CT, DENSITY AND MATERIAL HANDLING

RayStation 11B

ADVANCING CANCER TREATMENT

RaySearch Laboratories

CONTENTS

- Material handling for the photon CC dose engine and MC dose engine
- CT commissioning
- Image conversion algorithm commissioning

MATERIAL HANDLING

MATERIAL HANDLING – USER MODIFICATION

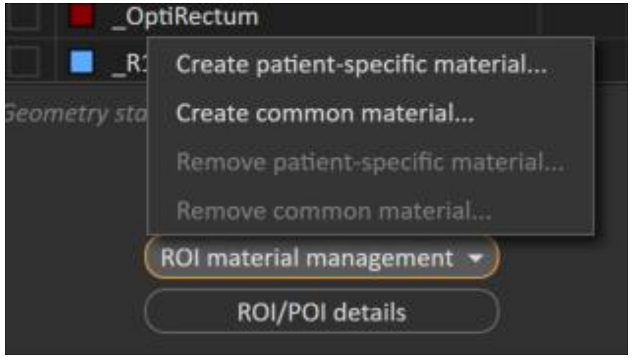
- Patient outline
  - Everything in the CT images outside the External ROI or the dose grid is regarded as vacuum in dose computations.
- Material override
  - ROI material overriding CT material or defining material outside External ROI
  - e.g.: Water, dental fillings, prosthetics
- Defining material outside External ROI
  - Boli (Must be associated with one or more beams and only present in the dose computation for those beams)
  - Fixations and supports (used for all beams)
- From 11B onwards, CT density will be used if no material override is assigned to the Bolus, Support and Fixations ROIs
  - Previously, a material override was required for ROIs of type bolus, support and fixation.

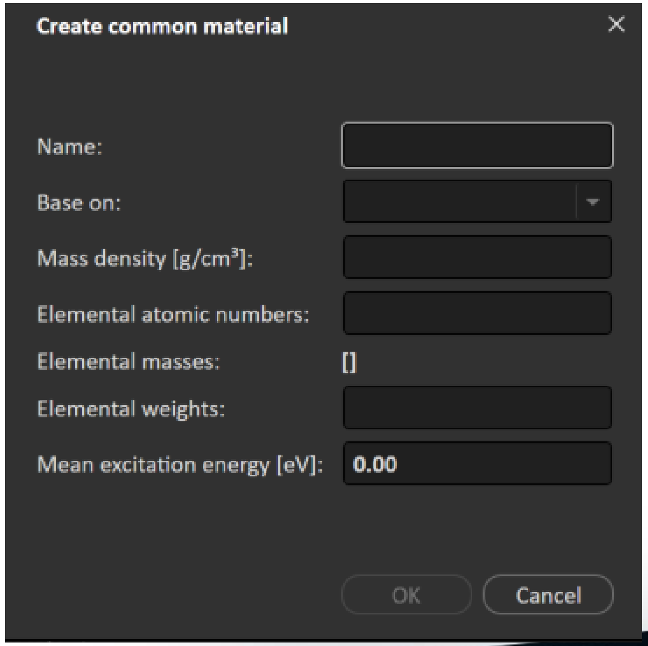
MATERIAL HANDLING – USER MODIFICATION

- Add new common materials

Two possible ways to add new materials for material overrrides:

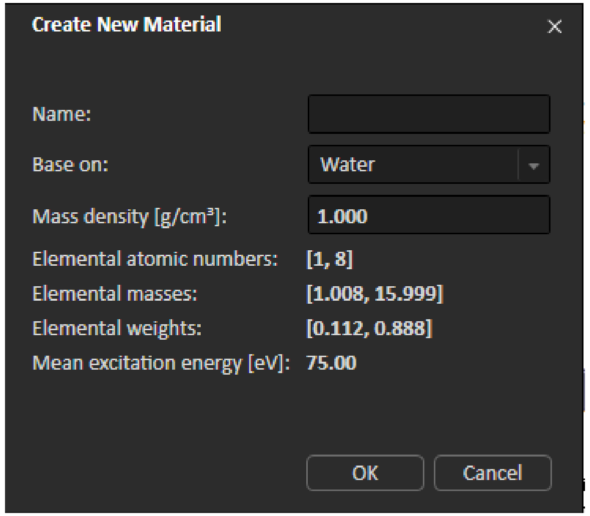
- Create patient-specific material (the new name for the previously existing new material functionality)
  - Material only for the currently selected patient
  - Only name and mass density of the material can be edited
- Create common material
  - Material available for all patients
  - Full elemental composition of the material can be edited
  - Administrator rights needed to create or remove common material

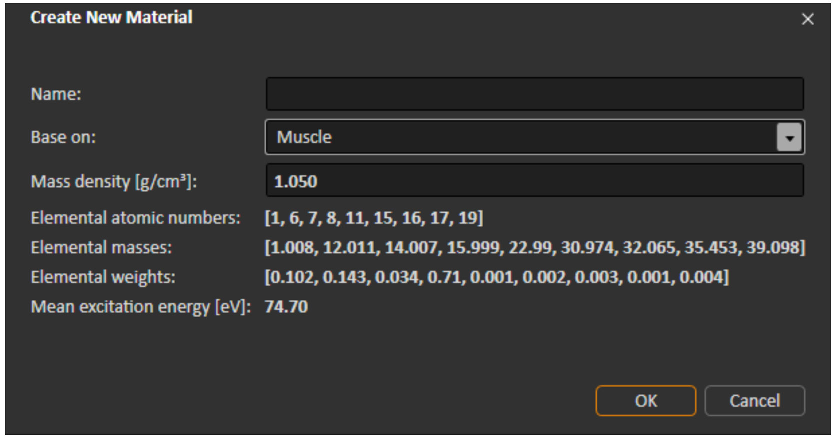


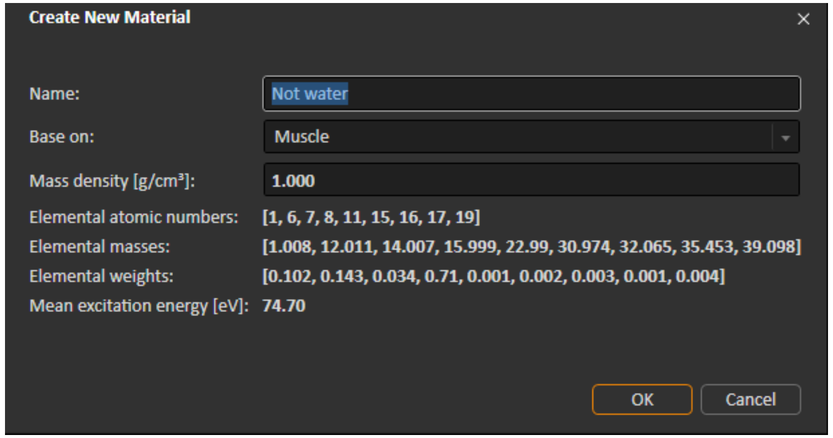


MATERIAL HANDLING – USER MODIFICATION

- Mass density 1.0 g/cm^3 not necessarily equal to water







MATERIAL HANDLING – USER MODIFICATION

- Material override ROIs of different materials must not overlap
- Bolus ROIs must not overlap each other or the outline
- Dose calculation is not allowed for overlapping material override ROIs, not possible to know which density is intended.

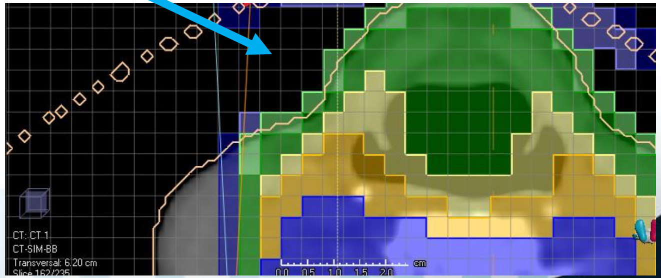
MATERIAL HANDLING - DENSITIES

- CT images provide info about the patient density expressed in Hounsfield Units:

$$HU = 1000\,\frac{\mu - \mu_{H_2O}}{\mu_{H_2O}}$$

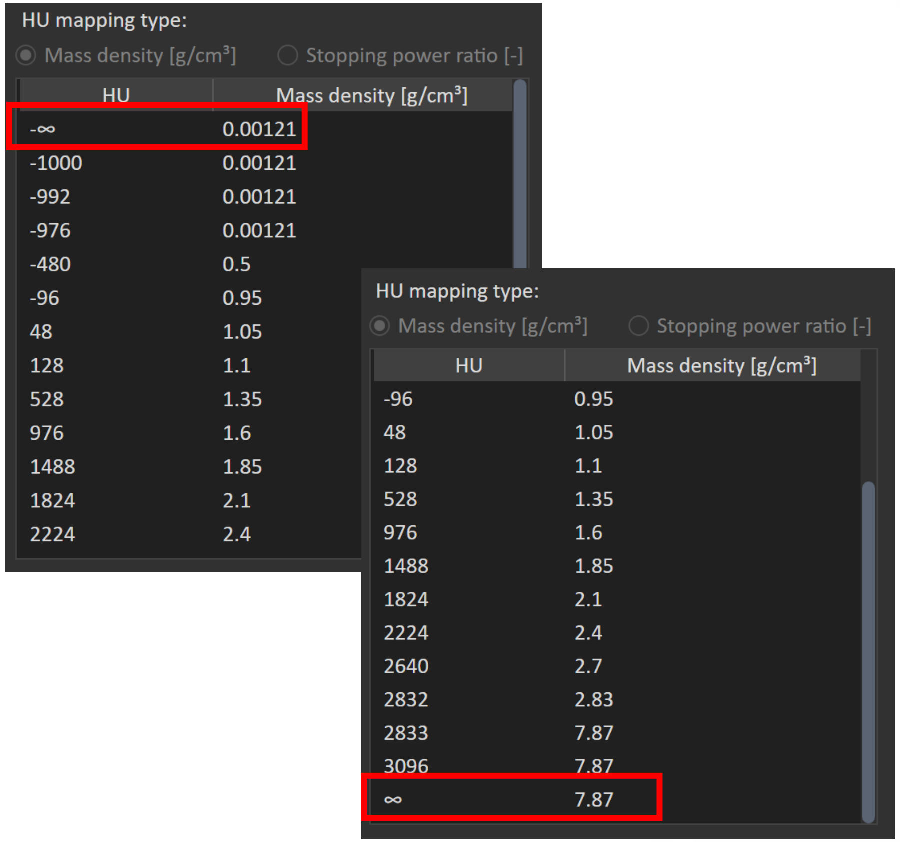
- The HU scale is defined as -1000 as air and 0 as water
- The HU density values are converted to a mass density through linear interpolation in a ***CT-to-density-table***.
- The HU density values from the CT scan are first **<u>resampled</u>** to the dose grid
- For each voxel inside the External ROI, converted to either mass density or stopping-power ratio
- The resampling averages the CT info over a dose grid voxel: the density in the part of the voxel covered by the External ROI may be overestimated if there is a material in the CT image outside the border.

