
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 inversly 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 recalculated 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. First, import the prostate patient into your workspace. The phantom is comprised of a 'ct' and 'cst' structure defining the CT images and the structure set. Make sure the matRad root directory with all its SUBDIRECTORIES is added to the Matlab search path.

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

Let's check the two variables, we have just imported. First, the 'ct' variable comprises the ct cube along with some meta information describing properties of the ct cube (cube dimensions, resolution, number of CT scenarios). Please note that mutple ct cubes (e.g. 4D CT) can be stored in the cell array ct.cube{ }

ct

ct =

struct with fields:

```

        cube: {[184×184×90 double]}
    resolution: [1×1 struct]
        cubeDim: [184 184 90]
    numOfCtScen: 1

```

The 'cst' cell array defines volumes of interests along with information required for optimization. Each row belongs to one certain VOI, whereas each column defines different properties. Specifically, the second and third column show the name and the type of the structure. The type can be set to OAR, TARGET or IGNORED. The fourth column depicts a linear index vector depicting voxels in the CT cube that are covered by the corresponding VOI. In total, 17 structures are defined in the cst

cst

cst =

10×6 cell array

Columns 1 through 5

[0]	'BODY'	'OAR'	{1×1 cell}	[1×1 struct]
[1]	'Bladder'	'OAR'	{1×1 cell}	[1×1 struct]
[2]	'Lt femoral head'	'OAR'	{1×1 cell}	[1×1 struct]
[3]	'Lymph Nodes'	'OAR'	{1×1 cell}	[1×1 struct]
[4]	'PTV 56'	'TARGET'	{1×1 cell}	[1×1 struct]
[5]	'PTV 68'	'TARGET'	{1×1 cell}	[1×1 struct]
[6]	'Penile bulb'	'OAR'	{1×1 cell}	[1×1 struct]
[7]	'Rectum'	'OAR'	{1×1 cell}	[1×1 struct]
[8]	'Rt femoral head'	'OAR'	{1×1 cell}	[1×1 struct]
[9]	'prostate bed'	'TARGET'	{1×1 cell}	[1×1 struct]

Column 6

```

[1×1 struct]
[1×1 struct]
[]
[]
[1×1 struct]
[1×1 struct]
[]
[1×1 struct]
[]
[]

```

The fifth column represents meta parameters used for optimization such as the overlap priority, which can be specified in double precision. A lower overlap priority indicates increased importance. In contrast,

a higher overlap priority indicates a structure with lower importance. The parameters `alphaX` and `betaX` depict the tissue's photon-radiosensitivity parameter of the linear quadratic model. These parameters are required for biological treatment planning using a variable RBE. Let's output the meta optimization parameter of the rectum, which is stored in the eighth row:

```
ixRectum = 8;
cst{ixRectum,2}
cst{ixRectum,5}

ans =

    'Rectum'

ans =

    struct with fields:

        TissueClass: 1
           alphaX: 0.1000
           betaX: 0.0500
        Priority: 3
        Visible: 1
```

The sixth column contains optimization information such as objectives and constraints which are required to calculate the objective function value. Please note, that multiple objectives/constraints can be defined for individual structures. As the rectum is an OAR, we have defined a squared overdosing objective so that it is considered to be expensive/costly for the optimizer delivering more than 50 Gy to the rectum.

```
cst{ixRectum,6}

ans =

    struct with fields:

        type: 'square overdosing'
    penalty: 300
        dose: 50
        EUD: NaN
    volume: NaN
    robustness: 'none'
```

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.

First of all, we need to define what kind of radiation modality we would like to use. Possible values are photons, protons or carbon. In this example we would like to use protons for treatment planning. Then, we need to define a treatment machine to correctly load the corresponding base data. Since we provide generic

base data we set the machine to 'Generic'. By this means matRad will look for 'proton_Generic.mat' in our root directory and will use the data provided in there for dose calculation

```
pln.radiationMode = 'protons';  
pln.machine       = 'Generic';
```

Define the flavour of biological optimization for treatment planning along with the quantity that should be used for optimization. Possible values are (none: physical optimization; const_RBExD: constant RBE of 1.1; LEMIV_effect: effect-based optimization; LEMIV_RBExD: optimization of RBE-weighted dose. As we use protons, we follow here the clinical standard and use a constant relative biological effectiveness of 1.1. Therefore we set bioOptimization to const_RBExD

```
pln.bioOptimization = 'const_RBExD';
```

Now we have to set some beam parameters. We can define multiple beam angles for the treatment and pass these to the plan as a vector. matRad will then interpret the vector as multiple beams. We define two opposing beams. For the first beam we set the gantry angle to 90 degree and the corresponding couch angle to 0 degree. The second beam possess a gantry angle of 270 degree and a couch angle of 0 degree. Furthermore, we want the lateral pencil beam spacing in x and y to be 3 mm in the iso-center plane which is perpendicular to the central beam ray. In total we are using 30 fractions. It is noteworthy that matRad is always optimizing the fraction dose.

```
pln.gantryAngles = [90 270];  
pln.couchAngles  = [0 0];  
pln.bixelWidth   = 3;  
pln.numOfFractions = 30;
```

