Example: Proton Treatment Plan with Manipulated CT values

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In this example we will show (i) how to load patient data into matRad (ii) how to setup a proton dose calculation (iii) how to inversely optimize the pencil beam intensities directly from command window in MATLAB. (iv) how to re-optimize a treatment plan (v) how to manipulate the CT cube by adding noise to the cube (vi) how to recalculate the dose considering the manipulated CT cube and the previously optimized pencil beam intensities (vii) how to compare the two results

Patient Data Import

Let's begin with a clear Matlab environment and import the prostate patient into your workspace.

```
clc,clear,close all;
load('PROSTATE.mat');
```

Treatment Plan

The next step is to define your treatment plan labeled as 'pln'. This structure requires input from the treatment planner and defines the most important cornerstones of your treatment plan.

```
pln.radiationMode   = 'protons';
pln.machine         = 'Generic';
pln.bioOptimization = 'const_RBExD';
pln.gantryAngles    = [90 270];
```

```
pln.couchAngles     = [0 0];
pln.bixelWidth      = 3;
pln.numOfFractions  = 30;
pln.numOfBeams      = numel(pln.gantryAngles);
pln.numOfVoxels     = prod(ct.cubeDim);
pln.voxelDimensions = ct.cubeDim;
pln.isoCenter       = ones(pln.numOfBeams,1) *
 matRad_getIsoCenter(cst,ct,0);
pln.runDAO        = 0;
pln.runSequencing = 0;
```

Generate Beam Geometry STF

```
stf = matRad_generateStf(ct,cst,pln);
```

```
matRad: Generating stf struct... Progress: 100.00 %
```

Dose Calculation

```
dij = matRad_calcParticleDose(ct,stf,pln,cst);
```

```
matRad: Using a constant RBE of 1.1
matRad: Particle dose calculation...
Beam 1 of 2:
matRad: calculate radiological depth cube...done.
matRad: calculate lateral cutoff...done.
Progress: 100.00 %
Beam 2 of 2:
matRad: calculate radiological depth cube...done.
matRad: calculate lateral cutoff...done.
Progress: 100.00 %
```

Inverse Optimization for IMPT

```
resultGUI = matRad_fluenceOptimization(dij,cst,pln);
```

```
******************************************************************************
This program contains Ipopt, a library for large-scale nonlinear
 optimization.
 Ipopt is released as open source code under the Eclipse Public
 License (EPL).
         For more information visit http://projects.coin-or.org/Ipopt
******************************************************************************

This is Ipopt version 3.11.8, running with linear solver ma57.

Number of nonzeros in equality constraint Jacobian...:        0
Number of nonzeros in inequality constraint Jacobian.:        0
Number of nonzeros in Lagrangian Hessian.............:        0

Total number of variables............................:    45574
                     variables with only lower bounds:    45574
```

```
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints.................:        0
Total number of inequality constraints...............:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
   0 4.3490711e+002 0.00e+000 1.07e+000   0.0 0.00e+000    -  0.00e
+000 0.00e+000   0
   1 4.0427541e+002 0.00e+000 7.37e-002  -1.1 7.77e-002    -
 9.91e-001 1.00e+000f  1
   2 7.0982048e+001 0.00e+000 1.97e-002  -1.7 1.37e+000    -
 9.96e-001 1.00e+000f  1
   3 3.6109959e+001 0.00e+000 1.27e-002  -3.4 3.84e-001    -
 9.75e-001 1.00e+000f  1
   4 2.9072905e+001 0.00e+000 1.06e-002  -3.9 2.77e-001    -
 9.87e-001 1.00e+000f  1
   5 2.3067104e+001 0.00e+000 1.03e-002  -4.7 4.22e-001    -
 9.99e-001 1.00e+000f  1
   6 1.9295712e+001 0.00e+000 1.36e-002  -5.5 6.66e-001    -  1.00e
+000 1.00e+000f  1
   7 1.6242709e+001 0.00e+000 7.13e-003  -6.0 2.70e-001    -  1.00e
+000 1.00e+000f  1
   8 1.5129109e+001 0.00e+000 5.99e-003  -7.2 2.09e-001    -  1.00e
+000 1.00e+000f  1
   9 1.3740190e+001 0.00e+000 4.75e-003  -8.5 3.81e-001    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  10 1.1965389e+001 0.00e+000 3.76e-003  -9.5 6.21e-001    -  1.00e
+000 1.00e+000f  1
  11 1.1479588e+001 0.00e+000 7.70e-003  -9.9 8.60e-001    -  1.00e
+000 6.53e-001f  1
  12 1.1466560e+001 0.00e+000 7.66e-003 -11.0 2.60e-001    -  1.00e
+000 7.48e-003f  1
  13 1.1465561e+001 0.00e+000 1.45e-002 -11.0 3.56e-001    -  1.00e
+000 4.09e-004f  1
  14 1.0213007e+001 0.00e+000 3.25e-003 -11.0 4.72e-001    -  1.00e
+000 6.09e-001f  1
  15 1.0205353e+001 0.00e+000 3.21e-003 -11.0 2.79e-001    -  1.00e
+000 1.07e-002f  1
  16 1.0205149e+001 0.00e+000 1.21e-002 -11.0 4.04e-001    -  1.00e
+000 1.94e-004f  1
  17 1.0116738e+001 0.00e+000 2.99e-003 -11.0 5.25e-001    -  1.00e
+000 6.49e-002f  1
  18 1.0105841e+001 0.00e+000 7.65e-003  -8.8 5.86e-001    -
 8.87e-001 6.98e-003f  1
  19 1.0022232e+001 0.00e+000 1.17e-002  -9.4 7.34e-001    -  1.00e
+000 4.42e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
```

```
  20 9.8338336e+000 0.00e+000 7.44e-003 -10.4 8.83e-001    -  1.00e
+000 9.00e-002f  1
  21 9.8218623e+000 0.00e+000 1.35e-002 -11.0 9.07e-001    -  1.00e
+000 6.01e-003f  1
  22 9.7326587e+000 0.00e+000 7.49e-003 -11.0 1.05e+000    -  1.00e
+000 4.17e-002f  1
  23 9.5583562e+000 0.00e+000 7.91e-003 -11.0 1.25e+000    -  1.00e
+000 7.39e-002f  1
  24 9.5339743e+000 0.00e+000 1.43e-002  -7.1 1.55e+000    -
 7.60e-001 8.64e-003f  1
  25 9.4272717e+000 0.00e+000 2.80e-002  -5.2 1.51e+000    -
 8.36e-001 4.07e-002f  1
  26 9.2245906e+000 0.00e+000 1.35e-002  -4.3 1.89e+000    -
 7.03e-001 7.85e-002f  1
  27 9.0902825e+000 0.00e+000 8.31e-003  -6.3 1.51e+000    -
 2.57e-001 5.81e-002f  1
  28 8.7127219e+000 0.00e+000 7.13e-003  -4.6 1.58e+000    -
 8.37e-001 1.87e-001f  1
  29 8.4541155e+000 0.00e+000 5.79e-003  -4.3 1.41e+000    -
 4.99e-001 1.54e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  30 8.3483122e+000 0.00e+000 8.72e-003 -10.4 1.07e+000    -
 3.79e-001 1.02e-001f  1
  31 8.2324208e+000 0.00e+000 6.02e-003  -4.9 1.72e+000    -
 9.95e-001 2.60e-001f  1
  32 8.2055840e+000 0.00e+000 3.46e-002  -4.6 5.96e-001    -  1.00e
+000 3.25e-002f  1
  33 7.8920138e+000 0.00e+000 2.55e-002  -3.7 6.32e-001    -
 9.74e-001 4.28e-001f  1
  34 7.7603808e+000 0.00e+000 1.13e-002  -4.4 4.73e-001    -
 5.53e-001 3.40e-001f  1
  35 7.6868406e+000 0.00e+000 9.15e-003  -4.0 4.11e-001    -
 7.93e-001 2.47e-001f  1
  36 7.5730659e+000 0.00e+000 7.71e-003  -4.0 4.69e-001    -
 7.89e-001 3.97e-001f  1
  37 7.5090417e+000 0.00e+000 6.82e-003  -5.0 5.12e-001    -
 5.23e-001 2.53e-001f  1
  38 7.3849350e+000 0.00e+000 4.00e-003  -4.3 4.83e-001    -
 5.13e-001 5.06e-001f  1
  39 7.3504179e+000 0.00e+000 6.71e-003  -4.6 4.77e-001    -
 8.12e-001 1.52e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  40 7.2463583e+000 0.00e+000 1.18e-002  -4.8 5.95e-001    -
 6.44e-001 4.41e-001f  1
  41 7.1774628e+000 0.00e+000 2.89e-003  -4.9 7.24e-001    -  1.00e
+000 2.49e-001f  1
  42 7.2768275e+000 0.00e+000 1.46e-002  -3.2 9.85e-001    -
 3.86e-001 1.00e+000f  1
  43 7.0024445e+000 0.00e+000 2.76e-003  -3.7 6.44e-001    -
 7.57e-001 1.00e+000f  1
  44 6.8758809e+000 0.00e+000 1.14e-003  -4.6 3.65e-001    -
 9.96e-001 8.71e-001f  1
```

```
  45 6.8630812e+000 0.00e+000 7.60e-003  -5.4 2.81e-001    -
 9.97e-001 1.61e-001f  1
  46 6.8078588e+000 0.00e+000 4.32e-003  -6.1 4.51e-001    -
 7.84e-001 4.48e-001f  1
  47 6.7824785e+000 0.00e+000 4.09e-003  -7.0 4.57e-001    -
 8.08e-001 1.84e-001f  1
  48 6.7318712e+000 0.00e+000 2.51e-003  -6.1 6.76e-001    -
 4.80e-001 2.58e-001f  1
  49 6.7006803e+000 0.00e+000 2.88e-003  -4.5 5.87e-001    -
 5.63e-001 1.48e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  50 6.6807285e+000 0.00e+000 2.71e-003  -4.8 6.32e-001    -
 2.42e-001 7.51e-002f  1
  51 6.6000364e+000 0.00e+000 2.58e-003  -3.9 5.76e-001    -
 2.76e-001 3.21e-001f  1
  52 7.1705913e+000 0.00e+000 2.39e-003  -2.3 1.19e+001    -
 1.20e-002 9.40e-002f  1
  53 6.5623589e+000 0.00e+000 2.01e-003  -4.1 1.59e+000    -
 1.32e-001 7.09e-001f  1
  54 6.5162253e+000 0.00e+000 8.59e-003  -4.5 6.85e-001    -
 9.91e-001 1.12e-001f  1
  55 6.4492613e+000 0.00e+000 1.18e-002  -4.8 5.09e-001    -
 9.97e-001 3.79e-001f  1
  56 6.3993245e+000 0.00e+000 5.81e-003  -5.2 4.43e-001    -
 9.94e-001 4.20e-001f  1
  57 6.3584296e+000 0.00e+000 3.35e-003  -5.7 4.54e-001    -
 9.74e-001 4.18e-001f  1
  58 6.3336977e+000 0.00e+000 4.89e-003  -6.8 5.67e-001    -
 7.77e-001 2.27e-001f  1
  59 6.3114075e+000 0.00e+000 5.24e-003  -4.6 4.63e-001    -
 4.32e-001 2.36e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  60 6.2655808e+000 0.00e+000 2.20e-003  -4.4 4.84e-001    -
 3.71e-001 4.40e-001f  1
  61 6.2300813e+000 0.00e+000 1.96e-003  -4.4 6.70e-001    -
 4.09e-001 2.48e-001f  1
  62 6.2161174e+000 0.00e+000 5.53e-003  -5.4 7.32e-001    -
 3.62e-001 8.21e-002f  1
  63 6.1611347e+000 0.00e+000 2.34e-003  -4.4 1.08e+000    -
 3.95e-001 2.85e-001f  1
  64 6.1553828e+000 0.00e+000 5.53e-003 -10.6 6.96e-001    -
 3.03e-001 3.10e-002f  1
  65 6.0956673e+000 0.00e+000 6.09e-003  -4.5 7.10e-001    -
 5.09e-001 2.92e-001f  1
  66 6.0717380e+000 0.00e+000 3.78e-003  -4.8 6.81e-001    -
 3.91e-001 1.29e-001f  1
  67 6.0206649e+000 0.00e+000 2.27e-003  -4.1 4.73e-001    -
 4.17e-001 3.71e-001f  1
  68 6.0000064e+000 0.00e+000 3.29e-003 -10.3 5.01e-001    -
 4.01e-001 1.87e-001f  1
  69 5.9666369e+000 0.00e+000 3.56e-003  -5.1 5.42e-001    -
 7.43e-001 3.02e-001f  1
```

```
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  70 5.9492554e+000 0.00e+000 4.28e-003  -5.2 5.31e-001    -
 8.06e-001 1.56e-001f  1
  71 5.9137852e+000 0.00e+000 5.99e-003  -5.1 6.17e-001    -
 9.63e-001 3.33e-001f  1
  72 5.8903674e+000 0.00e+000 1.80e-003  -4.8 5.61e-001    -
 7.76e-001 1.98e-001f  1
  73 5.8631878e+000 0.00e+000 8.91e-003  -4.3 6.28e-001    -
 7.41e-001 2.02e-001f  1
  74 6.7925850e+000 0.00e+000 1.12e-002  -2.4 4.55e+001    -
 3.32e-002 6.90e-002f  1
  75 5.9297116e+000 0.00e+000 1.08e-002  -3.9 2.26e+000    -
 7.67e-002 7.85e-001f  1
  76 5.8122623e+000 0.00e+000 6.73e-003  -3.9 3.75e-001    -
 5.94e-001 8.19e-001f  1
  77 5.7843265e+000 0.00e+000 1.04e-002  -4.7 4.33e-001    -
 7.15e-001 3.20e-001f  1
  78 5.7493480e+000 0.00e+000 5.44e-003  -4.9 5.16e-001    -
 9.54e-001 4.26e-001f  1
  79 5.7247047e+000 0.00e+000 3.97e-003  -5.5 5.74e-001    -
 9.63e-001 3.12e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  80 5.7009930e+000 0.00e+000 4.50e-003  -4.6 4.89e-001    -
 5.76e-001 3.67e-001f  1
  81 5.6781298e+000 0.00e+000 4.94e-003  -4.5 2.95e-001    -
 4.73e-001 5.67e-001f  1
  82 5.6530706e+000 0.00e+000 2.11e-003  -4.2 2.78e-001    -
 4.75e-001 5.01e-001f  1
  83 5.6504971e+000 0.00e+000 6.65e-003 -10.4 8.13e-001    -
 2.72e-001 1.85e-002f  1
  84 5.5936357e+000 0.00e+000 2.01e-003  -4.7 1.12e+000    -
 4.92e-001 3.27e-001f  1
  85 5.5779807e+000 0.00e+000 5.62e-003  -4.6 9.93e-001    -
 5.82e-001 8.92e-002f  1
  86 5.5401800e+000 0.00e+000 3.77e-003  -4.6 7.45e-001    -
 3.59e-001 3.27e-001f  1
  87 5.5152974e+000 0.00e+000 2.75e-003  -4.9 7.53e-001    -
 6.03e-001 2.51e-001f  1
  88 5.5005425e+000 0.00e+000 3.37e-003  -5.0 6.70e-001    -
 3.96e-001 1.78e-001f  1
  89 5.4777625e+000 0.00e+000 3.83e-003  -5.2 7.06e-001    -
 7.40e-001 2.76e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  90 5.4595663e+000 0.00e+000 3.62e-003  -7.1 8.75e-001    -
 3.65e-001 1.98e-001f  1
  91 5.4342043e+000 0.00e+000 2.37e-003  -4.7 6.15e-001    -
 4.37e-001 3.81e-001f  1
  92 5.4070272e+000 0.00e+000 3.61e-003  -4.3 2.62e-001    -
 4.87e-001 8.77e-001f  1
  93 5.4006834e+000 0.00e+000 2.06e-003  -4.8 6.12e-001    -
 4.55e-001 8.82e-002f  1
```

```
  94 5.3797485e+000 0.00e+000 3.30e-003 -10.6 7.27e-001    -
 3.07e-001 2.53e-001f  1
  95 5.3596690e+000 0.00e+000 1.28e-003  -4.9 9.10e-001    -
 3.21e-001 2.14e-001f  1
  96 5.3565448e+000 0.00e+000 4.75e-003 -10.8 5.35e-001    -
 3.38e-001 5.24e-002f  1
  97 5.3343806e+000 0.00e+000 4.09e-003  -5.2 6.79e-001    -
 7.61e-001 2.73e-001f  1
  98 5.6135977e+000 0.00e+000 3.98e-003  -3.4 5.23e+000    -
 5.08e-002 4.52e-001f  1
  99 5.3707802e+000 0.00e+000 3.98e-003  -4.7 2.11e+000    -
 1.27e-002 6.02e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 100 5.3460347e+000 0.00e+000 4.59e-003  -4.7 7.46e-001    -
 6.64e-001 1.90e-001f  1
 101 5.3032521e+000 0.00e+000 8.05e-003  -4.7 6.62e-001    -
 7.48e-001 4.35e-001f  1
 102 5.2777204e+000 0.00e+000 7.33e-003  -4.9 5.53e-001    -
 8.71e-001 4.52e-001f  1
 103 5.2701740e+000 0.00e+000 5.41e-003  -5.4 4.37e-001    -
 8.95e-001 1.92e-001f  1
 104 5.2612836e+000 0.00e+000 6.24e-003  -6.4 5.40e-001    -
 7.66e-001 1.90e-001f  1
 105 5.2475871e+000 0.00e+000 6.79e-003  -6.2 6.65e-001    -
 8.31e-001 2.48e-001f  1
 106 5.2402506e+000 0.00e+000 5.62e-003  -5.5 7.18e-001    -
 7.63e-001 1.20e-001f  1
 107 5.2202164e+000 0.00e+000 3.49e-003  -4.5 3.75e-001    -
 3.18e-001 6.81e-001f  1
 108 5.2090157e+000 0.00e+000 2.54e-003  -4.4 3.05e-001    -
 4.79e-001 1.00e+000f  1
 109 5.1724303e+000 0.00e+000 1.25e-003  -4.3 1.08e+000    -
 5.26e-001 7.04e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 110 5.1576221e+000 0.00e+000 5.17e-003  -4.7 6.40e-001    -
 9.06e-001 3.86e-001f  1
 111 5.1482006e+000 0.00e+000 7.88e-003  -5.1 5.61e-001    -
 9.52e-001 2.57e-001f  1
 112 5.1254942e+000 0.00e+000 2.28e-003  -5.6 1.11e+000    -
 7.39e-001 2.87e-001f  1
 113 5.1076357e+000 0.00e+000 3.40e-003  -5.5 2.10e+000    -
 7.31e-001 1.38e-001f  1
 114 5.0889109e+000 0.00e+000 5.70e-003  -4.5 3.60e-001    -
 3.38e-001 5.41e-001f  1
 115 5.0676087e+000 0.00e+000 1.22e-003  -4.4 3.45e-001    -
 3.74e-001 1.00e+000f  1
 116 5.0527819e+000 0.00e+000 1.21e-003  -4.6 4.90e-001    -
 5.34e-001 4.44e-001f  1
 117 5.0426034e+000 0.00e+000 4.93e-003  -5.0 6.24e-001    -
 9.85e-001 3.11e-001f  1
 118 5.0300487e+000 0.00e+000 3.21e-003  -5.3 7.98e-001    -
 8.92e-001 3.02e-001f  1
```

```
 119 5.0221356e+000 0.00e+000 5.64e-003  -6.5 1.00e+000    -
 6.67e-001 1.40e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 120 5.1321508e+000 0.00e+000 8.13e-003  -3.7 5.49e+000    -
 4.68e-002 2.69e-001f  1
 121 5.0681609e+000 0.00e+000 8.17e-003  -5.0 2.14e+000    -
 1.17e-002 3.20e-001f  1
 122 5.0261287e+000 0.00e+000 4.55e-003  -5.0 1.79e+000    -
 6.71e-001 2.72e-001f  1
 123 5.0046005e+000 0.00e+000 4.55e-003  -5.0 1.23e+000    -
 2.17e-001 2.37e-001f  1
 124 4.9931713e+000 0.00e+000 2.22e-003  -5.1 1.29e+000    -
 6.99e-001 1.30e-001f  1
 125 4.9665455e+000 0.00e+000 1.54e-003  -4.6 5.42e-001    -
 5.84e-001 8.38e-001f  1
 126 4.9596673e+000 0.00e+000 6.42e-003  -4.9 4.11e-001    -
 9.82e-001 2.00e-001f  1
 127 4.9470793e+000 0.00e+000 4.10e-003  -5.1 7.10e-001    -
 4.72e-001 2.04e-001f  1
 128 4.9339181e+000 0.00e+000 3.71e-003  -6.9 8.61e-001    -
 3.41e-001 1.91e-001f  1
 129 4.9245220e+000 0.00e+000 3.68e-003  -5.7 8.59e-001    -
 5.27e-001 1.44e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 130 4.9143430e+000 0.00e+000 3.64e-003  -5.4 8.44e-001    -
 5.53e-001 1.62e-001f  1
 131 4.9014864e+000 0.00e+000 2.62e-003  -4.9 6.94e-001    -
 5.17e-001 2.48e-001f  1
 132 4.8878477e+000 0.00e+000 3.15e-003  -5.1 7.73e-001    -
 3.57e-001 2.62e-001f  1
 133 4.8812957e+000 0.00e+000 4.70e-003  -5.8 9.62e-001    -
 4.88e-001 1.07e-001f  1
 134 4.8745146e+000 0.00e+000 6.13e-003  -6.1 1.00e+000    -
 7.11e-001 1.04e-001f  1
 135 4.8594474e+000 0.00e+000 3.21e-003  -5.7 1.19e+000    -
 5.42e-001 1.94e-001f  1
 136 4.8502984e+000 0.00e+000 2.65e-003  -7.3 1.11e+000    -
 3.06e-001 1.22e-001f  1
 137 4.8397409e+000 0.00e+000 3.19e-003  -4.8 6.46e-001    -
 5.66e-001 2.29e-001f  1
 138 5.0246298e+000 0.00e+000 3.44e-003  -3.3 1.42e+001    -
 1.27e-002 1.28e-001f  1
 139 4.9052149e+000 0.00e+000 2.87e-003  -4.8 2.73e+000    -
 4.26e-002 3.86e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 140 4.8352429e+000 0.00e+000 2.47e-003  -4.8 1.71e+000    -
 6.25e-001 4.32e-001f  1
 141 4.9899454e+000 0.00e+000 5.58e-003  -3.9 4.10e+000    -
 5.76e-002 4.11e-001f  1
 142 4.8930395e+000 0.00e+000 5.77e-003  -4.7 2.52e+000    -
 3.91e-001 4.67e-001f  1
```

