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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 | | | | |
|--------------------|-------|------|------|-------|
| 5-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 41 | 7 | 10 | 10 |
| 80 | 22 | 4 | 4 | 4 |
| 135 | 40 | 7 | 12 | 12 |
| 225 | 31 | 6 | 9 | 5 |
| 280 | 23 | 4 | 4 | 4 |
| 325 | 35 | 8 | 10 | 10 |
| Beam-On-Time | | | | |
| 5-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 346 | 180 | 200 | 200 |
| 80 | 186 | 100 | 100 | 100 |
| 135 | 321 | 160 | 240 | 240 |
| 225 | 375 | 140 | 180 | 180 |
| 280 | 224 | 120 | 120 | 120 |
| 325 | 430 | 220 | 200 | 200 |

| Number of Segments | | | | |
|---------------------|-------|------|------|-------|
| 10-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 41 | 12 | DNR | DNR |
| 80 | 32 | 11 | 18 | 15 |
| 135 | 42 | 13 | DNR | DNR |
| 225 | 33 | 12 | 18 | 18 |
| 280 | 25 | 6 | 15 | 15 |
| 325 | 33 | 10 | DNR | DNR |
| Beam-On-Time | | | | |
| 10-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 367 | 260 | DNR | DNR |
| 80 | 334 | 180 | 180 | 150 |
| 135 | 402 | 240 | DNR | DNR |
| 225 | 415 | 200 | 180 | 180 |
| 280 | 224 | 120 | 150 | 150 |
| 325 | 391 | 180 | DNR | DNR |

| Number of Segments | | | | |
|----------------------|-------|------|------|-------|
| 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 367 | 260 | DNR | DNR |
| 80 | 334 | 180 | 180 | 150 |
| 135 | 402 | 240 | DNR | DNR |
| 225 | 415 | 200 | 180 | 180 |
| 280 | 224 | 120 | 150 | 150 |
| 325 | 391 | 180 | DNR | DNR |
| Beam-On-Time | | | | |
| 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 405 | 239 | DNR | DNR |
| 80 | 220 | 160 | DNR | DNR |
| 135 | 290 | 192 | DNR | DNR |
| 225 | 406 | 280 | DNR | DNR |
| 280 | 233 | 144 | 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.)

| 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 |
| 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 |

| 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 |
| 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 |

| 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 | | | | |
| 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.)

| Number of Segments | | | | | Number of Segments | | | | | Number of Segments | | | | |
|--------------------|-------|------|------|-------|---------------------|-------|------|------|-------|----------------------|-------|------|------|-------|
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 0 | 62 | 20 | DNR | DNR | 0 | 74 | 19 | DNR | DNR | 0 | 96 | 51 | DNR | DNR |
| 51 | 62 | 15 | DNR | DNR | 51 | 81 | 18 | DNR | DNR | 51 | 90 | 50 | DNR | DNR |
| 103 | 45 | 21 | DNR | 14 | 103 | 54 | 18 | DNR | DNR | 103 | 69 | 39 | DNR | DNR |
| 154 | 51 | 16 | DNR | DNR | 154 | 67 | 22 | DNR | DNR | 154 | 81 | 57 | DNR | DNR |
| 206 | 63 | 26 | DNR | DNR | 206 | 88 | 21 | DNR | DNR | 206 | 97 | 65 | DNR | DNR |
| 257 | 45 | 10 | DNR | DNR | 257 | 59 | 16 | DNR | DNR | 257 | 82 | 38 | DNR | DNR |
| 308 | 53 | 8 | DNR | 8 | 308 | 63 | 10 | DNR | 16 | 308 | 75 | 37 | DNR | DNR |
| Beam-On-Time | | | | | Beam-On-Time | | | | | Beam-On-Time | | | | |
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 0 | 526 | 440 | DNR | DNR | 0 | 320 | 370 | DNR | DNR | 0 | 481 | 408 | DNR | DNR |
| 51 | 541 | 340 | DNR | DNR | 51 | 340 | 580 | DNR | DNR | 51 | 542 | 400 | DNR | DNR |
| 103 | 488 | 440 | DNR | 280 | 103 | 300 | 380 | DNR | DNR | 103 | 421 | 264 | DNR | DNR |
| 154 | 474 | 360 | DNR | DNR | 154 | 400 | 380 | DNR | DNR | 154 | 477 | 421 | DNR | DNR |
| 206 | 674 | 580 | DNR | DNR | 206 | 410 | 430 | DNR | DNR | 206 | 685 | 420 | DNR | DNR |
| 257 | 392 | 220 | DNR | DNR | 257 | 250 | 250 | DNR | DNR | 257 | 423 | 206 | DNR | DNR |
| 308 | 349 | 160 | DNR | 160 | 308 | 140 | 150 | DNR | 160 | 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.)