Obtain the number of beams and voxels from the existing variables and calculate the iso-center which is per default the mass of gravity of all target voxels.

```
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);
```

Disable sequencing and direct aperture optimization, since we have a particle plan.

```
pln.runDAO          = 0;  
pln.runSequencing   = 0;
```

and et voila our treatment plan is ready. Lets have a look at it:

```
pln
```

```
pln =
```

```
struct with fields:  
  
    radiationMode: 'protons'  
        machine: 'Generic'  
    bioOptimization: 'const_RBExD'  
    gantryAngles: [90 270]  
    couchAngles: [0 0]
```

```
bixelWidth: 3
numOfFractions: 30
numOfBeams: 2
numOfVoxels: 3047040
voxelDimensions: [184 184 90]
isoCenter: [2x3 double]
runDAO: 0
runSequencing: 0
```

Generatet Beam Geometry STF

This acronym stands for steering file and comprises the complet beam geomtry along with ray position, pencil beam positions and energies, source to axis distance (SAD) etc.

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

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

Let's display the beam geomtry information of the first beam

```
stf(1)
```

```
ans =
```

```
struct with fields:
```

```
gantryAngle: 90
couchAngle: 0
bixelWidth: 3
radiationMode: 'protons'
SAD: 10000
isoCenter: [263.2719 266.0622 124.0277]
numOfRays: 843
ray: [1x843 struct]
sourcePoint_bev: [0 -10000 0]
sourcePoint: [10000 0 0]
numOfBixelsPerRay: [1x843 double]
totalNumOfBixels: 22800
```

Start the GUI for Visualization

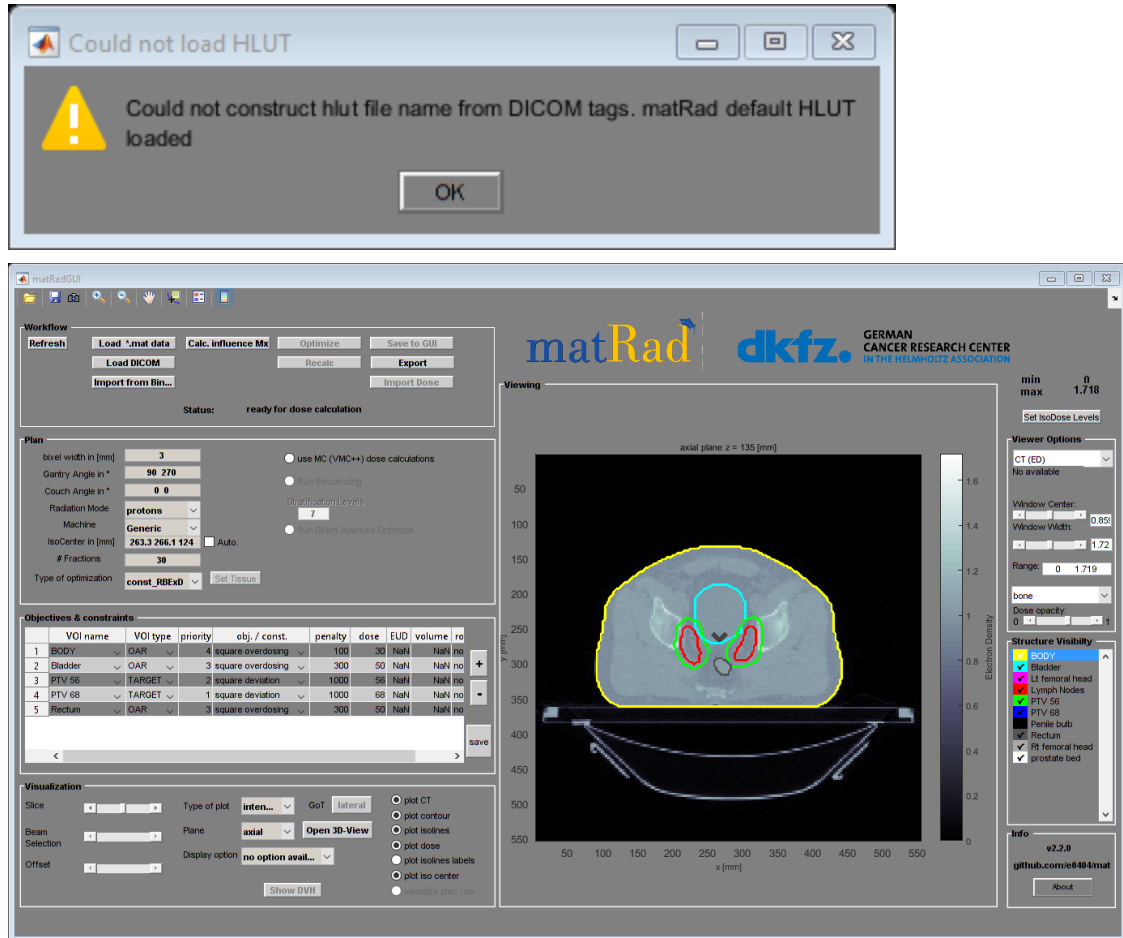
Show the ct cube along with contours. The graphical user interface (GUI) can be started at any time during treatment planning.

```
matRadGUI
```

```
Warning: matRad default HLUt loaded
```

```
Reconversion of HU values could not be done because HLUt is not
bijective.
```

