

Article

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Abstract. abstract here

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1. Results

The results are organized as follows. We first describe the comparison between our heuristic leaf sequencing algorithm and the Corvus results. The number of segments and MUs are compared for the plans obtained from version 4.0 of Corvus, while only the number of segments are compared (for purposes of brevity and relevance) for the plans obtained with version 5.0. Following this comparison we describe the results obtained from the BC implementation.

1.1. Corvus, version 4.0 and DM heuristic comparison

Tables 1, 2 and 3 show a beam-by-beam comparison of the number of segments and MUs for the head and neck, pancreas and prostate cases respectively obtained with plans generated in Corvus, v4.0. The results are shown for the plans with 5, 10 and 100 intensity levels and are denoted by Corvus4 for the results obtained from v. 4.0 in Corvus, DM for our heuristic algorithm, BC30 and BC120 for the BC implementation. The decreases in the total number of segments when our leaf sequence is applied in comparison with the leaf sequence available in Corvus4 was 81%, 69% and 50% for 5, 10 and 100 intensity levels in the head and neck case. The corresponding decreases in the number of MUs were 40%, 45% and 32% as a function of the number of intensity levels. The decreases in the number of segments for the pancreas case were 69%, 73% and 44% for 5, 10 and 100 intensity levels. The MUs were decreased by 25%, 30% and 30%, respectively. For the prostate case, the number of segments were decreased by 81%, 69% and 49% as a function of intensity levels. The Dif3 (NEED A BETTER NAME) heuristic consistently produces high quality (and sometimes optimal) segmentations within 3 minutes, and, in all cases, produces a plan with a number of segments that is smaller than the number produced by Corvus 4.0 and Corvus 5.0.

Figure 5: Comparison of the number of segments for the Corvus 4.0 prostate intensity maps.

Table 4, 5 and 6 summarize the comparison between number of segments produced by Corvus 5.0 and our heuristic. The reduction in the number of segments obtained with our algorithm in the head and neck case was 34% 42% and 28% for 5, 10 and 100 intensity levels. In the pancreas case, the decrease in the number of segments with our approach was 36%, 45%, 21% while in the prostate case, the corresponding decrease was 35%, 59% and 31% as a function of intensity levels. In general, a greater reduction was seen in the 10-intensity level cases than with 5 or 100 intensity for version 5.0. The improvement in the number of segments using our approach was less dramatic than with version 4.0. This may be attributed to the fact that the leaf-sequencing is more efficient in version 5.0 and hence the improvement achievable while still significant, is reduced.

Number of Segments					Beam-On-Time				
5-Intensity-Levels					5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120	Angle	Corv4	Dif3	BC30	BC120
35	41	7	10	10	35	346	180	200	200
80	22	4	4	4	80	186	100	100	100
135	40	7	12	12	135	321	160	240	240
225	31	6	9	5	225	375	140	180	180
280	23	4	4	4	280	224	120	120	120
325	35	8	10	10	325	430	220	200	200
Number of Segments					Beam-On-Time				
10-Intensity-Levels					10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120	Angle	Corv4	Dif3	BC30	BC120
35	41	12	DNR	DNR	35	367	260	DNR	DNR
80	32	11	18	15	80	334	180	180	150
135	42	13	DNR	DNR	135	402	240	DNR	DNR
225	33	12	18	18	225	415	200	180	180
280	25	6	15	15	280	224	120	150	150
325	33	10	DNR	DNR	325	391	180	DNR	DNR
Number of Segments					Beam-On-Time				
100-Intensity-Levels					100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120	Angle	Corv4	Dif3	BC30	BC120
35	367	260	DNR	DNR	35	405	239	DNR	DNR
80	334	180	180	150	80	220	160	DNR	DNR
135	402	240	DNR	DNR	135	290	192	DNR	DNR
225	415	200	180	180	225	406	280	DNR	DNR
280	224	120	150	150	280	233	144	DNR	DNR
325	391	180	DNR	DNR	325	295	220	DNR	DNR

Table 1. Intensity maps generated using Corvus 4.0 for a prostate case. (DNR indicates that a feasible solution could not be found within the time limit.)