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 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

| Number of Segments | | | | | Number of Segments | | | | | Number of Segments | | | | |
|--------------------|-------|------|------|-------|---------------------|-------|------|------|-------|----------------------|-------|------|------|-------|
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | 7 | 4 | 4 | 4 | 35 | 24 | 11 | DNR | 15 | 35 | 33 | 23 | DNR | DNR |
| 80 | 6 | 5 | 5 | 5 | 80 | 16 | 9 | 14 | 14 | 80 | 36 | 21 | DNR | DNR |
| 135 | 6 | 4 | 4 | 4 | 135 | 17 | 11 | 18 | 18 | 135 | 37 | 26 | DNR | DNR |
| 225 | 8 | 5 | 5 | 5 | 225 | 20 | 10 | DNR | DNR | 225 | 37 | 24 | DNR | DNR |
| 280 | 7 | 4 | 4 | 4 | 280 | 19 | 7 | 12 | 12 | 280 | 32 | 23 | DNR | DNR |
| 325 | 6 | 4 | 4 | 4 | 325 | 24 | 10 | 18 | 18 | 325 | 33 | 27 | DNR | DNR |
| Beam-On-Time | | | | | Beam-On-Time | | | | | Beam-On-Time | | | | |
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 35 | | 80 | 80 | 80 | 35 | | 210 | DNR | 150 | 35 | | 181 | DNR | DNR |
| 80 | | 100 | 100 | 100 | 80 | | 190 | 140 | 140 | 80 | | 160 | DNR | DNR |
| 135 | | 80 | 80 | 80 | 135 | | 170 | 150 | 180 | 135 | | 177 | DNR | DNR |
| 225 | | 100 | 100 | 100 | 225 | | 190 | DNR | DNR | 225 | | 213 | DNR | DNR |
| 280 | | 80 | 80 | 80 | 280 | | 130 | 120 | 120 | 280 | | 145 | DNR | DNR |
| 325 | | 80 | 80 | 80 | 325 | | 200 | 180 | 180 | 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 | | | | | Number of Segments | | | | | Number of Segments | | | | |
|--------------------|-------|------|------|-------|---------------------|-------|------|------|-------|----------------------|-------|------|------|-------|
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 55 | 11 | 8 | 7 | 7 | 55 | 22 | 15 | DNR | DNR | 55 | 36 | 28 | DNR | DNR |
| 165 | 16 | 12 | DNR | DNR | 165 | 23 | 12 | DNR | DNR | 165 | 48 | 33 | DNR | DNR |
| 245 | 14 | 9 | DNR | 9 | 245 | 19 | 13 | DNR | 14 | 245 | 35 | 29 | DNR | DNR |
| 290 | 11 | 8 | 6 | 6 | 290 | 16 | 8 | 7 | 6 | 290 | 40 | 25 | DNR | DNR |
| 350 | 19 | 10 | 13 | 9 | 350 | 23 | 12 | DNR | 14 | 350 | 42 | 29 | DNR | DNR |