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 143 4.8593134e+000 0.00e+000 1.17e-002  -4.7 1.24e+000    -  1.00e
+000 2.42e-001f  1
 144 4.8312118e+000 0.00e+000 5.21e-003  -4.7 7.80e-001    -
 8.12e-001 3.24e-001f  1
 145 4.8227437e+000 0.00e+000 9.05e-003  -5.3 8.00e-001    -
 9.28e-001 1.12e-001f  1
 146 4.7992027e+000 0.00e+000 8.71e-003  -6.7 9.03e-001    -
 7.75e-001 3.02e-001f  1
 147 4.7950905e+000 0.00e+000 8.35e-003  -7.0 6.21e-001    -
 6.10e-001 8.11e-002f  1
 148 4.7769291e+000 0.00e+000 8.36e-003  -7.0 9.31e-001    -
 7.74e-001 2.60e-001f  1
 149 4.7659430e+000 0.00e+000 5.89e-003  -6.1 8.29e-001    -
 6.81e-001 1.94e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 150 4.7536114e+000 0.00e+000 5.08e-003  -5.8 8.96e-001    -
 6.94e-001 2.16e-001f  1
 151 4.7478525e+000 0.00e+000 3.96e-003 -11.0 9.91e-001    -
 7.07e-001 9.39e-002f  1
 152 4.7376081e+000 0.00e+000 7.16e-003  -5.6 7.87e-001    -
 6.51e-001 2.12e-001f  1
 153 4.7293792e+000 0.00e+000 2.55e-003  -5.3 9.94e-001    -
 7.43e-001 1.36e-001f  1
 154 4.9080425e+000 0.00e+000 2.35e-003  -3.9 4.14e+000    -
 1.23e-002 5.29e-001f  1
 155 4.8175318e+000 0.00e+000 1.33e-003  -5.3 4.63e+000    -
 2.02e-001 2.38e-001f  1
 156 4.7293387e+000 0.00e+000 3.56e-003  -5.3 3.82e+000    -
 7.87e-001 2.71e-001f  1
 157 4.7077953e+000 0.00e+000 1.18e-003  -4.7 4.23e-001    -
 6.52e-001 7.70e-001f  1
 158 4.7009183e+000 0.00e+000 3.86e-003  -4.8 3.39e-001    -
 7.14e-001 3.19e-001f  1
 159 4.6855947e+000 0.00e+000 2.05e-003  -4.8 5.53e-001    -
 4.37e-001 4.42e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 160 4.6789128e+000 0.00e+000 5.59e-003  -5.1 6.85e-001    -
 5.66e-001 1.53e-001f  1
 161 4.6638348e+000 0.00e+000 2.95e-003  -5.3 1.04e+000    -
 5.17e-001 2.39e-001f  1
 162 4.6562587e+000 0.00e+000 2.11e-003  -6.4 1.29e+000    -
 4.40e-001 9.60e-002f  1
 163 4.6518499e+000 0.00e+000 5.28e-003 -11.0 1.06e+000    -
 4.60e-001 6.93e-002f  1
 164 4.6310441e+000 0.00e+000 4.82e-003  -6.7 1.59e+000    -
 2.55e-001 2.31e-001f  1
 165 4.6249851e+000 0.00e+000 1.06e-002  -4.8 3.69e-001    -
 5.45e-001 3.17e-001f  1
 166 4.6232901e+000 0.00e+000 2.29e-003  -4.6 1.05e-001    -
 4.65e-001 1.00e+000f  1
 167 4.6174714e+000 0.00e+000 3.00e-003  -5.6 7.45e-001    -
 4.93e-001 1.45e-001f  1
```

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 168 4.6059326e+000 0.00e+000 1.88e-003  -5.1 1.17e+000    -
 4.79e-001 1.99e-001f  1
 169 4.6023980e+000 0.00e+000 4.17e-003  -5.1 8.41e-001    -
 6.23e-001 8.07e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 170 4.5837393e+000 0.00e+000 4.10e-003  -5.1 1.23e+000    -
 6.50e-001 2.88e-001f  1
 171 4.5768137e+000 0.00e+000 2.48e-003  -7.2 1.60e+000    -
 3.01e-001 7.87e-002f  1
 172 4.5658820e+000 0.00e+000 2.45e-003 -11.0 1.28e+000    -
 6.60e-002 1.62e-001f  1
 173 4.5575992e+000 0.00e+000 2.16e-003  -6.4 1.36e+000    -
 3.66e-001 1.17e-001f  1
 174 4.5473314e+000 0.00e+000 4.42e-003  -5.2 1.10e+000    -
 4.99e-001 1.72e-001f  1
 175 4.5812473e+000 0.00e+000 4.24e-003  -3.8 5.91e+000    -
 1.73e-002 1.07e-001f  1
 176 4.5579659e+000 0.00e+000 3.81e-003  -5.2 2.17e+000    -
 6.21e-002 1.98e-001f  1
 177 4.5461480e+000 0.00e+000 1.13e-002  -5.2 1.60e+000    -
 4.99e-001 1.32e-001f  1
 178 4.5424873e+000 0.00e+000 3.91e-003 -11.0 1.50e+000    -
 3.72e-001 4.55e-002f  1
 179 4.5176030e+000 0.00e+000 1.29e-003  -4.9 1.14e+000    -
 7.31e-001 4.44e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 180 4.5094690e+000 0.00e+000 1.88e-003  -4.7 5.30e-001    -
 5.18e-001 7.23e-001f  1
 181 4.5075355e+000 0.00e+000 5.65e-003  -6.4 6.40e-001    -
 5.32e-001 6.57e-002f  1
 182 4.4970194e+000 0.00e+000 2.26e-003  -5.3 1.20e+000    -
 8.45e-001 2.41e-001f  1
 183 4.4872889e+000 0.00e+000 2.01e-003  -5.2 1.69e+000    -
 3.84e-001 1.94e-001f  1
 184 4.4839699e+000 0.00e+000 4.69e-003 -11.0 1.19e+000    -
 4.42e-001 8.24e-002f  1
 185 4.4764595e+000 0.00e+000 3.29e-003  -7.0 1.54e+000    -
 3.46e-001 1.27e-001f  1
 186 4.4703044e+000 0.00e+000 2.00e-003  -5.6 1.81e+000    -
 2.94e-001 9.48e-002f  1
 187 4.4636883e+000 0.00e+000 3.83e-003 -11.0 1.60e+000    -
 2.39e-001 1.13e-001f  1
 188 4.4554679e+000 0.00e+000 2.92e-003  -5.8 2.07e+000    -
 4.00e-001 1.14e-001f  1
 189 4.4486254e+000 0.00e+000 3.12e-003  -4.9 6.53e-001    -
 4.14e-001 2.80e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 190 4.4423426e+000 0.00e+000 9.88e-004  -4.7 1.81e-001    -
 3.00e-001 1.00e+000f  1
 191 4.4418497e+000 0.00e+000 6.62e-003  -5.3 6.35e-001    -
 5.50e-001 2.21e-002f  1
```
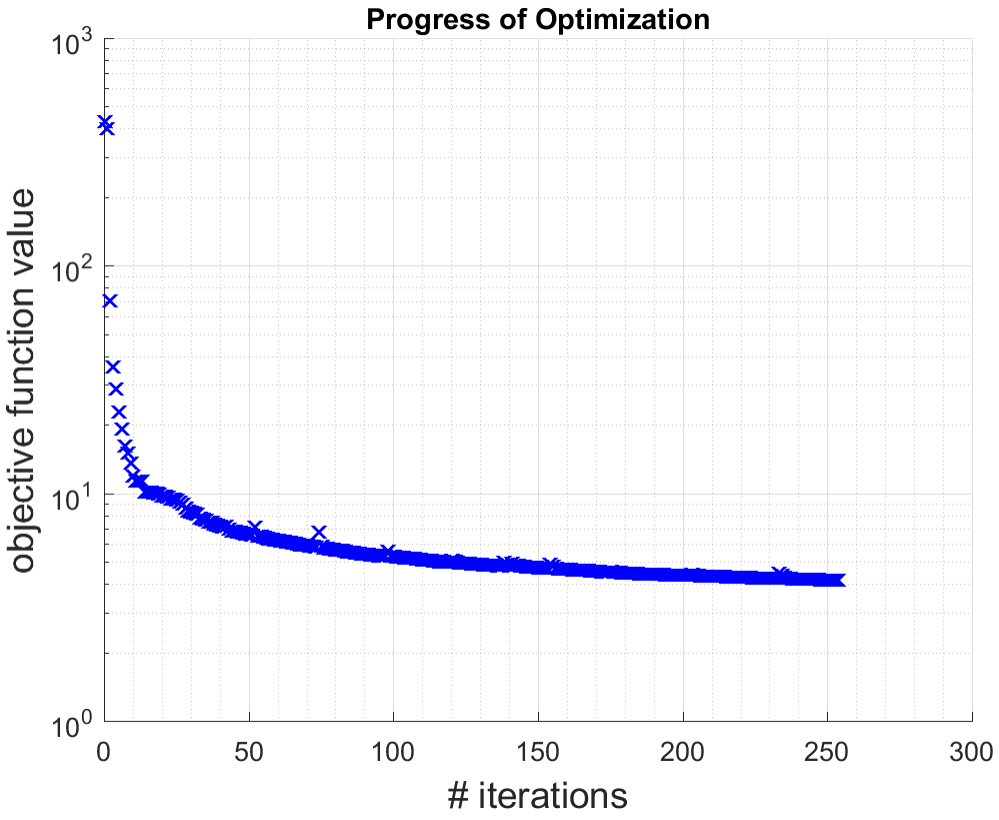

```
 192 4.4359968e+000 0.00e+000 2.44e-003  -4.8 7.21e-001    -
 5.65e-001 3.88e-001f  1
 193 4.4328624e+000 0.00e+000 9.28e-003  -5.2 5.15e-001    -
 7.88e-001 1.54e-001f  1
 194 4.4249194e+000 0.00e+000 7.45e-003  -5.6 8.07e-001    -
 7.44e-001 2.43e-001f  1
 195 4.4190046e+000 0.00e+000 5.66e-003  -5.0 7.17e-001    -
 1.54e-001 2.36e-001f  1
 196 4.4168992e+000 0.00e+000 2.60e-003  -5.3 7.15e-001    -
 4.54e-001 7.92e-002f  1
 197 4.4092729e+000 0.00e+000 4.37e-003  -5.0 5.88e-001    -
 2.95e-001 3.71e-001f  1
 198 4.4053230e+000 0.00e+000 3.22e-003  -5.2 5.48e-001    -
 5.30e-001 2.13e-001f  1
 199 4.4019562e+000 0.00e+000 3.15e-003  -5.3 5.98e-001    -
 6.55e-001 1.63e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 200 4.3960399e+000 0.00e+000 3.28e-003  -5.3 6.43e-001    -
 4.88e-001 2.65e-001f  1
 201 4.3928333e+000 0.00e+000 2.25e-003  -6.2 7.02e-001    -
 4.32e-001 1.27e-001f  1
 202 4.3883469e+000 0.00e+000 3.19e-003  -6.1 9.59e-001    -
 6.43e-001 1.25e-001f  1
 203 4.4526888e+000 0.00e+000 3.28e-003  -3.7 8.99e+000    -
 2.11e-002 1.63e-001f  1
 204 4.4291752e+000 0.00e+000 3.24e-003  -5.3 2.00e+000    -
 8.26e-003 1.88e-001f  1
 205 4.4186553e+000 0.00e+000 2.78e-003  -5.3 1.78e+000    -
 4.51e-001 9.95e-002f  1
 206 4.3876022e+000 0.00e+000 6.17e-003  -5.3 1.64e+000    -
 4.47e-001 3.70e-001f  1
 207 4.3766507e+000 0.00e+000 6.25e-003  -4.9 5.88e-001    -
 9.27e-001 3.85e-001f  1
 208 4.3703600e+000 0.00e+000 8.91e-003  -5.0 2.30e-001    -
 8.93e-001 6.56e-001f  1
 209 4.3669725e+000 0.00e+000 3.82e-003  -5.1 2.40e-001    -
 8.20e-001 3.68e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 210 4.3607758e+000 0.00e+000 1.99e-003  -5.2 4.85e-001    -
 5.58e-001 3.49e-001f  1
 211 4.3570178e+000 0.00e+000 2.27e-003  -5.9 6.64e-001    -
 6.29e-001 1.53e-001f  1
 212 4.3505635e+000 0.00e+000 2.43e-003  -6.2 1.09e+000    -
 5.43e-001 1.57e-001f  1
 213 4.3530460e+000 0.00e+000 1.24e-003  -4.7 1.80e-001    -
 3.67e-001 1.00e+000f  1
 214 4.3497240e+000 0.00e+000 1.28e-003  -5.2 6.47e-001    -
 5.79e-001 1.24e-001f  1
 215 4.3363643e+000 0.00e+000 1.44e-003  -5.8 1.30e+000    -
 3.88e-001 2.56e-001f  1
 216 4.3334083e+000 0.00e+000 5.60e-004  -4.7 9.83e-001    -
 3.39e-001 5.90e-001f  1
```

```
 217 4.3307562e+000 0.00e+000 2.19e-003  -5.7 6.47e-001    -
 5.54e-001 1.02e-001f  1
 218 4.3258191e+000 0.00e+000 3.83e-003  -6.3 7.69e-001    -
 4.06e-001 1.54e-001f  1
 219 4.3206024e+000 0.00e+000 4.37e-003  -5.5 7.33e-001    -
 4.87e-001 1.72e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 220 4.3209135e+000 0.00e+000 2.73e-003  -4.8 8.03e-001    -
 2.13e-001 8.35e-001f  1
 221 4.3172121e+000 0.00e+000 1.71e-003  -5.3 7.49e-001    -
 5.32e-001 1.15e-001f  1
 222 4.3097042e+000 0.00e+000 3.82e-003  -5.0 3.51e-001    -
 4.61e-001 4.94e-001f  1
 223 4.3018036e+000 0.00e+000 2.77e-003  -5.1 6.50e-001    -
 5.61e-001 2.93e-001f  1
 224 4.2934939e+000 0.00e+000 2.67e-003  -5.5 8.45e-001    -
 4.78e-001 2.43e-001f  1
 225 4.2920178e+000 0.00e+000 3.15e-003  -5.7 6.97e-001    -
 4.91e-001 5.10e-002f  1
 226 4.2831729e+000 0.00e+000 2.36e-003  -5.8 1.21e+000    -
 4.53e-001 1.88e-001f  1
 227 4.2802664e+000 0.00e+000 1.75e-003  -5.0 5.75e-001    -
 1.45e-001 1.28e-001f  1
 228 4.2709377e+000 0.00e+000 1.31e-003  -4.8 3.31e-001    -
 1.43e-001 8.83e-001f  1
 229 4.2681270e+000 0.00e+000 1.48e-003  -5.0 3.27e-001    -
 6.95e-001 3.11e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 230 4.2657188e+000 0.00e+000 3.89e-003  -5.3 4.79e-001    -
 8.35e-001 1.86e-001f  1
 231 4.2606683e+000 0.00e+000 2.41e-003  -5.7 7.64e-001    -
 7.47e-001 2.16e-001f  1
 232 4.2591376e+000 0.00e+000 3.75e-003  -6.0 7.85e-001    -
 5.67e-001 6.01e-002f  1
 233 4.5007957e+000 0.00e+000 4.13e-003  -3.7 1.50e+001    -
 1.55e-002 2.47e-001f  1
 234 4.3938442e+000 0.00e+000 4.14e-003  -5.2 3.80e+000    -
 4.02e-002 2.83e-001f  1
 235 4.3166292e+000 0.00e+000 3.76e-003  -5.2 2.87e+000    -
 5.35e-001 3.49e-001f  1
 236 4.2774569e+000 0.00e+000 7.44e-003  -5.2 1.68e+000    -
 5.50e-001 3.60e-001f  1
 237 4.2594959e+000 0.00e+000 7.01e-003  -5.2 1.01e+000    -
 7.85e-001 3.19e-001f  1
 238 4.2555723e+000 0.00e+000 4.24e-003  -5.2 5.23e-001    -
 5.20e-001 1.40e-001f  1
 239 4.2504925e+000 0.00e+000 1.10e-003  -4.9 1.44e-001    -
 3.86e-001 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 240 4.2483438e+000 0.00e+000 6.08e-003  -5.6 4.94e-001    -  1.00e
+000 1.09e-001f  1
```

```
 241 4.2420273e+000 0.00e+000 6.51e-003  -5.5 5.84e-001    -
 8.93e-001 2.79e-001f  1
 242 4.2354161e+000 0.00e+000 1.58e-003  -5.0 1.80e-001    -
 7.94e-001 1.00e+000f  1
 243 4.2328254e+000 0.00e+000 1.38e-003  -5.2 2.60e-001    -
 4.84e-001 2.78e-001f  1
 244 4.2284939e+000 0.00e+000 1.87e-003  -5.3 6.59e-001    -
 4.52e-001 1.78e-001f  1
 245 4.2203052e+000 0.00e+000 8.72e-004  -5.2 9.14e-001    -
 7.50e-001 2.78e-001f  1
 246 4.2188917e+000 0.00e+000 2.00e-003 -11.0 7.81e-001    -
 1.76e-001 5.17e-002f  1
 247 4.2145975e+000 0.00e+000 1.27e-003  -5.6 1.12e+000    -
 4.23e-001 1.15e-001f  1
 248 4.2075353e+000 0.00e+000 2.62e-003 -11.0 1.52e+000    -
 3.18e-001 1.36e-001f  1
 249 4.2064371e+000 0.00e+000 3.83e-003  -7.7 9.33e-001    -
 2.67e-001 3.65e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 250 4.1991106e+000 0.00e+000 2.87e-003  -5.8 1.11e+000    -
 4.65e-001 2.17e-001f  1
 251 4.1945354e+000 0.00e+000 1.53e-003  -5.4 7.75e-001    -
 3.18e-001 1.93e-001f  1
 252 4.1930819e+000 0.00e+000 3.12e-003  -5.8 6.20e-001    -
 4.26e-001 8.10e-002f  1
 253 4.1889720e+000 0.00e+000 2.01e-003  -5.1 2.22e-001    -
 3.49e-001 6.53e-001f  1
 254 4.1870701e+000 0.00e+000 1.80e-003  -5.1 3.28e-001    -
 4.70e-001 2.25e-001f  1

Number of Iterations....: 254

                                   (scaled)                 (unscaled)
Objective...............:  4.1870701025738564e+000
 4.1870701025738564e+000
Dual infeasibility......:  1.8038287480841529e-003
 1.8038287480841529e-003
Constraint violation....:  0.0000000000000000e+000
 0.0000000000000000e+000
Complementarity.........:  8.4111383756812913e-006
 8.4111383756812913e-006
Overall NLP error.......:  1.8038287480841529e-003
 1.8038287480841529e-003


Number of objective function evaluations             = 255
Number of objective gradient evaluations             = 255
Number of equality constraint evaluations            = 0
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 0
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 0
Total CPU secs in IPOPT (w/o function evaluations)   =     24.531
```

```
Total CPU secs in NLP function evaluations          =     85.325

EXIT: Solved To Acceptable Level.
Calculating final cubes...
matRad: applying a constant RBE of 1.1
```