HU	Mass density [g/cm³]
-∞	0.00121
-1000	0.00121
-992	0.00121
-976	0.00121
-480	0.5
-96	0.95
48	1.05
128	1.1
528	1.35
976	1.6
1488	1.85
1824	2.1
2224	2.4



MASS DENSITY MAPPING

- CT-to-density table can be created by the user and should represent mass density behaviour over the full range from air, lung, soft tissue, bone and metal inserts
- If CT images have voxels with higher HU than contained in the table, the density is assumed to be identical to the density for the highest HU in the table
  - Users can choose to define other material density by contouring the ROI and assigning a material override
- Similarly voxels with HU lower than the lowest HU entry are given density for the lowest HU in the table



HU mapping type:

Mass density [g/cm³] Stopping power ratio [-]

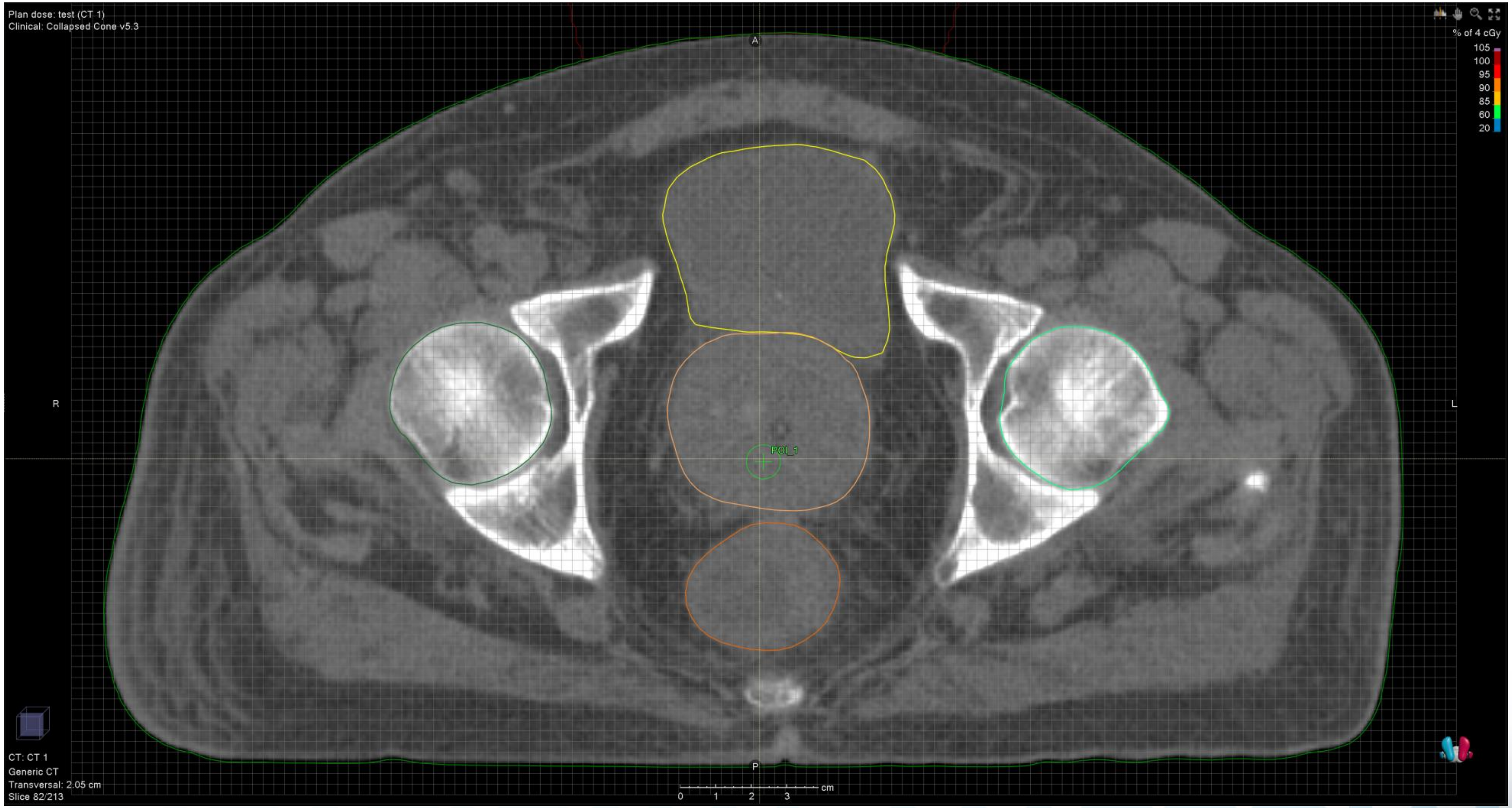
HU	Mass density [g/cm³]
-∞	0.00121
-1000	0.00121
-992	0.00121
-976	0.00121
-480	0.5
-96	0.95
48	1.05
128	1.1
528	1.35
976	1.6
1488	1.85
1824	2.1
2224	2.4

HU mapping type:

Mass density [g/cm³] Stopping power ratio [-]

HU	Mass density [g/cm³]
-96	0.95
48	1.05
128	1.1
528	1.35
976	1.6
1488	1.85
1824	2.1
2224	2.4
2640	2.7
2832	2.83
2833	7.87
3096	7.87
∞	7.87

CT DATA



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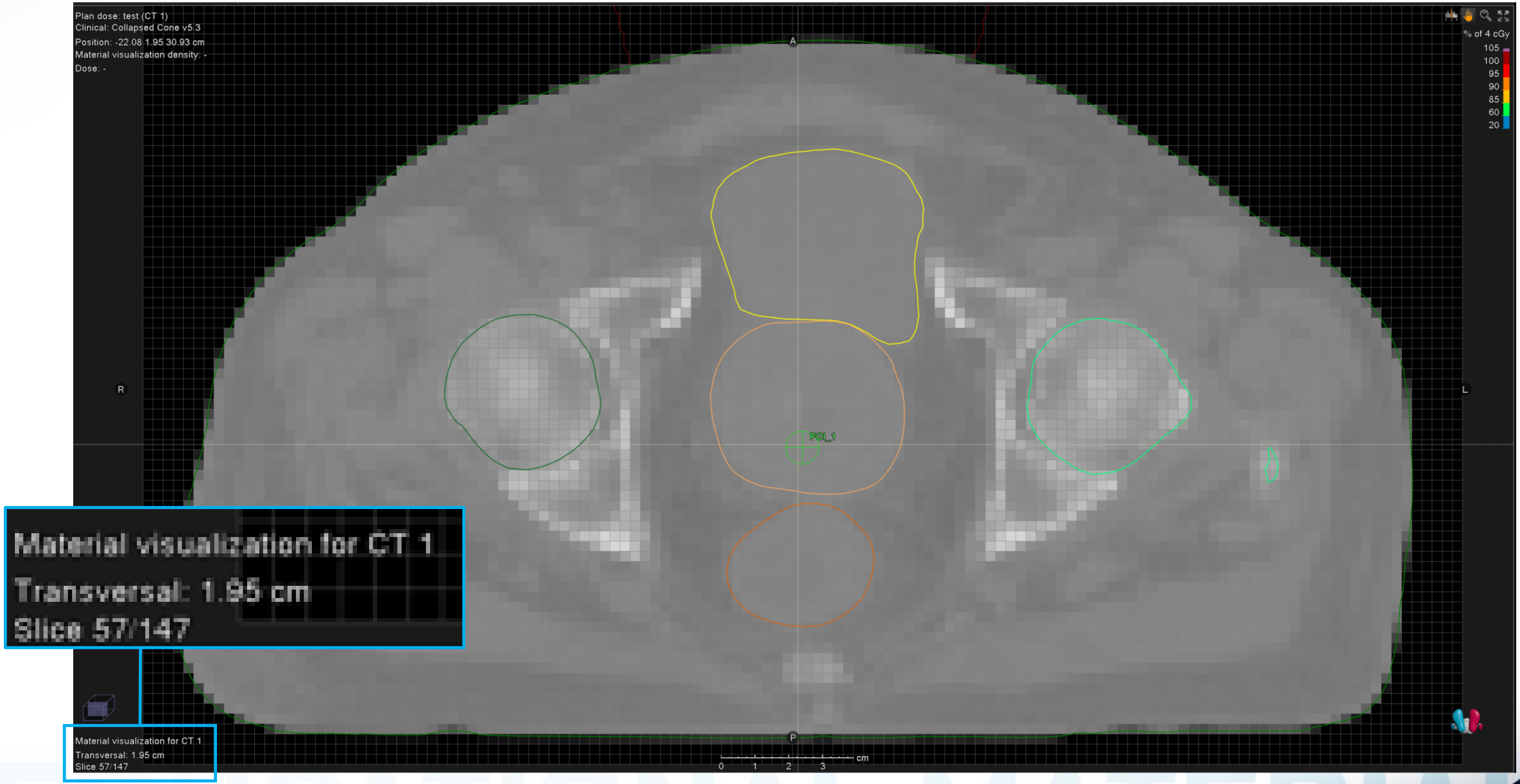
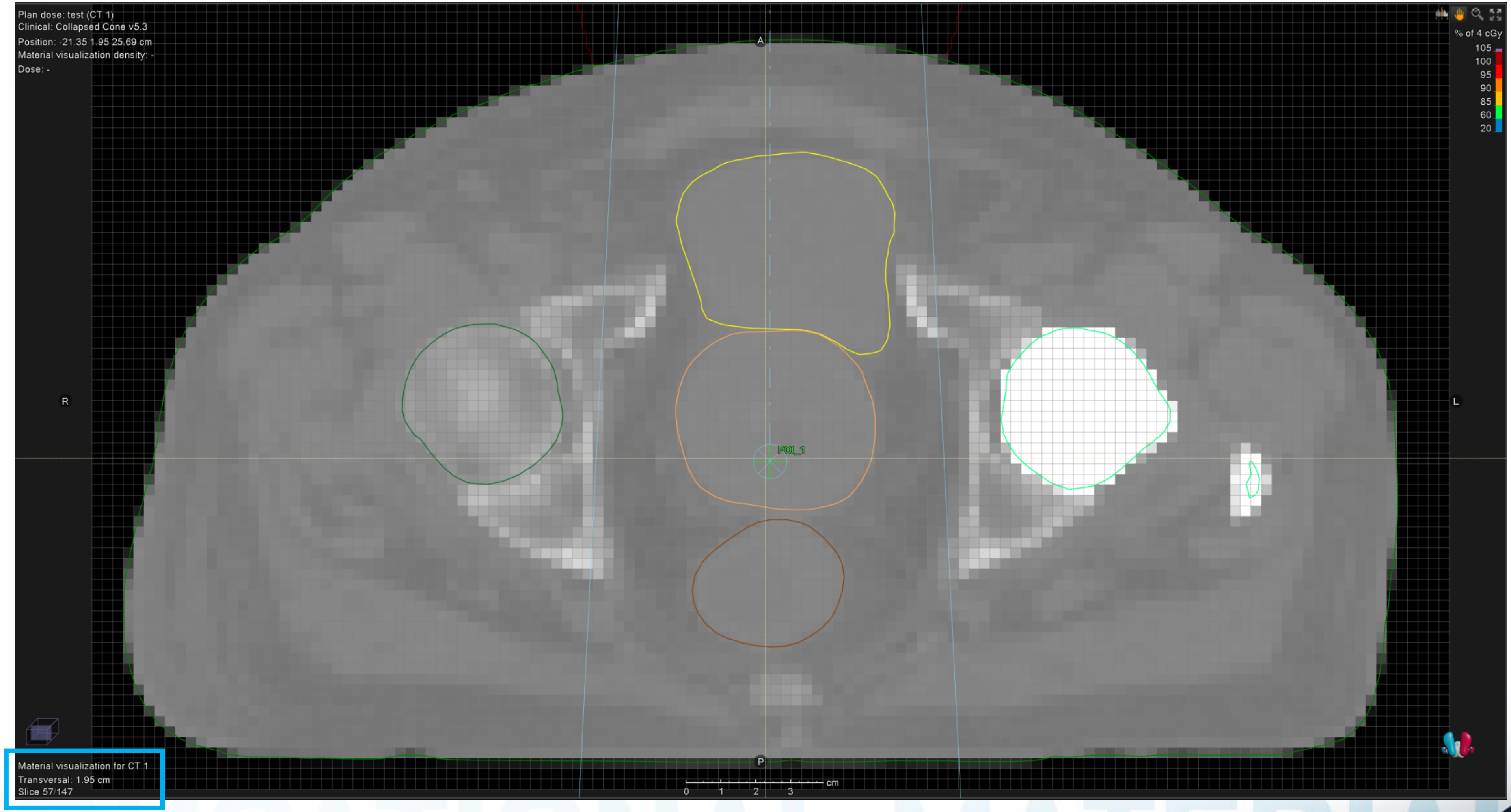
MATERIAL VISUALIZATION