| Beam-On-Time | | | | | Beam-On-Time | | | | | Beam-On-Time | | | | |
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 55 | | 180 | 160 | 160 | 55 | | 200 | DNR | DNR | 55 | | 178 | DNR | DNR |
| 165 | | 340 | DNR | DNR | 165 | | 250 | DNR | DNR | 165 | | 336 | DNR | DNR |
| 245 | | 220 | DNR | 180 | 245 | | 220 | DNR | 140 | 245 | | 233 | DNR | DNR |
| 290 | | 160 | 120 | 120 | 290 | | 120 | 70 | 60 | 290 | | 148 | DNR | DNR |
| 350 | | 200 | 260 | 180 | 350 | | 230 | DNR | 140 | 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 | | | | | Number of Segments | | | | | Number of Segments | | | | |
|--------------------|-------|------|------|-------|---------------------|-------|------|------|-------|----------------------|-------|------|------|-------|
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 0 | 23 | 15 | DNR | DNR | 0 | 34 | 17 | DNR | DNR | 0 | 62 | 53 | DNR | DNR |
| 51 | 21 | 13 | DNR | DNR | 51 | 40 | 25 | DNR | DNR | 51 | 67 | 49 | DNR | DNR |
| 103 | 12 | 11 | DNR | DNR | 103 | 28 | 13 | DNR | DNR | 103 | 63 | 46 | DNR | DNR |
| 154 | 17 | 13 | DNR | DNR | 154 | 29 | 18 | DNR | DNR | 154 | 55 | 50 | DNR | DNR |
| 206 | 25 | 13 | DNR | DNR | 206 | 41 | 23 | DNR | DNR | 206 | 72 | 55 | DNR | DNR |
| 257 | 21 | 11 | 10 | 9 | 257 | 31 | 17 | DNR | DNR | 257 | 52 | 45 | DNR | DNR |
| 308 | 16 | 11 | DNR | 12 | 308 | 28 | 15 | DNR | DNR | 308 | 56 | 40 | DNR | DNR |
| Beam-On-Time | | | | | Beam-On-Time | | | | | Beam-On-Time | | | | |
| 5-Intensity-Levels | | | | | 10-Intensity-Levels | | | | | 100-Intensity-Levels | | | | |
| Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 | Angle | Corv4 | Dif3 | BC30 | BC120 |
| 0 | | 300 | DNR | DNR | 0 | | 250 | DNR | DNR | 0 | | 404 | DNR | DNR |
| 51 | | 320 | DNR | DNR | 51 | | 390 | DNR | DNR | 51 | | 287 | DNR | DNR |
| 103 | | 220 | DNR | DNR | 103 | | 220 | DNR | DNR | 103 | | 394 | DNR | DNR |
| 154 | | 320 | DNR | DNR | 154 | | 290 | DNR | DNR | 154 | | 386 | DNR | DNR |
| 206 | | 340 | DNR | DNR | 206 | | 430 | DNR | DNR | 206 | | 486 | DNR | DNR |
| 257 | | 240 | 200 | 260 | 257 | | 270 | DNR | DNR | 257 | | 328 | DNR | DNR |
| 308 | | 220 | DNR | 240 | 308 | | 250 | DNR | DNR | 308 | | 306 | DNR | DNR |