1.2. BC implementation

The BC approach, given a sufficiently large amount of computing time (-2 hours per beam angle), can occasionally produce lower cardinality segmentations than 3 minute runs of our heuristics for 5-intensity-level maps, BC is brittle in the sense that it sometimes fails to produce any solutions for 5-intensity-level cases (the DNR notation in the tables below stands for Did Not Run, indicating that no feasible solution was obtained within the time allowed), and BC generally fails for 10 (or higher)-intensity-level cases. The column headings BC30 and BC120 indicate the branch-and-cut method with 30 minutes and 120 minute time limits. Dif3 was allowed a time limit of approximately 3 minutes. Since Corvus does not allow segmentation to be performed as a separate task, it is difficult to assign a time to the Corvus runs.

Figures 1, 2 and 3 show a comparison of the calculated dose from the intensity maps in a water phantom for the head and neck, pancreas and prostate cases and a representative beam angle between the DM and Corvus v. 4.0 leaf sequencing algorithms. The dose calculation (Naqvi et al 2003) is performed at a depth of 2 cm. As

Number of Segments				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	44	6	9	7
165	43	10	DNR	DNR
245	35	9	8	6
290	33	7	9	9
350	46	8	DNR	10

Number of Segments				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	49	13	23	23
165	41	12	18	18
245	47	13	DNR	DNR
290	44	8	17	17
350	50	13	DNR	DNR

Number of Segments				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	55	31	DNR	DNR
165	56	28	DNR	DNR
245	58	25	DNR	DNR
290	50	24	DNR	DNR
350	62	32	DNR	DNR

Beam-On-Time				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	382	160	180	140
165	292	300	DNR	DNR
245	381	200	160	140
290	342	180	180	180
350	347	200	DNR	200

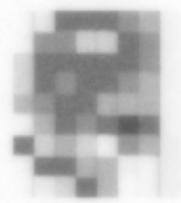
Beam-On-Time				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	391	190	230	230
165	278	210	180	180
245	377	300	DNR	DNR
290	308	160	170	170
350	479	220	DNR	DNR

Beam-On-Time				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	387	233	DNR	DNR
165	313	255	DNR	DNR
245	236	173	DNR	DNR
290	274	158	DNR	DNR
350	436	303	DNR	DNR

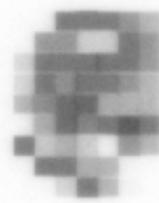
Table 2. Intensity maps generated using Corvus 4.0 for a challenging head and neck case. (DNR indicates that a feasible solution could not be found within the time limit.)

can be seen from these figures, the calculated dose maps agree well for all three cases and intensity levels. However, there are two noticeable differences between the dose maps calculated using the DM and the Corvus v. 4.0 algorithms. First, tongue-and-groove effects are seen in the DM leaf sequence and minimized in the Corvus leaf sequence. This is because the Corvus leaf sequence forces the leaves to move in one direction only during step-and-shoot delivery. Second, noticeable leakage is visible on the Corvus dose maps due to the partial transmission through backup Y-diaphragm present in the Elekta SL20 linac.

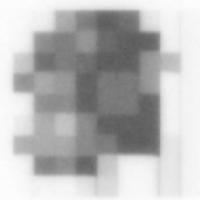
Despite these differences in the dose maps the quantity of real consequence is the 3-D dose distribution. Figures 4, 5 and 6 show the comparison between the 3-D dose distribution from the step-and-shoot delivery sequence using the DM and Corvus v4.0 algorithms for the head and neck, pancreas and prostate cases respectively. It is seen that an overlay of the dose distributions show that the isodose lines agree very well. Minor discrepancies in the isodose line comparison were not considered clinically significant.



