Optimization of Metal Density Definition in Dose Calculation Algorithms

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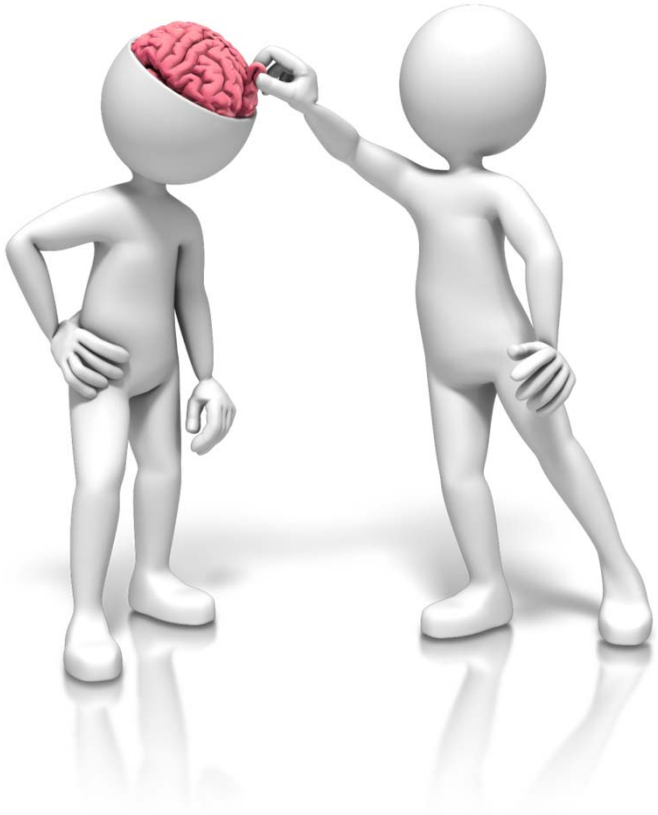
Overview

1. Background / physics
2. Algorithms AAA and Acuros XB
3. HU density curves
4. Extended range HU density curves
5. Metal artifact reduction
6. Examples

What planning system do you use?

A. Eclipse
B. Raystation
C. Monico
D. Oncentra
E. Pinnacle
F. Other



High density materials in human body

Material	Mass Density (g/cc)	ReD	Uses	Size example (cm)
Titanium Alloy	4.5	3.73	Femur rods, some hip prostheses, some spinal fixation	1-2
Neodymium	7.3-7.5		Breast expander magnets	2.5
Stainless steel	8		Surgical wires, screws, some spinal fixation	0.07 0.5 0.5
Cobalt Chromium	8.4 – 8.8		Hip prostheses head	3
Amalgam	14 - 16		Teeth filling	0.5
Gold	19.3	13.96	Fiducial markers	0.08

Attenuation

$$I = I_o * e^{-\mu x}$$

- I is the transmitted intensity
- I_o is the incident intensity
- μ is the linear attenuation coefficient
- x is the thickness of material

μ of 0.01 cm^{-1} means that 1% attenuation per cm of material

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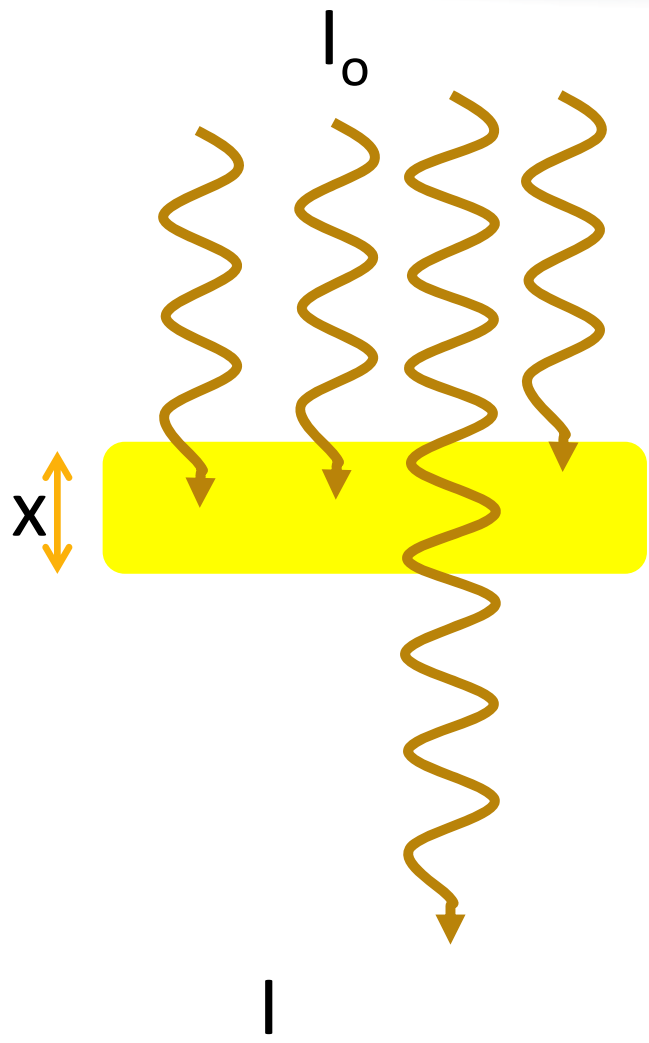


Hounsfield Unit (HU)

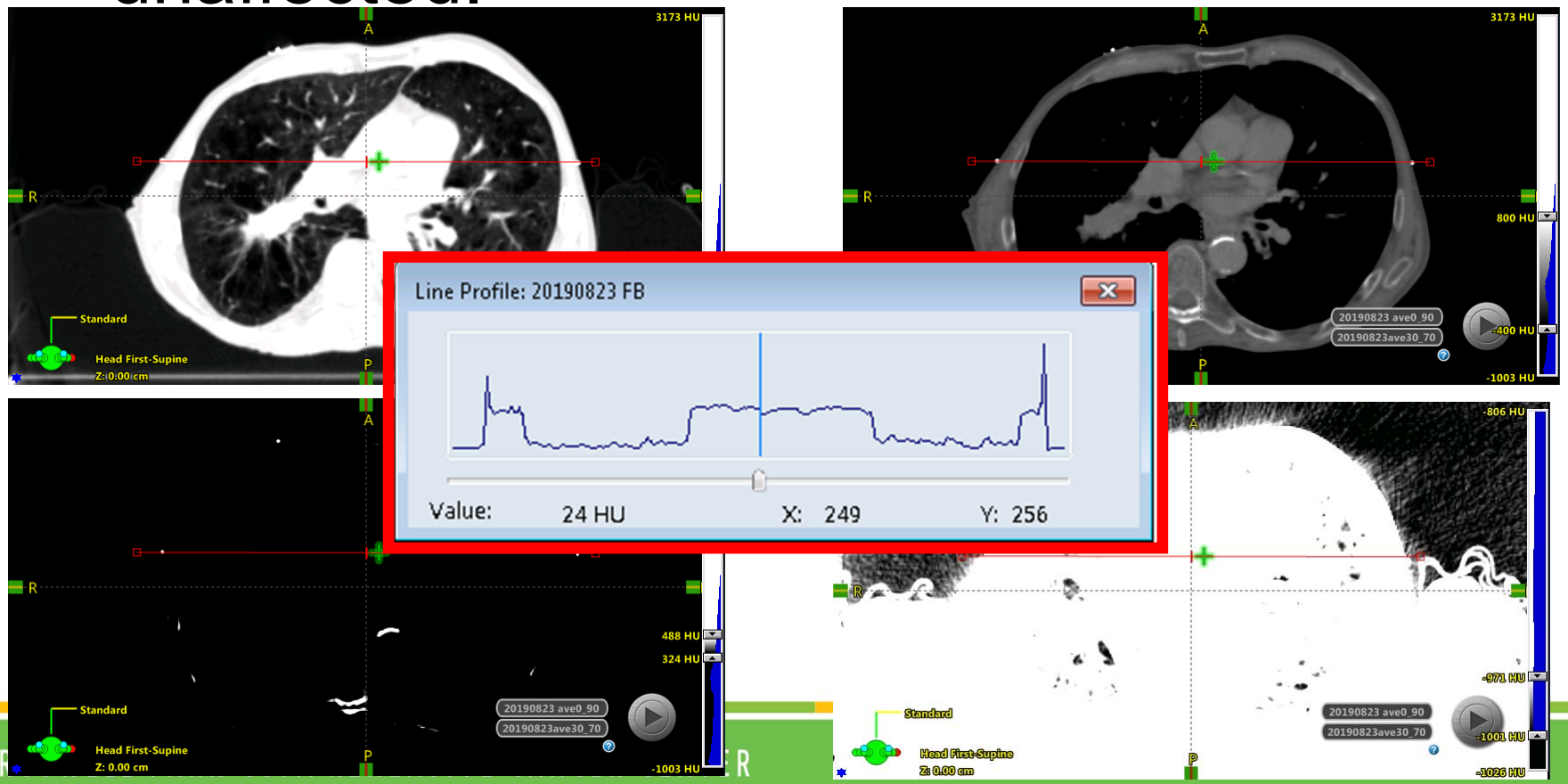
$$HU = \frac{(\mu tissue - \mu_{water})}{\mu_{water}} * 1000$$

HU	Material	Appearance*
-1000	Air	Dark (Black)
- 600 to -800	Lung	
-100	Fat	
0	Water	
100	Muscle	
1000	Bone	Light (White)

- Appearance will depend on the display window and level
- HU is independent of the display window and level

HU versus screen display

- Window and level changes the computer pixel intensity but the HU remain unaffected.



The HU of an imaged CT pixel is dependent on the radiologic (x-ray) properties of the tissue.

A. True

B. False

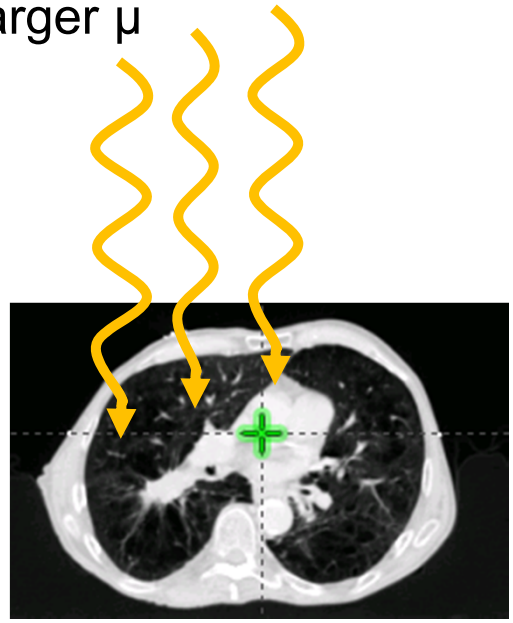
kV CT – μ – HU – density – MV dose

- Since a CT is acquired with x-rays (kV energy range), information about the attenuation of the material is known (i.e. μ).
- This in turn can be used to define a Hounsfield unit that is
  - used to display the image
  - Supply x-ray attenuation information about the material

kV CT and MV RT

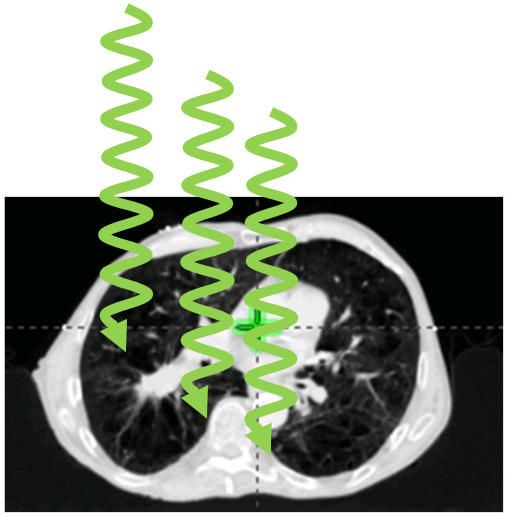
kV CT

- 80 to 140 kV
- Primary photoelectric
- High Z dependence
- Less transmission
- Larger μ



MV RT

- 6 to 18 MV
- Primarily Compton
- Low Z dependence
- Higher transmission
- Smaller μ



BUT the μ derived from kV CT can be used to determine the material density which can then be applied to the interaction of the MV therapy x-rays.