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

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.

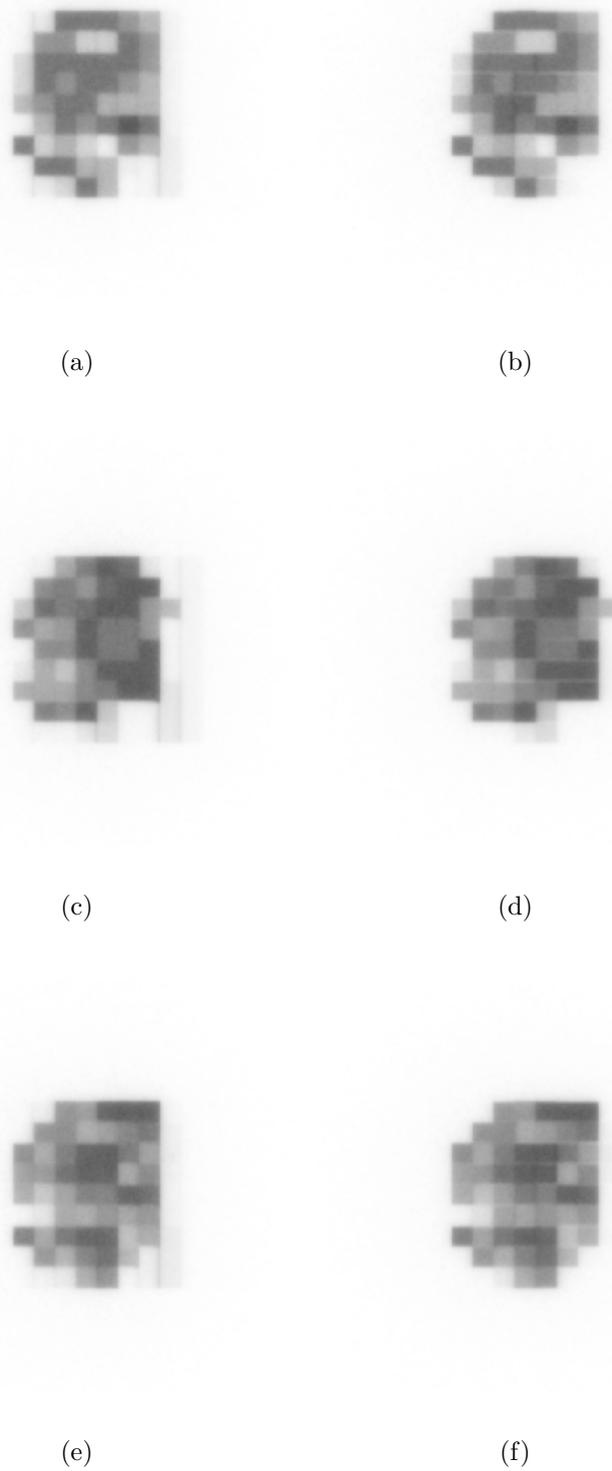


Figure 1. Head/Neck case: comparison of dose maps calculated in a water phantom at a depth of 2 cm. (a), (c) and (e) are the dose maps from Corvus, v4.0 for 5, 10 and 100 intensity levels. (b), (d) and (e) are the corresponding dose maps obtained using our heuristic approach