Example: Proton Treatment Plan with Manipulated CT values



Dose Calculation

Lets generate dosimetric information by pre-computing dose influence matrices for unit beamlet intensities. Having dose influences available allows then later on inverse optimization.

```
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 Optimizaiton for IMPT

The goal of the fluence optimization is to find a set of bixel/spot weights which yield the best possible dose distribution according to the clinical objectives and constraints underlying the radiation treatment

Example: Proton Treatment Plan
with Manipulated CT values

```
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
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							

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

Example: Proton Treatment Plan
with Manipulated CT values

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			

Example: Proton Treatment Plan
with Manipulated CT values

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			

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

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			
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			

Example: Proton Treatment Plan
with Manipulated CT values

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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
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

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Example: Proton Treatment Plan
with Manipulated CT values

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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

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Example: Proton Treatment Plan
with Manipulated CT values

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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

```

Example: Proton Treatment Plan
with Manipulated CT values

```

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)

Example: Proton Treatment Plan
with Manipulated CT values

```

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

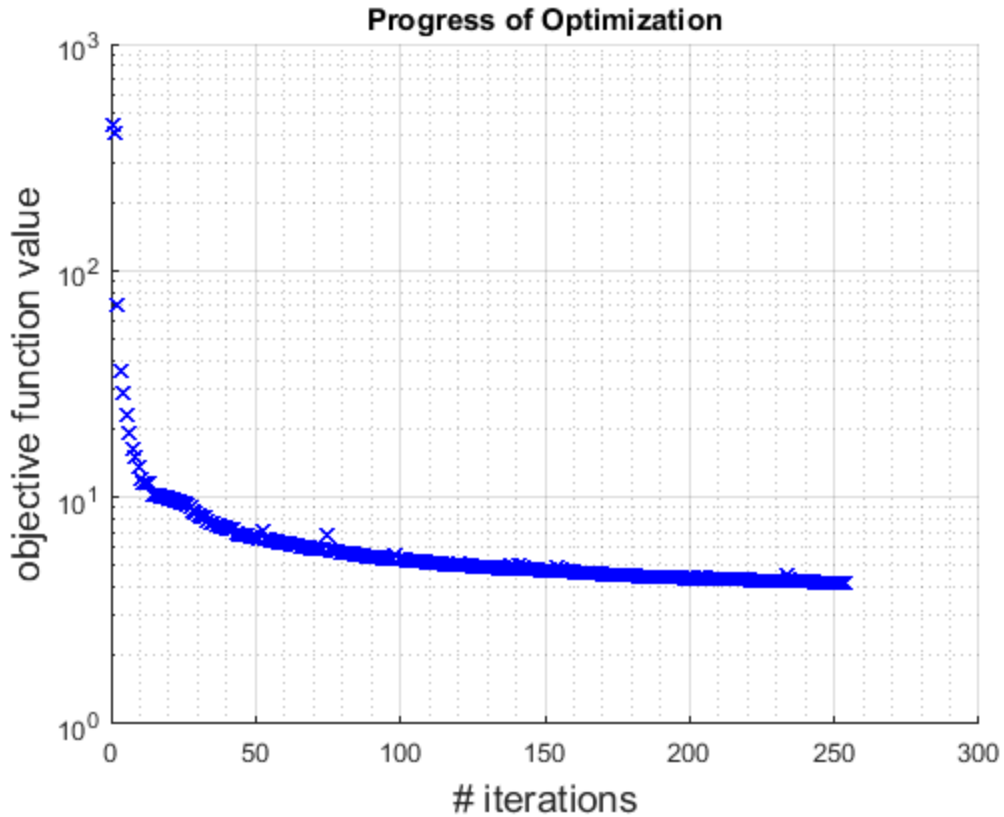
```

```

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) = 13.922
Total CPU secs in NLP function evaluations    = 67.521