Concerns of metals in radiotherapy dose calculations

- Poor object delineation
  - Over and under dose
- Lower dose in shadow
  - (less with VMAT than 3D CRT)
- Higher dose at metal interface
- Misleading dose statistics (max dose in metal)
- Dose optimization may result in high fluence gradients
  - (less with VMAT than IMRT)

CT Density curves

- AAA requires
  - HU to relative electron density (per volume)
  - Dose to scaled density water
- Acuros XB
  - HU to mass density
  - Dose to actual material
  - Converges to monte carlo solution

Relative electron density per volume

$$ReD = \left\{ \frac{\left[\frac{Z * Na}{A} * \rho\right]_{material}}{\left[\frac{Z * Na}{A} * \rho\right]_{water}} \right\}$$

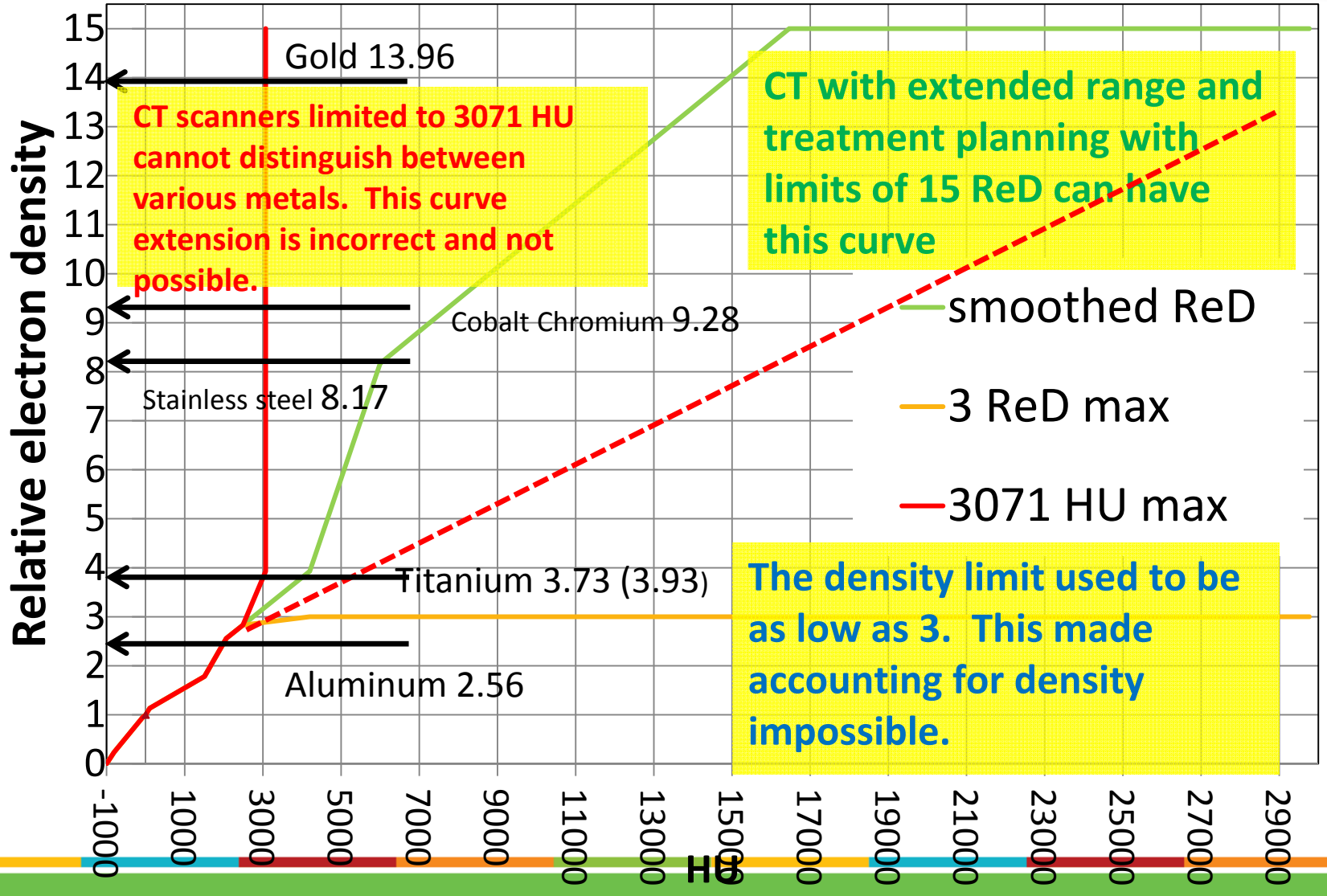
Z is atomic number

A is mass number

ρ is mass density

Na is Avagadro's number (6.02×10^{23})

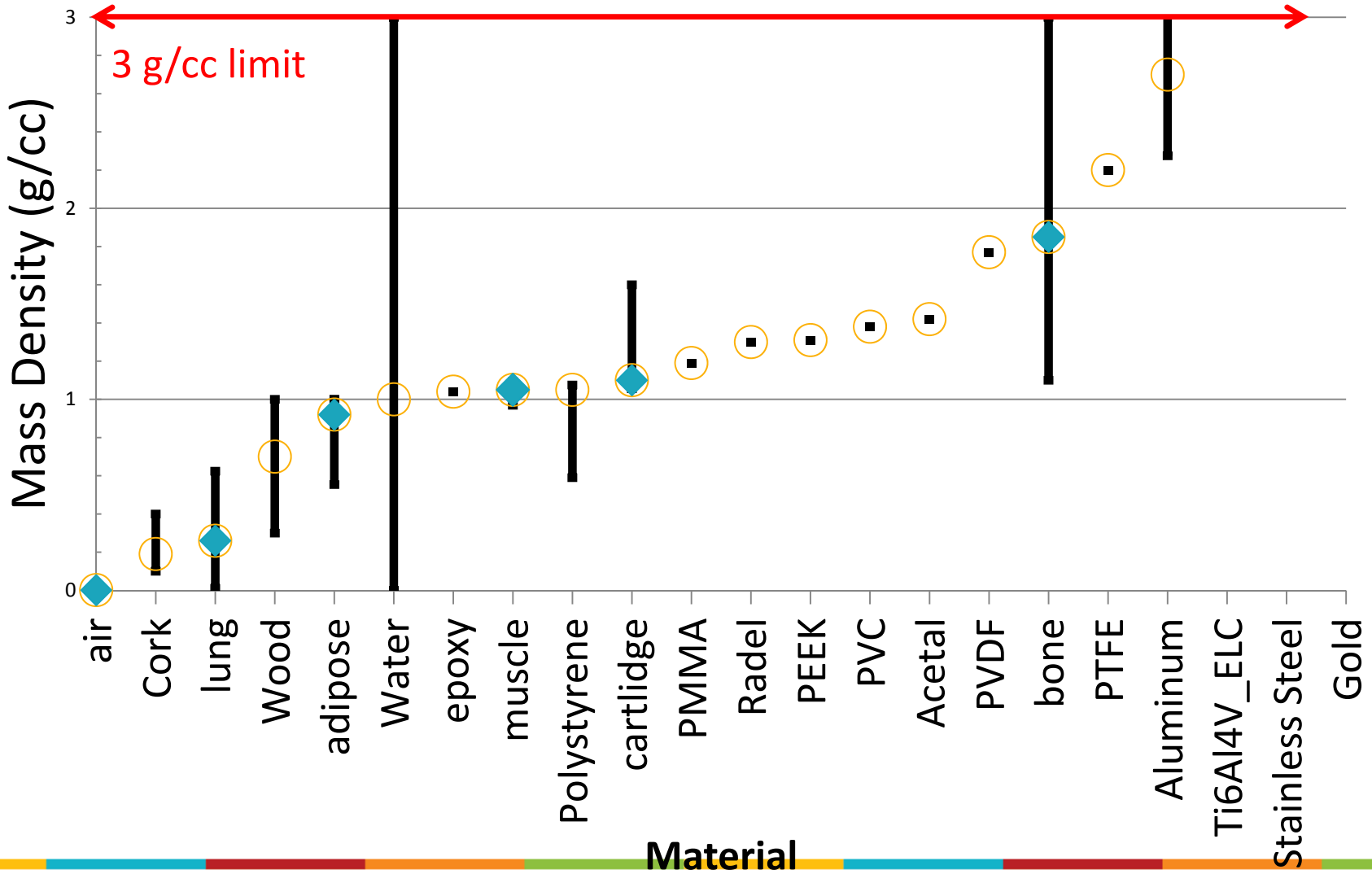
Hounsfield Unit (HU) versus relative electron density



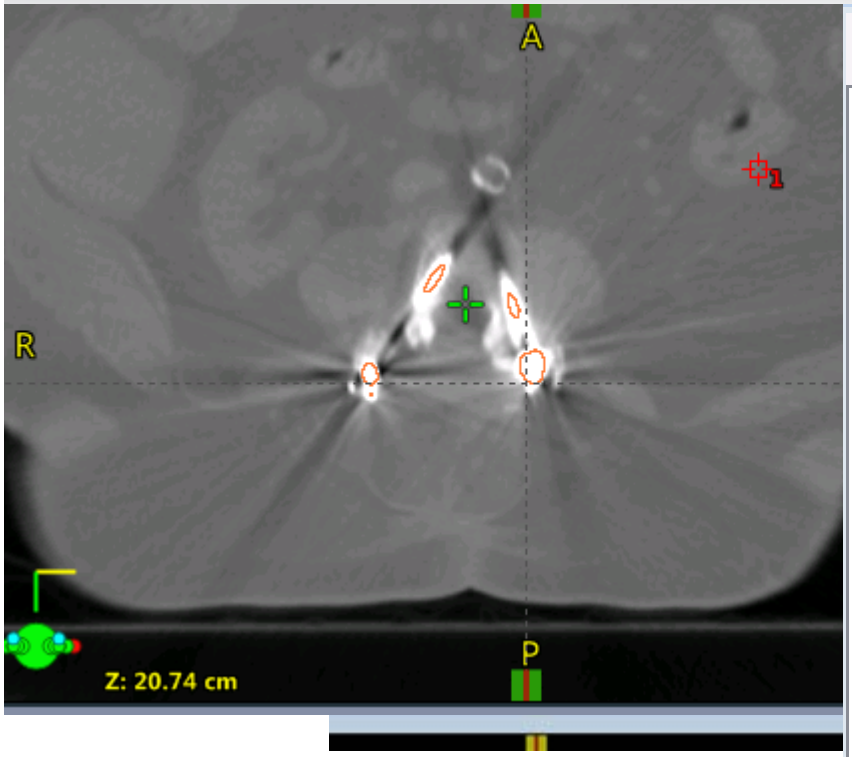
Acuros XB

- Will assign a material to tissue based on HU
- Then the material properties and **mass** density are used to determine radiation interactions
- Can be a mixture of materials (i.e. Adipose and muscle)
- Limit of 3 g/cc
- All higher densities must be user defined

Acuros physical density table



Physical material based on HU



Dose | Physical Properties

CT Value:	-19 HU
Assigned CT Value:	HU
Mass Density:	0.987 g/cm3
Relative Electron Density:	0.987
Relative Proton Stopping Power:	1.001

Physical Material Composition:

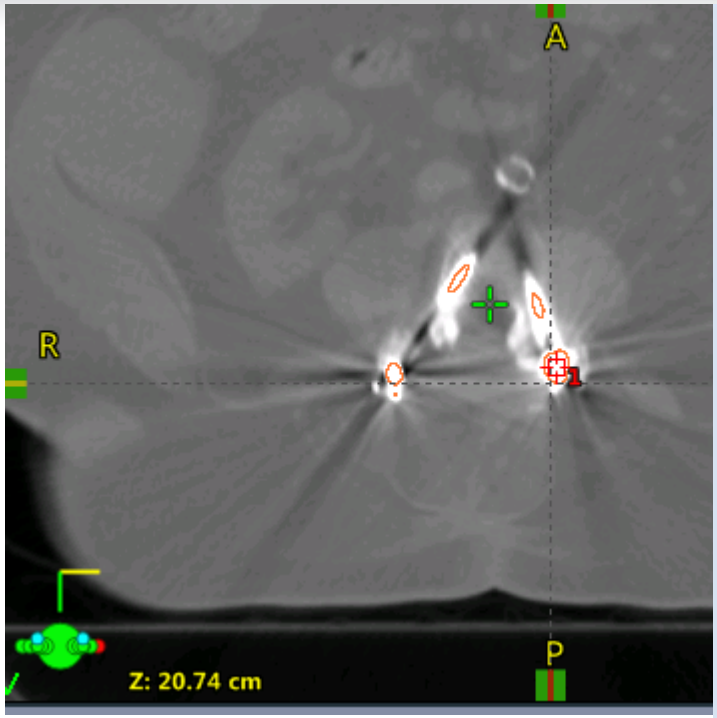
44% Adipose Tissue [ID: Adipose_Tissue]
56% Muscle Skeletal [ID: Muscle_Skeletal]

44% Adipose Tissue
56% Muscle Skeletal

Location [cm]: 11.82 -5.43 20.74

Close

Physical material based on HU



Dose | Physical Properties

CT Value:	5529 HU
Assigned CT Value:	4304 HU
Mass Density:	4.420 g/cm3
Relative Electron Density:	4.175
Relative Proton Stopping Power:	N/A

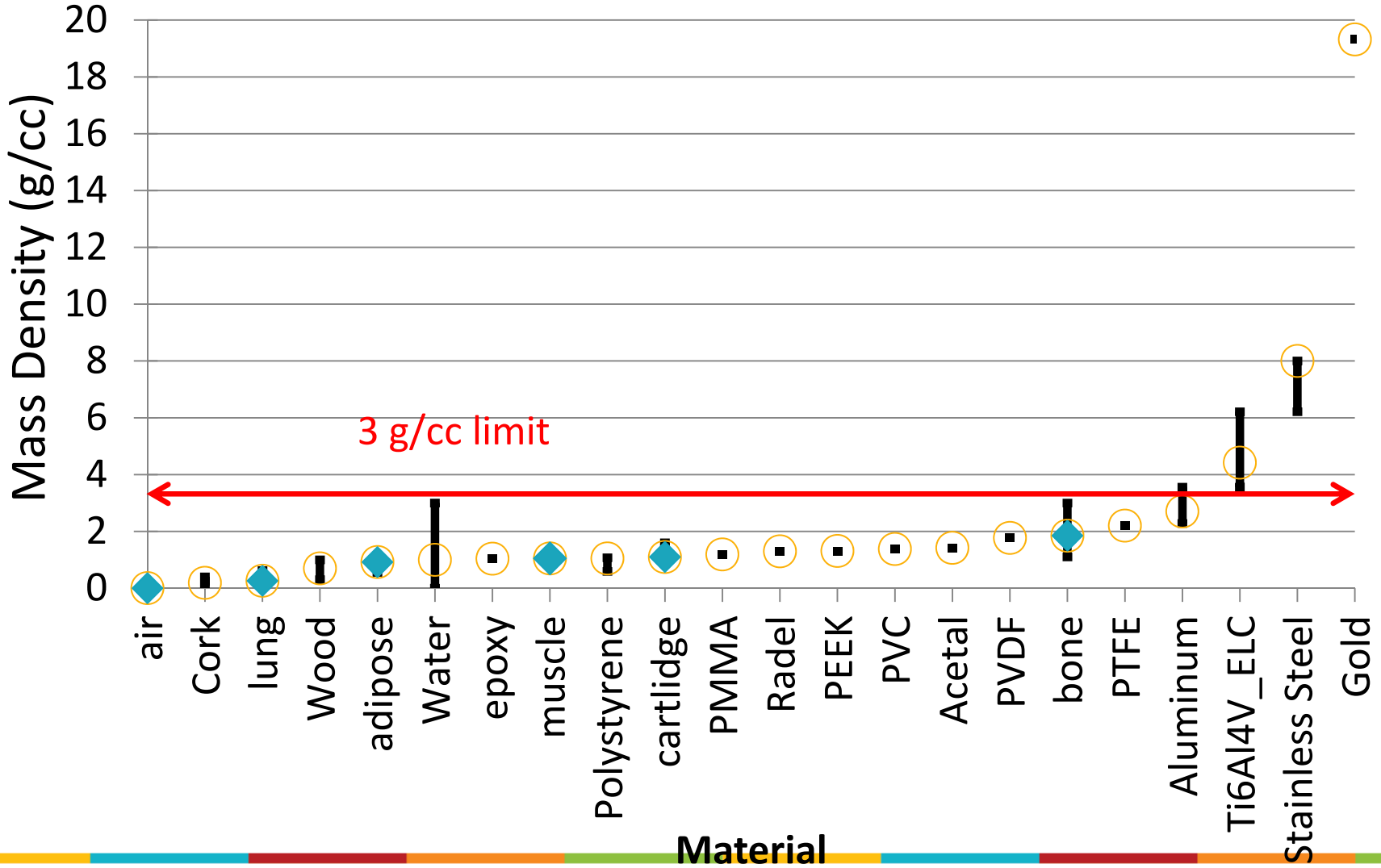
Physical Material Composition:

Titanium Alloy [ID: Ti6Al4V_ELC] (Assigned)

Location [cm]: 2.66 2.51 20.74

Close

Acuros physical density table



Metals in Acuros XB

- Any pixels that convert to >3 g/cc **must** be assigned.
- There is a special tool called “segment high density structure”
  - Defines structure as high resolution
  - Finds all pixels greater than 3 g/cc
  - Expands this by 1 mm in all directions
  - User needs to assign material

Extended HU range

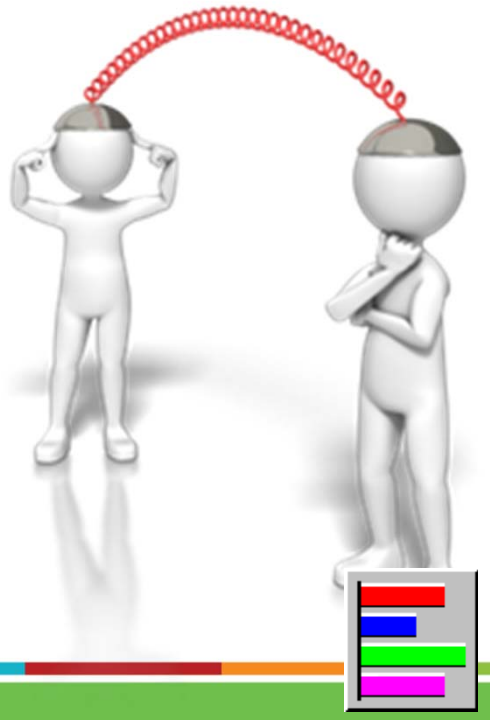
- Many CT scanners have a display limit of 3071 HU. For diagnostic imaging this is not a concern.
- By extending the HU range, the radiotherapy user can better delineate the borders of high density foreign materials and the measured HU may give information to help determine the material.

Does your radiation therapy CT scanner have extended HU range?

