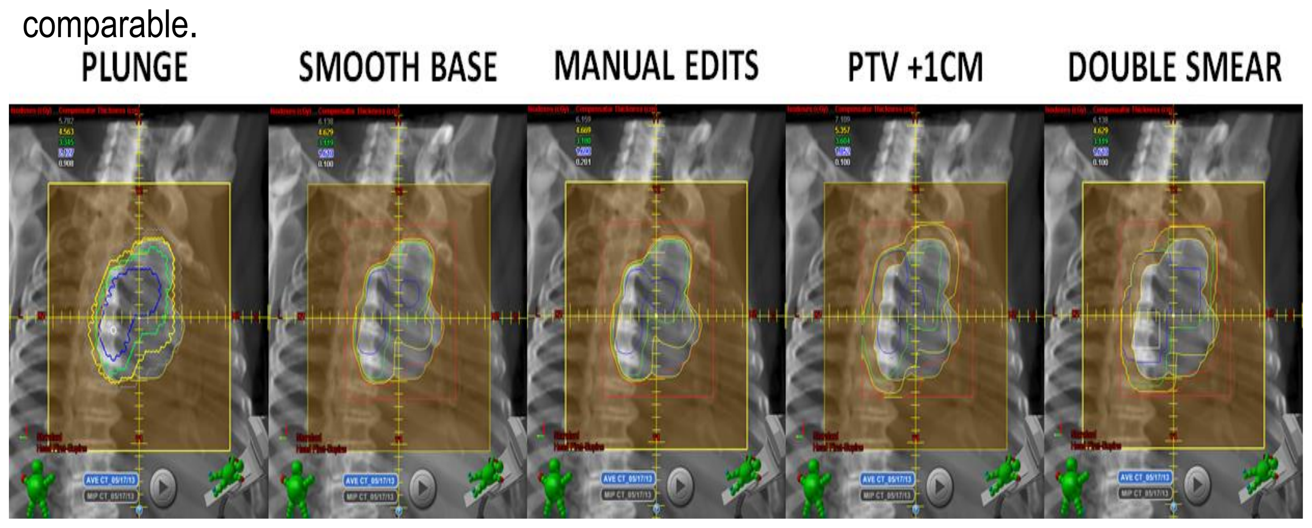


Figure 1. Compensator designs for each smooth compensator technique for a lung patient.

Multi-criteria (MCA) plan quality metrics was used for plan assessment and comparison. Each criterion was given a metric score in proportion to its priority. The metric values for all criterions totaled a maximum score of 150. The parameter ranges were based on the range of dosimetric results from the plunged-depth plans for each criterion rather than clinical constraints so that metric results would be meaningful with small differences between the plans

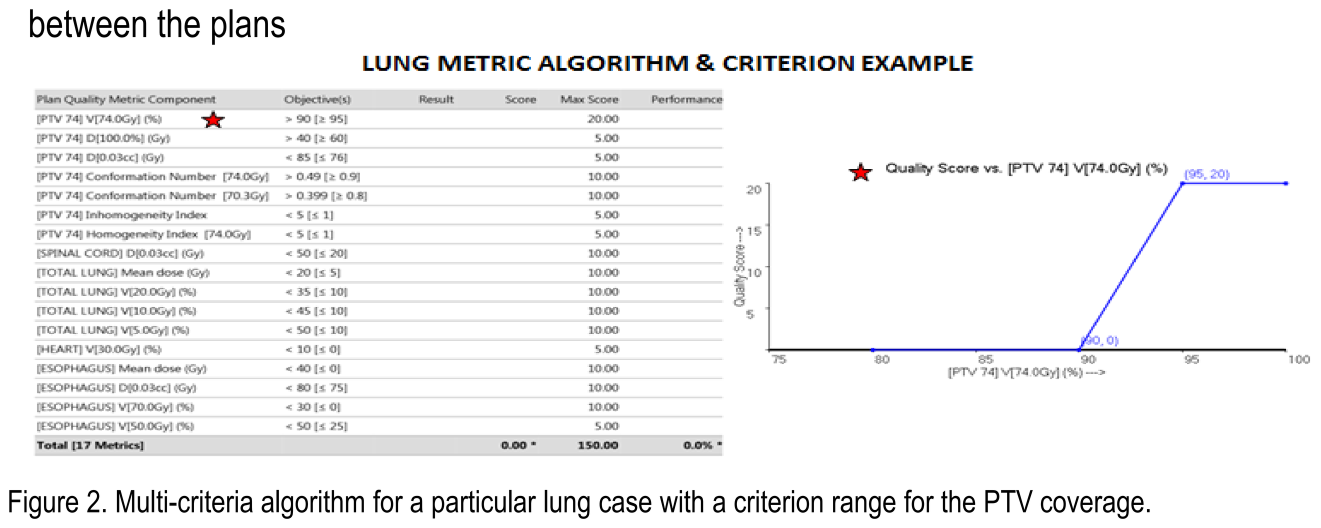


Figure 2. Multi-criteria algorithm for a particular lung case with a criterion range for the PTV coverage.