```

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



Re-optimization

Let's calculate treatment plan quality indicators. As the rectum is considered to be an organ at risk we especially want to pay attention to this structure and show the dose level that is delivered to 5% percent of the rectum.

```
cst = matRad_indicatorWrapper(cst,pln,resultGUI);  
D5_rectum = cst{ixRectum,9}{1}.D5
```

```
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, D98% =  
0.00 Gy, D95% = 0.00 Gy,  
          V0Gy = 100.00%, V0.474Gy = 14.25%,  
V0.948Gy = 11.44%, V1.42Gy = 3.51%, V1.9Gy = 1.26%, V2.37Gy =  
0.00%,
```

```
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, D98% =  
0.00 Gy, D95% = 0.00 Gy,  
          V0Gy = 100.00%, V0.474Gy = 49.85%,  
V0.948Gy = 41.72%, V1.42Gy = 24.59%, V1.9Gy = 16.48%, V2.37Gy =  
0.00%,
```

```
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% = 1.22 Gy, D98% =  
0.00 Gy, D95% = 0.00 Gy,  
          V0Gy = 100.00%, V0.474Gy = 61.91%,  
V0.948Gy = 46.11%, V1.42Gy = 0.00%, V1.9Gy = 0.00%, V2.37Gy =  
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, D98% =  
1.84 Gy, D95% = 1.85 Gy,  
          V0Gy = 100.00%, V0.474Gy = 100.00%,  
V0.948Gy = 100.00%, V1.42Gy = 100.00%, V1.9Gy = 12.50%, V2.37Gy =  
0.00%,
```

```
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, D98% =  
1.83 Gy, D95% = 1.84 Gy,  
          V0Gy = 100.00%, V0.474Gy = 100.00%,  
V0.948Gy = 100.00%, V1.42Gy = 100.00%, V1.9Gy = 15.06%, V2.37Gy =  
0.01%,  
          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)
```

Example: Proton Treatment Plan
with Manipulated CT values

$D2\% = 2.31 \text{ Gy}$, $D5\% = 2.30 \text{ Gy}$, $D98\% = 2.12 \text{ Gy}$, $D95\% = 2.17 \text{ Gy}$,
 $V0\text{Gy} = 100.00\%$, $V0.474\text{Gy} = 100.00\%$,
 $V0.948\text{Gy} = 100.00\%$, $V1.42\text{Gy} = 100.00\%$, $V1.9\text{Gy} = 100.00\%$, $V2.37\text{Gy} = 0.01\%$,
 $CI = 0.9178$, $HI = 5.85$ for reference dose
of 2.3 Gy

6 Penile bulb - Mean dose = $0.04 \text{ Gy} \pm 0.06 \text{ Gy}$ (Max dose = 0.16 Gy , Min dose = 0.00 Gy)
 $D2\% = 0.16 \text{ Gy}$, $D5\% = 0.16 \text{ Gy}$, $D98\% = 0.00 \text{ Gy}$, $D95\% = 0.00 \text{ Gy}$,
 $V0\text{Gy} = 100.00\%$, $V0.474\text{Gy} = 0.00\%$,
 $V0.948\text{Gy} = 0.00\%$, $V1.42\text{Gy} = 0.00\%$, $V1.9\text{Gy} = 0.00\%$, $V2.37\text{Gy} = 0.00\%$,

7 Rectum - Mean dose = $0.85 \text{ Gy} \pm 0.67 \text{ Gy}$ (Max dose = 2.36 Gy , Min dose = 0.00 Gy)
 $D2\% = 2.27 \text{ Gy}$, $D5\% = 2.11 \text{ Gy}$, $D98\% = 0.00 \text{ Gy}$, $D95\% = 0.00 \text{ Gy}$,
 $V0\text{Gy} = 100.00\%$, $V0.474\text{Gy} = 62.30\%$,
 $V0.948\text{Gy} = 49.38\%$, $V1.42\text{Gy} = 16.89\%$, $V1.9\text{Gy} = 7.09\%$, $V2.37\text{Gy} = 0.00\%$,

8 Rt femoral head - Mean dose = $0.63 \text{ Gy} \pm 0.49 \text{ Gy}$ (Max dose = 1.37 Gy , Min dose = 0.00 Gy)
 $D2\% = 1.26 \text{ Gy}$, $D5\% = 1.21 \text{ Gy}$, $D98\% = 0.00 \text{ Gy}$, $D95\% = 0.00 \text{ Gy}$,
 $V0\text{Gy} = 100.00\%$, $V0.474\text{Gy} = 60.61\%$,
 $V0.948\text{Gy} = 41.31\%$, $V1.42\text{Gy} = 0.00\%$, $V1.9\text{Gy} = 0.00\%$, $V2.37\text{Gy} = 0.00\%$,

9 prostate bed - Mean dose = $2.26 \text{ Gy} \pm 0.01 \text{ Gy}$ (Max dose = 2.33 Gy , Min dose = 2.21 Gy)
 $D2\% = 2.29 \text{ Gy}$, $D5\% = 2.28 \text{ Gy}$, $D98\% = 2.24 \text{ Gy}$, $D95\% = 2.24 \text{ Gy}$,
 $V0\text{Gy} = 100.00\%$, $V0.474\text{Gy} = 100.00\%$,
 $V0.948\text{Gy} = 100.00\%$, $V1.42\text{Gy} = 100.00\%$, $V1.9\text{Gy} = 100.00\%$, $V2.37\text{Gy} = 0.00\%$,

Warning: target has no objective that penalizes underdosage,

$D5_{\text{rectum}} =$

2.1109

Let's change the optimization parameter of the rectum in such a way that it will be better spared. We increase the importance 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);
```

Example: Proton Treatment Plan
with Manipulated CT values