A. Yes

B. No, limited to 3071 HU or similar

C. Not sure

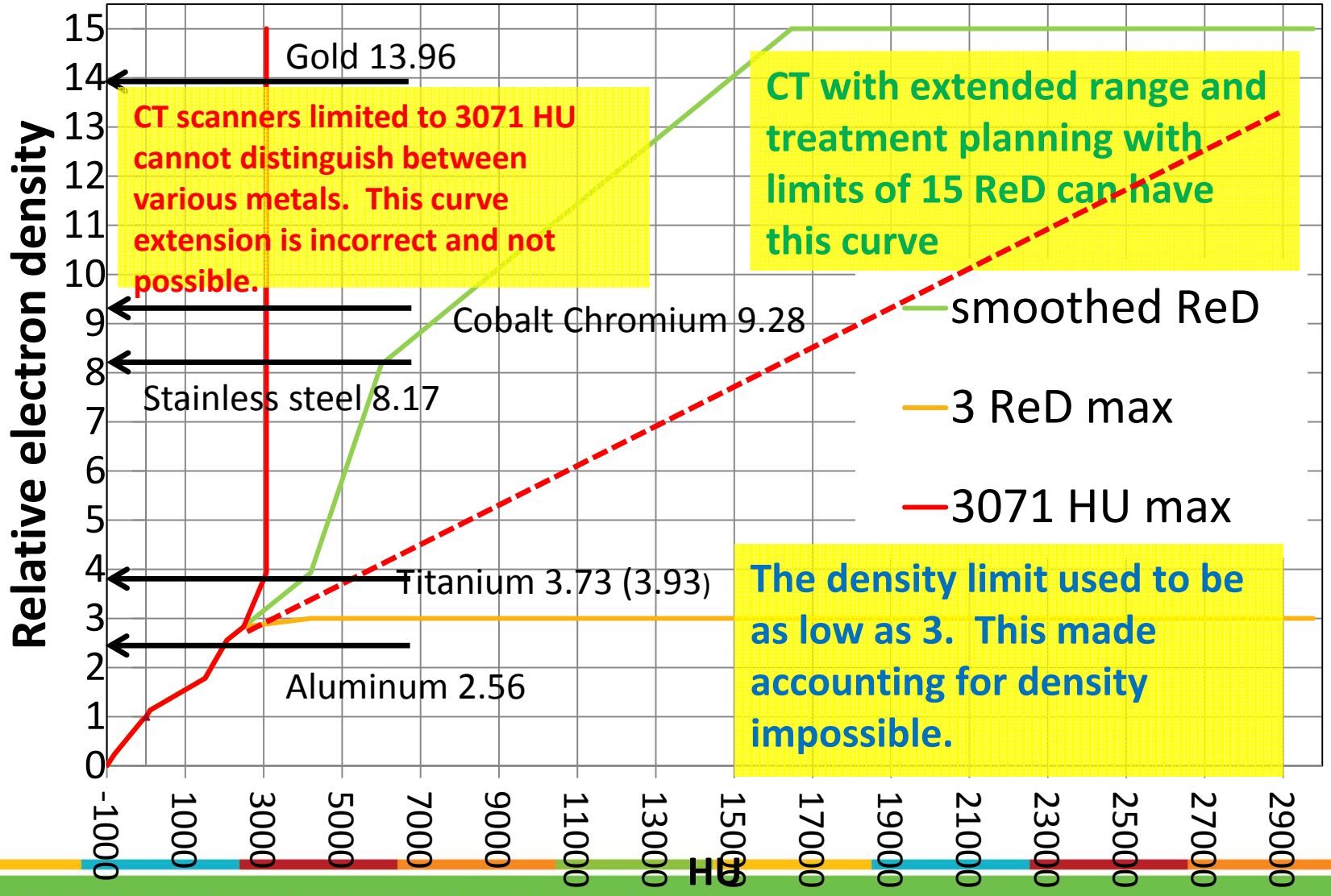


Our HU limits

- GE Discovery 31743
- Eclipse 29768

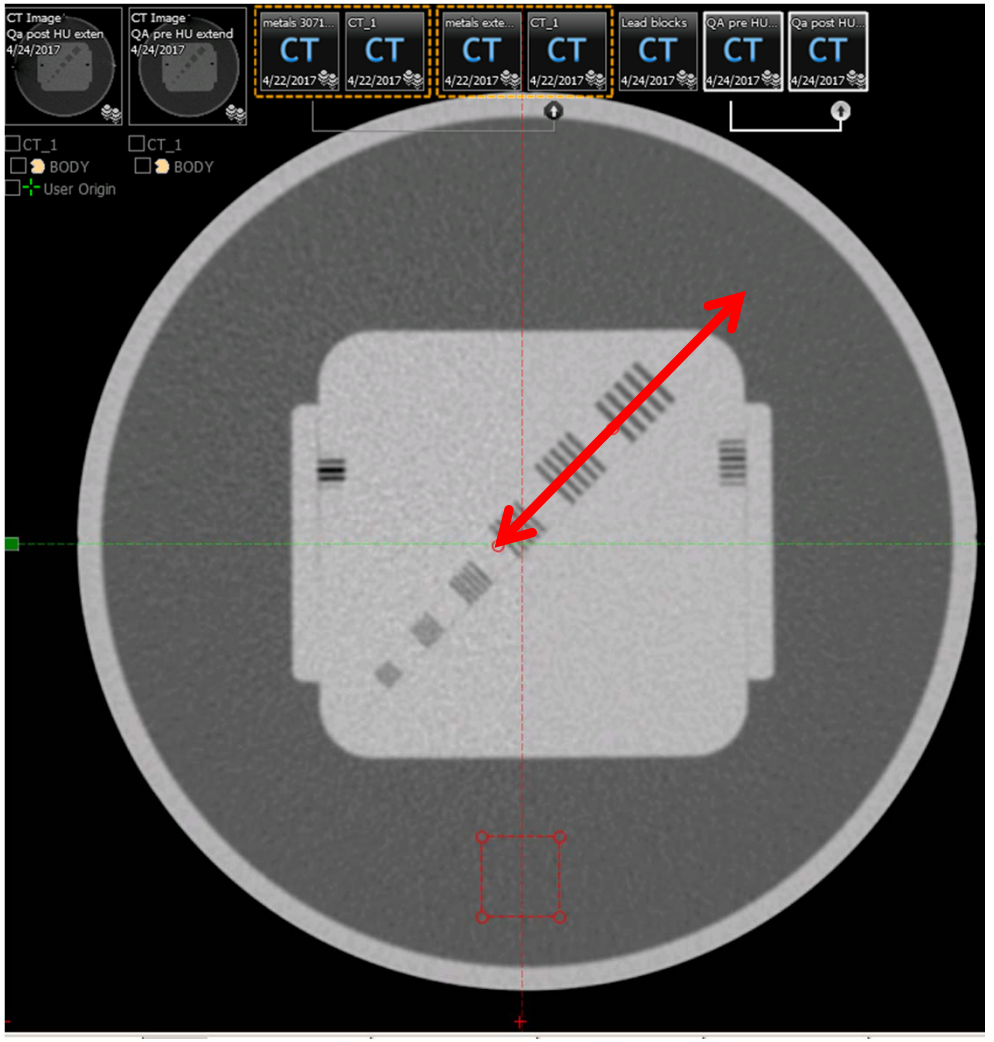
- Some times we get eclipse warning that CT HU exceed calibration curve will assign maximum density (HU)