Calculate quality indicators

```
cst       = matRad_indicatorWrapper(cst,pln,resultGUI);
ixRectum  = 8;
D5_rectum = cst{ixRectum,9}{1}.D_5
```

```
  0                BODY - Mean dose =  0.18 Gy +/-  0.46 Gy (Max dose
 =  2.37 Gy, Min dose =  0.00 Gy)
                           D2% =  1.86 Gy, D5% =  1.22 Gy, D50% =
 0.00 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                           V0Gy = 100.00%, V0.4Gy =  14.65%, V0.9Gy =
 12.03%, V1.4Gy =   3.59%, V1.8Gy =   2.58%, V2.3Gy =   0.06%,

  1             Bladder - Mean dose =  0.79 Gy +/-  0.85 Gy (Max dose
 =  2.35 Gy, Min dose =  0.00 Gy)
                           D2% =  2.29 Gy, D5% =  2.27 Gy, D50% =
 0.46 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                           V0Gy = 100.00%, V0.4Gy =  50.96%, V0.9Gy =
 42.68%, V1.4Gy =  25.03%, V1.8Gy =  18.40%, V2.3Gy =   1.20%,
```

```
 2      Lt femoral head - Mean dose =  0.65 Gy +/-  0.50 Gy (Max dose
=  1.40 Gy, Min dose =  0.00 Gy)
                          D2% =  1.27 Gy, D5% =  1.21 Gy, D50% =
0.89 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =  62.55%, V0.9Gy =
49.14%, V1.4Gy =   0.02%, V1.8Gy =   0.00%, V2.3Gy =   0.00%,

 3          Lymph Nodes - Mean dose =  1.90 Gy +/-  0.10 Gy (Max dose
=  2.33 Gy, Min dose =  1.82 Gy)
                          D2% =  2.29 Gy, D5% =  2.19 Gy, D50% =
1.87 Gy, D95% =  1.85 Gy, D98% =  1.84 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.8Gy = 100.00%, V2.3Gy =   1.07%,

 4               PTV 56 - Mean dose =  1.91 Gy +/-  0.12 Gy (Max dose
=  2.37 Gy, Min dose =  1.76 Gy)
                          D2% =  2.29 Gy, D5% =  2.26 Gy, D50% =
1.87 Gy, D95% =  1.84 Gy, D98% =  1.83 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.8Gy =  99.79%, V2.3Gy =   1.17%,
                          CI = 0.5189, HI = 22.54 for reference dose
of 1.9 Gy

 5               PTV 68 - Mean dose =  2.26 Gy +/-  0.04 Gy (Max dose
=  2.37 Gy, Min dose =  1.95 Gy)
                          D2% =  2.31 Gy, D5% =  2.30 Gy, D50% =
2.27 Gy, D95% =  2.17 Gy, D98% =  2.12 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.8Gy = 100.00%, V2.3Gy =   6.56%,
                          CI = 0.9178, HI =  5.84 for reference dose
of 2.3 Gy

 6          Penile bulb - Mean dose =  0.04 Gy +/-  0.06 Gy (Max dose
=  0.16 Gy, Min dose =  0.00 Gy)
                          D2% =  0.16 Gy, D5% =  0.16 Gy, D50% =
0.00 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =   0.00%, V0.9Gy =
 0.00%, V1.4Gy =   0.00%, V1.8Gy =   0.00%, V2.3Gy =   0.00%,

 7               Rectum - Mean dose =  0.85 Gy +/-  0.67 Gy (Max dose
=  2.36 Gy, Min dose =  0.00 Gy)
                          D2% =  2.27 Gy, D5% =  2.11 Gy, D50% =
0.93 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =  65.08%, V0.9Gy =
50.68%, V1.4Gy =  17.74%, V1.8Gy =   8.22%, V2.3Gy =   1.13%,

 8      Rt femoral head - Mean dose =  0.63 Gy +/-  0.49 Gy (Max dose
=  1.37 Gy, Min dose =  0.00 Gy)
                          D2% =  1.26 Gy, D5% =  1.21 Gy, D50% =
0.85 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =  61.77%, V0.9Gy =
46.35%, V1.4Gy =   0.00%, V1.8Gy =   0.00%, V2.3Gy =   0.00%,
```

```
 9         prostate bed - Mean dose =  2.26 Gy +/-  0.01 Gy (Max dose
=  2.33 Gy, Min dose =  2.21 Gy)
                          D2% =  2.29 Gy, D5% =  2.28 Gy, D50% =
2.27 Gy, D95% =  2.24 Gy, D98% =  2.24 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.8Gy = 100.00%, V2.3Gy =   0.58%,
                          Warning: target has no objective that
penalizes underdosage,

D5_rectum =

    2.1108
```