Density visualization: Density re-sampled on the dose grid resolution for dose computation. Note the slice thickness in *Material Visualization* is different if dose grid is different from CT slice thickness.

MATERIAL VISUALIZATION



<u>Density visualization:</u> In order to see *Material Visualization*, dose have to be computed first.

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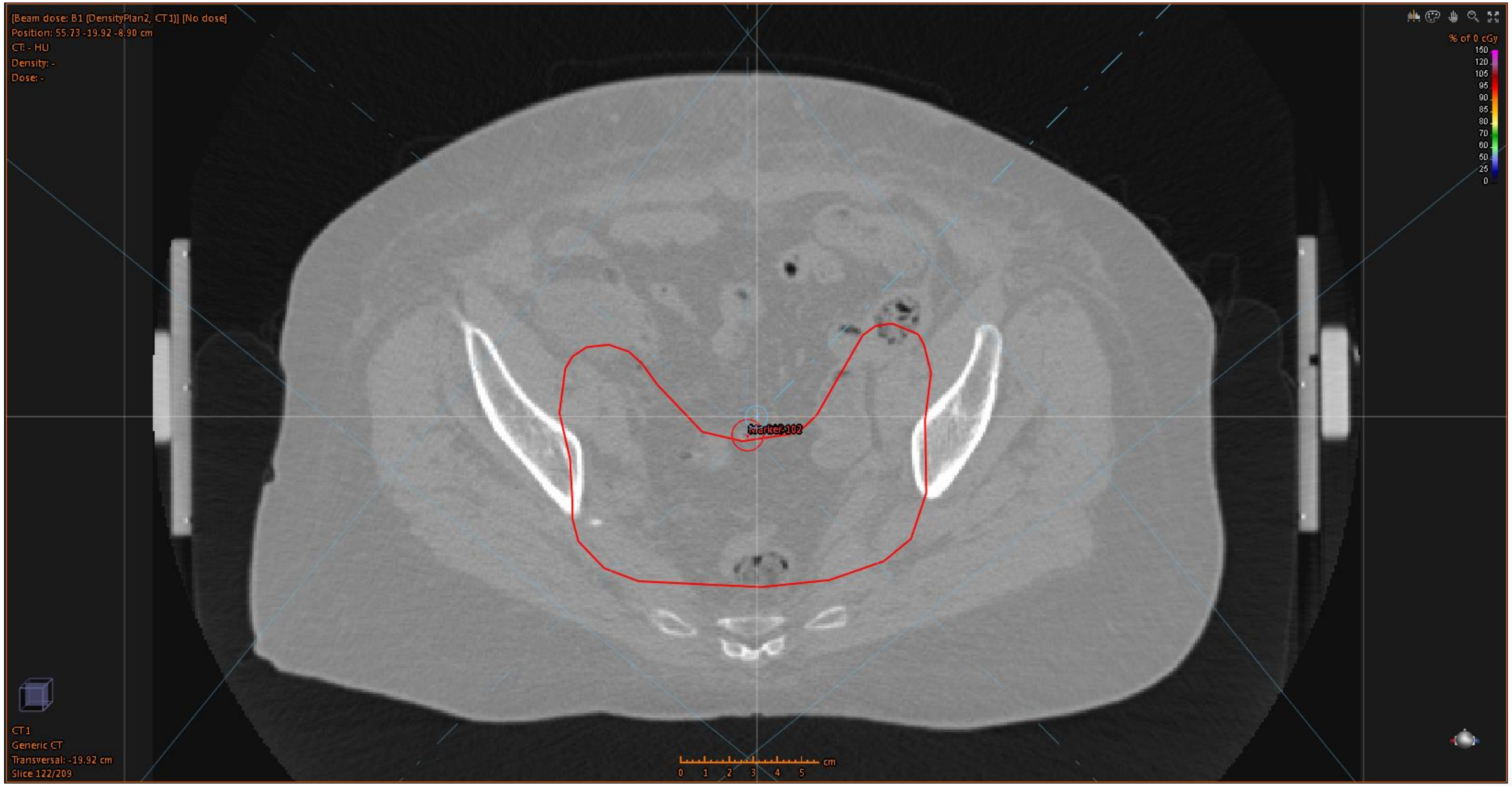
CT DATA



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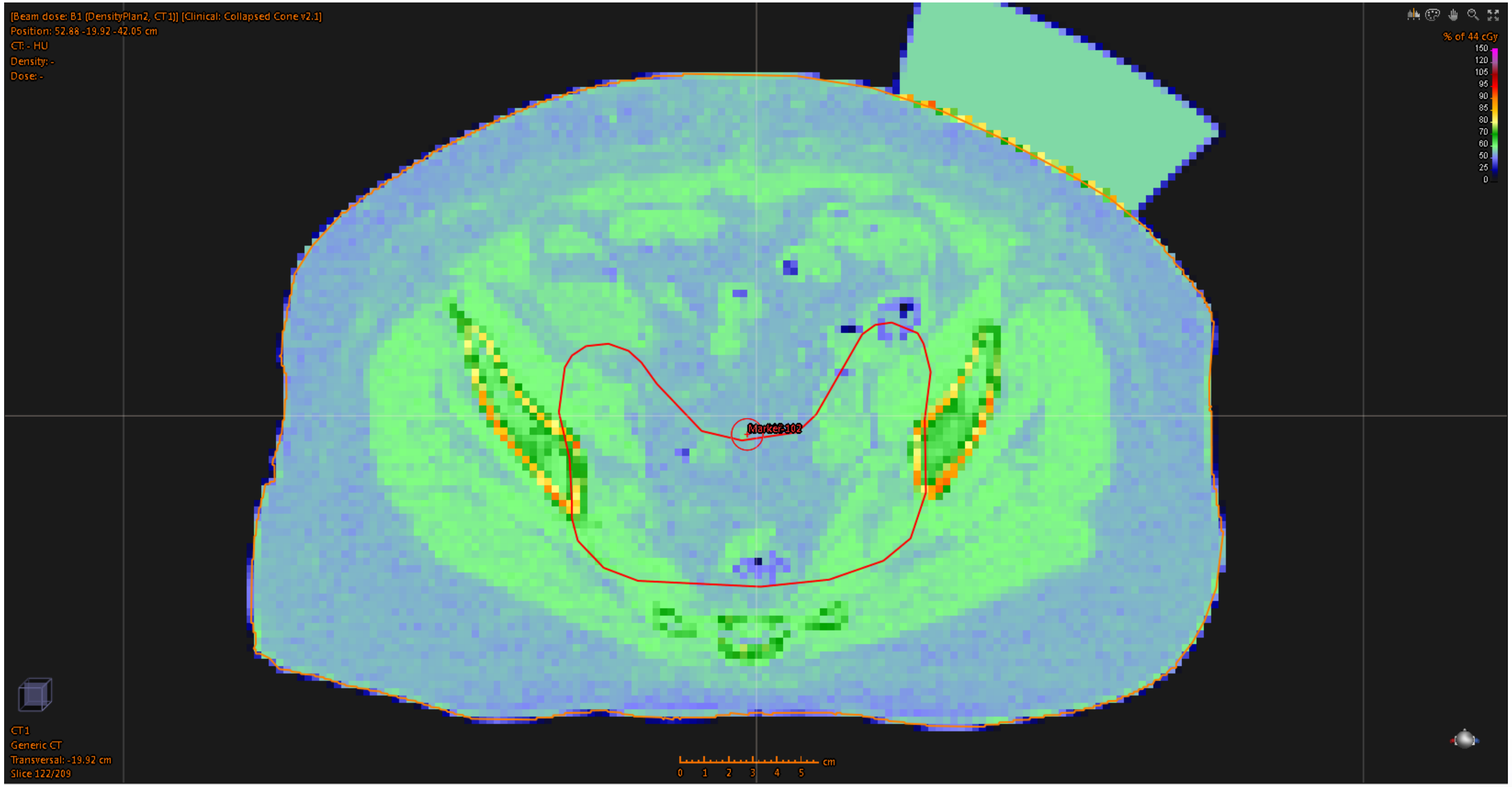
THE ACTUAL VOXEL DENSITIES