Hounsfield Unit (HU) versus relative electron density

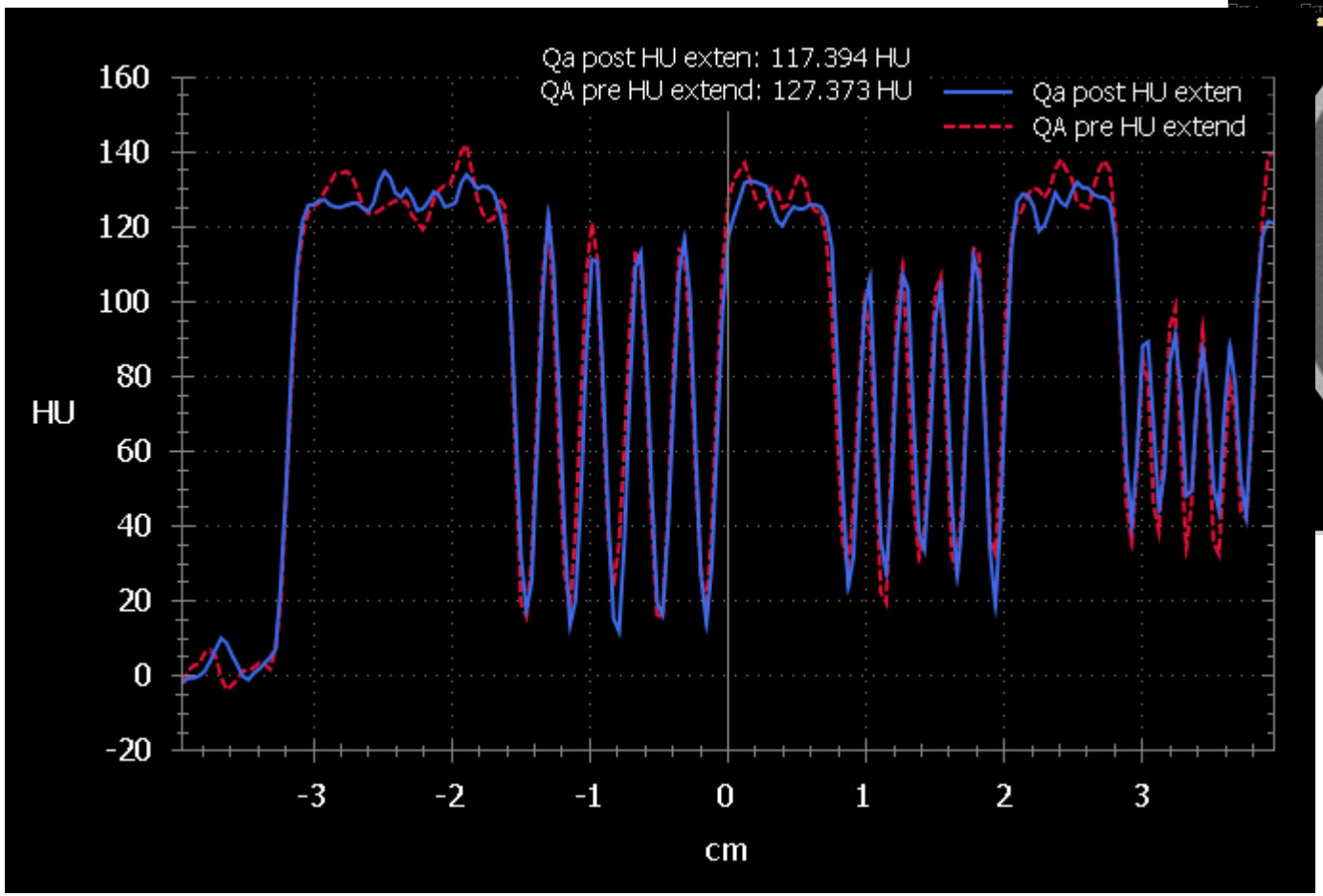


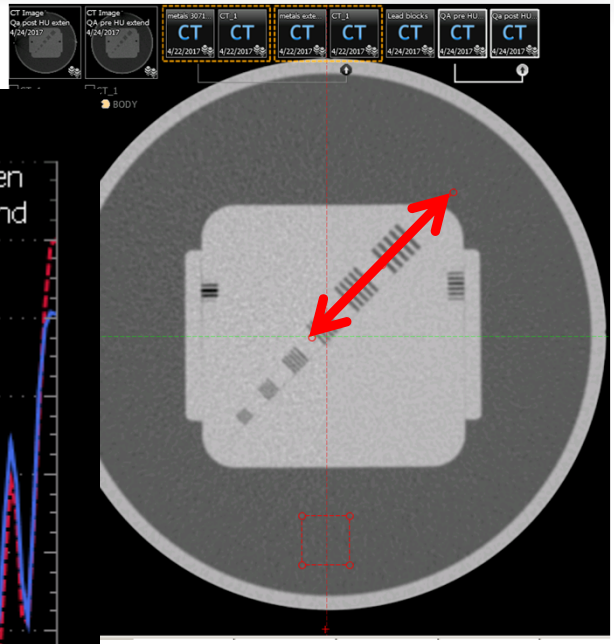
Extended HU range – HU 0 to 200

- CT QA Phantom
- HU profile through resolution pattern



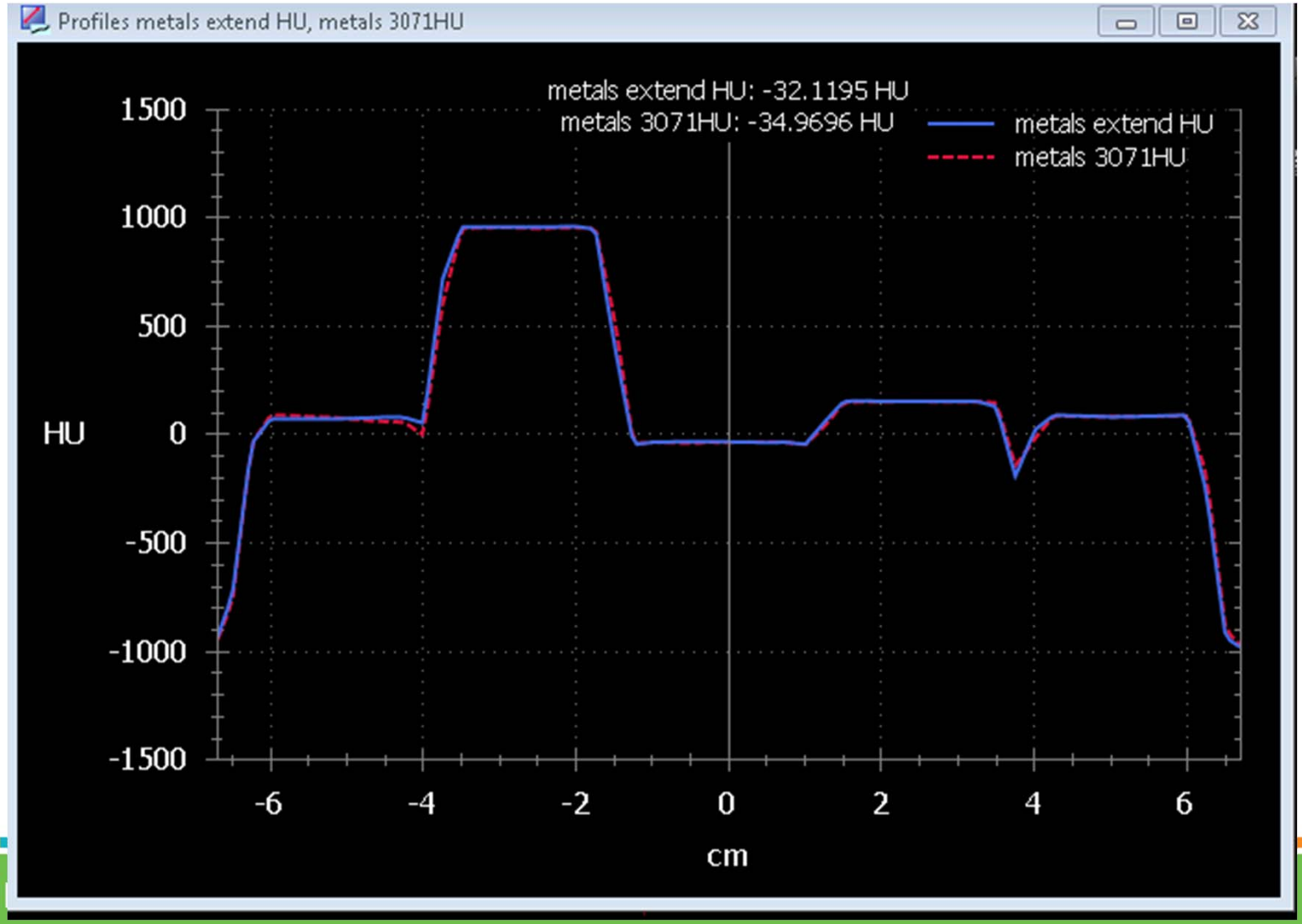
Extended HU range – HU 0 to 200