Let's change the optimization parameter of the rectum in such a way that it will be better spared. We increase the penalty and lower the threshold of the squared overdose objective function. Afterwards we re-optimize the treatment plan and evaluate dose statistics one more time.

```
cst{ixRectum,6}.penalty = 500;
cst{ixRectum,6}.dose    = 40;
resultGUI               = matRad_fluenceOptimization(dij,cst,pln);
cst                     = matRad_indicatorWrapper(cst,pln,resultGUI);
D5_rectum               = cst{ixRectum,9}{1}.D_5


******************************************************************************
This program contains Ipopt, a library for large-scale nonlinear
 optimization.
 Ipopt is released as open source code under the Eclipse Public
 License (EPL).
         For more information visit http://projects.coin-or.org/Ipopt
******************************************************************************

This is Ipopt version 3.11.8, running with linear solver ma57.

Number of nonzeros in equality constraint Jacobian...:        0
Number of nonzeros in inequality constraint Jacobian.:        0
Number of nonzeros in Lagrangian Hessian.............:        0

Total number of variables............................:    45574
                     variables with only lower bounds:    45574
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints.................:        0
Total number of inequality constraints...............:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
   0 4.5126899e+002 0.00e+000 1.07e+000   0.0 0.00e+000    -  0.00e
+000 0.00e+000   0
   1 4.1900964e+002 0.00e+000 7.37e-002  -1.1 7.77e-002    -
 9.91e-001 1.00e+000f  1
```

```
   2 7.5771347e+001 0.00e+000 1.98e-002  -1.7 1.36e+000    -  1.00e
+000 1.00e+000f  1
   3 4.2647075e+001 0.00e+000 1.28e-002  -3.4 3.77e-001    -
 9.78e-001 1.00e+000f  1
   4 3.5508864e+001 0.00e+000 1.08e-002  -3.9 2.79e-001    -
 9.90e-001 1.00e+000f  1
   5 2.9252883e+001 0.00e+000 1.04e-002  -4.8 4.24e-001    -  1.00e
+000 1.00e+000f  1
   6 2.4862755e+001 0.00e+000 1.34e-002  -5.5 7.74e-001    -  1.00e
+000 1.00e+000f  1
   7 2.1455438e+001 0.00e+000 7.42e-003  -6.1 3.56e-001    -  1.00e
+000 1.00e+000f  1
   8 2.0144609e+001 0.00e+000 6.08e-003  -7.3 2.18e-001    -  1.00e
+000 1.00e+000f  1
   9 1.8383132e+001 0.00e+000 4.90e-003  -8.5 4.73e-001    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  10 1.6751008e+001 0.00e+000 3.94e-003  -9.3 7.93e-001    -  1.00e
+000 6.85e-001f  1
  11 1.6742636e+001 0.00e+000 3.93e-003 -10.0 1.61e+000    -  1.00e
+000 1.69e-003f  1
  12 1.6732189e+001 0.00e+000 5.85e-002 -10.6 1.17e+000    -  1.00e
+000 2.77e-003f  1
  13 1.6500186e+001 0.00e+000 3.88e-003 -11.0 1.66e+000    -  1.00e
+000 4.53e-002f  1
  14 1.6259903e+001 0.00e+000 3.52e-002 -11.0 2.42e+000    -  1.00e
+000 3.41e-002f  1
  15 1.5987624e+001 0.00e+000 3.22e-002  -6.2 2.06e+000    -
 4.36e-001 4.36e-002f  1
  16 1.5688774e+001 0.00e+000 2.67e-002  -6.9 2.11e+000    -
 9.40e-001 4.84e-002f  1
  17 1.5442504e+001 0.00e+000 6.97e-002  -7.6 2.11e+000    -  1.00e
+000 4.37e-002f  1
  18 1.4933838e+001 0.00e+000 1.86e-002  -5.0 2.13e+000    -
 7.09e-001 9.29e-002f  1
  19 1.4860556e+001 0.00e+000 6.06e-002  -5.4 2.23e+000    -  1.00e
+000 1.38e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  20 1.4344534e+001 0.00e+000 1.83e-002  -5.9 2.76e+000    -  1.00e
+000 9.27e-002f  1
  21 1.4036259e+001 0.00e+000 2.19e-002  -3.8 2.19e+000    -
 3.87e-001 6.84e-002f  1
  22 1.3723953e+001 0.00e+000 1.53e-002 -10.2 2.07e+000    -
 3.63e-001 8.49e-002f  1
  23 1.3342374e+001 0.00e+000 2.12e-002  -4.5 2.79e+000    -
 9.96e-001 8.76e-002f  1
  24 1.2993932e+001 0.00e+000 4.28e-002  -3.9 1.61e+000    -
 9.49e-001 1.52e-001f  1
  25 1.2397905e+001 0.00e+000 1.27e-002  -4.7 1.90e+000    -
 8.52e-001 2.97e-001f  1
  26 1.2178304e+001 0.00e+000 2.36e-002  -4.1 1.79e+000    -
 9.85e-001 1.23e-001f  1
```

```
  27 1.1900344e+001 0.00e+000 1.42e-002  -5.0 1.43e+000    -
 8.04e-001 2.43e-001f  1
  28 1.1636863e+001 0.00e+000 1.31e-002  -5.2 1.91e+000    -  1.00e
+000 2.35e-001f  1
  29 1.1507544e+001 0.00e+000 1.51e-002  -3.7 9.16e-001    -
 6.18e-001 2.29e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  30 1.1414615e+001 0.00e+000 1.27e-002  -6.0 1.08e+000    -
 4.45e-001 1.57e-001f  1
  31 1.1220304e+001 0.00e+000 7.08e-003  -4.4 1.67e+000    -
 7.59e-001 2.40e-001f  1
  32 1.1074330e+001 0.00e+000 1.17e-002  -3.6 9.66e-001    -
 6.41e-001 3.15e-001f  1
  33 1.1027891e+001 0.00e+000 1.42e-002  -4.5 1.12e+000    -
 5.12e-001 8.92e-002f  1
  34 1.0861161e+001 0.00e+000 9.58e-003  -4.0 1.52e+000    -
 3.87e-001 2.46e-001f  1
  35 1.0700064e+001 0.00e+000 8.45e-003  -4.1 1.58e+000    -
 6.94e-001 2.29e-001f  1
  36 1.0588445e+001 0.00e+000 8.65e-003  -4.0 1.39e+000    -
 4.43e-001 1.91e-001f  1
  37 1.0387507e+001 0.00e+000 4.85e-003  -4.4 1.82e+000    -
 5.96e-001 3.18e-001f  1
  38 1.0276433e+001 0.00e+000 4.97e-003  -4.3 1.61e+000    -
 3.07e-001 1.76e-001f  1
  39 1.0187263e+001 0.00e+000 6.81e-003  -5.2 1.36e+000    -
 5.07e-001 1.92e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  40 1.0088660e+001 0.00e+000 5.29e-003  -4.2 1.65e+000    -
 5.75e-001 1.98e-001f  1
  41 1.1957274e+001 0.00e+000 7.90e-003  -2.3 1.05e+001    -
 2.77e-002 3.35e-001f  1
  42 1.0201622e+001 0.00e+000 8.17e-003  -3.8 3.52e+000    -
 6.56e-002 7.16e-001f  1
  43 9.8839474e+000 0.00e+000 8.70e-002  -3.8 3.85e+000    -
 8.51e-001 7.35e-001f  1
  44 9.8251134e+000 0.00e+000 1.64e-002  -5.0 8.85e-001    -
 8.19e-001 2.19e-001f  1
  45 9.7511081e+000 0.00e+000 1.41e-002  -5.1 1.26e+000    -
 6.97e-001 3.65e-001f  1
  46 9.6881847e+000 0.00e+000 7.26e-003  -5.4 1.43e+000    -
 7.76e-001 3.15e-001f  1
  47 9.6589427e+000 0.00e+000 1.16e-002  -6.1 1.47e+000    -
 7.17e-001 1.16e-001f  1
  48 9.5662846e+000 0.00e+000 8.59e-003  -4.4 1.78e+000    -
 2.07e-001 3.61e-001f  1
  49 9.5241011e+000 0.00e+000 4.63e-003  -4.0 7.26e-001    -
 4.70e-001 3.07e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  50 9.4634342e+000 0.00e+000 3.76e-003  -4.5 1.97e+000    -
 1.98e-001 1.72e-001f  1
```

```
  51 1.0514551e+001 0.00e+000 7.31e-003  -2.3 4.39e+001    -
 1.11e-002 7.09e-002f  1
  52 9.5859005e+000 0.00e+000 3.84e-003  -4.0 4.27e+000    -
 3.69e-003 5.65e-001f  1
  53 9.5674912e+000 0.00e+000 9.74e-002  -4.0 1.79e+001    -
 1.57e-001 5.00e-001f  2
  54 9.3575455e+000 0.00e+000 4.86e-002  -4.0 2.50e+000    -
 5.02e-001 4.01e-001f  1
  55 9.2548150e+000 0.00e+000 7.30e-003  -4.1 1.72e+000    -
 8.57e-001 3.21e-001f  1
  56 9.1868374e+000 0.00e+000 8.28e-003  -4.3 2.12e+000    -
 7.56e-001 1.83e-001f  1
  57 1.0294796e+001 0.00e+000 5.67e-003  -2.2 4.39e+001    -
 8.00e-003 1.40e-001f  1
  58 9.6536881e+000 0.00e+000 5.65e-003  -4.0 5.63e+000    -
 1.24e-002 3.64e-001f  1
  59 9.4599082e+000 0.00e+000 1.62e-002  -4.0 3.83e+000    -
 7.92e-001 1.87e-001f  3
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  60 9.0793497e+000 0.00e+000 1.07e-002  -4.0 2.59e+000    -
 7.05e-001 7.18e-001f  1
  61 9.0333727e+000 0.00e+000 9.07e-003  -4.7 1.32e+000    -
 9.94e-001 2.37e-001f  1
  62 8.9704156e+000 0.00e+000 5.71e-003  -4.8 1.74e+000    -
 8.81e-001 2.59e-001f  1
  63 1.0447818e+001 0.00e+000 4.93e-003  -2.8 1.58e+001    -
 2.14e-002 3.55e-001f  1
  64 8.9371737e+000 0.00e+000 5.79e-003  -4.3 6.82e+000    -
 2.55e-002 8.69e-001f  1
  65 8.8393716e+000 0.00e+000 1.49e-002  -4.8 2.12e+000    -  1.00e
+000 1.59e-001f  1
  66 8.8151985e+000 0.00e+000 8.70e-003  -4.4 4.49e-001    -
 7.36e-001 3.35e-001f  1
  67 8.7562896e+000 0.00e+000 1.99e-003  -4.1 3.27e-001    -
 6.29e-001 1.00e+000f  1
  68 8.7337677e+000 0.00e+000 5.82e-003  -4.4 5.76e-001    -
 8.76e-001 2.95e-001f  1
  69 8.6911106e+000 0.00e+000 4.99e-003  -4.9 1.42e+000    -
 8.46e-001 2.16e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  70 8.6627554e+000 0.00e+000 6.22e-003  -5.7 2.00e+000    -
 3.30e-001 9.75e-002f  1
  71 8.6084497e+000 0.00e+000 6.21e-003  -5.1 2.58e+000    -
 4.40e-001 1.41e-001f  1
  72 8.5607714e+000 0.00e+000 4.38e-003  -7.0 2.56e+000    -
 2.45e-001 1.24e-001f  1
  73 8.5121429e+000 0.00e+000 4.36e-003  -5.3 3.15e+000    -
 4.83e-001 9.83e-002f  1
  74 8.4759288e+000 0.00e+000 6.54e-003  -5.9 2.20e+000    -
 1.95e-001 1.08e-001f  1
  75 8.4102834e+000 0.00e+000 3.31e-003  -5.7 3.62e+000    -
 4.47e-001 1.39e-001f  1
```

```
  76 8.4047548e+000 0.00e+000 1.03e-002 -11.0 1.83e+000    -
 2.36e-001 2.00e-002f  1
  77 8.3431723e+000 0.00e+000 9.07e-003  -4.6 2.54e+000    -
 3.55e-001 1.68e-001f  1
  78 8.3210726e+000 0.00e+000 4.59e-003  -4.6 2.03e+000    -
 2.93e-001 6.19e-002f  1
  79 8.2961456e+000 0.00e+000 6.32e-003  -4.2 1.43e+000    -
 3.99e-001 1.07e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  80 8.2339258e+000 0.00e+000 6.54e-003  -4.1 1.56e+000    -
 3.89e-001 2.98e-001f  1
  81 8.2196767e+000 0.00e+000 7.93e-003  -4.8 1.47e+000    -
 4.15e-001 6.60e-002f  1
  82 8.1841161e+000 0.00e+000 6.75e-003  -4.7 1.96e+000    -
 3.76e-001 1.52e-001f  1
  83 8.1339097e+000 0.00e+000 7.69e-003  -4.7 2.10e+000    -
 8.78e-001 2.00e-001f  1
  84 8.6370802e+000 0.00e+000 6.41e-003  -2.6 2.58e+001    -
 9.63e-003 1.56e-001f  1
  85 8.4111516e+000 0.00e+000 6.54e-003  -4.4 4.19e+000    -
 2.67e-002 2.57e-001f  1
  86 8.2481661e+000 0.00e+000 5.77e-003  -4.4 3.37e+000    -
 7.04e-001 2.57e-001f  1
  87 8.1561737e+000 0.00e+000 2.96e-002  -4.4 2.34e+000    -
 6.21e-001 2.38e-001f  1
  88 8.0980872e+000 0.00e+000 2.92e-002  -4.4 1.92e+000    -
 9.42e-001 2.22e-001f  1
  89 8.0123129e+000 0.00e+000 9.76e-003  -4.1 1.60e+000    -