Results

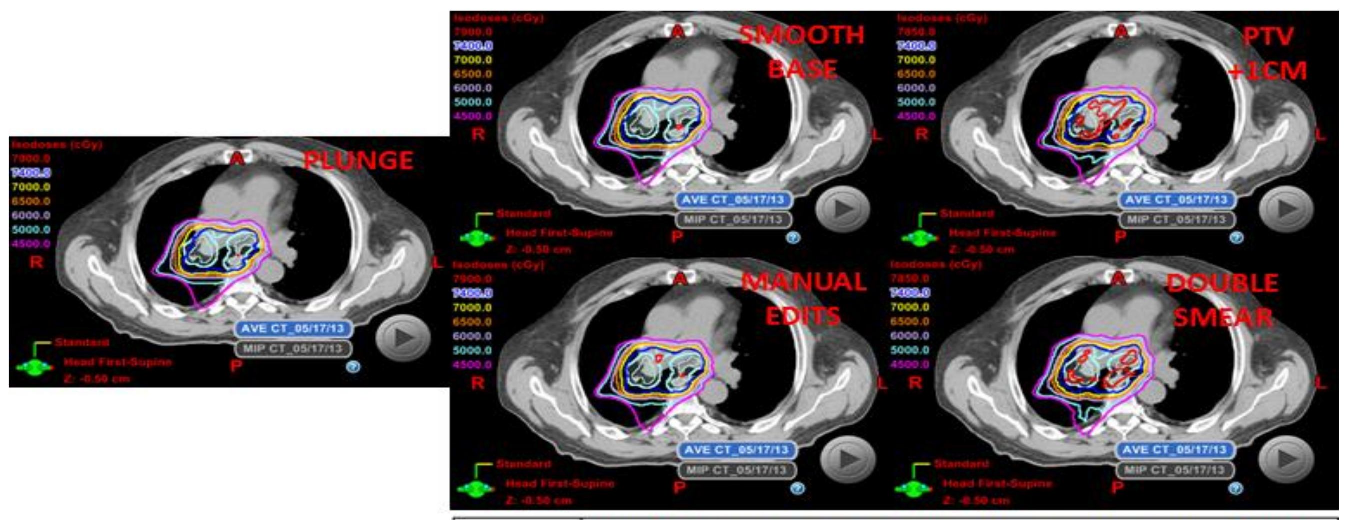
Dosimetric Results:

In comparison to the plunged-depth plan, the ME plans had similar or better results for all five sites. (Table 1) On average for all five sites, the ME plans performed better than the other smooth compensator techniques.