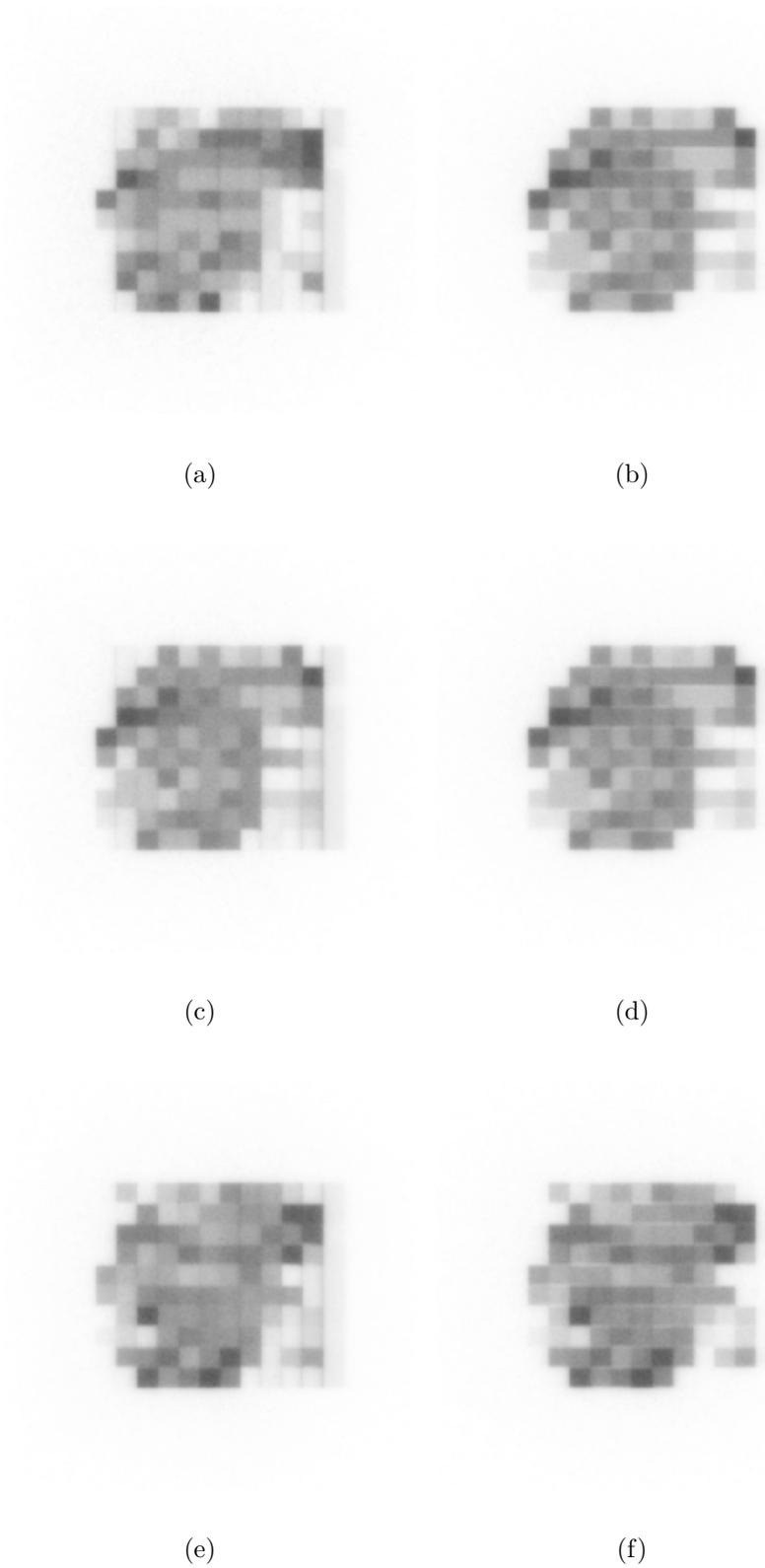


Figure 2. Pancreas case: comparison of dose maps calculated in a water phantom at a depth of 2 cm. (a), (c) and (e) are the dose maps from Corvus, v4.0 for 5, 10 and 100 intensity levels. (b), (d) and (e) are the corresponding dose maps obtained using our heuristic approach