 7.28e-001 6.31e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  90 7.9882433e+000 0.00e+000 1.30e-002  -5.2 1.10e+000    -
 7.96e-001 2.18e-001f  1
  91 7.9603024e+000 0.00e+000 6.85e-003  -5.5 1.68e+000    -  1.00e
+000 1.64e-001f  1
  92 7.9183367e+000 0.00e+000 5.08e-003  -4.5 1.94e+000    -
 2.57e-001 2.48e-001f  1
  93 7.9095354e+000 0.00e+000 1.43e-002  -4.7 8.57e-001    -
 5.12e-001 9.96e-002f  1
  94 7.8695065e+000 0.00e+000 7.31e-003  -4.9 1.70e+000    -
 4.30e-001 2.35e-001f  1
  95 7.8441226e+000 0.00e+000 3.56e-003  -5.0 1.75e+000    -
 4.71e-001 1.44e-001f  1
  96 7.8318087e+000 0.00e+000 4.89e-003  -6.3 1.78e+000    -
 3.69e-001 6.80e-002f  1
  97 7.7993718e+000 0.00e+000 8.01e-003  -5.4 2.02e+000    -
 5.56e-001 1.64e-001f  1
  98 7.7825350e+000 0.00e+000 4.79e-003  -5.6 1.88e+000    -
 2.97e-001 8.88e-002f  1
  99 8.0562732e+000 0.00e+000 8.66e-003  -3.3 1.65e+001    -
 2.00e-002 2.18e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
```

```
 100 7.9977175e+000 0.00e+000 8.72e-003  -4.8 4.48e+000    -
 8.62e-002 9.49e-002f  1
 101 7.8061749e+000 0.00e+000 1.10e-002  -4.8 5.26e+000    -
 7.08e-001 3.34e-001f  1
 102 7.7722359e+000 0.00e+000 5.22e-003  -4.8 3.09e+000    -
 3.89e-001 8.44e-002f  1
 103 7.7505086e+000 0.00e+000 2.67e-002  -4.5 1.39e+000    -
 8.05e-001 1.23e-001f  1
 104 7.7060438e+000 0.00e+000 1.37e-002  -4.3 1.21e+000    -
 6.99e-001 3.28e-001f  1
 105 7.6938352e+000 0.00e+000 1.83e-002  -6.5 1.24e+000    -
 4.90e-001 9.12e-002f  1
 106 7.6565437e+000 0.00e+000 5.20e-003  -4.6 1.56e+000    -
 7.78e-001 2.58e-001f  1
 107 7.6346168e+000 0.00e+000 1.01e-002  -5.2 1.49e+000    -
 6.97e-001 1.81e-001f  1
 108 7.6142463e+000 0.00e+000 1.17e-002  -5.4 1.77e+000    -
 8.32e-001 1.48e-001f  1
 109 7.5943082e+000 0.00e+000 6.90e-003  -5.7 1.80e+000    -
 7.67e-001 1.39e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 110 7.5764977e+000 0.00e+000 1.21e-002  -5.7 1.72e+000    -
 6.64e-001 1.29e-001f  1
 111 7.5646211e+000 0.00e+000 8.71e-003  -7.0 2.85e+000    -
 4.69e-001 5.04e-002f  1
 112 7.5152243e+000 0.00e+000 7.34e-003  -6.9 2.96e+000    -
 6.96e-001 2.14e-001f  1
 113 7.5017363e+000 0.00e+000 4.95e-003  -4.3 1.06e+000    -
 3.06e-001 5.05e-001f  1
 114 7.4882008e+000 0.00e+000 8.95e-003  -4.5 4.31e-001    -
 6.82e-001 2.57e-001f  1
 115 7.4747599e+000 0.00e+000 6.51e-003  -5.4 1.20e+000    -
 4.13e-001 1.04e-001f  1
 116 7.4517887e+000 0.00e+000 8.71e-003  -5.3 1.37e+000    -
 4.53e-001 1.75e-001f  1
 117 7.4444633e+000 0.00e+000 7.78e-003  -5.4 1.14e+000    -
 4.31e-001 6.98e-002f  1
 118 7.4246062e+000 0.00e+000 5.33e-003  -5.2 1.40e+000    -
 5.21e-001 1.67e-001f  1
 119 7.4046524e+000 0.00e+000 1.22e-002  -4.9 1.04e+000    -
 6.28e-001 2.44e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 120 7.4006129e+000 0.00e+000 9.76e-003  -6.0 9.51e-001    -
 4.32e-001 5.60e-002f  1
 121 7.3866918e+000 0.00e+000 1.53e-002  -5.8 1.24e+000    -
 6.85e-001 1.53e-001f  1
 122 7.3672755e+000 0.00e+000 8.20e-003  -5.5 1.54e+000    -
 7.39e-001 1.83e-001f  1
 123 7.3499331e+000 0.00e+000 9.11e-003  -5.8 1.52e+000    -
 7.05e-001 1.76e-001f  1
 124 7.3377577e+000 0.00e+000 6.90e-003  -5.0 1.28e+000    -
 6.86e-001 1.46e-001f  1
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 125 7.3223734e+000 0.00e+000 3.49e-003  -4.6 1.17e+000    -
 4.26e-001 2.03e-001f  1
 126 7.3317416e+000 0.00e+000 1.19e-003  -4.1 1.30e-001    -
 4.09e-001 1.00e+000f  1
 127 7.3153754e+000 0.00e+000 1.13e-003  -4.5 1.14e+000    -
 5.36e-001 2.08e-001f  1
 128 7.2783382e+000 0.00e+000 1.92e-003  -4.5 1.39e+000    -
 6.11e-001 3.67e-001f  1
 129 7.2756502e+000 0.00e+000 6.97e-003  -6.6 1.40e+000    -
 3.50e-001 2.38e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 130 7.2530746e+000 0.00e+000 5.49e-003  -5.5 1.87e+000    -
 4.63e-001 1.58e-001f  1
 131 7.2331205e+000 0.00e+000 5.12e-003  -5.3 1.76e+000    -
 4.16e-001 1.55e-001f  1
 132 7.2113374e+000 0.00e+000 4.13e-003  -5.0 1.65e+000    -
 3.80e-001 1.88e-001f  1
 133 7.1860065e+000 0.00e+000 4.20e-003  -4.6 1.41e+000    -
 4.60e-001 2.66e-001f  1
 134 7.4494725e+000 0.00e+000 2.63e-003  -3.3 5.81e+000    -
 3.08e-002 4.20e-001f  1
 135 7.2105664e+000 0.00e+000 2.59e-003  -4.5 3.43e+000    -
 7.74e-003 6.55e-001f  1
 136 7.2076383e+000 0.00e+000 5.25e-002  -4.5 7.64e+000    -
 2.45e-001 2.50e-001f  3
 137 7.1851912e+000 0.00e+000 1.51e-002  -4.5 1.58e+000    -
 7.03e-001 2.00e-001f  1
 138 7.1748409e+000 0.00e+000 6.06e-003  -4.9 1.39e+000    -
 9.46e-001 1.01e-001f  1
 139 7.1395458e+000 0.00e+000 3.90e-003  -4.2 9.12e-001    -
 6.01e-001 6.16e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 140 7.1292772e+000 0.00e+000 8.81e-003  -4.6 1.53e+000    -
 6.90e-001 2.79e-001f  1
 141 7.1221720e+000 0.00e+000 4.82e-003  -4.6 1.58e+000    -
 3.53e-001 1.93e-001f  1
 142 7.1099711e+000 0.00e+000 4.35e-003  -5.9 4.15e+000    -
 4.38e-001 1.75e-001f  1
 143 7.0907485e+000 0.00e+000 4.35e-003  -5.4 6.77e+000    -
 6.51e-001 1.96e-001f  1
 144 7.0720088e+000 0.00e+000 3.44e-003  -4.7 6.73e+000    -
 2.50e-001 2.47e-001f  1
 145 7.0565647e+000 0.00e+000 3.08e-003  -4.3 2.16e+000    -
 5.01e-001 7.12e-001f  1
 146 7.0521739e+000 0.00e+000 2.40e-003  -5.1 6.63e+000    -
 4.54e-001 5.47e-002f  1
 147 7.0365013e+000 0.00e+000 7.80e-003  -4.8 5.04e+000    -
 3.40e-001 3.01e-001f  1
 148 7.0333387e+000 0.00e+000 4.65e-003  -4.9 6.70e+000    -
 4.17e-001 4.56e-002f  1
 149 7.0063562e+000 0.00e+000 4.45e-003  -5.6 1.28e+001    -
 3.33e-001 2.01e-001f  1
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iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 150 7.0035634e+000 0.00e+000 4.58e-003  -4.6 4.40e+000    -
 2.82e-001 5.74e-002f  1
 151 6.9828724e+000 0.00e+000 4.43e-003  -5.7 8.88e+000    -
 1.13e-001 2.13e-001f  1
 152 6.9646342e+000 0.00e+000 1.81e-003  -4.9 1.29e+001    -
 3.76e-001 1.32e-001f  1
 153 6.9610343e+000 0.00e+000 2.62e-003 -10.9 7.40e+000    -
 1.15e-001 4.42e-002f  1
 154 6.9425955e+000 0.00e+000 4.14e-003  -5.0 1.22e+001    -
 4.32e-001 1.39e-001f  1
 155 7.1351478e+000 0.00e+000 3.73e-003  -3.5 3.79e+001    -
 3.70e-003 3.42e-001f  1
 156 7.0031245e+000 0.00e+000 1.62e-003  -4.9 2.89e+001    -
 2.17e-001 3.16e-001f  1
 157 6.9383503e+000 0.00e+000 1.32e-003  -4.9 1.90e+001    -
 3.65e-001 2.53e-001f  1
 158 6.9335394e+000 0.00e+000 1.35e-002  -4.4 6.43e-001    -  1.00e
+000 3.87e-001f  1
 159 6.9173996e+000 0.00e+000 8.66e-003  -4.4 1.97e+000    -
 4.88e-001 6.54e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 160 6.9060723e+000 0.00e+000 1.14e-002  -4.7 3.73e+000    -
 9.53e-001 2.42e-001f  1
 161 6.8973568e+000 0.00e+000 4.10e-003  -4.4 2.00e+000    -
 5.14e-001 3.53e-001f  1
 162 6.8851076e+000 0.00e+000 7.00e-003  -4.7 4.98e+000    -
 7.92e-001 2.04e-001f  1
 163 6.8640773e+000 0.00e+000 7.21e-003  -5.3 7.77e+000    -
 8.60e-001 2.33e-001f  1
 164 6.8524290e+000 0.00e+000 6.57e-003  -6.5 6.41e+000    -
 3.86e-001 1.58e-001f  1
 165 6.8258746e+000 0.00e+000 4.31e-003  -5.8 1.05e+001    -
 9.72e-001 2.31e-001f  1
 166 6.8142478e+000 0.00e+000 5.84e-003  -5.0 6.76e+000    -
 4.99e-001 1.48e-001f  1
 167 6.7988560e+000 0.00e+000 3.74e-003  -4.6 2.81e+000    -
 4.44e-001 4.88e-001f  1
 168 6.7888791e+000 0.00e+000 2.54e-003  -4.6 2.81e+000    -
 3.54e-001 3.48e-001f  1
 169 6.7813151e+000 0.00e+000 3.93e-003  -5.7 7.40e+000    -
 2.86e-001 9.90e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 170 6.7631413e+000 0.00e+000 1.44e-003  -4.6 5.99e+000    -
 5.10e-001 3.16e-001f  1
 171 6.7549155e+000 0.00e+000 9.60e-003  -4.7 4.47e+000    -
 5.45e-001 1.75e-001f  1
 172 6.7436791e+000 0.00e+000 3.68e-003  -4.8 6.90e+000    -
 4.27e-001 1.51e-001f  1
 173 6.7348187e+000 0.00e+000 4.77e-003  -6.2 9.66e+000    -
 3.81e-001 7.83e-002f  1
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 174 6.7215652e+000 0.00e+000 5.33e-003  -6.2 9.52e+000    -
 2.64e-001 1.18e-001f  1
 175 6.7056471e+000 0.00e+000 4.80e-003  -5.8 1.06e+001    -
 1.35e-001 1.28e-001f  1
 176 6.8886302e+000 0.00e+000 4.45e-003  -3.1 1.91e+002    -
 5.90e-003 5.49e-002f  1
 177 6.8506696e+000 0.00e+000 4.19e-003  -5.0 2.24e+001    -
 4.42e-002 9.41e-002f  1
 178 6.8000875e+000 0.00e+000 1.21e-002  -5.0 1.84e+001    -
 4.95e-001 1.47e-001f  1
 179 6.7350793e+000 0.00e+000 7.06e-003  -5.0 1.65e+001    -
 2.79e-001 2.55e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 180 6.6978408e+000 0.00e+000 9.17e-003  -5.0 1.05e+001    -
 5.16e-001 2.34e-001f  1
 181 6.6909005e+000 0.00e+000 4.59e-003  -4.7 4.40e+000    -
 6.49e-001 1.03e-001f  1
 182 6.6844758e+000 0.00e+000 1.24e-002  -5.3 3.93e+000    -
 3.87e-001 1.01e-001f  1
 183 6.8587110e+000 0.00e+000 9.36e-003  -3.3 6.99e+001    -
 1.74e-002 1.55e-001f  1
 184 6.6811983e+000 0.00e+000 8.66e-003  -4.7 1.90e+001    -
 7.35e-002 6.13e-001f  1
 185 6.6667548e+000 0.00e+000 1.53e-002  -5.3 9.26e+000    -
 7.51e-001 8.80e-002f  1
 186 6.6671223e+000 0.00e+000 5.51e-003  -4.4 4.90e-001    -
 4.00e-001 1.00e+000f  1
 187 6.6615158e+000 0.00e+000 7.09e-003  -4.7 4.24e+000    -
 8.71e-001 1.02e-001f  1
 188 6.6465846e+000 0.00e+000 1.33e-002  -5.1 6.10e+000    -
 9.95e-001 1.93e-001f  1
 189 6.6226707e+000 0.00e+000 1.70e-002  -5.4 6.47e+000    -
 8.15e-001 3.01e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 190 6.6118645e+000 0.00e+000 1.02e-002  -5.5 7.25e+000    -
 8.33e-001 1.27e-001f  1
 191 6.6586341e+000 0.00e+000 7.26e-003  -4.3 3.29e+000    -
 2.22e-001 1.00e+000f  1
 192 6.6538465e+000 0.00e+000 3.98e-003  -4.9 8.10e+000    -
 5.01e-001 4.28e-002f  1
 193 6.6030946e+000 0.00e+000 8.65e-003  -4.9 8.29e+000    -
 4.55e-001 4.52e-001f  1