```
cst                = matRad_indicatorWrapper(cst,pln,resultGUI);
D5_rectum         = cst{ixRectum,9}{1}.D5
```

```
*****
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					

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

```

 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

```

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

Example: Proton Treatment Plan
with Manipulated CT values

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					
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					

Example: Proton Treatment Plan
with Manipulated CT values

```

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
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

```

Example: Proton Treatment Plan
with Manipulated CT values

```

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
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

```

Example: Proton Treatment Plan
with Manipulated CT values

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			
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			

Example: Proton Treatment Plan
with Manipulated CT values

```

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
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

```

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

Example: Proton Treatment Plan
with Manipulated CT values

```
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) = 13.817
Total CPU secs in NLP function evaluations    = 68.678
```

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, D98% =
0.00 Gy, D95% = 0.00 Gy,
          V0Gy = 100.00%, V0.483Gy = 14.21%,
V0.965Gy = 11.42%, V1.45Gy = 3.48%, V1.93Gy = 1.21%, V2.41Gy =
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, D98% =
0.00 Gy, D95% = 0.00 Gy,
          V0Gy = 100.00%, V0.483Gy = 49.91%,
V0.965Gy = 41.68%, V1.45Gy = 24.22%, V1.93Gy = 16.25%, V2.41Gy =
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, D98% =
