
Example: Proton Treatment Plan with Manipulated CT values

Table of Contents

.....	1
Patient Data Import	1
Treatment Plan	3
Generatet Beam Geometry STF	4
Dose Calculation	5
Inverse Optimizaiton for IMPT	5
Plot the Resulting Dose Slice	17
Recalculate Plan	18
Visual Comparison of results	19
Quantitative Comparison of results	20

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In this example we will show how to load patient data into matRad and how to setup a proton dose calculation including optimizing the beamlet intensities. Next we inverslye optimize the treatment plan directly from command window in MatLab. Next, we add noise to the CT cube and will perform a forward dose calculation.

Patient Data Import

Let's begin with a clear Matlab environment. Next, import the protstate case into your workspace. The patient is comprised of a 'ct' and 'cst' structure defining the CT images and the structure set. Make sure the matRad root directy 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 mutiple ct cubes (e.g. 4D CT) can be stored in the cell array ct.cube{ }

```
ct
```

```
ct =
```

```
struct with fields:
```

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

The 'cst' cell array defines volumes of interest 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 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 which are required for biological treatment planning using a variable RBE. Let's output the meta optimization parameter of the rectum the rectum:

```

cst{8,2}
cst{8,5}

```

```
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 and squared overdosing objective so that it is considered to be expensive for the optimizer delivering more than 50 Gy to the rectum.

```
cst{8,6}  
  
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 slice. 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, as 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 beam geomtry along with the ray and pencil beam positions

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

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

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

stf(2)

ans =

    struct with fields:

        gantryAngle: 270
        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: 22774
```

Dose Calculation

Calculate dose influence matrix for unit pencil beam intensities.

```
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.

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

Example: Proton Treatment Plan
with Manipulated CT values

```
*****
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							
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							

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

Example: Proton Treatment Plan
with Manipulated CT values

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			

Example: Proton Treatment Plan
with Manipulated CT values

```

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
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

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Example: Proton Treatment Plan
with Manipulated CT values

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			
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			

Example: Proton Treatment Plan
with Manipulated CT values

```

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

```

Example: Proton Treatment Plan
with Manipulated CT values

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				

Example: Proton Treatment Plan
with Manipulated CT values

```

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

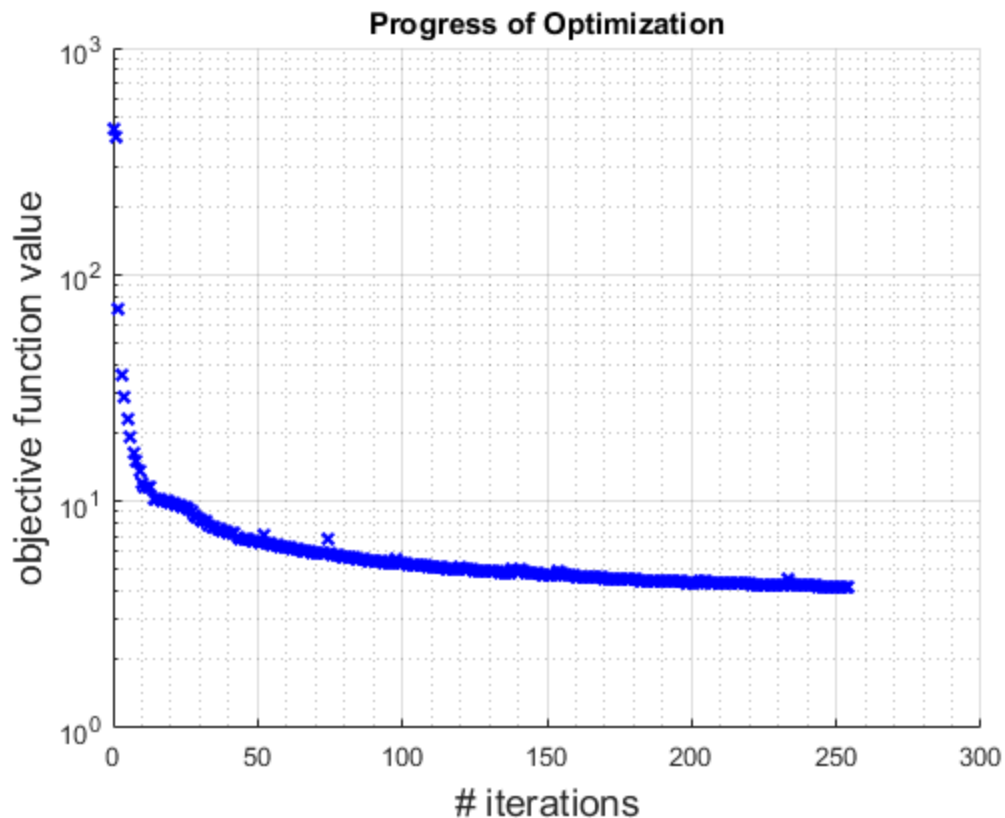
```


Example: Proton Treatment Plan
with Manipulated CT values

```
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) = 13.267
Total CPU secs in NLP function evaluations    = 64.264
```