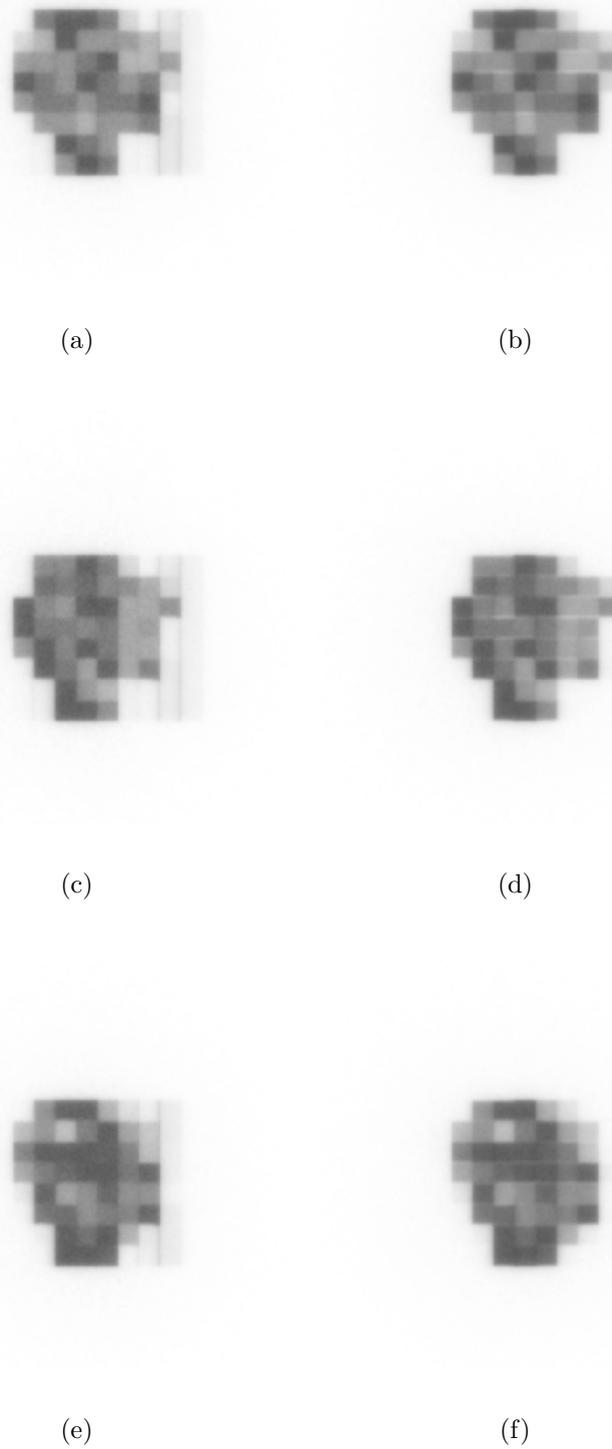
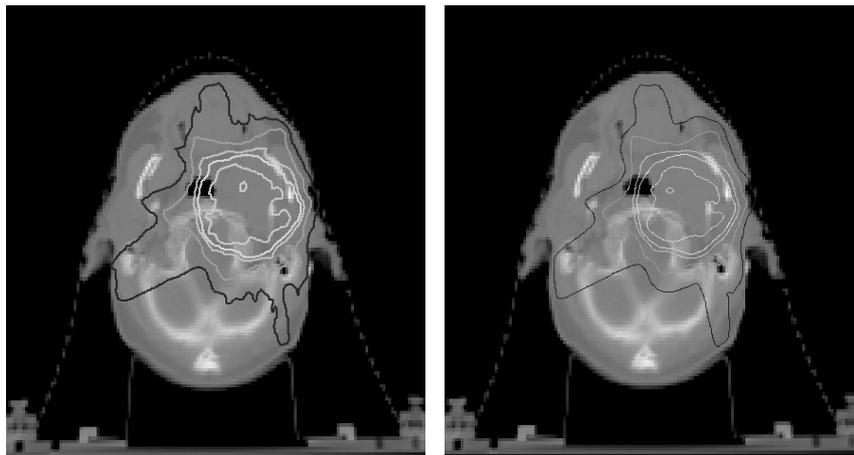
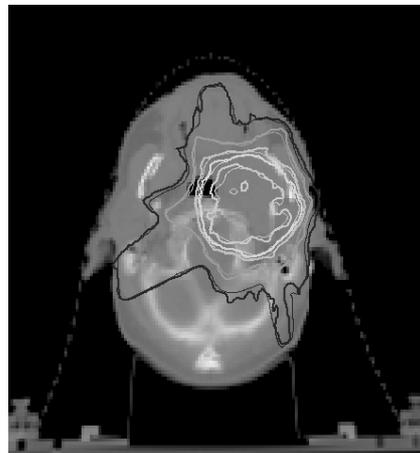


Figure 3. Prostate case: comparison of dose maps calculated in a water phantom at a depth of 2 cm. (a), (c) and (e) are the dose maps from Corvus, v4.0 for 5, 10 and 100 intensity levels. (b), (d) and (e) are the corresponding dose maps obtained using our heuristic approach



(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.