		Scoring Metric Range	Max Points	Priority	Plunge	SB	ME	PTV +1	DS
BRAIN									
[PTV 50.4 CGE]	D[0.03cc]	≤ 50 [< 56]	5	3%	53.8	1.9	0.1	1.0	1.0
	V[50.4] (%)	≥ 100 [> 80]	20	13%	93.2	**-5.0^**	0.5	1.8	**-1.8^**
	D[100.0%]	≥ 50.4 [> 40]	5	3%	39.1	-2.1	1.2	4.7	2.7
	Conformation Number [100%]	> 0.499	10	7%	0.64	-	-	-	**-0.02^**
	Conformation Number [95%]	> 0.399	10	7%	0.54	**-0.03***	-	-	-
	Inhomog. Index	< 0.5	5	3%	0.29	0.1	-	-0.1	-
	Homog. Index [100%]	< 0.5	5	3%	0.10	-	-	0.0	-
[NORMAL TISSUE]	[OPTIC CHIASM] D[0.03cc]	≤ 0 [< 54]	15	10%	30.7	0.2	0.2	0.2	-0.1
	[BRAINSTEM] D[0.03cc]	≤ 0 [< 54]	15	10%	31.2	0.1	0.1	0.2	-0.1
	[RT OPTIC NERVE] D[0.03cc]	≤ 0 [< 54]	15	10%	20.4	-1.1	0.3	2.6	0.7
	[LT OPTIC NERVE] D[0.03cc]	≤ 0 [< 54]	15	10%	29.4	-0.2	0.1	0.2	0.2
	[SPINAL CORD] D[0.03cc]	≤ 0 [< 10]	15	10%	0.1	-	-	-0.1	-
	[BRAIN] V[30.0] (%)	≤ 0 [< 30]	10	7%	10.8	**-0.9***	-0.6	0.4	0.4
	[BRAIN] Mean	≤ 0 [< 15]	5	3%	7.4	-0.4	-0.2	0.2	0.2
LUNG									
[PTV 74 CGE]	D[0.03cc]	≤ 76 [< 85]	5	3%	83.4	2.9	1.3	1.9	1.1
	V[74.0] (%)	≥ 95 [> 90]	20	13%	94.9	**-2.3^**	**1.1***	-1.8	-0.9
	D[100.0%]	≥ 60 [> 40]	5	3%	49.7	-3.1	0.3	9.1	1.5
	Conformation Number [100%]	> 0.499	10	7%	0.70	**-0.02***	-	-	**-0.04^**
	Conformation Number [95%]	> 0.399	10	7%	0.62	**-0.02***	-	-	**-0.03^**
	Inhomog. Index	< 0.5	5	3%	0.44	**-0.1^**	-	-0.1	-
	Homog.Index [100%]	< 0.5	5	3%	0.17	**-0.2^**	**-0.01***	-	-
[NORMAL TISSUE]	[SPINAL CORD] D[0.03cc]	≤ 20 [< 50]	10	7%	34.5	-0.8	-0.5	0.4	1.0
	[TOTAL LUNG] Mean	≤ 5 [< 20]	10	7%	14.1	**-0.7***	**-0.5***	-0.3	**0.6^**
	[TOTAL LUNG] V[20.0] (%)	≤ 10 [< 35]	10	7%	25.1	**-1.6***	-1.0	-0.9	**1.2^**
	[TOTAL LUNG] V[10.0] (%)	≤ 10 [< 45]	10	7%	30.1	**-1.4***	**-1.0***	-0.3	**1.4^**
	[TOTAL LUNG] V[5.0] (%)	≤ 10 [< 50]	10	7%	32.9	**-1.7***	**-1.2***	-0.4	**1.7^**
	[HEART] V[30.0Gy] (%)	≤ 0 [< 10]	5	3%	5.8	-1.6	-1.4	-1.7	0.9
	[ESOPHAGUS] Mean	≤ 0 [< 40]	10	7%	22.9	-3.0	-2.5	-2.9	**1.7^**
	[ESOPHAGUS] D[0.03cc]	≤ 75 [< 80]	10	7%	62.5	0.9	0.7	1.9	**2.3^**
	[ESOPHAGUS] V[70.0] (%)	≤ 0 [< 30]	10	7%	13.4	-2.3	-1.9	-2.2	**2.3^**
	[ESOPHAGUS] V[50.0] (%)	≤ 25 [< 50]	5	3%	25.2	-5.2	-4.5	-3.3	**3.0^**
PROSTATE									
[PTV 78CGE]	D[0.03cc]	≤ 85.8 [< 89.70]	10	7%	83.5	0.2	n/a	-	**-0.9***