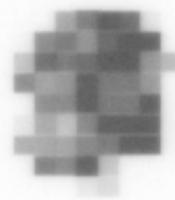
(a)



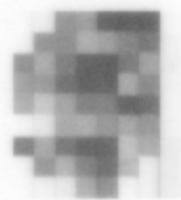
(b)



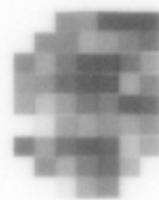
(c)



(d)



(e)



(f)

Figure 1. Head/Neck case: comparison of dose maps calculated in a water phantom at a depth of 2 cm. (a), (c) and (e) are the dose maps from Corvus, v4.0 for 5, 10 and 100 intensity levels. (b), (d) and (e) are the corresponding dose maps obtained using our heuristic approach

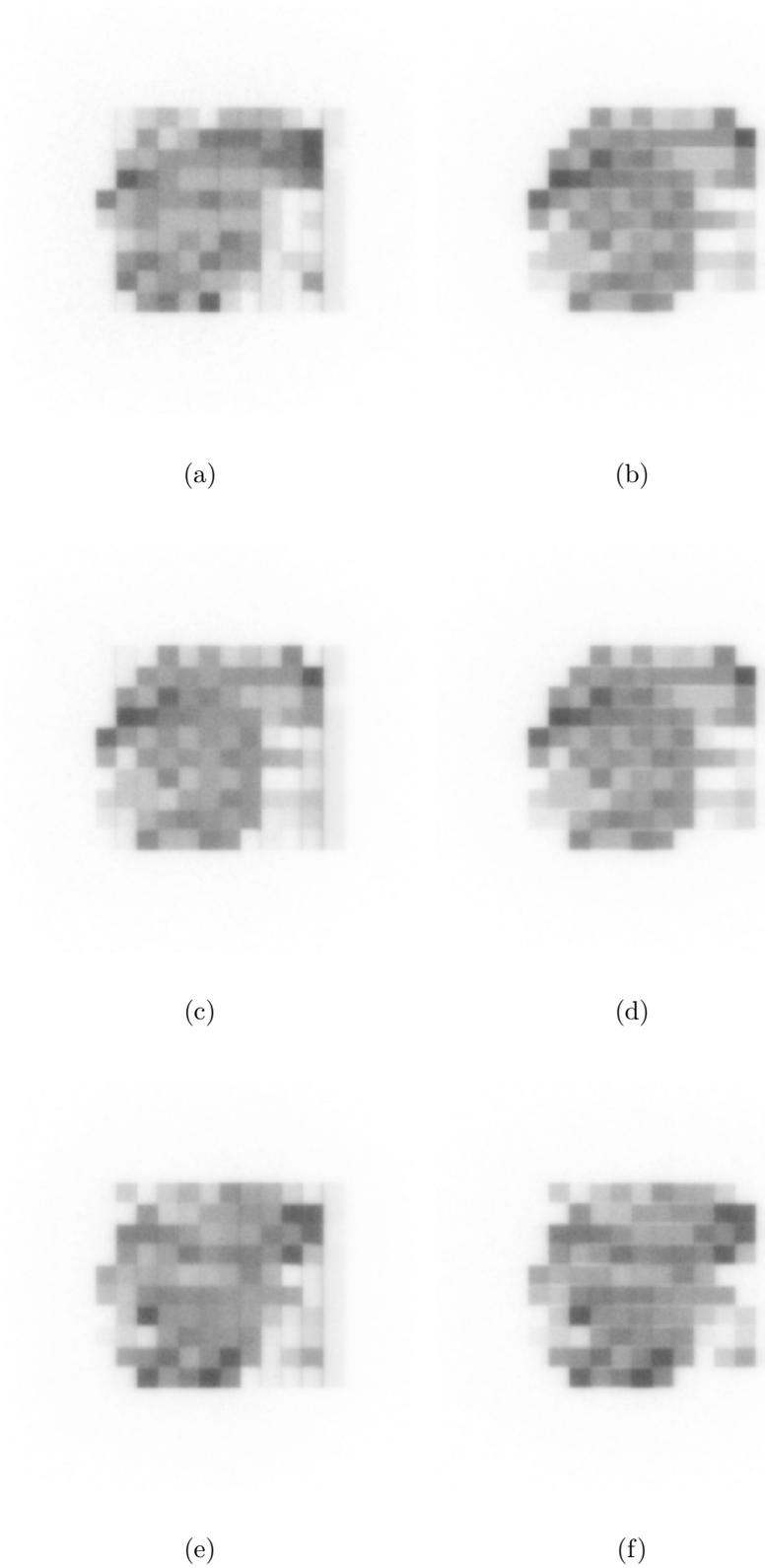


Figure 2. Pancreas case: comparison of dose maps calculated in a water phantom at a depth of 2 cm. (a), (c) and (e) are the dose maps from Corvus, v4.0 for 5, 10 and 100 intensity levels. (b), (d) and (f) are the corresponding dose maps obtained using our heuristic approach