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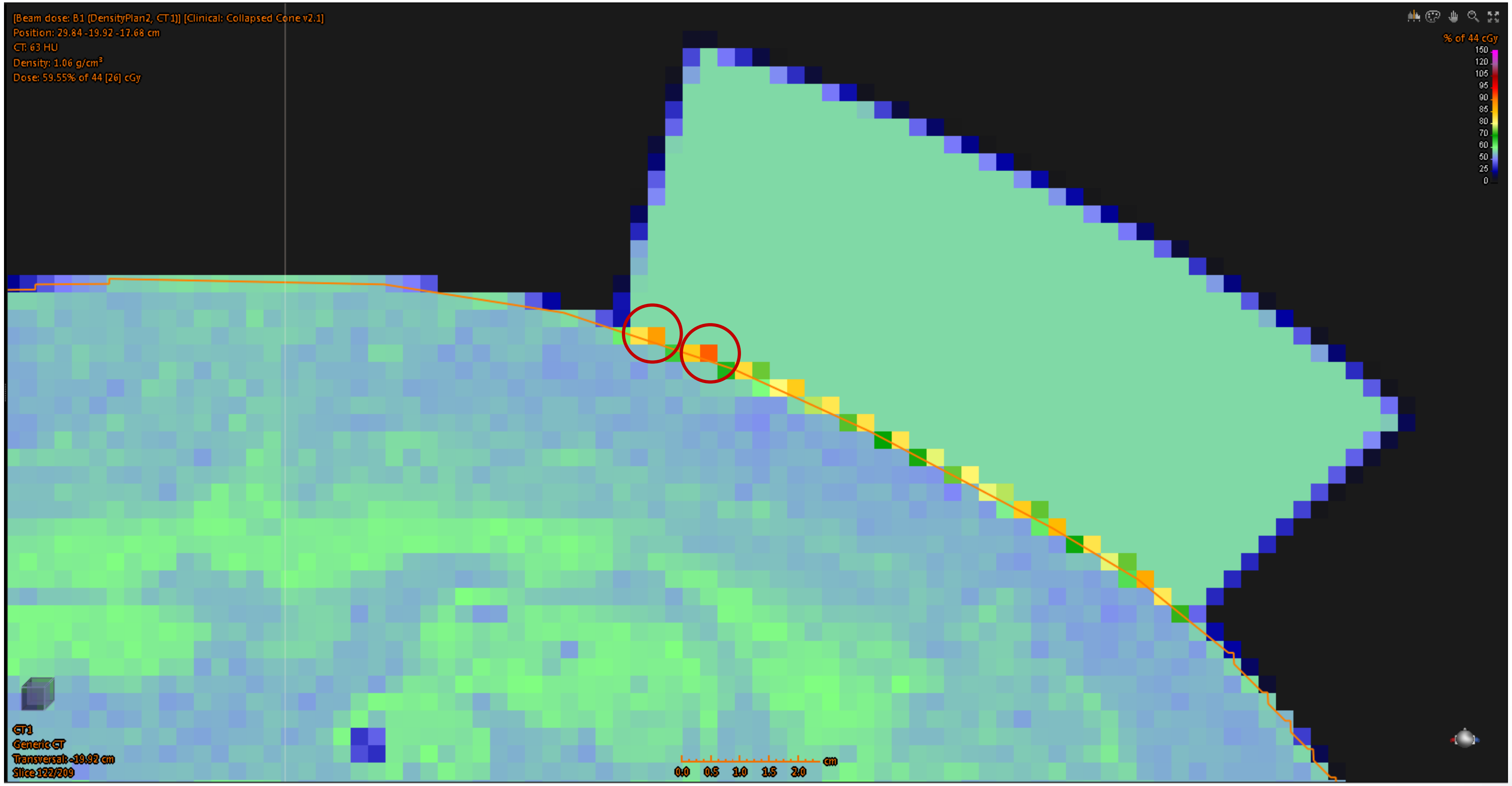
DENSITY ARTEFACT NEAR BOLUS/OUTLINE



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EXTERNAL AND BOLUS/SUPPORT/FIXATION INTERFACE

FSN 84236 – Fix in 11B

Background of the problem:

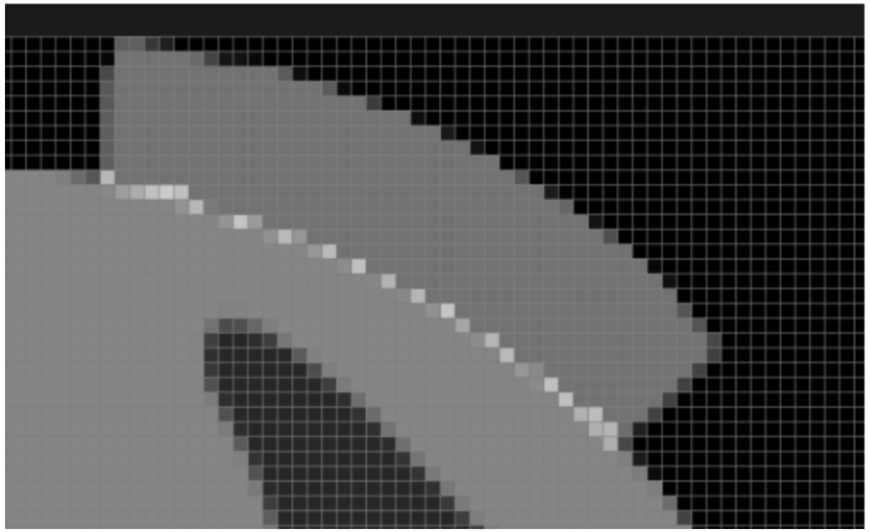
- As seen in previous slide, when surface voxels covered by both External ROI and B/S/F ROIs may get unexpected density, both under- and over-estimated.
- To accurately mix densities from both External ROI and B/S/F ROIs, it is necessary to know how large fraction of the voxel is covered by the different ROIs. This is not known by the code that computes the density for each dose grid voxel!

Fix in 11B:

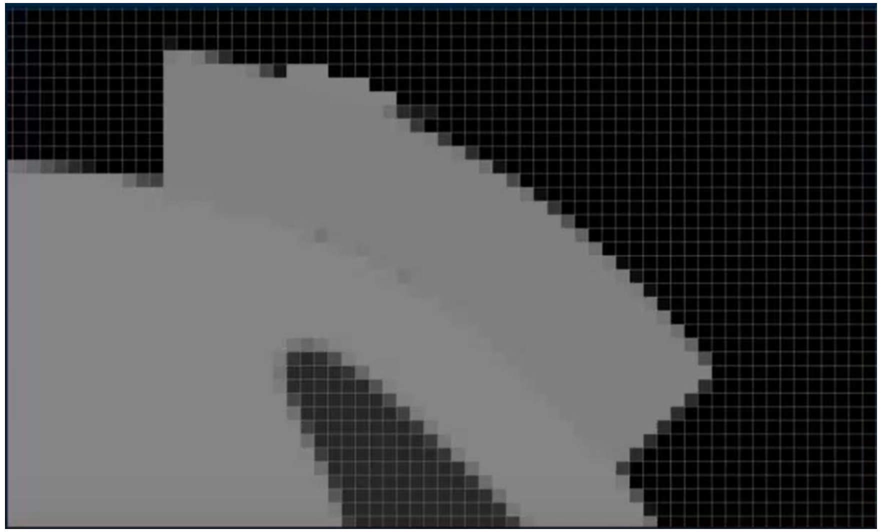
- Assumption that the density inside External is 1.0 g/cm^3 , is introduced (which is good approximation for skin or soft tissue)
- Based on this assumption, we calculate how much of the voxel is covered by the External ROI.
- This information will be used when combining the CT density (External ROI) with the B/S/F ROI densities

EXTERNAL AND BOLUS/SUPPORT/FIXATION INTERFACE

FSN 84236 – Fix in 11B



- Prior to 11B: Example where density is overestimated at the interface

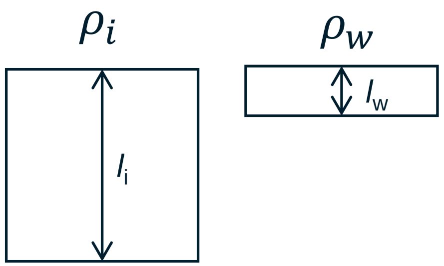


- In 11B: For some voxels the density can still be wrong but to a lesser extent than before.
- There will never be any guarantee that the coverage of the External ROI corresponds to the density in the surface voxels.