	V[78.0] (%)	≥ 100 [> 98]	30	20%	98.8	-0.2	n/a	0.7	0.3
	D[100.0%]	≥ 78 [> 74]	30	20%	76.4	-0.6	n/a	**0.6***	0.3
	Conformation Number [100%]	> 0.499	10	7%	0.69	**0.03***	n/a	**-0.1^**	**-0.1^**
	Conformation Number [95%]	> 0.399	10	7%	0.55	**0.02***	n/a	**-0.1^**	**-0.1^**
	Inhomog. Index	< 0.5	5	3%	0.09	-	n/a	-	**-0.02***
	Homog.Index [100%]	< 0.5	5	3%	0.07	-	n/a	-	**-0.02***
[NORMAL TISSUE]	[RECTUM] V[80.0Gy] (%)	≤ 0 [< 3]	5	3%	1.6	0.1	n/a	0.4	-0.5
	[RECTUM] V[75.6Gy] (%)	≤ 0 [< 10]	5	3%	6.8	-	n/a	0.2	**0.4^**
	[RECTUM] V[70.0Gy] (%)	≤ 7 [< 13]	10	7%	10.6	-	n/a	-	**0.4^**
	[RECTUM] D[0.03cc]	≤ 80 [< 85]	5	3%	81.9	-0.1	n/a	0.1	-0.6
	[ANT. RECT WALL] V[70.0] (%)	≤ 25 [< 40]	10	7%	32.7	-	n/a	-	**1.1^**
	[FEMORAL HEADS] V[45.0] (%)	≤ 36 [< 40]	5	3%	0.0	-	n/a	-	-
	[BLADDER] V[70.0] (%)	≤ 0 [< 20]	10	7%	10.6	-0.2	n/a	1.1	1.0
LIVER									
[PTV 67.5 CGE]	D[0.03cc]	≤ 70 [< 76]	5	3%	73.6	**1.3^**	0.9	**1.4^**	-0.1
	V[67.5] (%)	≥ 100 [> 80]	20	13%	88.7	-0.9	0.6	**1.7***	0.5
	D[100.0%]	≥ 60.8 [> 35]	10	7%	42.3	-0.6	0.2	0.4	0.3
	Conformation Number [100%]	> 0.499	10	7%	0.73	-	-	**-0.05^**	-
	Inhomog. Index	> 0.399	5	3%	0.46	-	-	-	-
	Homog.Index [100%]	< 0.5	5	3%	0.27	**0.3^**	-	-	-
[NORMAL TISSUE]	[LIVER - GTV] Mean	≤ 10 [< 30]	15	10%	20.8	**-0.1***	-0.7	1.7	1.0
	[LIVER - GTV] V[30.0] (%)	≤ 15 [< 45]	15	10%	30.9	**-1.5***	-1.3	2.3	1.7
	[SPINAL CORD] D[0.03cc]	≤ 25 [< 50]	15	10%	27.3	-1.2	-1.8	2.1	1.2
	[RT KIDNEY] V[14.0] (%)	≤ 0 [< 30]	15	10%	15.0	-0.6	-0.3	1.7	0.4
	[LT KIDNEY] V[14.0] (%)	≤ 0 [< 30]	15	10%	4.1	-	-	-	-
	[HEART] D[0.03cc]	≤ 0 [< 45]	10	7%	41.9	-3.8	2.7	-0.5	6.5
	[HEART] V[40.0] (%)	≤ 0 [< 5]	10	7%	1.6	-0.2	-0.2	0.6	0.5
CRANIOSPINAL									
[TARGET 36.0 CGE]	D[0.03cc]	≤ 36 [< 39]	15	10%	41.5	0.6	0.2	0.7	0.1
	V[36.0 CGE] (%)	≥ 100 [> 90]	45	30%	93.1	-2.5	0.8	-1.7	**-2.4^**
	D[100.0%]	≥ 100 [> 95]	45	30%	27.0	2.1	2.8	2.6	2.9
	Conformation Number [100%]	> 0.499	15	10%	0.2	**-0.01^**	-	-	-
	Conformation Number [95%]	> 0.399	15	10%	0.1	-	-	-	-
	Inhomog. Index	< 0.5	7.5	5%	0.4	-	-0.1	-	-0.1
	Homog.Index [100%]	< 0.5	7.5	5%	0.1	**0.02^**	0.0	**0.02^**	**0.01^**
NT	[SPINAL CORD] V[38.5] (%)	< 50.40	0	0%	1.5	3.8	2.0	**3.1**	2.2