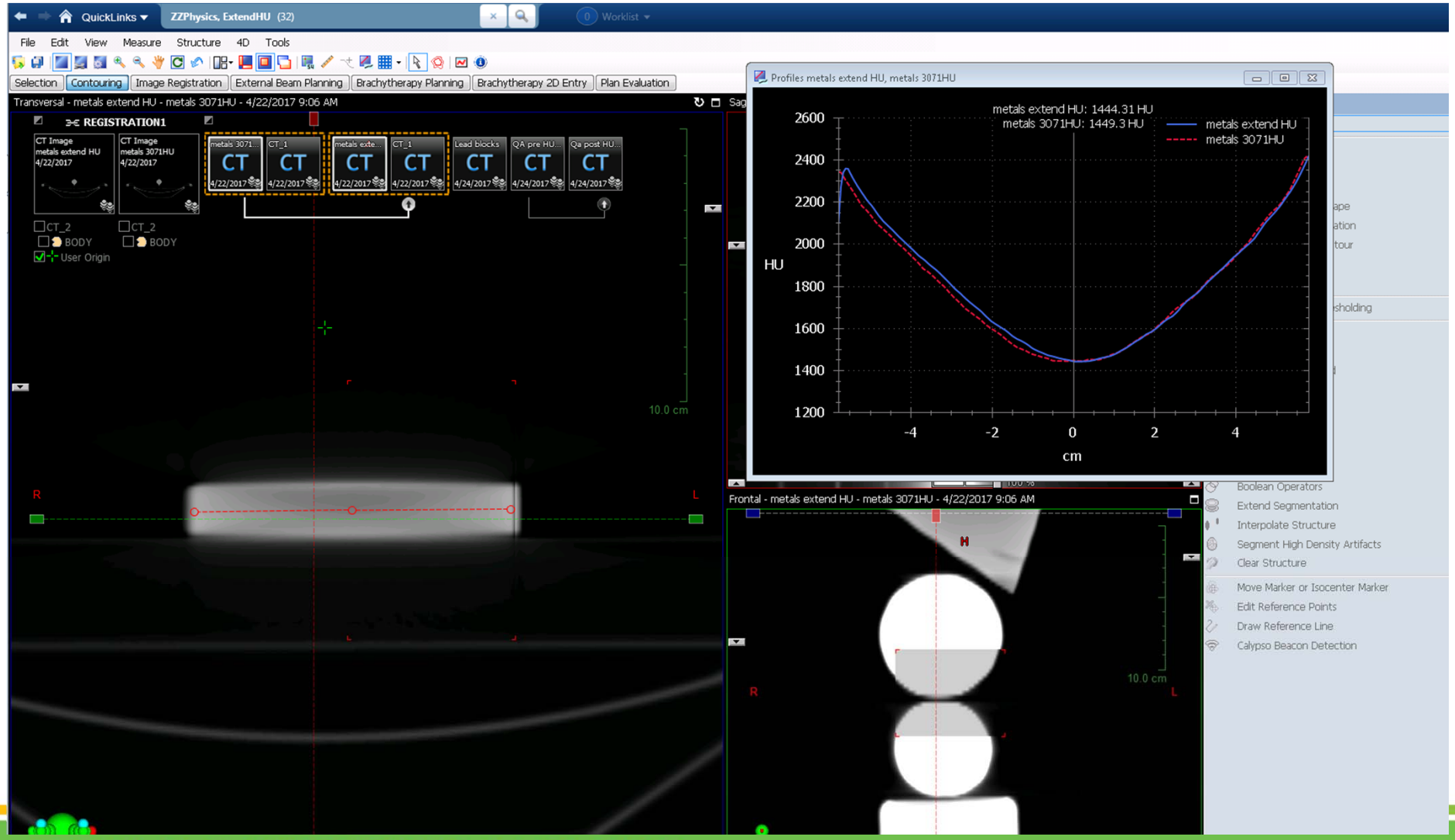


Effect of Extended HU range on HU from 0 to 1000

Effect of Extended HU range on HU from 0 to 1000



Extended HU in Aluminum



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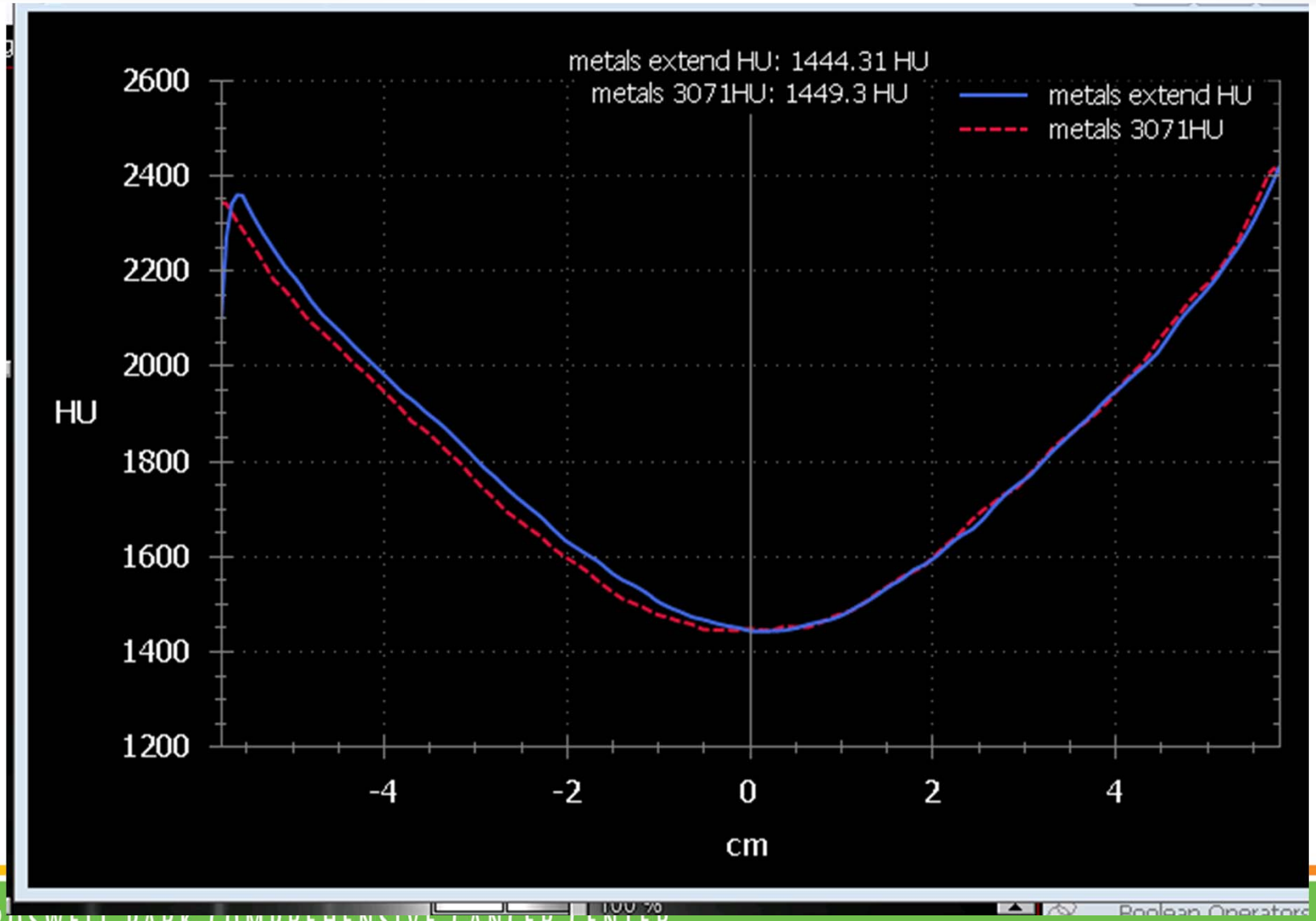
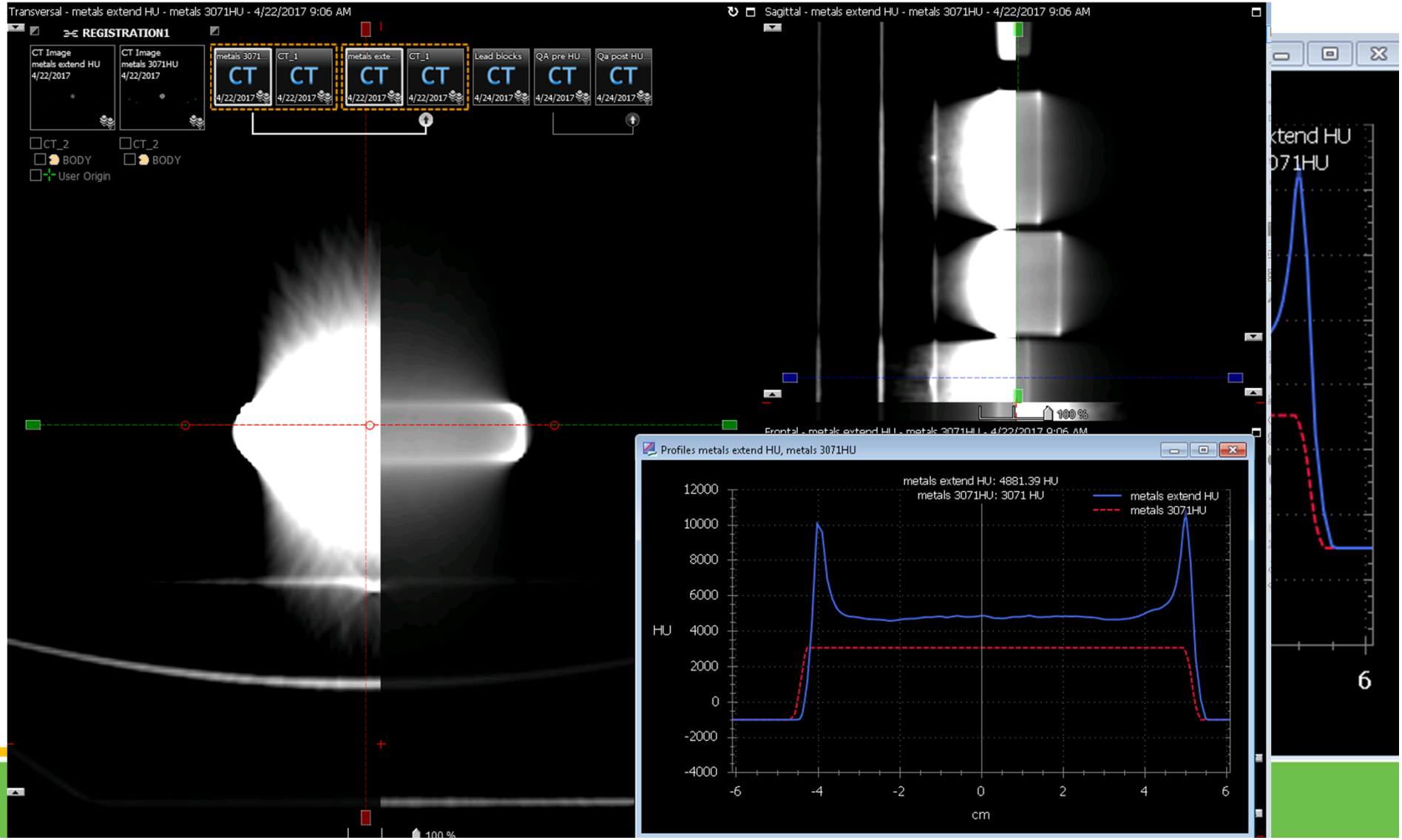
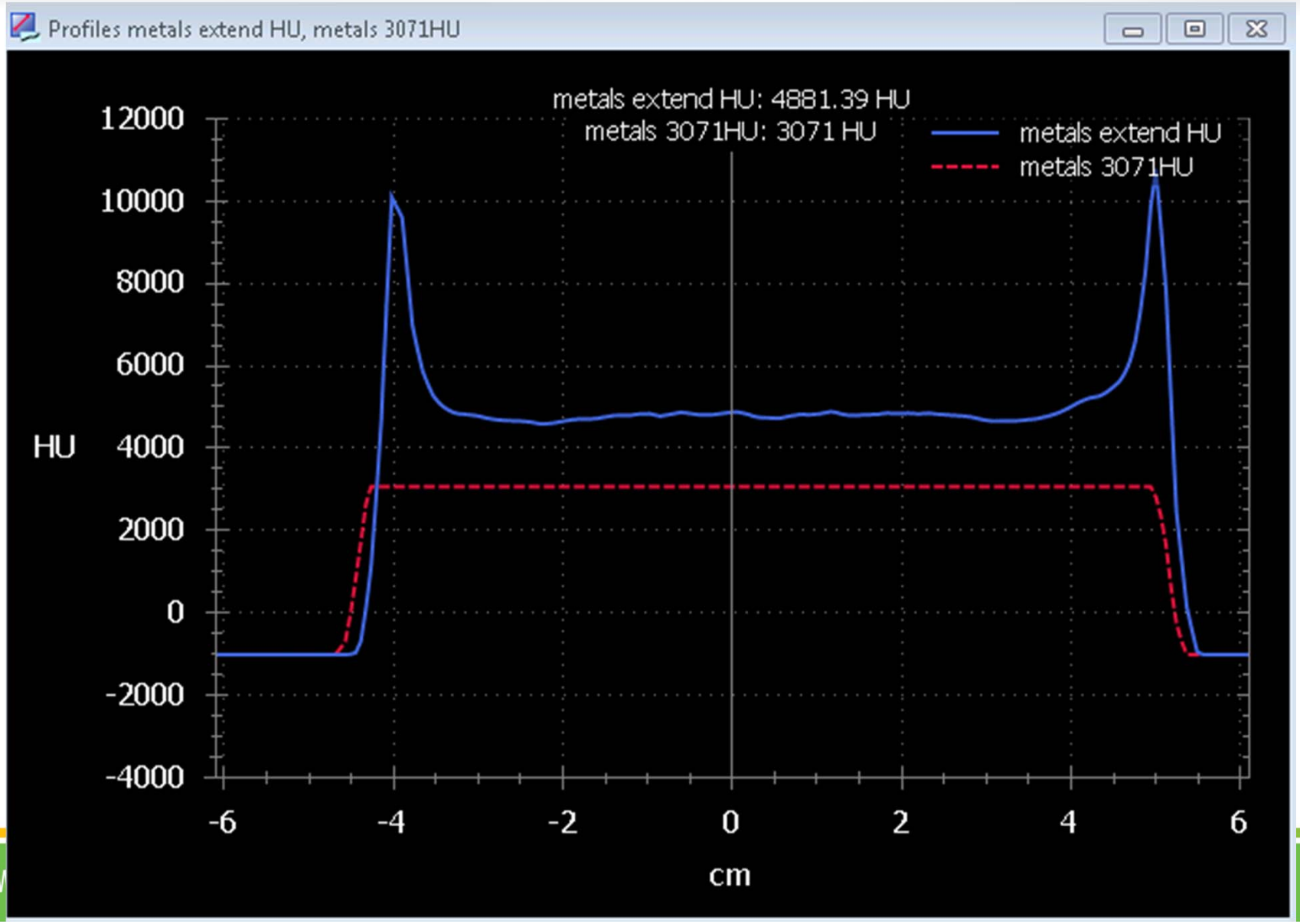