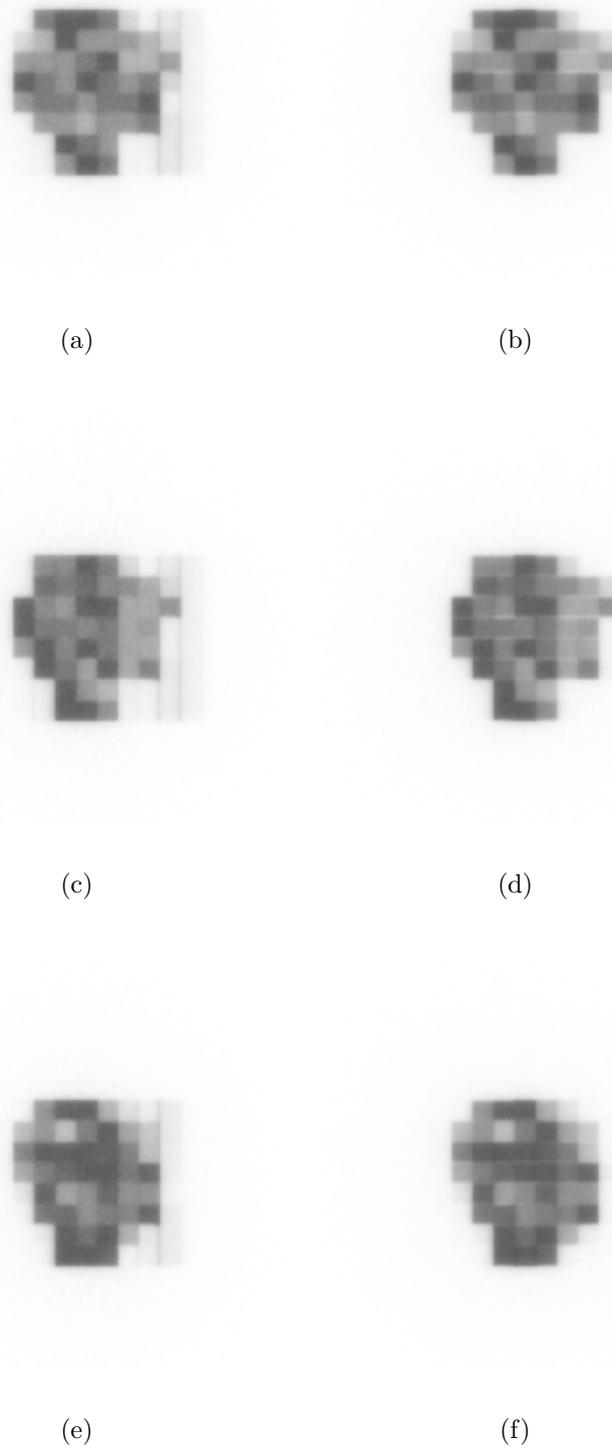


Figure 3. Prostate case: comparison of dose maps calculated in a water phantom at a depth of 2 cm. (a), (c) and (e) are the dose maps from Corvus, v4.0 for 5, 10 and 100 intensity levels. (b), (d) and (e) are the corresponding dose maps obtained using our heuristic approach

Number of Segments				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	62	20	DNR	DNR
51	62	15	DNR	DNR
103	45	21	DNR	14
154	51	16	DNR	DNR
206	63	26	DNR	DNR
257	45	10	DNR	DNR
308	53	8	DNR	8

Number of Segments				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	74	19	DNR	DNR
51	81	18	DNR	DNR
103	54	18	DNR	DNR
154	67	22	DNR	DNR
206	88	21	DNR	DNR
257	59	16	DNR	DNR
308	63	10	DNR	16

Number of Segments				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	96	51	DNR	DNR
51	90	50	DNR	DNR
103	69	39	DNR	DNR
154	81	57	DNR	DNR
206	97	65	DNR	DNR
257	82	38	DNR	DNR
308	75	37	DNR	DNR