*Statistical Significance (p-value < 0.05): ^Plung Depth Plan, *Smooth Compensator Plan*

Table 1. The following table displays the dosimetric results for each plan relative to the plunge depth plan. The values for the smooth compensator plans are the absolute differences from the plunge depth result. The point value and priority of each criterion is listed out of a total 150 points.



	PTV 100%	PTV Max	Eso. Mean	Eso. Max	Cord Mean	Cord Max
Plunge	96.6%	8089	2353	7847	422	2324
SB	93.7%	8227	2184	7911	400	2272
ME	97.7%	8201	2274	7854	400	2222
PTV +1cm	97.1%	8200	2440	7970	435	2343
DS	90.8%	8546	2498	8086	435	2337

Figure 3. Slice comparison with dose parameters for each technique for a lung plan. The ME plan resulted in better coverage and sparing of the esophagus and cord.

Metric and Performance Results:

Table 2 compares the plan metric and performance results for each smooth compensator technique compared to the plunged-depth plans. The only technique with an increase in the metric and performance results for all five sites was the ME technique with an average metric and performance improvement of +3.0 and +2.0%, respectively.

Results (continued)

	METRIC RESULT						METRIC PERFORMANCE RESULT					
	Plunge	SB	ME	PTV +1	DS	AVG.	Plunge	SB	ME	PTV +1	DS	AVG.
BRAIN	**88.1**	**83.4**	**89.4**	**87.3**	**84.9**	**86.6**	**58.7%**	**55.6%**	**59.6%**	**58.2%**	**56.6%**	**57.7%**
Abs Diff.		-4.7	1.3	-0.8	-3.2	-1.9		-3.1%	0.9%	-0.5%	-2.1%	-1.2%
LUNG	**83.9**	**81.5**	**89.4**	**83.4**	**72.2**	**82.1**	**55.9%**	**54.3%**	**59.6%**	**55.6%**	**48.1%**	**54.7%**
Abs Diff.		-2.4	5.5	-0.5	-11.7	-2.3		-1.6%	3.7%	-0.3%	-7.8%	-1.5%
PROSTATE	**82.6**	**76.8**	**-**	**92.0**	**86.1**	**84.4**	**55.0%**	**51.2%**	**-**	**61.3%**	**57.4%**	**56.2%**
Abs Diff.		-5.8	-	9.5	3.5	2.4		-3.8%	-	6.3%	2.4%	1.6%
LIVER	**88.7**	**89.9**	**90.4**	**83.2**	**85.1**	**87.5**	**59.1%**	**60.0%**	**60.3%**	**55.5%**	**56.7%**	**58.3%**
Abs Diff.		1.2	1.7	-5.5	-3.6	-1.6		0.8%	1.1%	-3.7%	-2.4%	-1.0%
CSI	**28.9**	**20.7**	**32.3**	**21.5**	**20.2**	**24.7**	**19.3%**	**13.8%**	**21.5%**	**14.3%**	**13.5%**	**16.5%**
Abs Diff.		-8.2	3.4	-7.4	-8.7	-5.2		-5.5%	2.2%	-5.0%	-5.8%	-3.5%
AVERAGE	**74.4**	**70.5**	**77.4**	**73.5**	**69.7**	**73.0**	**49.6%**	**47.0%**	**50.2%**	**49.0%**	**46.5%**	**48.7%**
Abs. Diff.		-4.0	3.0	-1.0	-4.7	-1.7		-2.6%	2.0%	-0.6%	-3.2%	-1.1%

Manufacturing Time

The manufacturing process for smooth compensators reduces the overall time by an average of 43.5%, with a range of 31.4% to 64.2% per field. %. The average absolute time savings was 20.8 minutes per fields with a range of 10 min. to 39.5 min.

	COMPENSATOR MANUFACTURING DATA					SMOOTH COMPENSATOR QA RESULTS				
	Depth (mm/in.)	Smooth Compensator Time (min.)	Plunge Depth Time (min.)	Absolute Difference (min.)	Percent Difference	Planned Thickness	Measured Thickness	CT Calculated Thickness	Passing Rate- 1 mm	Passing Rate- 2 mm
Brain	50/1.968	14.0	32.25	-18.3	-56.6%	5.33	5.35	5.31	98.8	100
Lung	85/3.346	32.0	41.95	-10.0	-23.7%	8.82	8.84	8.88	88.8	98.9
Prostate	46.42/1.827	14.0	39.13	-25.1	-64.2%	4.64	4.60	4.63	97.5	100.0
Liver	95/3.740	55.0	94.52	-39.5	-41.8%	10.54	10.55	10.56	76.2	88.3
Craniospinal	46.34/1.822	24.0	34.98	-11.0	-31.4%	4.65	4.60	4.63	96.1	98.7
Average		**27.8**	**48.6**	**-20.8**	**-43.5%**				**91.5**	**97.2**

Table 3. Milling and QA results for five smooth compensator plans, one from each treatment site evaluated.

Discussion/Conclusion

Utilization of smooth compensators for passively scattered proton therapy are dosimetrically equal or better than the plunged technique depending on the technique used. Overall, the ME achieves the best dosimetric results but the PTV +1cm technique is a suitable alternative for the brain, lung and liver sites. In conclusion, smooth compensators have a clinical benefit over plunged-depth compensators, achieving similar or better coverage as well as reduced dose to most critical structures. More importantly smooth compensators significantly reduce the manufacturing time by an average of 43.5%, which will improve operational efficiencies. Future studies are needed to verify the robustness and best practices for quality assurance of smooth compensators.

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