0.00 Gy, D95% = 0.00 Gy,
          V0Gy = 100.00%, V0.483Gy = 61.66%,
V0.965Gy = 47.54%, V1.45Gy = 0.00%, V1.93Gy = 0.00%, V2.41Gy =
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, D98% =
1.84 Gy, D95% = 1.85 Gy,
          V0Gy = 100.00%, V0.483Gy = 100.00%,
V0.965Gy = 100.00%, V1.45Gy = 100.00%, V1.93Gy = 11.02%, V2.41Gy =
0.00%,
```


Example: Proton Treatment Plan
with Manipulated CT values

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, D98% =
1.83 Gy, D95% = 1.84 Gy,
V0Gy = 100.00%, V0.483Gy = 100.00%,
V0.965Gy = 100.00%, V1.45Gy = 100.00%, V1.93Gy = 13.69%, V2.41Gy =
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, D98% =
2.10 Gy, D95% = 2.16 Gy,
V0Gy = 100.00%, V0.483Gy = 100.00%,
V0.965Gy = 100.00%, V1.45Gy = 100.00%, V1.93Gy = 99.62%, V2.41Gy =
0.01%,
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, D98% =
0.00 Gy, D95% = 0.00 Gy,
V0Gy = 100.00%, V0.483Gy = 0.00%,
V0.965Gy = 0.00%, V1.45Gy = 0.00%, V1.93Gy = 0.00%, V2.41Gy =
0.00%,

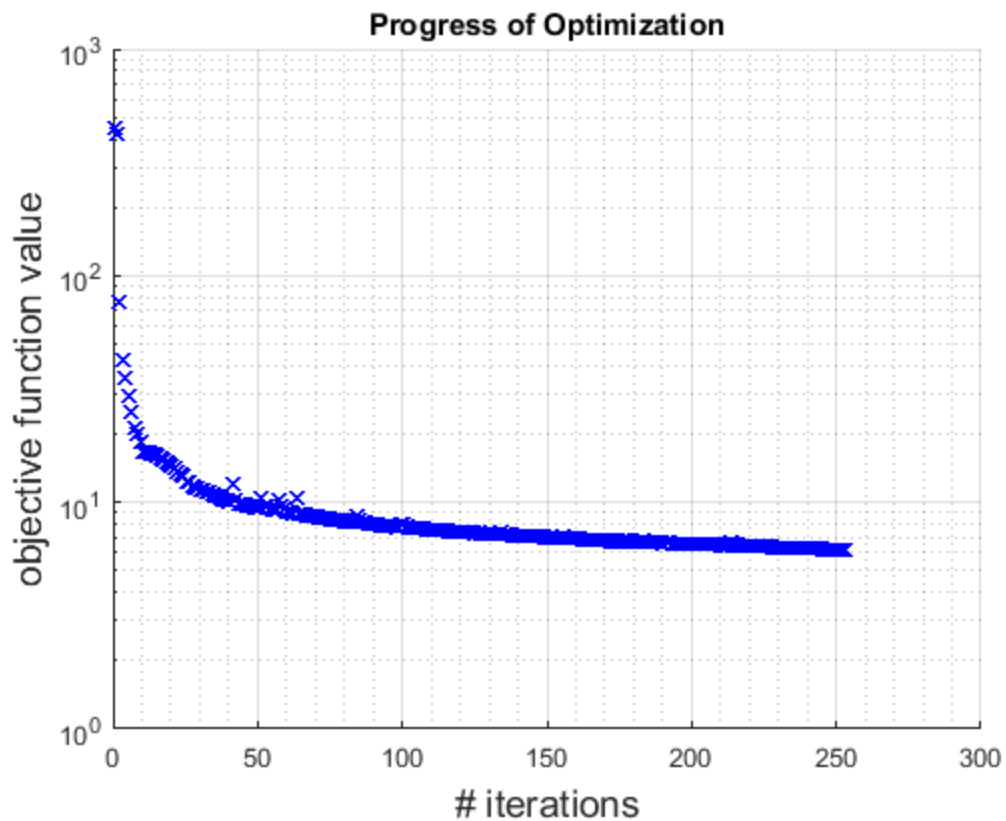
7 Rectum - Mean dose = 0.68 Gy +/- 0.60 Gy (Max dose
= 2.41 Gy, Min dose = 0.00 Gy)
D2% = 2.25 Gy, D5% = 1.95 Gy, D98% =
0.00 Gy, D95% = 0.00 Gy,
V0Gy = 100.00%, V0.483Gy = 56.86%,
V0.965Gy = 31.29%, V1.45Gy = 9.24%, V1.93Gy = 5.39%, V2.41Gy =
0.00%,

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, D98% =
0.00 Gy, D95% = 0.00 Gy,
V0Gy = 100.00%, V0.483Gy = 60.60%,
V0.965Gy = 43.02%, V1.45Gy = 0.00%, V1.93Gy = 0.00%, V2.41Gy =
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, D98% =
2.23 Gy, D95% = 2.24 Gy,
V0Gy = 100.00%, V0.483Gy = 100.00%,
V0.965Gy = 100.00%, V1.45Gy = 100.00%, V1.93Gy = 100.00%, V2.41Gy =
0.00%,

Warning: target has no objective that
penalizes underdosage,

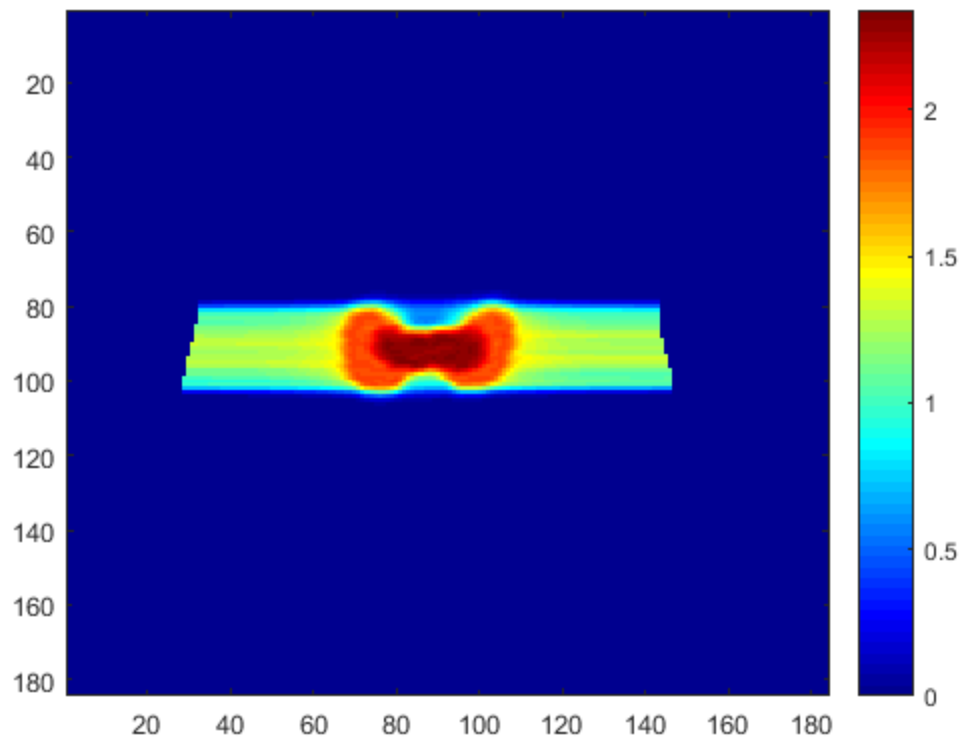
```
D5_rectum =  
1.9549
```



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 an range undershoot by scaling the relative stopping power cube by 3.5% percent