Extended HU in Titanium



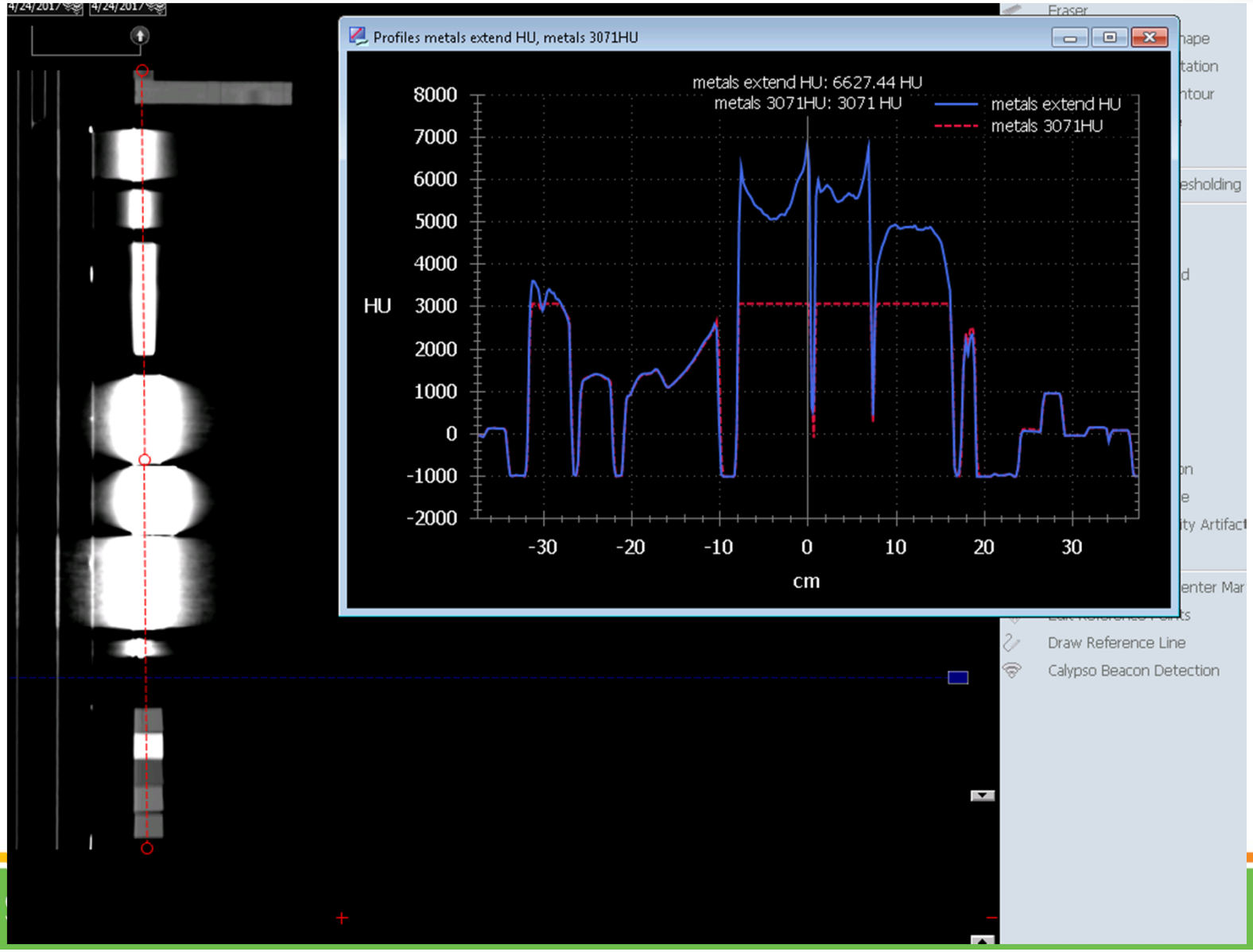
Extended HU in Titanium



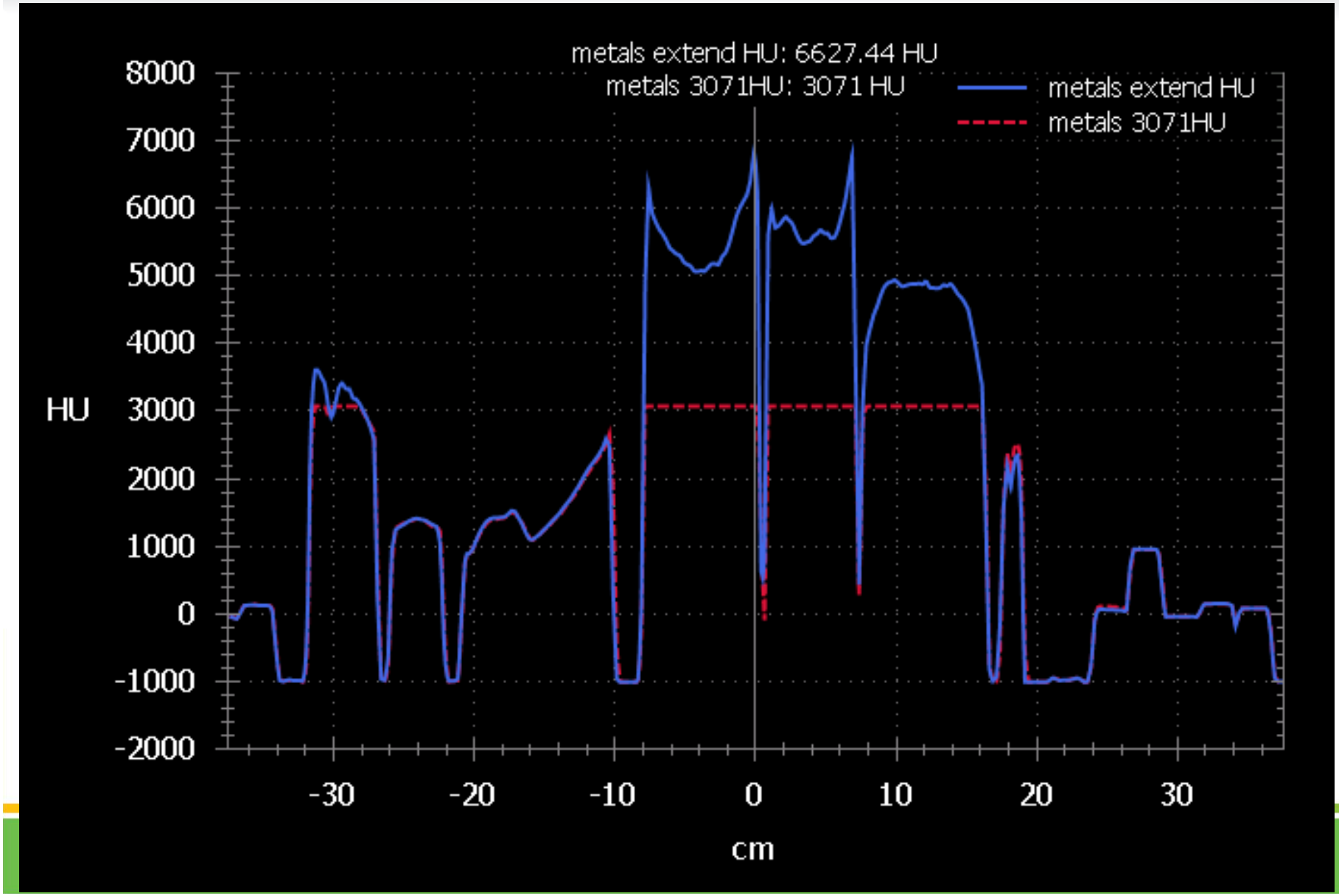
The HU in a uniform piece of metal is

A. Uniform
B. Non-uniform (higher at edges)
C. Non-uniform (lower at edges)
D. 42

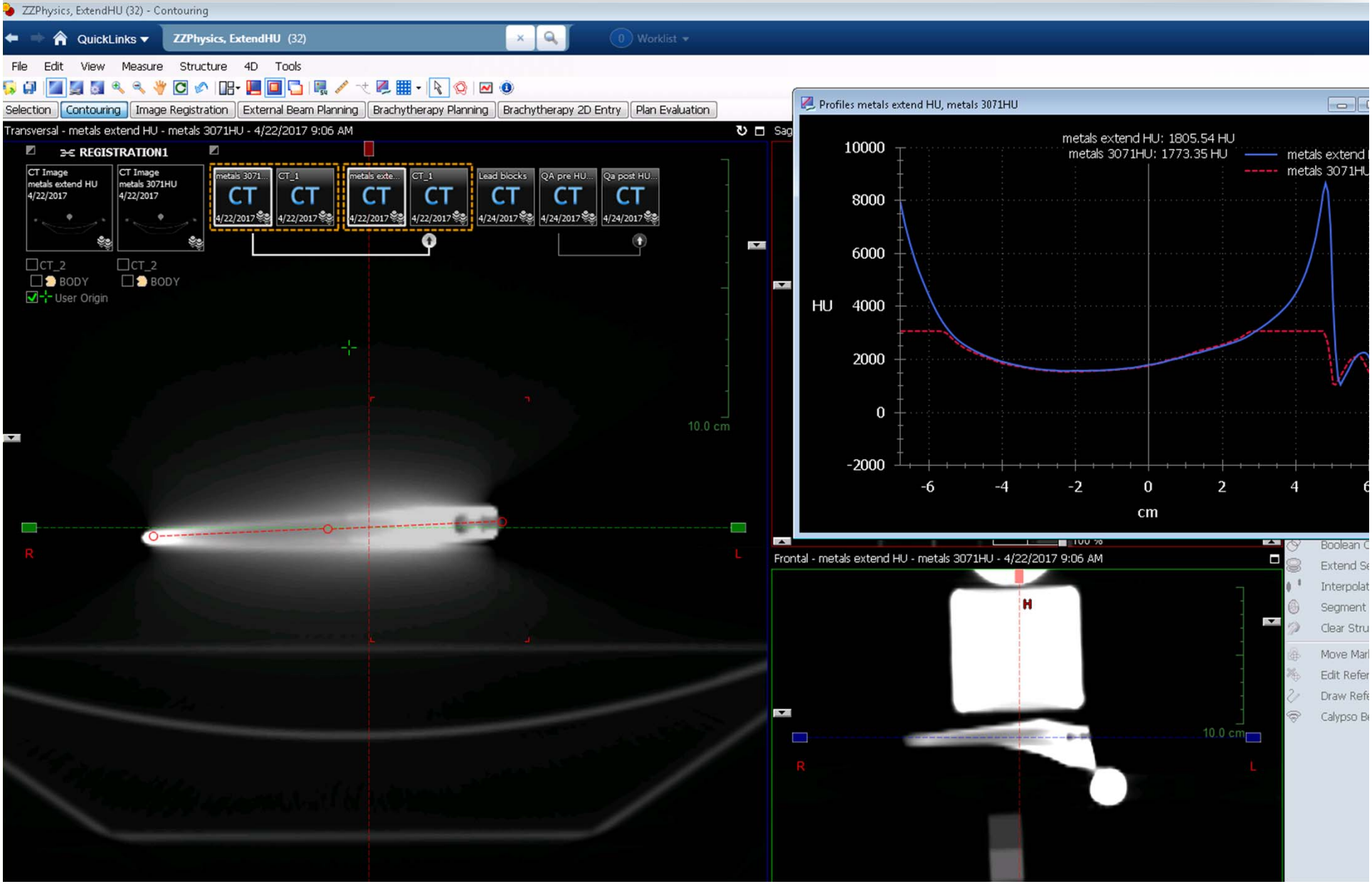
Extended HU through metals



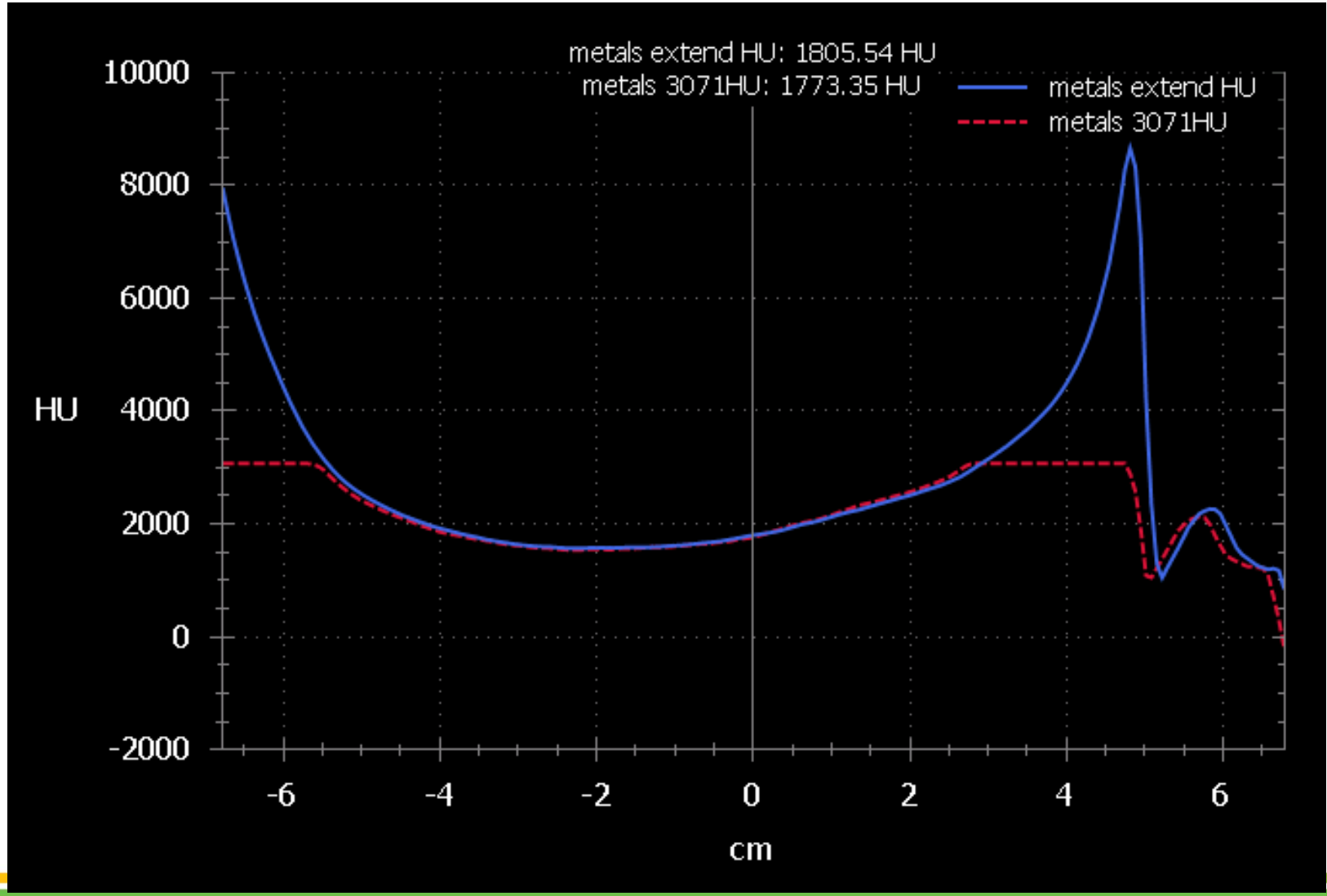
Extended HU through metals



Extended HU through hip prosthesis



Extended HU through hip prosthesis



Do you like to go white water kayaking?

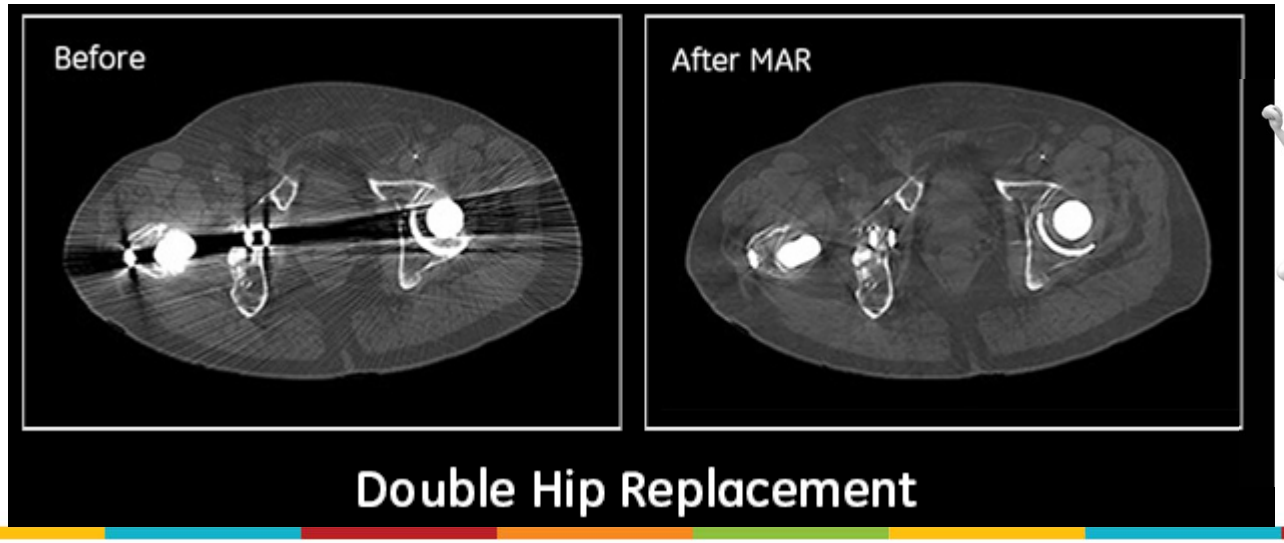
A. Yes

B. No

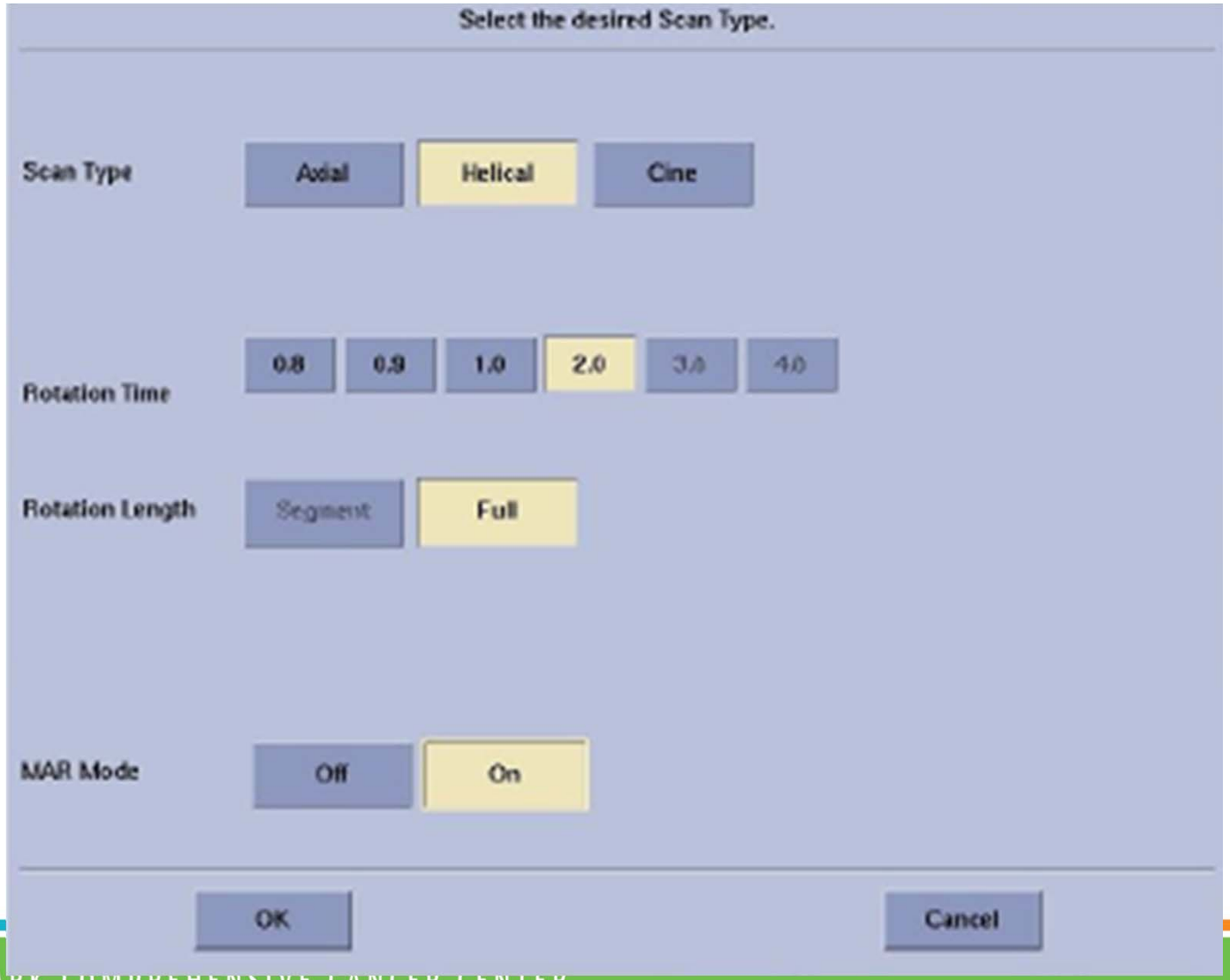
ROSWELL PARK

Metal Artifact Reduction (MAR)