 194 6.5928869e+000 0.00e+000 1.60e-002  -4.9 4.41e+000    -
 9.18e-001 1.83e-001f  1
 195 6.5884451e+000 0.00e+000 4.42e-003  -4.6 1.58e+000    -
 6.51e-001 2.11e-001f  1
 196 6.5809340e+000 0.00e+000 5.92e-003  -4.7 1.92e+000    -
 4.01e-001 3.21e-001f  1
 197 6.5739486e+000 0.00e+000 7.47e-003  -5.4 3.63e+000    -
 6.41e-001 1.63e-001f  1
 198 6.5673819e+000 0.00e+000 6.88e-003  -5.1 3.71e+000    -
 7.61e-001 1.48e-001f  1
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 199 6.5572350e+000 0.00e+000 6.53e-003  -5.1 4.23e+000    -
 3.56e-001 1.97e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 200 6.5474555e+000 0.00e+000 3.96e-003  -5.5 6.25e+000    -
 3.20e-001 1.30e-001f  1
 201 6.5356788e+000 0.00e+000 4.63e-003  -4.9 4.37e+000    -
 8.10e-001 2.28e-001f  1
 202 6.5314655e+000 0.00e+000 3.96e-003  -4.6 1.23e+000    -
 2.59e-001 4.11e-001f  1
 203 6.5269024e+000 0.00e+000 4.28e-003  -4.9 2.58e+000    -
 5.35e-001 1.48e-001f  1
 204 6.5192146e+000 0.00e+000 2.52e-003  -4.9 3.66e+000    -
 4.03e-001 1.70e-001f  1
 205 6.5150822e+000 0.00e+000 1.45e-003  -4.6 2.01e+000    -
 3.04e-001 1.71e-001f  1
 206 6.5058965e+000 0.00e+000 1.00e-002  -5.0 3.30e+000    -
 5.77e-001 1.97e-001f  1
 207 6.4987186e+000 0.00e+000 5.22e-003  -5.4 5.41e+000    -
 3.55e-001 9.43e-002f  1
 208 6.4899184e+000 0.00e+000 4.29e-003  -5.1 6.07e+000    -
 3.29e-001 1.00e-001f  1
 209 6.4828471e+000 0.00e+000 7.01e-003 -11.0 7.06e+000    -
 1.87e-001 6.91e-002f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 210 6.4779898e+000 0.00e+000 5.12e-003  -5.2 7.26e+000    -
 4.36e-001 4.57e-002f  1
 211 6.4671193e+000 0.00e+000 5.42e-003  -4.5 1.81e+000    -
 3.26e-001 4.74e-001f  1
 212 6.4630203e+000 0.00e+000 5.62e-003  -4.6 1.59e+000    -
 4.32e-001 1.95e-001f  1
 213 6.6228305e+000 0.00e+000 4.38e-003  -3.3 7.71e+001    -
 9.36e-003 1.01e-001f  1
 214 6.5756843e+000 0.00e+000 3.95e-003  -4.6 1.04e+001    -
 7.75e-002 2.08e-001f  1
 215 6.5036567e+000 0.00e+000 7.96e-003  -4.6 8.10e+000    -
 6.16e-001 4.44e-001f  1
 216 6.4700618e+000 0.00e+000 3.84e-003  -4.6 4.56e+000    -
 5.54e-001 4.09e-001f  1
 217 6.4625044e+000 0.00e+000 2.54e-003  -4.6 2.46e+000    -
 5.38e-001 1.65e-001f  1
 218 6.4465484e+000 0.00e+000 3.43e-003  -4.6 2.26e+000    -
 6.13e-001 3.77e-001f  1
 219 6.4280959e+000 0.00e+000 7.44e-003  -4.7 2.32e+000    -
 6.48e-001 4.57e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 220 6.4137326e+000 0.00e+000 2.06e-003  -4.7 1.69e+000    -
 6.59e-001 5.23e-001f  1
 221 6.4065996e+000 0.00e+000 4.70e-003  -5.6 4.95e+000    -
 5.33e-001 9.56e-002f  1
 222 6.3945293e+000 0.00e+000 5.11e-003  -6.8 6.07e+000    -
 5.32e-001 1.38e-001f  1
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 223 6.3805060e+000 0.00e+000 1.86e-003  -4.9 3.52e+000    -
 6.32e-001 2.92e-001f  1
 224 6.3794001e+000 0.00e+000 7.60e-003  -5.0 1.32e+000    -
 4.37e-001 5.61e-002f  1
 225 6.3658950e+000 0.00e+000 3.03e-003  -4.6 1.86e+000    -
 3.50e-001 5.13e-001f  1
 226 6.3595973e+000 0.00e+000 9.38e-003  -4.9 2.39e+000    -
 5.15e-001 1.77e-001f  1
 227 6.3546538e+000 0.00e+000 7.97e-003  -5.1 2.85e+000    -
 7.31e-001 1.16e-001f  1
 228 6.3426939e+000 0.00e+000 4.04e-003  -5.3 4.40e+000    -
 5.59e-001 1.85e-001f  1
 229 6.3311491e+000 0.00e+000 4.94e-003  -5.7 4.48e+000    -
 6.16e-001 1.82e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 230 6.3284204e+000 0.00e+000 3.76e-003  -6.9 3.60e+000    -
 1.72e-001 5.23e-002f  1
 231 6.3181339e+000 0.00e+000 2.32e-003  -6.9 6.33e+000    -
 3.39e-001 1.14e-001f  1
 232 6.3064382e+000 0.00e+000 4.84e-003  -4.8 1.17e+000    -
 7.72e-001 7.25e-001f  1
 233 6.2998394e+000 0.00e+000 4.16e-003  -4.9 1.24e+000    -
 4.76e-001 3.75e-001f  1
 234 6.2963881e+000 0.00e+000 4.68e-003  -4.9 2.21e+000    -
 4.31e-001 1.10e-001f  1
 235 6.2898000e+000 0.00e+000 1.92e-003  -4.9 4.06e+000    -
 3.66e-001 1.01e-001f  1
 236 6.2794818e+000 0.00e+000 8.87e-003  -5.2 3.69e+000    -
 4.02e-001 1.78e-001f  1
 237 6.2704900e+000 0.00e+000 5.15e-003  -5.6 5.08e+000    -
 3.81e-001 1.12e-001f  1
 238 6.2624995e+000 0.00e+000 3.24e-003  -5.4 6.81e+000    -
 7.21e-001 7.44e-002f  1
 239 6.2459836e+000 0.00e+000 5.59e-003  -7.0 6.82e+000    -
 2.09e-001 1.52e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 240 6.2382876e+000 0.00e+000 8.09e-003  -5.8 4.92e+000    -
 5.25e-001 9.92e-002f  1
 241 6.2648127e+000 0.00e+000 2.69e-003  -4.5 4.81e-001    -
 5.64e-001 1.00e+000f  1
 242 6.2542630e+000 0.00e+000 2.05e-003  -4.8 2.69e+000    -
 3.92e-001 1.82e-001f  1
 243 6.2433130e+000 0.00e+000 2.52e-003  -4.8 1.90e+000    -
 2.31e-001 2.32e-001f  1
 244 6.2324184e+000 0.00e+000 3.31e-003  -4.8 1.24e+000    -
 2.45e-001 3.42e-001f  1
 245 6.2291528e+000 0.00e+000 3.55e-003  -4.8 1.29e+000    -
 6.11e-001 1.20e-001f  1
 246 6.2204115e+000 0.00e+000 6.64e-003  -4.8 1.30e+000    -
 5.91e-001 3.64e-001f  1
 247 6.2166800e+000 0.00e+000 4.26e-003  -4.9 1.28e+000    -
 9.49e-001 1.83e-001f  1
```
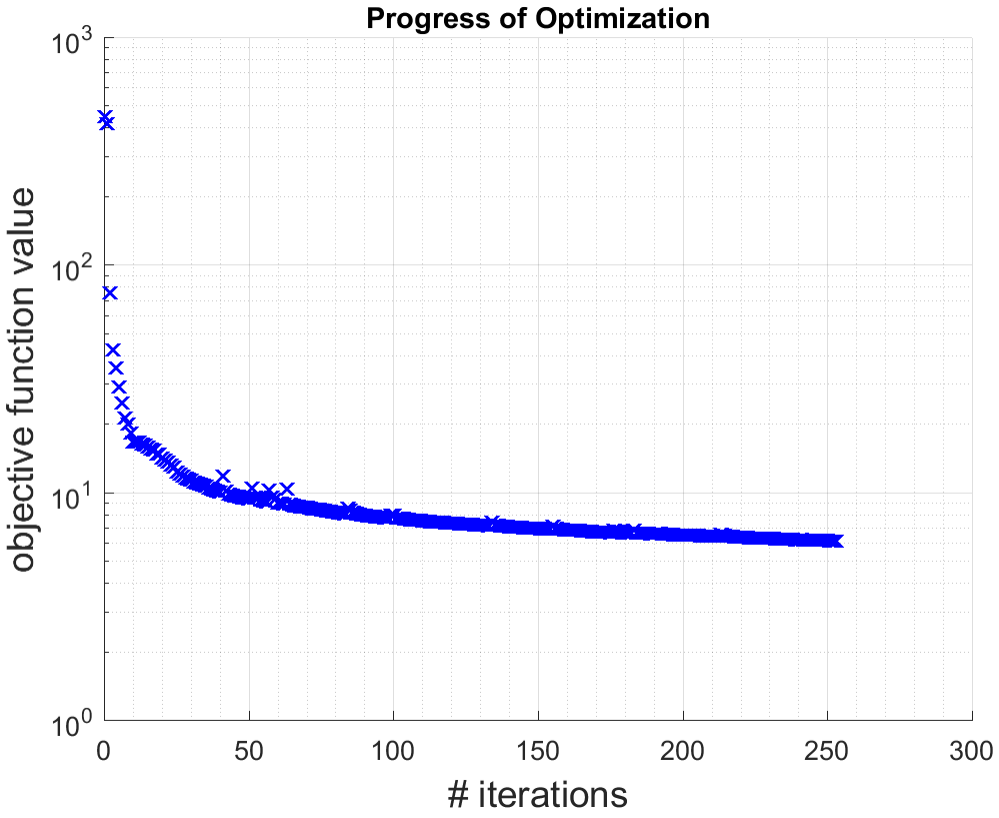

```
 248 6.2076471e+000 0.00e+000 9.27e-003  -5.0 1.45e+000    -
 8.69e-001 4.30e-001f  1
 249 6.2036804e+000 0.00e+000 3.96e-003  -5.2 1.79e+000    -
 9.44e-001 1.55e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 250 6.1949925e+000 0.00e+000 8.72e-003  -5.4 2.42e+000    -
 8.52e-001 2.51e-001f  1
 251 6.1892913e+000 0.00e+000 6.34e-003  -4.8 1.16e+000    -
 6.54e-001 3.42e-001f  1
 252 6.1898868e+000 0.00e+000 1.29e-003  -4.7 7.28e-002    -
 5.32e-001 4.90e-001f  1
 253 6.1874041e+000 0.00e+000 2.91e-003  -4.9 9.60e-001    -
 3.41e-001 2.01e-001f  1

Number of Iterations....: 253

                                   (scaled)                 (unscaled)
Objective...............:  6.1874040873685523e+000
 6.1874040873685523e+000
Dual infeasibility......:  2.9079619852336097e-003
 2.9079619852336097e-003
Constraint violation....:  0.0000000000000000e+000
 0.0000000000000000e+000
Complementarity.........:  1.9722846371354605e-005
 1.9722846371354605e-005
Overall NLP error.......:  2.9079619852336097e-003
 2.9079619852336097e-003


Number of objective function evaluations             = 271
Number of objective gradient evaluations             = 254
Number of equality constraint evaluations            = 0
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 0
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 0
Total CPU secs in IPOPT (w/o function evaluations)   =     23.492
Total CPU secs in NLP function evaluations           =     86.138

EXIT: Solved To Acceptable Level.
Calculating final cubes...
matRad: applying a constant RBE of 1.1
  0                BODY - Mean dose =  0.19 Gy +/-  0.47 Gy (Max dose
 =  2.41 Gy, Min dose =  0.00 Gy)
                           D2% =  1.86 Gy, D5% =  1.25 Gy, D50% =
 0.00 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                           V0Gy = 100.00%, V0.4Gy =  14.65%, V0.9Gy =
 12.12%, V1.4Gy =   3.69%, V1.9Gy =   1.25%, V2.4Gy =   0.00%,

  1             Bladder - Mean dose =  0.79 Gy +/-  0.85 Gy (Max dose
 =  2.34 Gy, Min dose =  0.00 Gy)
                           D2% =  2.29 Gy, D5% =  2.27 Gy, D50% =
 0.47 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
```

```
                          V0Gy = 100.00%, V0.4Gy =  51.07%, V0.9Gy =
42.88%, V1.4Gy =  25.19%, V1.9Gy =  16.49%, V2.4Gy =   0.00%,

 2      Lt femoral head - Mean dose =  0.66 Gy +/-  0.51 Gy (Max dose
=  1.44 Gy, Min dose =  0.00 Gy)
                          D2% =  1.30 Gy, D5% =  1.24 Gy, D50% =
0.91 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =  62.33%, V0.9Gy =
50.41%, V1.4Gy =   0.12%, V1.9Gy =   0.00%, V2.4Gy =   0.00%,

 3          Lymph Nodes - Mean dose =  1.90 Gy +/-  0.10 Gy (Max dose
=  2.33 Gy, Min dose =  1.81 Gy)
                          D2% =  2.29 Gy, D5% =  2.19 Gy, D50% =
1.87 Gy, D95% =  1.85 Gy, D98% =  1.84 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.9Gy =  12.22%, V2.4Gy =   0.00%,

 4               PTV 56 - Mean dose =  1.91 Gy +/-  0.12 Gy (Max dose
=  2.37 Gy, Min dose =  1.50 Gy)
                          D2% =  2.29 Gy, D5% =  2.26 Gy, D50% =
1.87 Gy, D95% =  1.84 Gy, D98% =  1.83 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.9Gy =  15.06%, V2.4Gy =   0.00%,
                          CI = 0.5182, HI = 22.58 for reference dose
of 1.9 Gy

 5               PTV 68 - Mean dose =  2.26 Gy +/-  0.05 Gy (Max dose
=  2.41 Gy, Min dose =  1.70 Gy)
                          D2% =  2.33 Gy, D5% =  2.31 Gy, D50% =
2.27 Gy, D95% =  2.16 Gy, D98% =  2.10 Gy,
                          V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
100.00%, V1.4Gy = 100.00%, V1.9Gy =  99.69%, V2.4Gy =   0.03%,
                          CI = 0.9081, HI =  6.67 for reference dose
of 2.3 Gy

 6          Penile bulb - Mean dose =  0.04 Gy +/-  0.06 Gy (Max dose
=  0.16 Gy, Min dose =  0.00 Gy)
                          D2% =  0.16 Gy, D5% =  0.16 Gy, D50% =
0.00 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =   0.00%, V0.9Gy =
 0.00%, V1.4Gy =   0.00%, V1.9Gy =   0.00%, V2.4Gy =   0.00%,

 7               Rectum - Mean dose =  0.68 Gy +/-  0.60 Gy (Max dose
=  2.41 Gy, Min dose =  0.00 Gy)
                          D2% =  2.25 Gy, D5% =  1.95 Gy, D50% =
0.68 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
                          V0Gy = 100.00%, V0.4Gy =  59.81%, V0.9Gy =
36.34%, V1.4Gy =  10.54%, V1.9Gy =   5.61%, V2.4Gy =   0.06%,

 8      Rt femoral head - Mean dose =  0.64 Gy +/-  0.50 Gy (Max dose
=  1.43 Gy, Min dose =  0.00 Gy)
                          D2% =  1.29 Gy, D5% =  1.24 Gy, D50% =
0.87 Gy, D95% =  0.00 Gy, D98% =  0.00 Gy,
```