Beam-On-Time				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	526	440	DNR	DNR
51	541	340	DNR	DNR
103	488	440	DNR	280
154	474	360	DNR	DNR
206	674	580	DNR	DNR
257	392	220	DNR	DNR
308	349	160	DNR	160

Beam-On-Time				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	320	370	DNR	DNR
51	340	580	DNR	DNR
103	300	380	DNR	DNR
154	400	380	DNR	DNR
206	410	430	DNR	DNR
257	250	250	DNR	DNR
308	140	150	DNR	160

Beam-On-Time				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	481	408	DNR	DNR
51	542	400	DNR	DNR
103	421	264	DNR	DNR
154	477	421	DNR	DNR
206	685	420	DNR	DNR
257	423	206	DNR	DNR
308	306	189	DNR	DNR

Table 3. Intensity maps generated using Corvus 4.0 for a difficult pancreas case. (DNR indicates that a feasible solution could not be found within the time limit.)

Number of Segments					Beam-On-Time				
5-Intensity-Levels					5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120	Angle	Corv4	Dif3	BC30	BC120
35	7	4	4	4	35		80	80	80
80	6	5	5	5	80		100	100	100
135	6	4	4	4	135		80	80	80
225	8	5	5	5	225		100	100	100
280	7	4	4	4	280		80	80	80
325	6	4	4	4	325		80	80	80

Number of Segments					Beam-On-Time				
10-Intensity-Levels					10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120	Angle	Corv4	Dif3	BC30	BC120
35	24	11	DNR	15	35		210	DNR	150
80	16	9	14	14	80		190	140	140
135	17	11	18	18	135		170	150	180
225	20	10	DNR	DNR	225		190	DNR	DNR
280	19	7	12	12	280		130	120	120
325	24	10	18	18	325		200	180	180

Number of Segments					Beam-On-Time				
100-Intensity-Levels					100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120	Angle	Corv4	Dif3	BC30	BC120
35	33	23	DNR	DNR	35		181	DNR	DNR
80	36	21	DNR	DNR	80		160	DNR	DNR
135	37	26	DNR	DNR	135		177	DNR	DNR
225	37	24	DNR	DNR	225		213	DNR	DNR
280	32	23	DNR	DNR	280		145	DNR	DNR
325	33	27	DNR	DNR	325		262	DNR	DNR

Table 4. : Intensity maps generated using Corvus 5.0 for a prostate case. Dif generates the optimal solution in those cases in which BC is able to establish an optimal solution. (DNR indicates that a feasible solution could not be found within the time limit.)

Number of Segments				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	11	8	7	7
165	16	12	DNR	DNR
245	14	9	DNR	9
290	11	8	6	6
350	19	10	13	9

Number of Segments				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	22	15	DNR	DNR
165	23	12	DNR	DNR
245	19	13	DNR	14
290	16	8	7	6
350	23	12	DNR	14

Number of Segments				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55	36	28	DNR	DNR
165	48	33	DNR	DNR
245	35	29	DNR	DNR
290	40	25	DNR	DNR
350	42	29	DNR	DNR

Beam-On-Time				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55		180	160	160
165		340	DNR	DNR
245		220	DNR	180
290		160	120	120
350		200	260	180

Beam-On-Time				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55		200	DNR	DNR
165		250	DNR	DNR
245		220	DNR	140
290		120	70	60
350		230	DNR	140

Beam-On-Time				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
55		178	DNR	DNR
165		336	DNR	DNR
245		233	DNR	DNR
290		148	DNR	DNR
350		216	DNR	DNR

Table 5. Intensity maps generated using Corvus 5.0 for a challenging head and neck case. These results illustrate that the BC approach has difficulty with more complex cases.