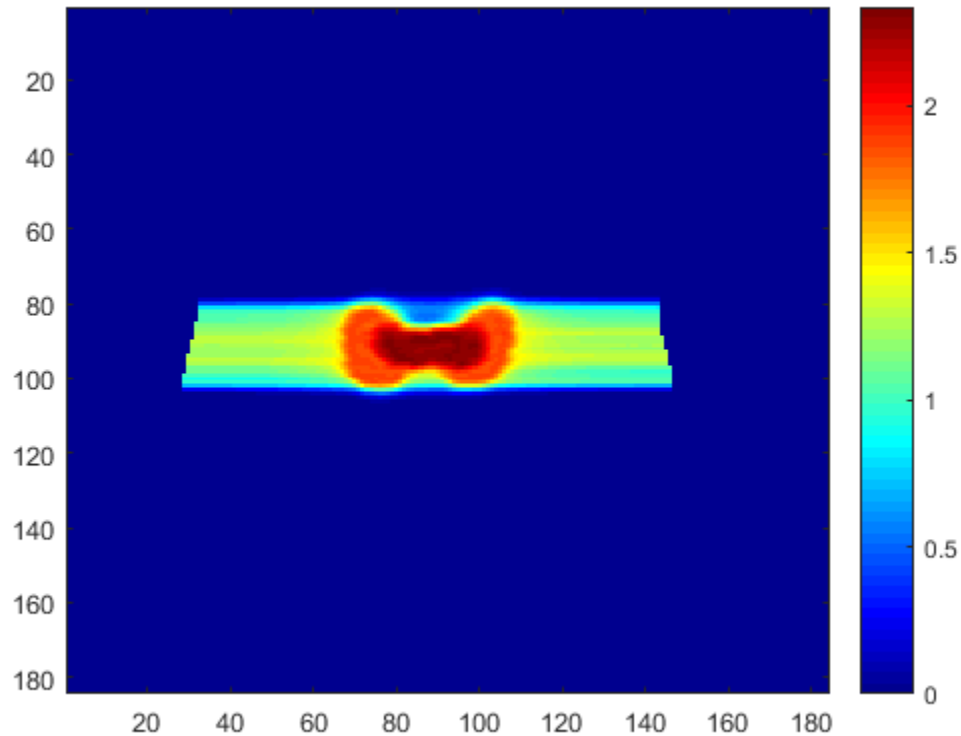
```
EXIT: Solved To Acceptable Level.
Calculating final cubes...
matRad: applying a constant RBE of 1.1
```



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 overshoot by scaling the relative stopping power cube 3.5% percent

```
ct_manip          = ct;  
noise              = ct.cube{1} .* 0.035; % ct.cube{1} *0.03 *  
                  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);
```

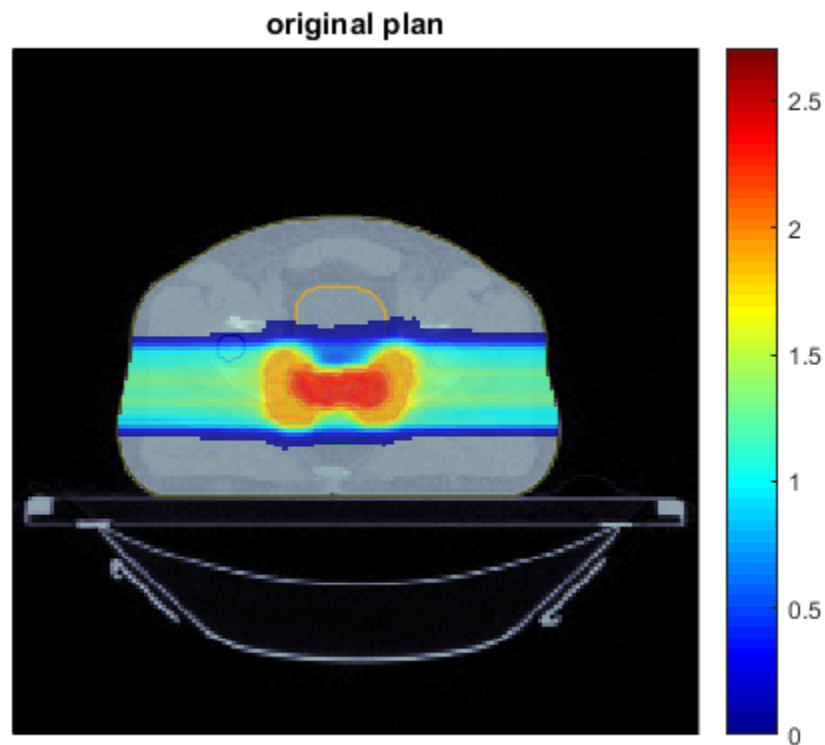
```
matRad: Using a constant RBE of 1.1  
matRad: Particle dose calculation...  
Beam 1 of 2:  
matRad: calculate radiological depth cube...done.  
matRad: calculate lateral cutoff...done.  
Progress: 100.00 %  
Beam 2 of 2:  
matRad: calculate radiological depth cube...done.
```