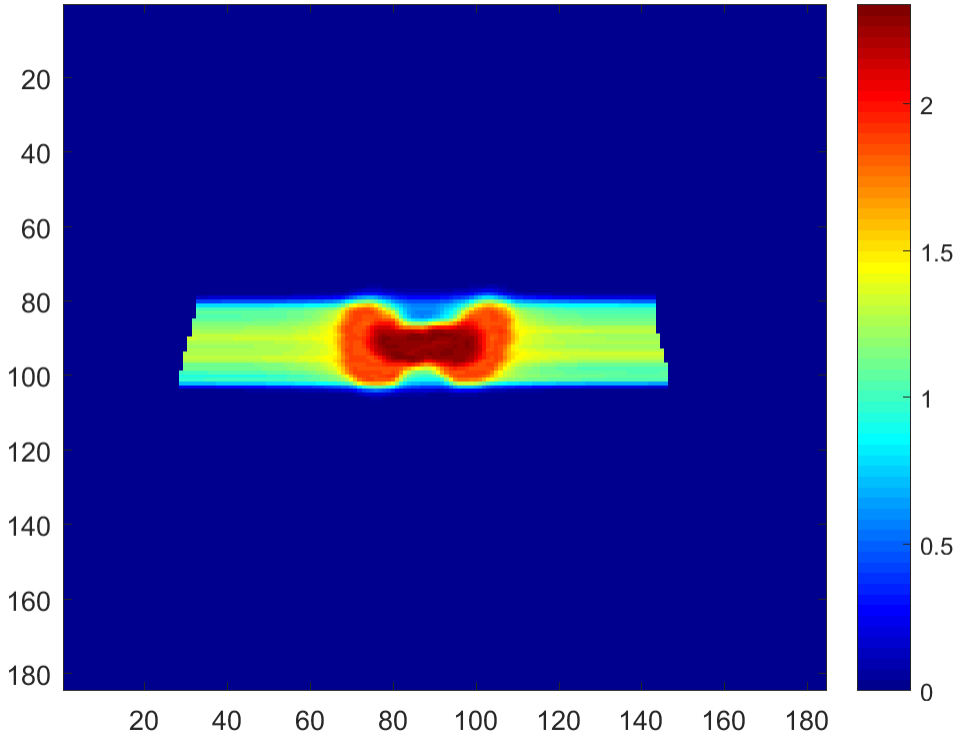
```
                              V0Gy = 100.00%, V0.4Gy =  61.35%, V0.9Gy =
 47.96%, V1.4Gy =   0.12%, V1.9Gy =   0.00%, V2.4Gy =   0.00%,

  9         prostate bed - Mean dose =  2.26 Gy +/-  0.02 Gy (Max dose
 =  2.39 Gy, Min dose =  2.21 Gy)
                              D2% =  2.30 Gy, D5% =  2.29 Gy, D50% =
 2.26 Gy, D95% =  2.24 Gy, D98% =  2.23 Gy,
                              V0Gy = 100.00%, V0.4Gy = 100.00%, V0.9Gy =
 100.00%, V1.4Gy = 100.00%, V1.9Gy = 100.00%, V2.4Gy =   0.00%,
                              Warning: target has no objective that
 penalizes underdosage,

D5_rectum =

    1.9543
```