Number of Segments				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	23	15	DNR	DNR
51	21	13	DNR	DNR
103	12	11	DNR	DNR
154	17	13	DNR	DNR
206	25	13	DNR	DNR
257	21	11	10	9
308	16	11	DNR	12

Number of Segments				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	34	17	DNR	DNR
51	40	25	DNR	DNR
103	28	13	DNR	DNR
154	29	18	DNR	DNR
206	41	23	DNR	DNR
257	31	17	DNR	DNR
308	28	15	DNR	DNR

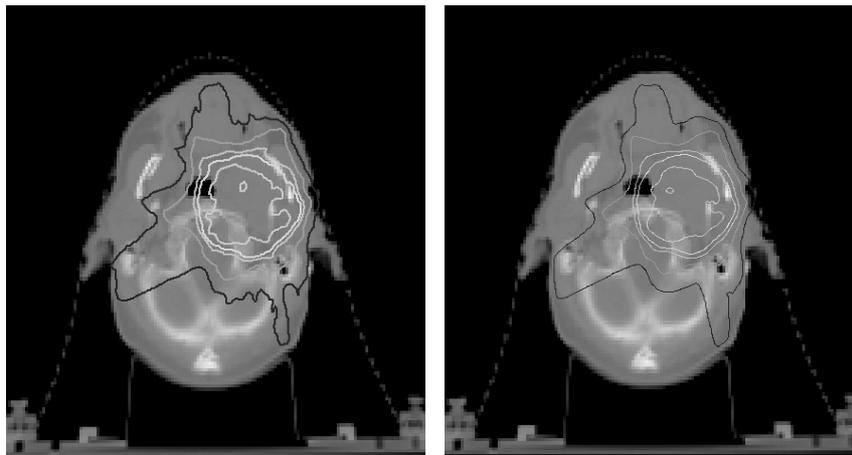
Number of Segments				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0	62	53	DNR	DNR
51	67	49	DNR	DNR
103	63	46	DNR	DNR
154	55	50	DNR	DNR
206	72	55	DNR	DNR
257	52	45	DNR	DNR
308	56	40	DNR	DNR

Beam-On-Time				
5-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0		300	DNR	DNR
51		320	DNR	DNR
103		220	DNR	DNR
154		320	DNR	DNR
206		340	DNR	DNR
257		240	200	260
308		220	DNR	240

Beam-On-Time				
10-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0		250	DNR	DNR
51		390	DNR	DNR
103		220	DNR	DNR
154		290	DNR	DNR
206		430	DNR	DNR
257		270	DNR	DNR
308		250	DNR	DNR

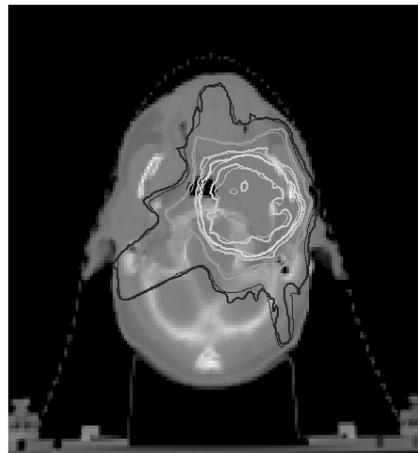
Beam-On-Time				
100-Intensity-Levels				
Angle	Corv4	Dif3	BC30	BC120
0		404	DNR	DNR
51		287	DNR	DNR
103		394	DNR	DNR
154		386	DNR	DNR
206		486	DNR	DNR
257		328	DNR	DNR
308		306	DNR	DNR

Table 6. Intensity maps generated using Corvus 5.0 for a difficult pancreas case.



(a)

(b)



(c)

Figure 4. Head/Neck case: 3D dose distribution obtained from (a) original Corvus, v4.0 and (b) difference matrix based leaf sequence. (c) Overlay of dose distributions from Corvus and difference matrix leaf-sequences.