```
ct_manip      = ct;  
noise         = ct.cube{1} .* 0.035;  
noise2        = ct.cube{1} .* 0.04 .* randn(ct.cubeDim);  
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 %
```

Visual Comparison of results

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

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

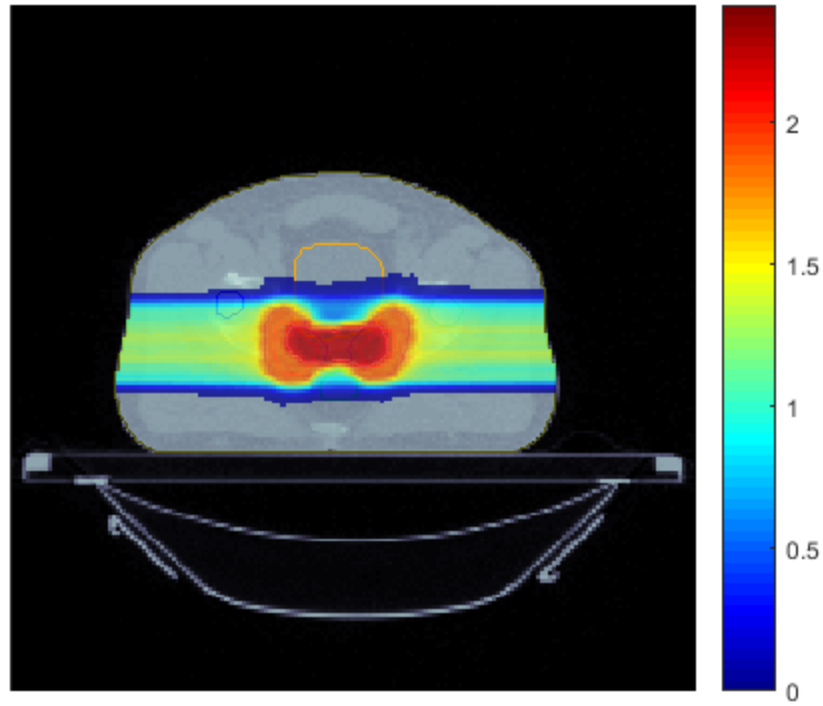
figure,title('original plan')
[~,~,~,~,~] =
    matRad_plotSliceWrapper(gca,ct,cst,1,resultGUI.RBExDose,plane,slice,
    [],0.75,colorcube,[],doseWindow,[]);
figure,title('manipulated plan')
[~,~,~,~,~] =
    matRad_plotSliceWrapper(gca,ct_manip,cst,1,resultGUI_noise.RBExDose,plane,slice,
    [],0.75,colorcube,[],doseWindow,[]);

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

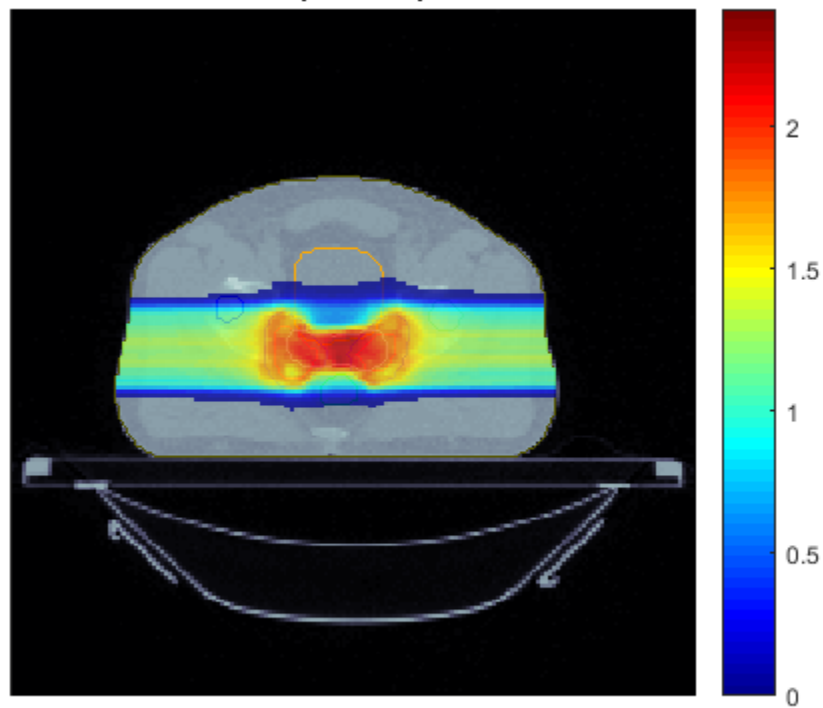
profileOriginal = resultGUI.RBExDose(:,ixProfileY,slice);
profileNoise    = resultGUI_noise.RBExDose(:,ixProfileY,slice);

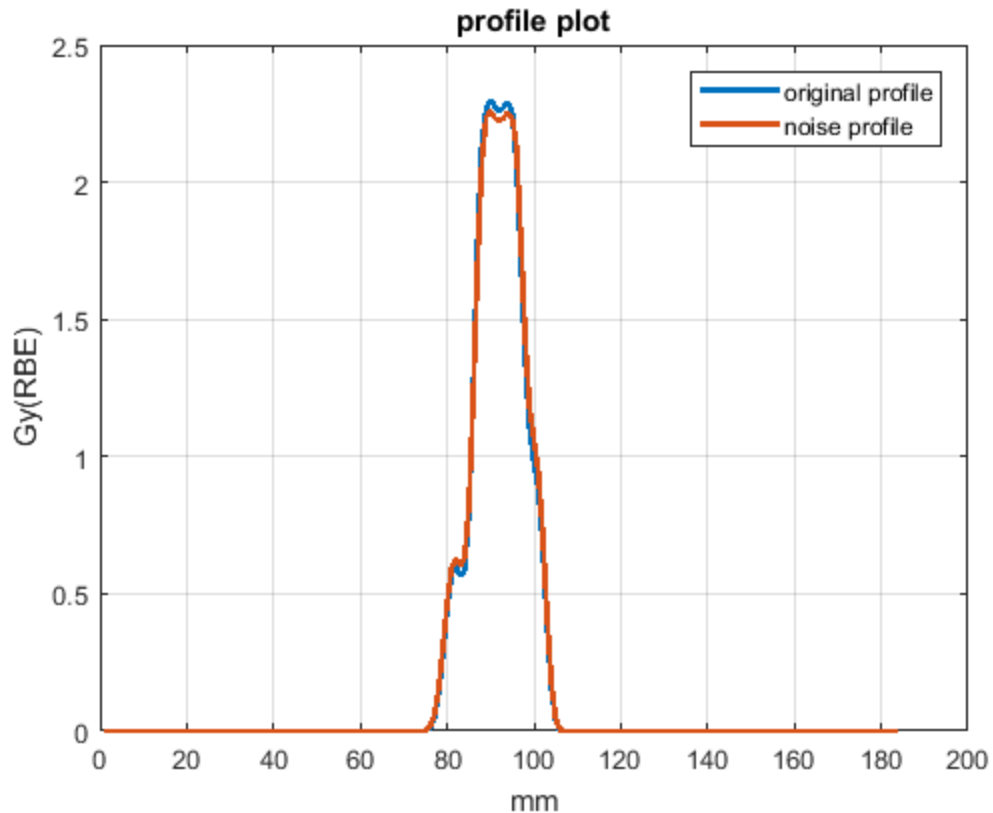
figure,plot(profileOriginal,'LineWidth',2),grid on,hold on,
    plot(profileNoise,'LineWidth',2),legend({'original
    profile','noise profile'}),
    xlabel('mm'),ylabel('Gy(RBE)'),title('profile plot')
```