Plot the Resulting Dose Slice

Let's plot the transversal iso-center dose slice

```
slice = round(pln.isoCenter(1,3)./ct.resolution.z);
figure
imagesc(resultGUI.RBExDose(:,:,slice)),colorbar, colormap(jet)
```



Now let's simulate a range undershoot by scaling the relative stopping power cube by 3.5% percent

```
ct_manip         = ct;
noise            = ct.cube{1} .* 0.035;
ct_manip.cube{1} = ct_manip.cube{1} + noise;
```

Recalculate Plan

Let's use the existing optimized pencil beam weights and recalculate the RBE weighted dose

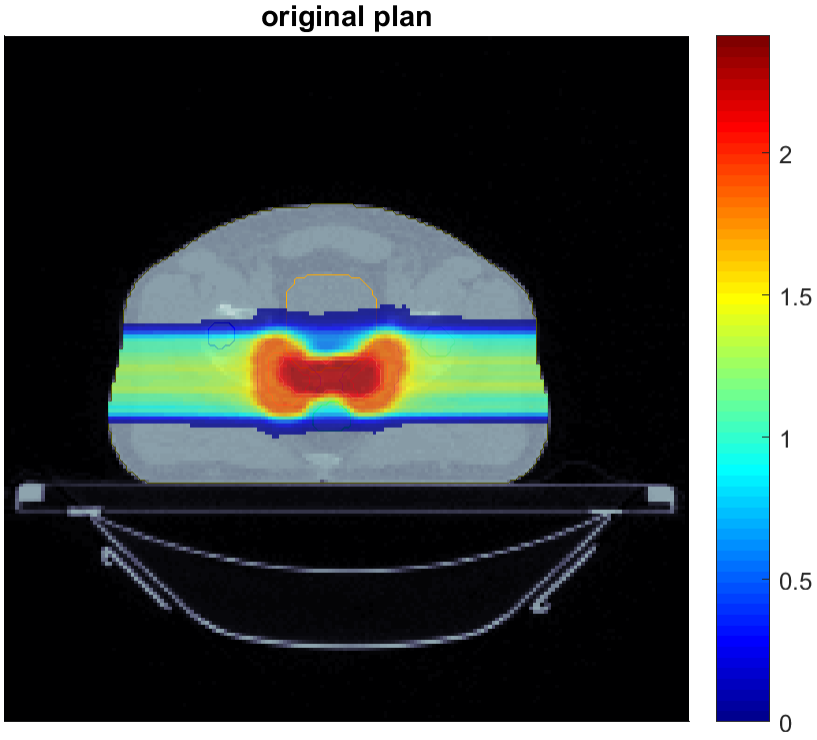
```
resultGUI_noise =
 matRad_calcDoseDirect(ct_manip,stf,pln,cst,resultGUI.w);
```

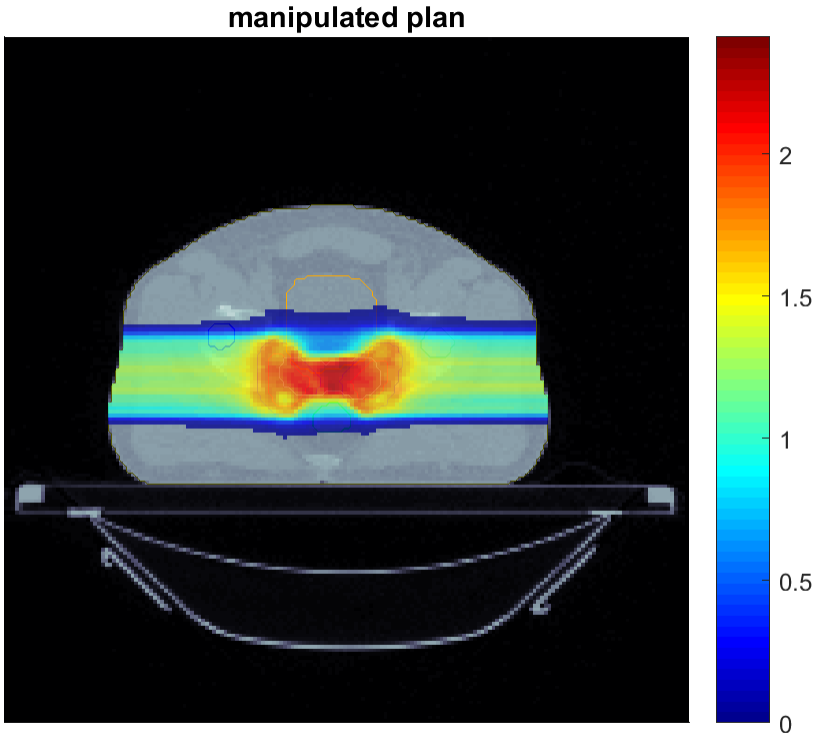
```
matRad: Using a constant RBE of 1.1
matRad: Particle dose calculation...
Beam 1 of 2:
matRad: calculate radiological depth cube...done.
matRad: calculate lateral cutoff...done.
Progress: 100.00 %
Beam 2 of 2:
matRad: calculate radiological depth cube...done.
matRad: calculate lateral cutoff...done.
Progress: 100.00 %
matRad: applying a constant RBE of 1.1
```

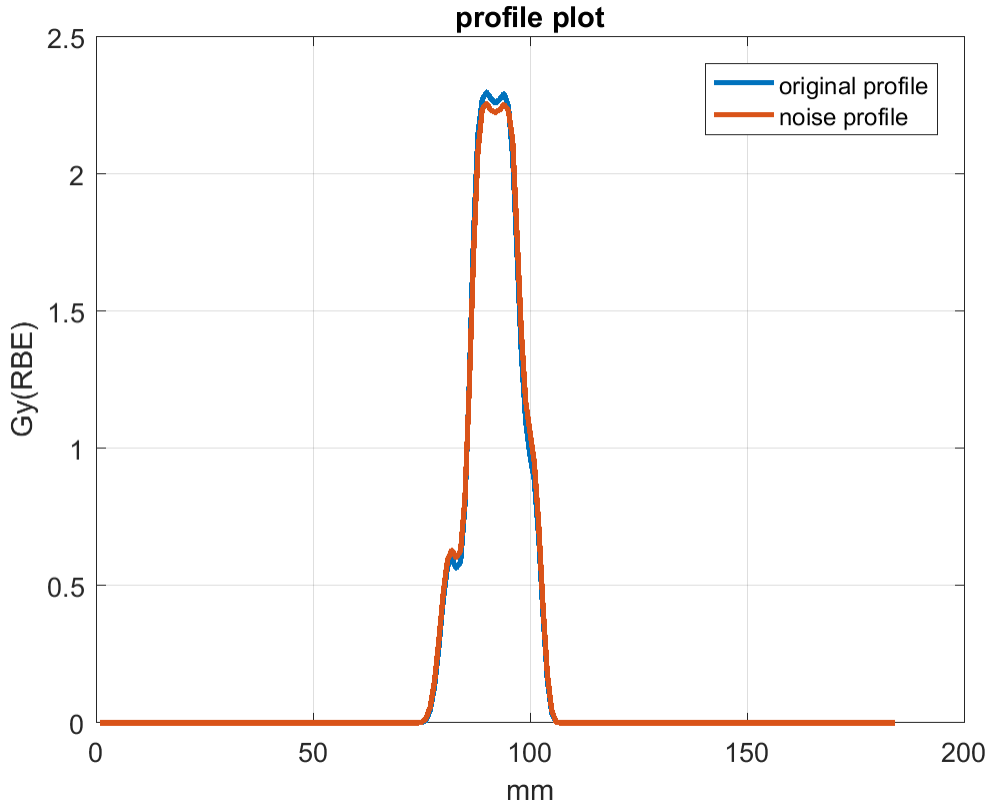
Visual Comparison of results

Let's compare the new recalculation against the optimization result.

```
plane = 3;
doseWindow = [0 max([resultGUI.RBExDose(:);
 resultGUI_noise.RBExDose(:)])];

figure,title('original plan')
matRad_plotSliceWrapper(gca,ct,cst,1,resultGUI.RBExDose,plane,slice,
[],0.75,colorcube,[],doseWindow,[]);
figure,title('manipulated plan')
matRad_plotSliceWrapper(gca,ct_manip,cst,1,resultGUI_noise.RBExDose,plane,slice,
[],0.75,colorcube,[],doseWindow,[]);

% Let's plot single profiles along the beam direction
ixProfileY = round(pln.isoCenter(1,1)./ct.resolution.x);

profileOrginal = resultGUI.RBExDose(:,ixProfileY,slice);
profileNoise   = resultGUI_noise.RBExDose(:,ixProfileY,slice);

figure,plot(profileOrginal,'LineWidth',2),grid on,hold on,
       plot(profileNoise,'LineWidth',2),legend({'original
 profile','noise profile'}),
       xlabel('mm'),ylabel('Gy(RBE)'),title('profile plot')
```



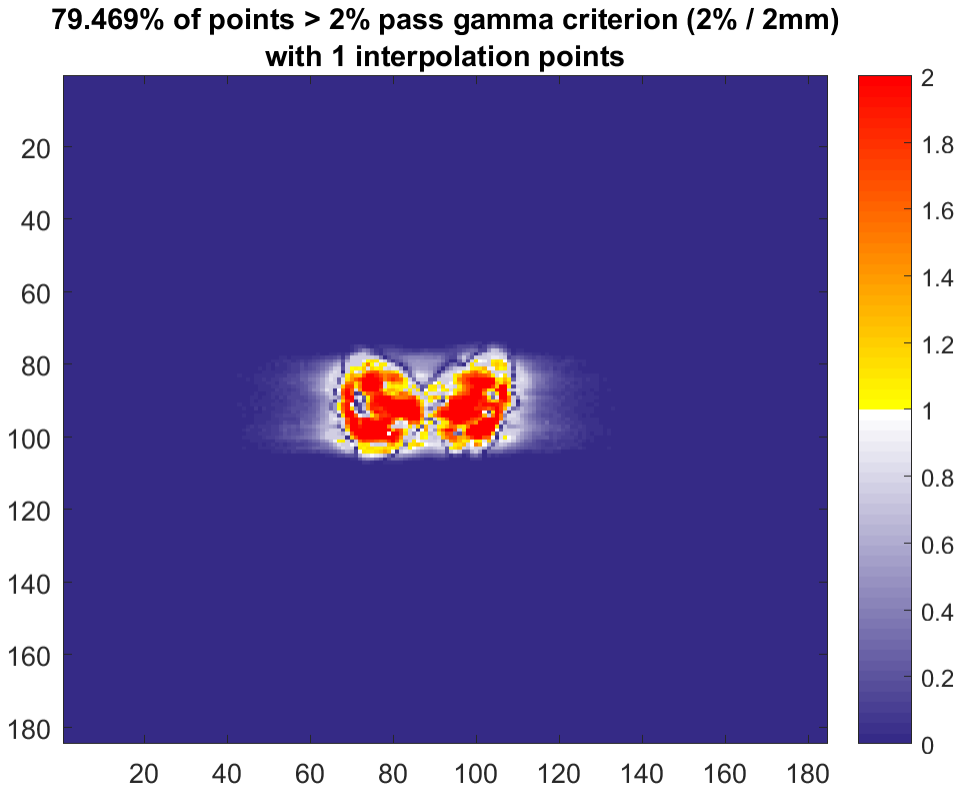

manipulated plan
2
1.5
1
0.5
0


profile plot
original profile
noise profile
Gy(RBE)
2.5
2
1.5
1
0.5
0
0
50
100
150
200
mm

Quantitative Comparison of results

Compare the two dose cubes using a gamma-index analysis.

```
doseDifference   = 2;
distToAgreement  = 2;
n        = 1;

[gammaCube,gammaPassRateCell] = matRad_gammaIndex(...
    resultGUI_noise.RBExDose,resultGUI.RBExDose,...
    [ct.resolution.x, ct.resolution.y, ct.resolution.z],...
    [doseDifference distToAgreement],slice,n,'global',cst);
```



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