MATERIAL HANDLING – CC DOSE ENGINE

MATERIAL HANDLING – MASS DENSITIES

- In determination of radiological depth in dose computation: All material is water
- What is the path length in water resulting in the same attenuation as for some corresponding path length in any other material *i* ?
- Core technique in radiation transport: equivalent path-length scaling based on *mass density*



Equivalent path length in water:

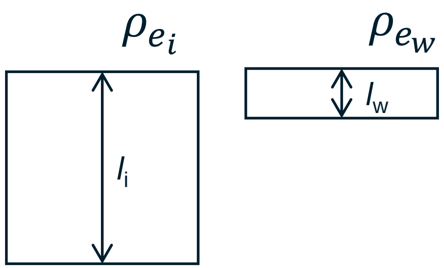
$$l_w = l_i \frac{\rho_i}{\rho_w}$$

ρ_i … Mass density of material *i*
ρ_w ... Mass density of water

- Seco and Evans (Med. Phys. 33:540, 2006) found rather **large discrepancies** however:
  - Fluence at 10 cm equivalent path lenght in water overestimated by about 5% for air/bone for 1 MeV photons.
  - Other tissue materials by about 1%, plastics by about 2%.

MATERIAL HANDLING – ELECTRON DENSITIES

- *Electron density* is a more relevant physical quantity for 1 MeV photons where Compton dominates.



Equivalent path length in water scaled according to electron densities:

$$l_w = l_i \frac{\rho_{e_i}}{\rho_{e_w}}$$

ρ_{e_i} ... Electron density of material *i*
ρ_{e_w} ... Electron density of water

- Fluence error at 10 cm water-equivalent depth for 1 MeV photons < 1% air/bone/tissue/plastics.
- However, for **higher energies pair-production plays an increasingly important role**.

MATERIAL HANDLING – EFFECTIVE DENSITIES

- In RayStation for TERMA calculation, point-spread-kernel tracing and electron-contamination dose calculation: equivalent path length in water scaled according to the ***EFFECTIVE DENSITY***

Close to electron density but slightly modified to take pair production into account

Photon attenuation in CT → HU → Mass density → Elemental Composition → Electron density → Effective density

Equivalent path lengths with an **error of <1% for 0.5 – 20 MeV**
(Seco and Evans, Med. Phys. 33:540 (2006))

MATERIAL HANDLING – EFFECTIVE DENSITIES

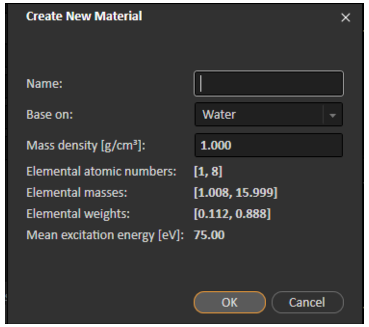
$$\rho_e = < Z/A > \rho$$

$$\frac{\rho_{eff-material}}{\rho_{eff-water}} = \frac{\rho_{e-material}}{\rho_{e-water}} \frac{1 + \alpha \cdot (1 + < Z >_{material}) \ln E \cdot E}{1 + \alpha \cdot (1 + < Z >_{water}) \ln E \cdot E} \quad \text{[Eq. 5]}$$

Table 2.2: The mass density relative to water and the atomic mass composition (%) of tissue materials used in RayStation 9A for effective density calculation.

	$\frac{\rho_{e-material}}{\rho_{e-water}}$	H	C	N	O	Na	Mg	P	S	Cl	Ar	K	Ca
Z		1	6	7	8	11	12	15	16	17	18	19	20
Z/A		0.992	0.5	0.5	0.5	0.478	0.494	0.484	0.499	0.479	0.451	0.486	0.499
Air	0.001203			75.5	23.2						1.3		
Lung	0.26	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3		0.2	
Adi-pose	0.95	11.4	59.8	0.7	27.8	0.1			0.1	0.1			
Tissue	1	10.12	11.1	2.6	76.18								
Muscle	1.05	10.2	14.3	3.4	71	0.1		0.2	0.3	0.1		0.4	
Carti-lage	1.1	9.6	9.9	2.2	74.4	0.5		2.2	0.9	0.3			
Bone	1.85	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3				22.5
Alu-minum	2.7												
Iron	7.87												
Gold	19.32												
Osmi-um	22.57												

Material override



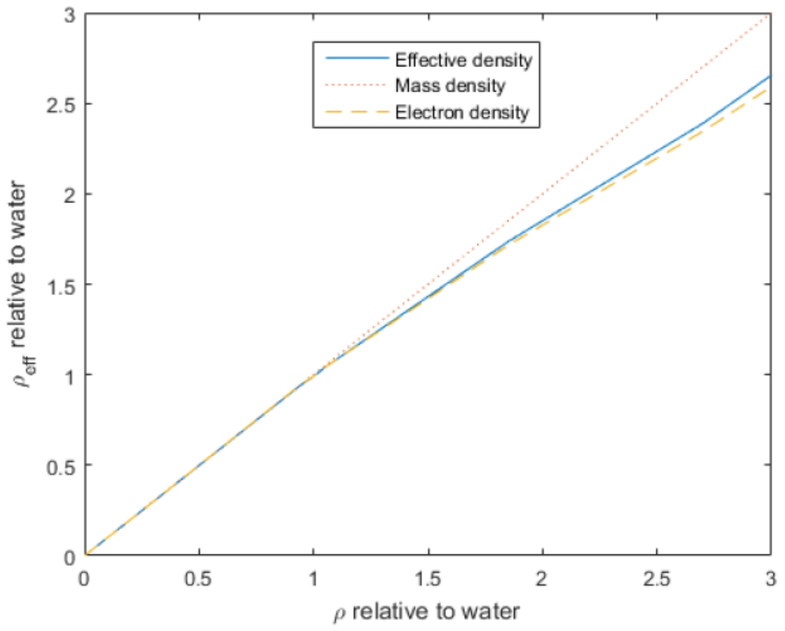


Figure 1. A typical conversion from mass density to electron and effective density for a 6 MV beam. The effective density is used both in TERMA-tracing, point spread kernel tracing and electron dose computation.

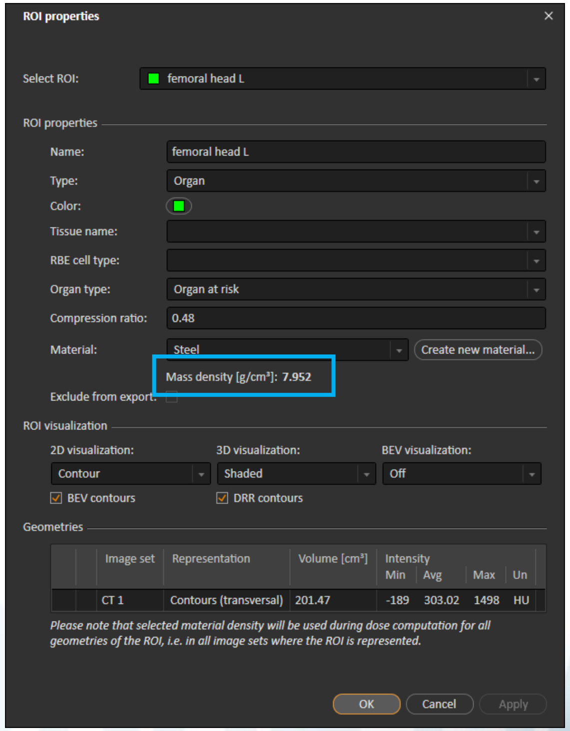
Reference Manual, RayStation 9A

Each density corresponds to a certain material with a material specific elemental composition according to an internal table of tissue materials

- E.g. a voxel with mass density 1.075 g/cm3 is associated with a 50/50% mixture of muscle and cartilage (linear interpolation).
- Water ***NOT*** in the table of tissue materials → for water phantoms a material override should be used!

MATERIAL HANDLING – IMPORT FROM OTHER SOFTWARE

- In Raystation densities are displayed as mass densities, this is not necessarily the case with other TPS or contouring software
- When importing structures with override densities, please be careful to the density used by Raystation for dose computation by checking it in the *ROI properties*



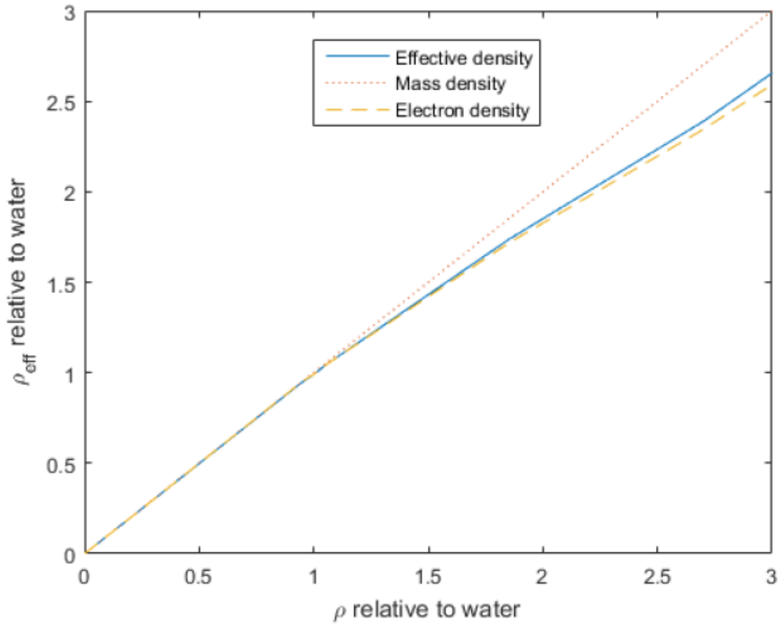


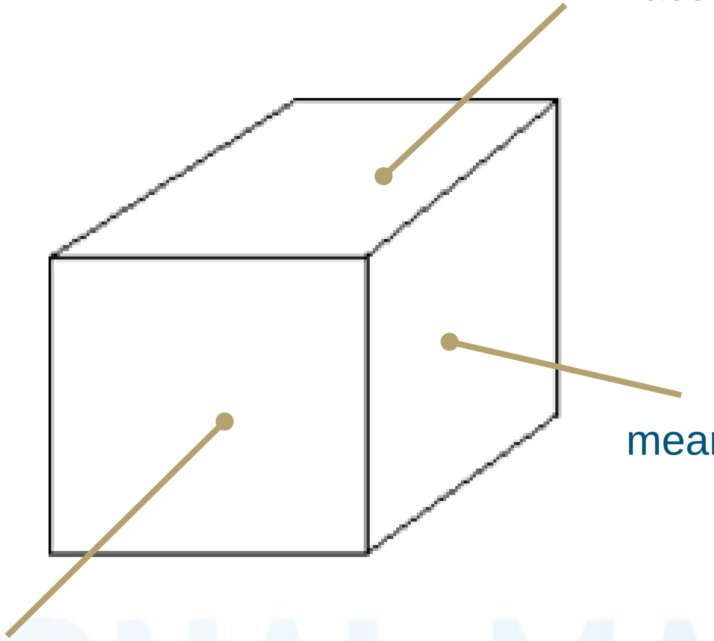
Figure 1. A typical conversion from mass density to electron and effective density for a 6 MV beam. The effective density is used both in TERMA-tracing, point spread kernel tracing and electron dose computation.