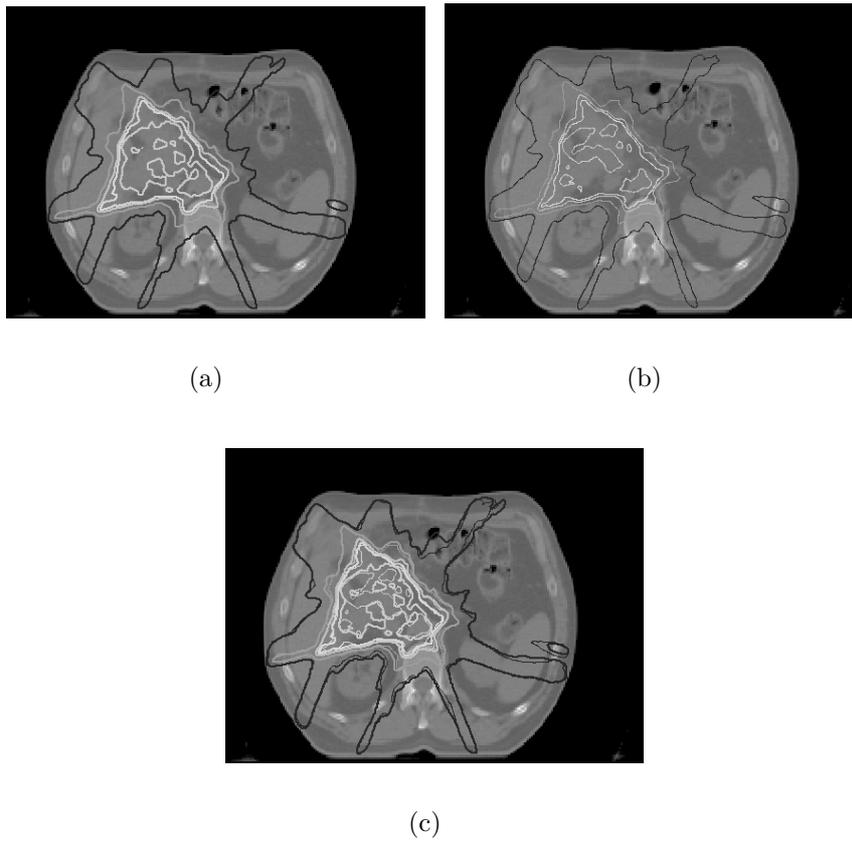


Figure 5. Pancreas case: 3D dose distribution obtained from (a) original Corvus, v4.0 and (b) difference matrix based leaf sequence. (c) Overlay of dose distributions from Corvus and difference matrix leaf-sequences.

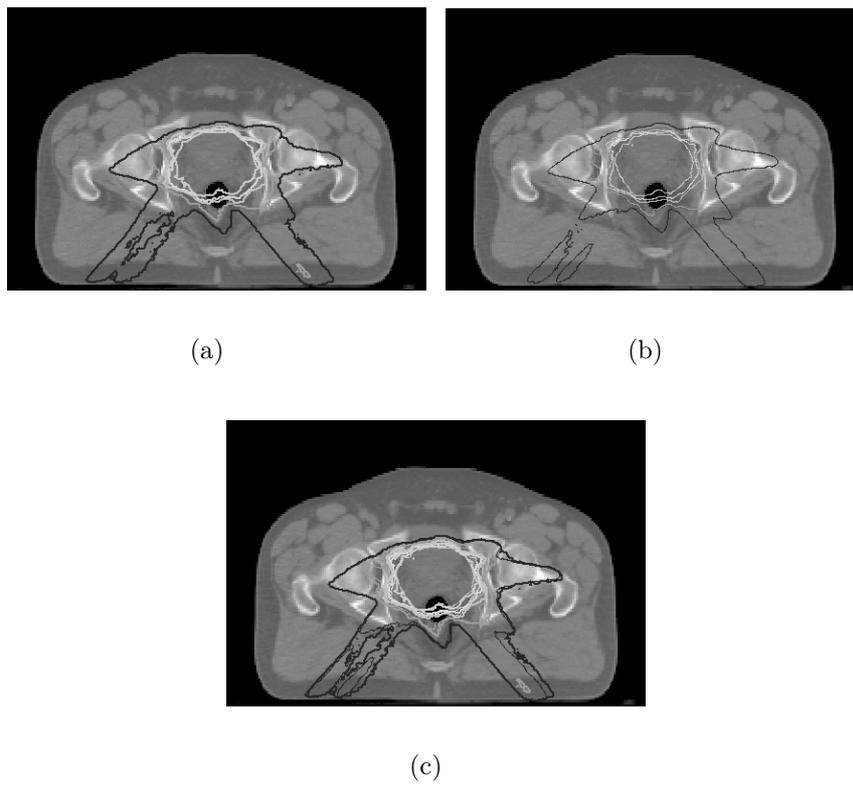


Figure 6. Prostate case: 3D dose distribution obtained from (a) original Corvus, v4.0 and (b) difference matrix based leaf sequence. (c) Overlay of dose distributions from Corvus and difference matrix leaf-sequences.