original plan



manipulated plan

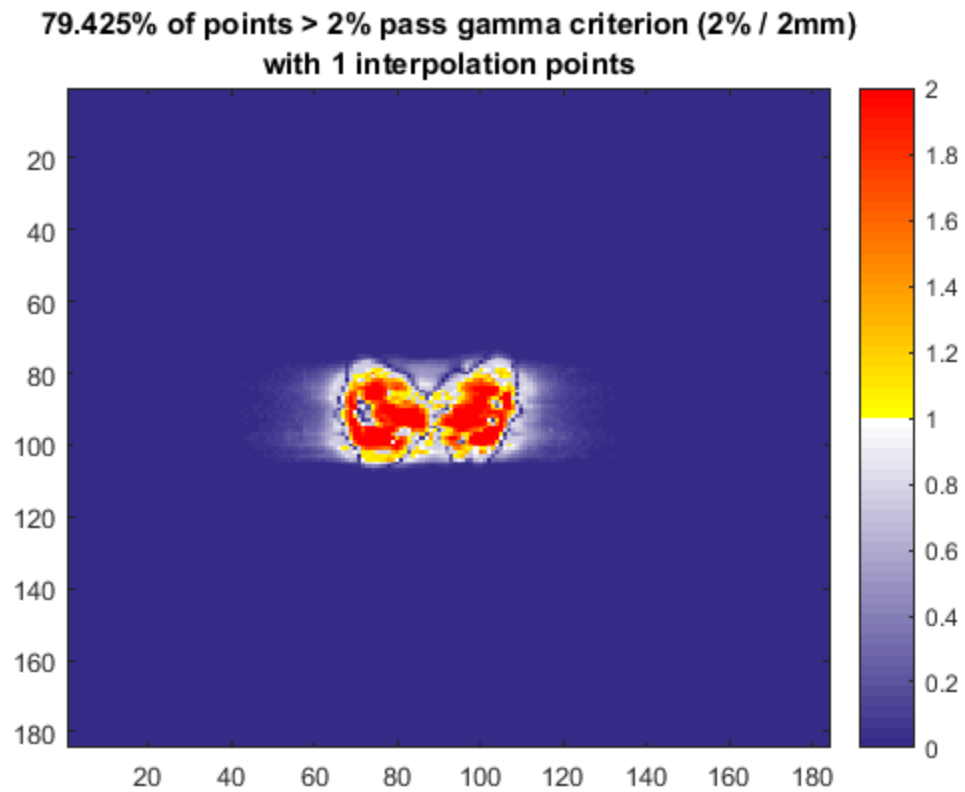




Quantitative Comparison of results

Compare the two dose cubes using a gamma-index analysis. The gamma index is a composite quality distribution equally taking into account a dose difference and a distance to criteria in order to reveal differences between two dose cubes. A gamma-index value of smaller than 1 indicates a successful test and a value greater than 1 illustrates a failed test.

```
doseDifference    = 2;  
distToAgreement  = 2;  
n                = 1;  
  
[gammaCube,gammaPassRateCell] = matRad_gammaIndex(...  
    resultGUI_noise.RBExDose,resultGUI.RBExDose,...  
    [ct.resolution.x, ct.resolution.y, ct.resolution.z],...  
    slice,[doseDifference distToAgreement],n,'global',cst);  
  
.  
.  
.  
.  
.  
.
```



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