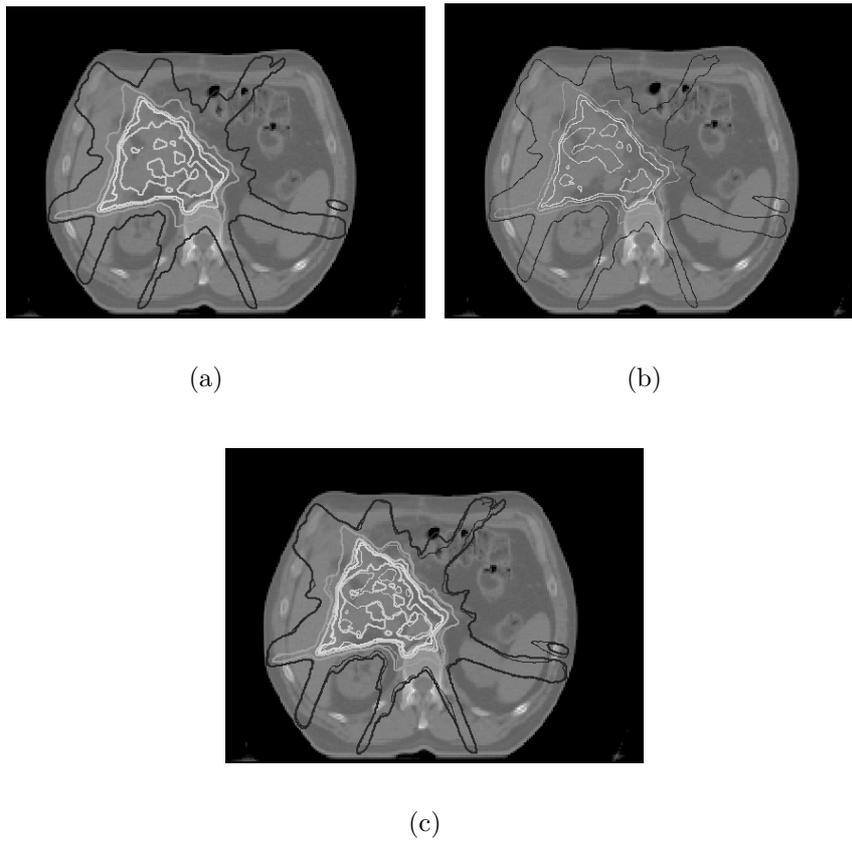


Figure 5. Pancreas case: 3D dose distribution obtained from (a) original Corvus, v4.0 and (b) difference matrix based leaf sequence. (c) Overlay of dose distributions from Corvus and difference matrix leaf-sequences.

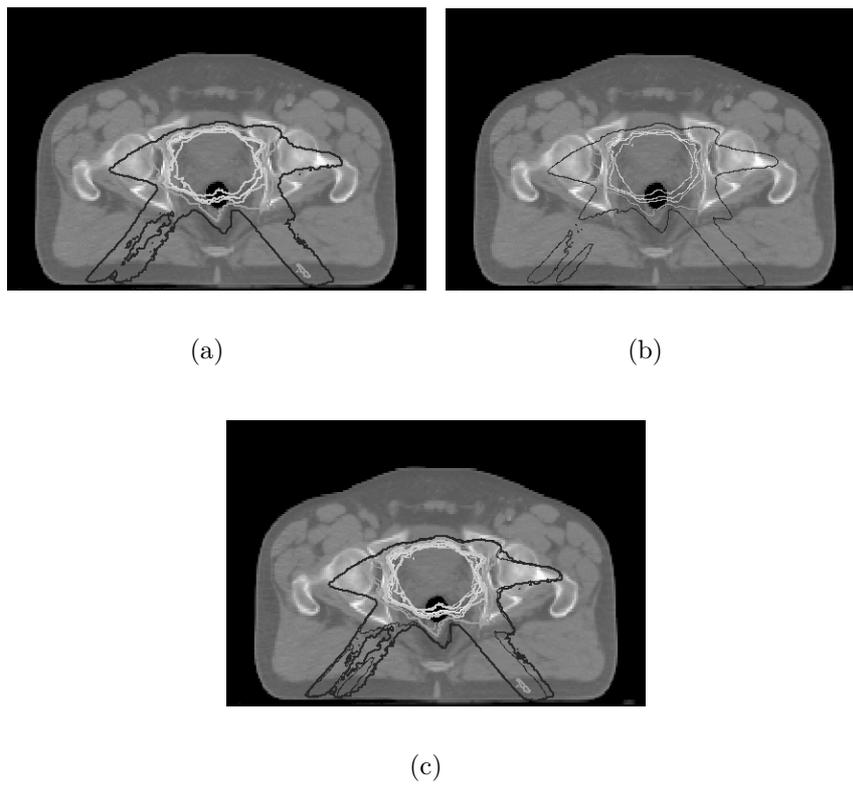


Figure 6. Prostate case: 3D dose distribution obtained from (a) original Corvus, v4.0 and (b) difference matrix based leaf sequence. (c) Overlay of dose distributions from Corvus and difference matrix leaf-sequences.