Reference Manual, RayStation 9A

MATERIAL HANDLING – MC DOSE ENGINE

MATERIAL HANDLING – MC DOSE ENGINE

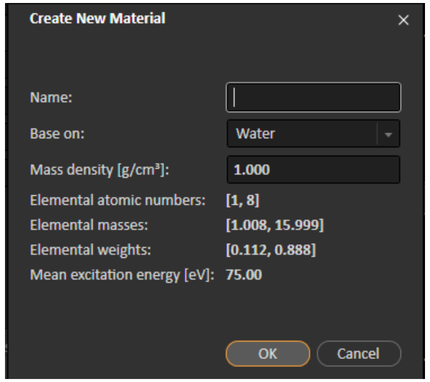
- Models in the photon transport algorithms in RayStation rely on the assumption that each point of the patient and any beam limiting device is associated with a mass density ρ and a material, defined by its elemental composition (Z, A) and mean ionization energy I.



MATERIAL HANDLING – MC DOSE ENGINE

- Mass density
- Material composition
- Mean excitation energy (*I*)

Material override



Photon attenuation in CT → HU → Mass density → Material → Elemental Composition and *I*

- 10 Core Materials
- 55 Interpolated Materials

MASS DENSITY TO MATERIAL

Core Materials

	density	I (eV)	H	C	N	O	Na	Mg	Al	P	S	Cl	Ar	K	Ca	Fe	Zn
Z			1	6	7	8	11	12	13	15	16	17	18	19	20	26	30
Z/A			0,992	0,5	0,5	0,5	0,478	0,494	0,482	0,484	0,499	0,479	0,451	0,486	0,499	0,466	0,459
Air	0,001 21	85,7			75,5	23,2							1,3				
Lung	0,26	75,3	10,3	10,5	3,1	74,9	0,2			0,2	0,3	0,3		0,2			
Adipose	0,95	63,2	11,4	59,8	0,7	27,8	0,1				0,1	0,1					
Muscle	1,05	74,7	10,2	14,3	3,4	71	0,1			0,2	0,3	0,1		0,4			
Cartilage	1,1	75,0	9,6	9,9	2,2	74,4	0,5			2,2	0,9	0,3					
Bone (ICRP23)	1,85	106,4	4,7234	14,433	4,199	44,6096		0,22		10,497	0,315				20,993		0,01
Bone (ICRP23)+	2,1	106,4	4,7234	14,433	4,199	44,6096		0,22		10,497	0,315				20,993		0,01
Aluminum	2,7	166							100								
Aluminum+	2,83	166							100								
Iron	7,87	286														100	

- A number of "Core" materials defined
- Hard coded in RayStation 10A
- REMEMBER Material override for water phantoms!

The mass density relative to water, the mean ionization energies (I), and the atomic mass composition (%) of the template materials used in RayStation for the photon MC dose computation (ICRU49 , ICRU44 and ICRP 23).

MASS DENSITY TO MATERIAL

Mapping

- Example of how HU can map to the ten base materials
- X-axis in Figure 1 depends on which CT-to-density table is used
- 50 fixed materials have been shown to be sufficient for patient-like geometries
- The material closest in mass density will be associated with a CT based voxel

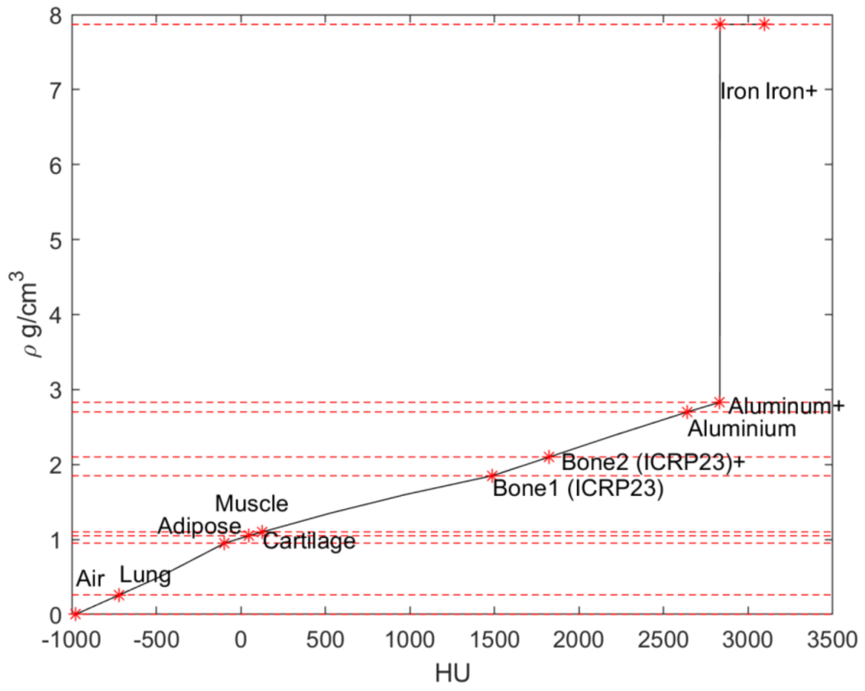


Figure 1. An example of an HU-to-density table. In red is the mapping from mass density to the ten core materials used for the photon Monte Carlo dose engine, the electron dose engine and all proton and light ion dose engines.

MASS DENSITY TO MATERIAL

Material Interpolation

- CT to Material mapping
  - Use voxel mass density for linear interpolation in a table of materials to find (approximate) elemental composition
  - E.g. a voxel with mass density 1.075 g/cm3 will be associated with a 50/50% mixture of muscle and cartilage
- ~50 CT mapping materials defined by interpolation from the 10 Core materials
- Each voxel associated with a mass density ρ (form CT) and a material, defined by its elemental composition *(Z, A)* and mean ionization number *I*
- Material properties used for on-the-fly computation

$$w(Z)^c = w^a w\left(Z\right)^a + w^b w\left(Z\right)^b,$$

$$\ln I^c = \frac{w^a < Z/A >^a \ln I^a + w^b < Z/A >^b \ln I^b}{< Z/A >^c}$$

$$w^a = \frac{f^a \rho^a}{\rho^c}, \quad w^b = \frac{f^b \rho^b}{\rho^c}$$

$$f^a = \frac{V^a}{V^a + V^b} = \frac{\rho^b - \rho^c}{\rho^b - \rho^a}, \; f^b = 1 - f^a$$

MASS DENSITY TO MATERIAL

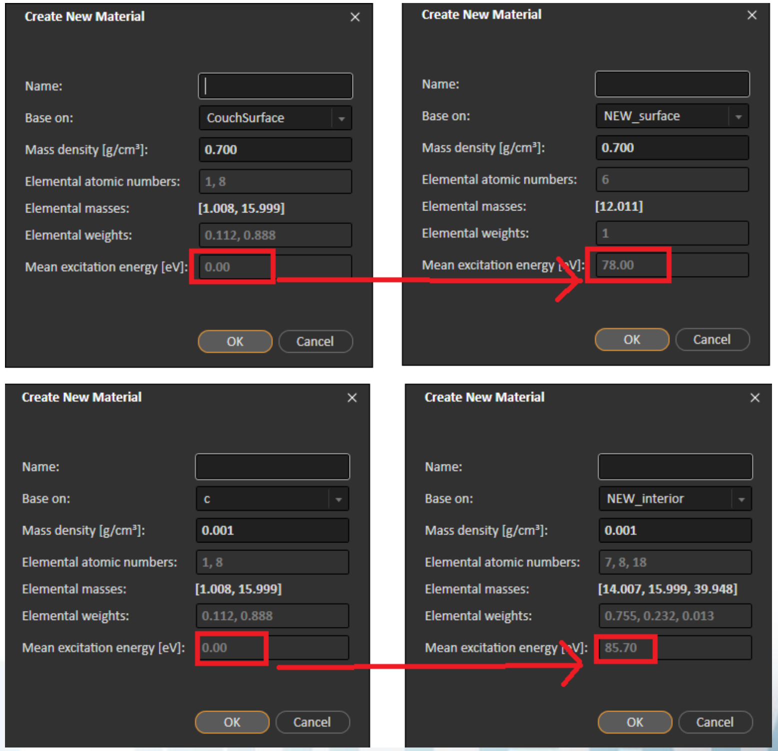
Interpolated materials

- 55 interpolated materials evenly distributed in the biological tissue density range
- 5 materials in the high density range
- More detailed information about the interpolated materials are given upon request

```
4       Density = 0.190125 g/cm3        nElements = 10   I = 75.3152 eV
        0       1       1.00794 0.102823
        1       6       12.0107 0.10482
        2       7       14.0067 0.0322441
        3       8       15.9994 0.748112
        4       11      22.9898 0.00199656
        5       15      30.9738 0.00199656
        6       16      32.065  0.00299484
        7       17      35.453  0.00299484
        8       18      39.948  2.23389e-05
        9       19      39.0983 0.00199656

5       Density = 0.244101 g/cm3        nElements = 10   I = 75.3027 eV
        0       1       1.00794 0.102969
        1       6       12.0107 0.104968
        2       7       14.0067 0.0312205
        3       8       15.9994 0.748843
        4       11      22.9898 0.00199939
        5       15      30.9738 0.00199939
        6       16      32.065  0.00299909
        7       17      35.453  0.00299909
        8       18      39.948  3.95894e-06
        9       19      39.0983 0.00199939

6       Density = 0.298077 g/cm3        nElements = 9    I = 72.9976 eV
        0       1       1.00794 0.104935
        1       6       12.0107 0.191707
        2       7       14.0067 0.026779
        3       8       15.9994 0.666162
        4       11      22.9898 0.00182412
        5       15      30.9738 0.00164825
        6       16      32.065  0.00264825
        7       17      35.453  0.00264825
        8       19      39.0983 0.00164825

7       Density = 0.352053 g/cm3        nElements = 9    I = 70.6705 eV
        0       1       1.00794 0.10696
        1       6       12.0107 0.28248
        2       7       14.0067 0.02236
        3       8       15.9994 0.57944
        4       11      22.9898 0.00164
        5       15      30.9738 0.00128
        6       16      32.065  0.00228
        7       17      35.453  0.00228
        8       19      39.0983 0.00128
```