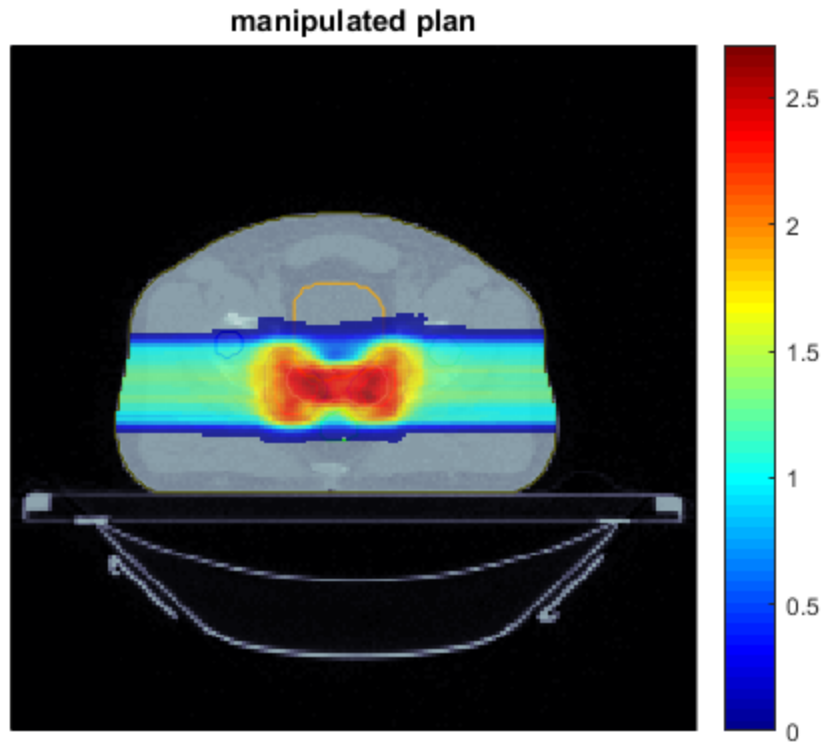
```
matRad: calculate lateral cutoff...done.  
Progress: 100.00 %
```

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,[]);
```

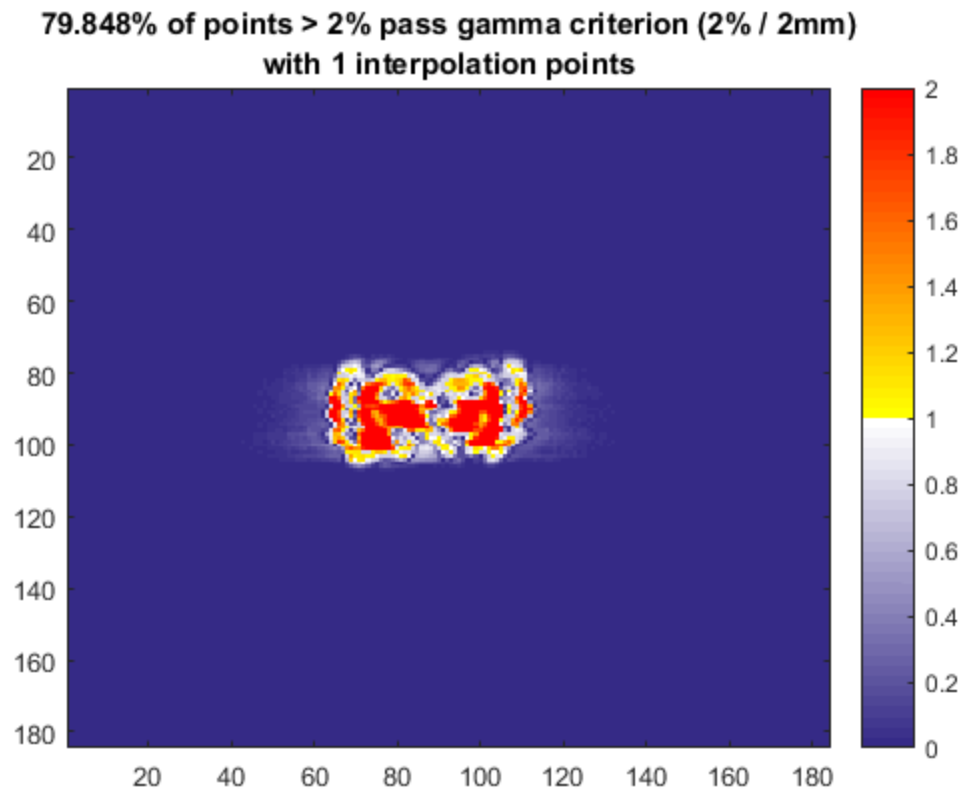




Quantitative Comparison of results

Compare the two dose cubes using a gamma-index analysis. To do so, we need to define thresholds for passing the gamma-index test. In this example, we set dose difference to 2 % and the distance-to criteria to 2 mm. Additionally, we set the number of interpolations for the gamma index calculation to 1.

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



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