MASS DENSITY TO MATERIAL – COMPUTATION ERROR

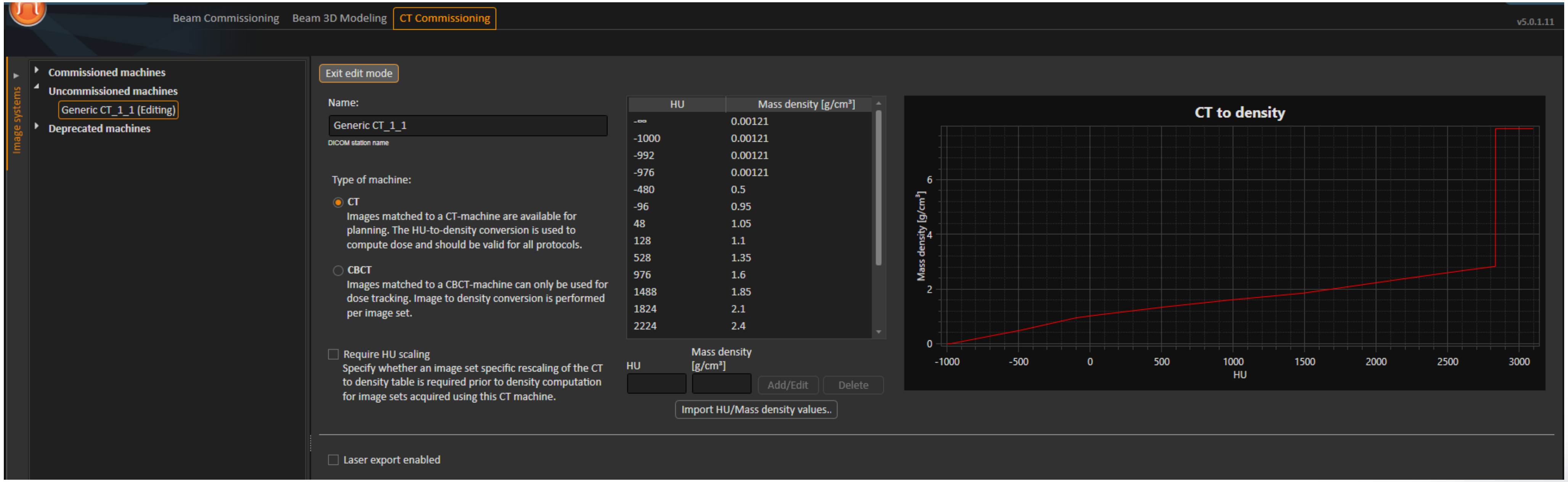
- When using or importing structures template from older Raystation versions, it is likely Raystation won't be able to compute dose with photon MC
- The reason is at that time, Raystation didn't propose to fill the mean excitation energy when creating new material



CT COMMISSIONING

CT COMMISSIONING WORKSPACE

- Define CT machines with HU to mass-density table
- Define CT machines with HU to Stopping Power Ratio (SPR) table (for protons and light ions)
- Define CBCT machines



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CT MACHINE TREE VIEW

- ***Commissioned***, ***Uncommissioned*** or ***Deprecated***
- No template machines, but example machines installed with the system
- Name maximum 81 characters (DICOM)
- Unique names, unique date
- Edit mode (only one CT or LINAC can be in edit mode at once)

CT NAME

- For automatic mapping of CT-dataset to a specific CT during import, use the same name for the CT as used in the DICOM-data tag ***[Station name;0008,1010]***
- To use different CT to density tables for different protocols, use the name convention “***StationName:ProtocolName”*** where the protocol name corresponds to DICOM-data tag ***[Protocol name;0018,1030]***
- Name can be no longer than **81 characters**

CT COMMISSIONING WORKFLOW

- Copy an existing machine
- Enter ***Edit mode***
- Select machine type: ***CT*** or ***CBCT***
- For a CT machine, edit the HU to mass-density table
  - Possible to import HU to mass-density table on csv format
  - Possible to import HU to SPR table on csv format
- For CBCT machines, edit the CBCT parameters
- Exit *Edit mode*
- Commission machine

Much easier than Beam Commissioning!

IMAGE CONVERSION ALGORITHM COMMISSIONING FOR CBCT CONVERSION

IMAGE CONVERSION ALGORITHM COMMISSIONING

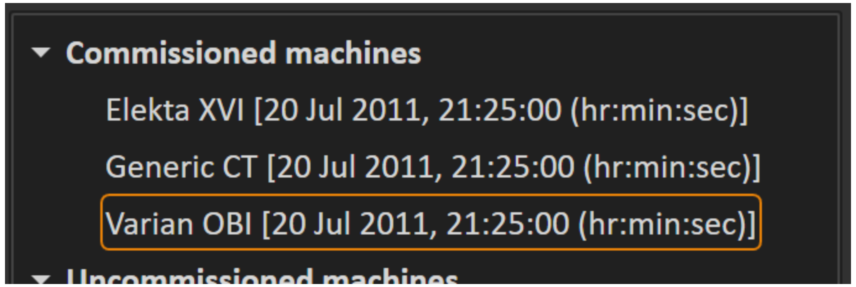
- RayStation includes two algorithms for image conversion:
  - corrected CBCT
  - virtual CT
- An image conversion algorithm **must be commissioned** before images generated with that algorithm can be **approved and considered as a clinical image in RayStation**
- Commissioning an algorithm means that the algorithm has been deemed capable of generating **clinically acceptable images**
- Before commissioning an algorithm, a **validation of converted images** generated by the algorithm shall be performed.
- Image conversion algorithm commissioning can only be performed on commissioned **imaging systems of type CBCT**

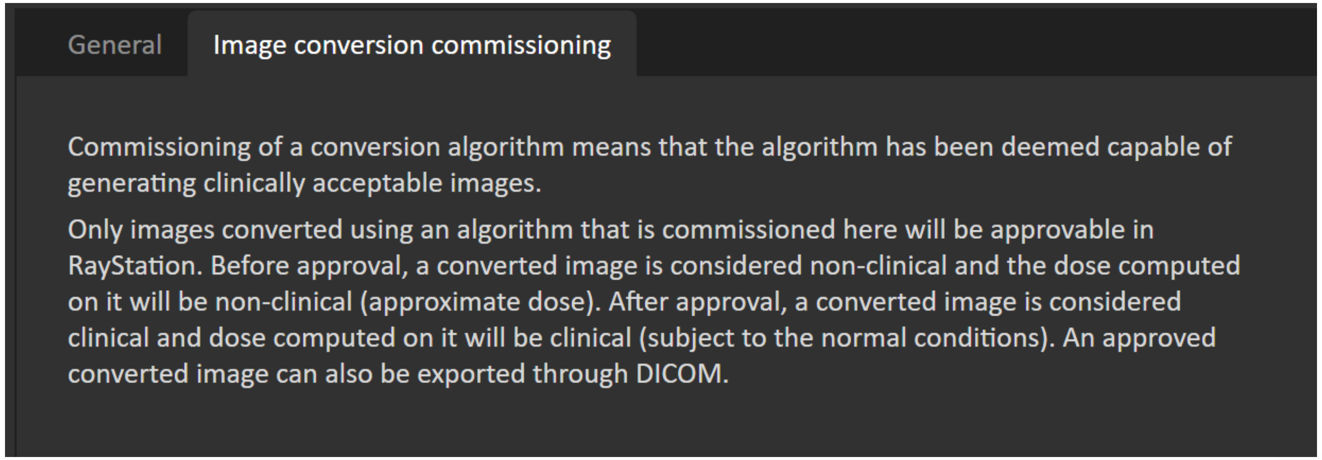
ALGORITHM VALIDATION

- Algorithm validation shall include:
- Dose comparison with CT images (of clinical quality) or ground truth image, where the CT patient anatomy is as close as possible to the anatomy in the image to be converted
- Impact of anatomical differences can be reduced by **using images from the same day** and by **density override in regions with major anatomical differences**
- If only differences due to the converted image values are wanted, make sure to use the same external (intersection of externals), include couch and material overrides for reference image
- Must cover sufficient number of cases of all possible imaging protocols and anatomical sites

COMMISSIONING AN ALGORITHM

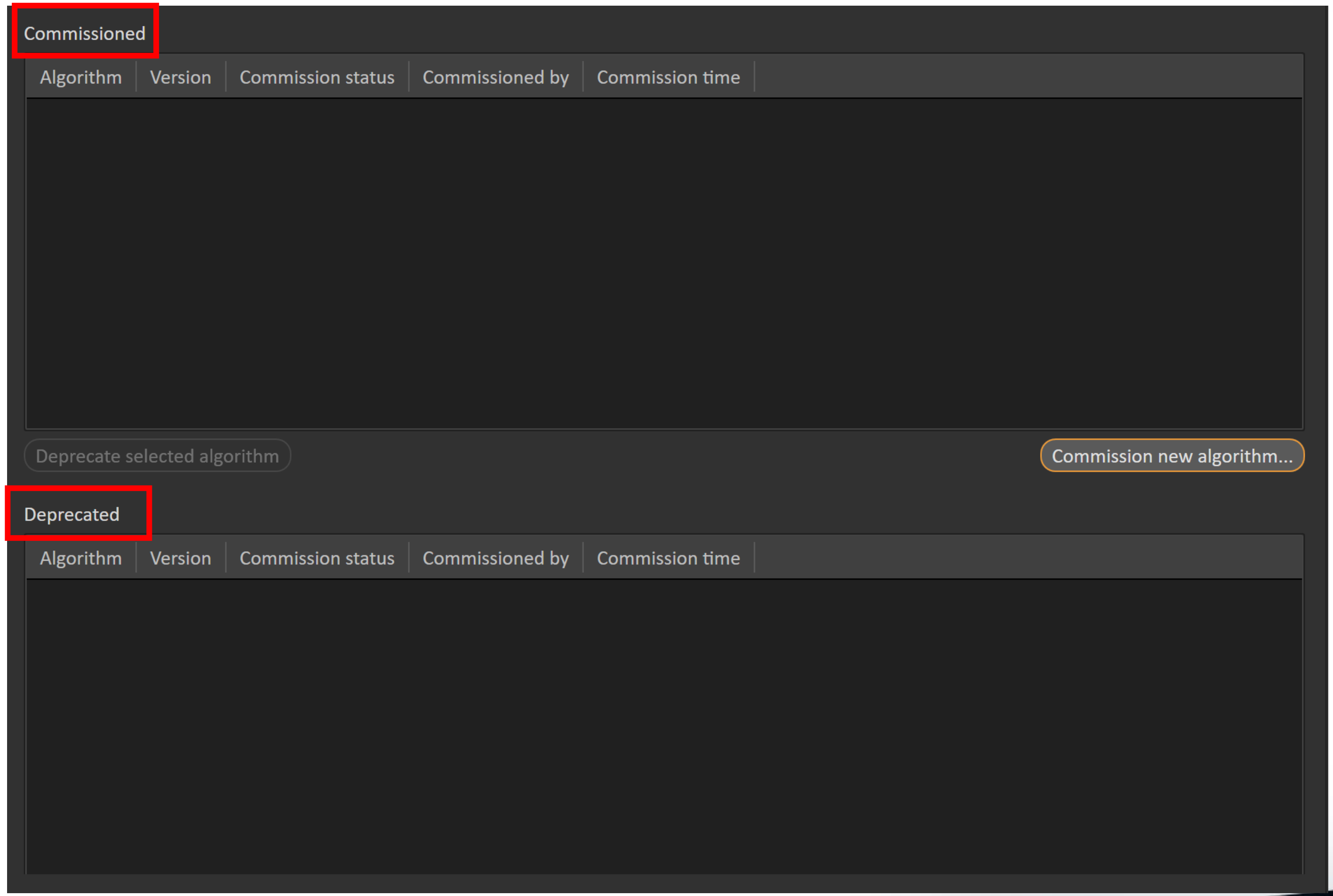
- Commission a machine of type CBCT first. Only after commissioning a CBCT machine, will the Image Conversion Commissioning tab appear.





COMMISSIONING AN ALGORITHM

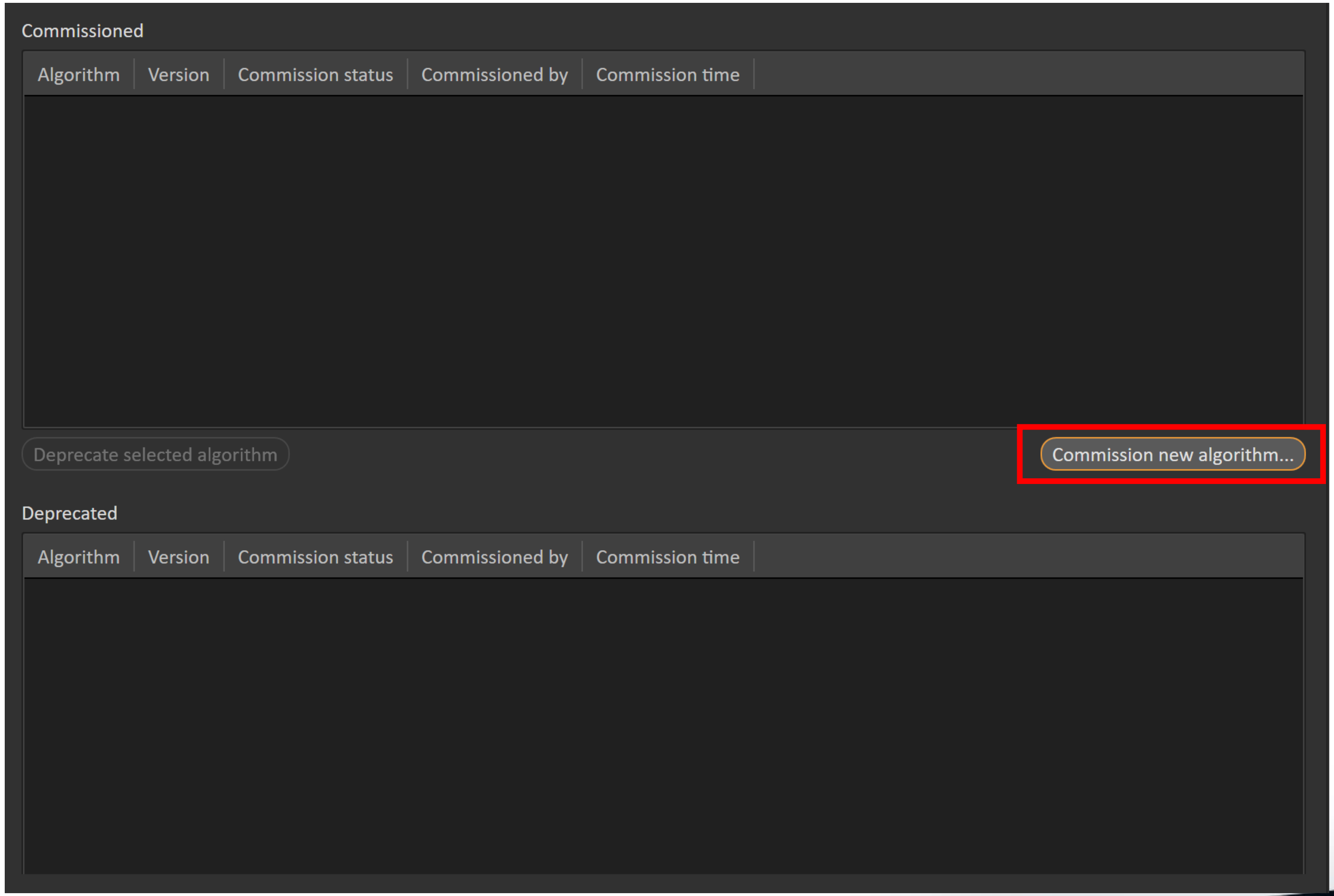
- There are two lists of algorithms:
  - Commissioned: Currently commissioned algorithms
  - Deprecated: Previously commissioned but now deprecated, not suitable for clinical use



COMMISSIONING AN ALGORITHM

- To commission an algorithm:

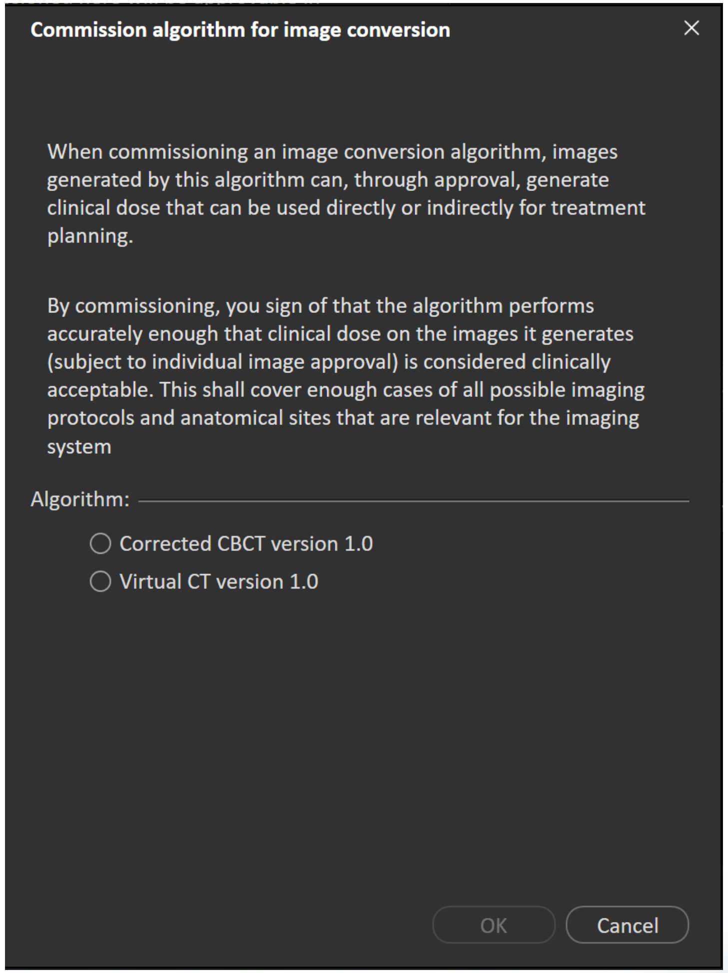
1. Click the **Commission new algorithm** button. This opens the Commission algorithm for image conversion dialog



COMMISSIONING AN ALGORITHM

- To commission an algorithm:

1. Click the **Commission new algorithm** button. This opens the Commission algorithm for image conversion dialog
2. Carefully read the information and consider whether the algorithm has been successfully validated to commission it. If so, select the algorithm to commission
3. Click **OK**
4. Enter credentials



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THANK YOU!