- Helps to reduce photon starvation, beam hardening and streak artifacts caused by metal in the body, such as hip implants.
- Uses same projections as normal CT



MAR selection on GE discovery RT



Benefits of MAR

- Metal implants are more easily delineated.
- No affect on image quality if there is no metal
- Artifact is minimal visually and has negligible inaccuracy on dose calculations
- Save time contouring the artifacts

Limitation of MAR

- Patient anatomy must not extend beyond the 50cm scan field-of-view.
- There will always be a non MAR scan as well.
- Extend additional scan range at both edges of the metal no less than 18mm.
- Must be helical (not axial or cine)
- No gantry tilt

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Amalgam	14 - 16		Teeth filling	0.5
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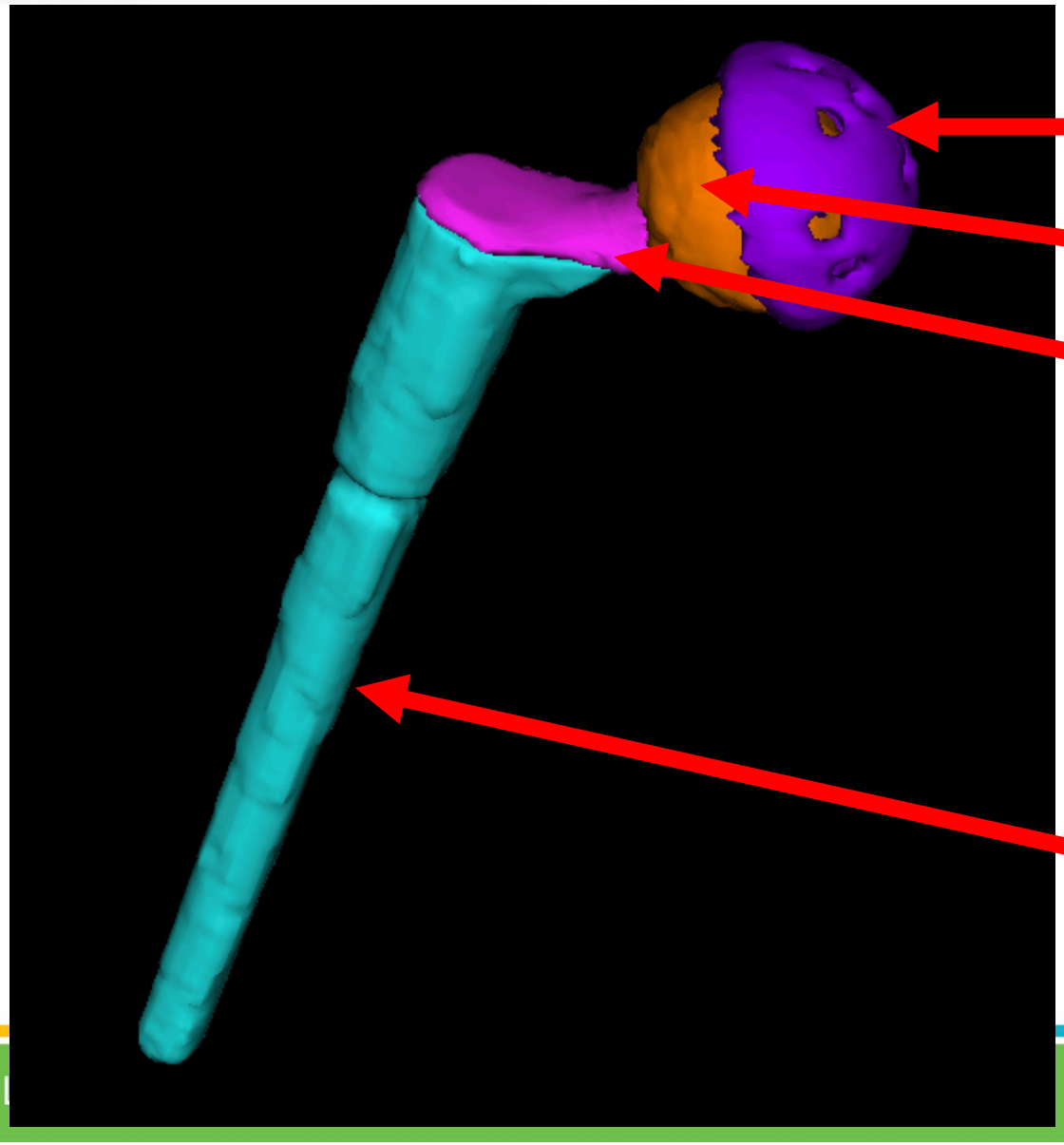
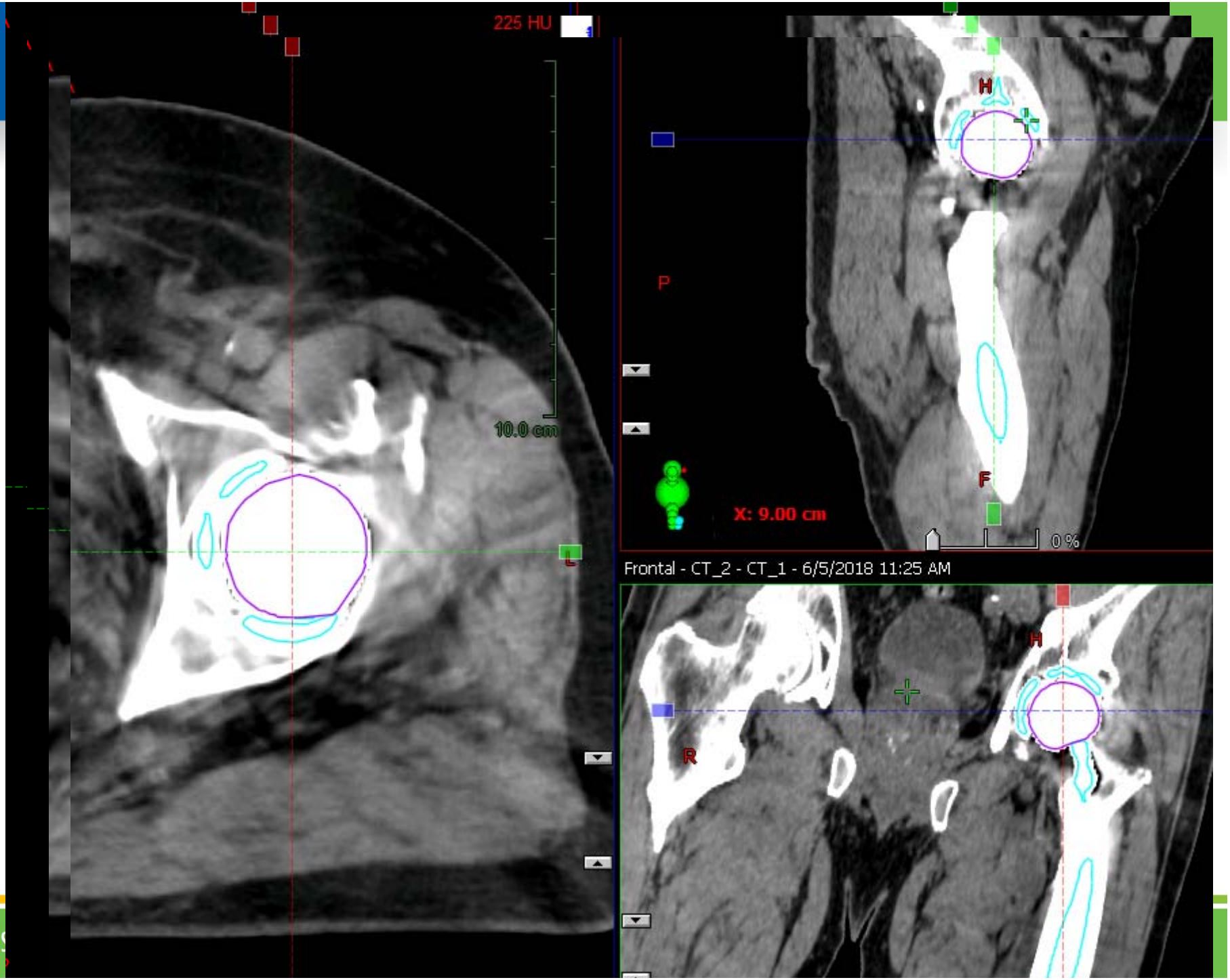
Hip prosthesis

- Neck typically titanium alloy
- Head can be titanium or cobalt-chromium
- Cobalt chromium density 8.4-8.8 g/cc

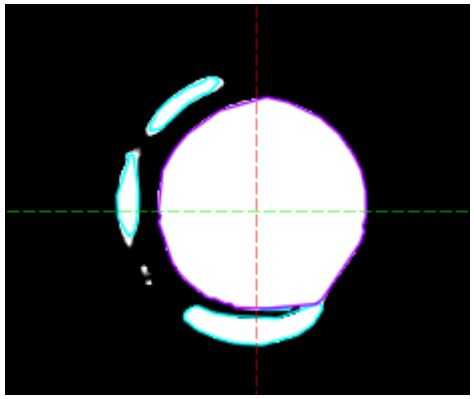
Hip prosthesis assigned densities

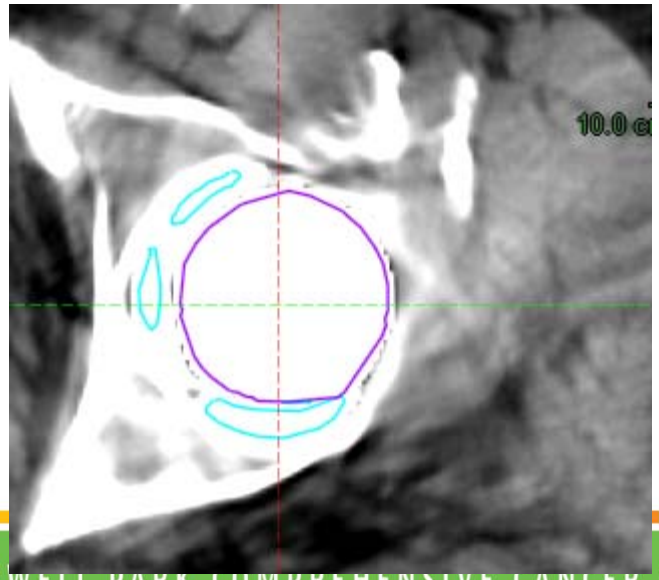



225 HU
10.0 cm
H
P
F
X: 9.00 cm
0 %
Frontal - CT_2 - CT_1 - 6/5/2018 11:25 AM
H
R

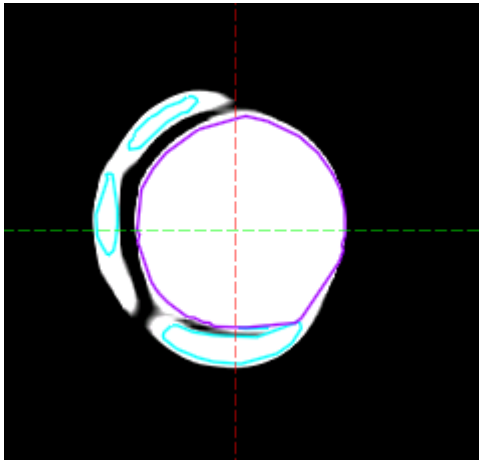
MAR and window/level

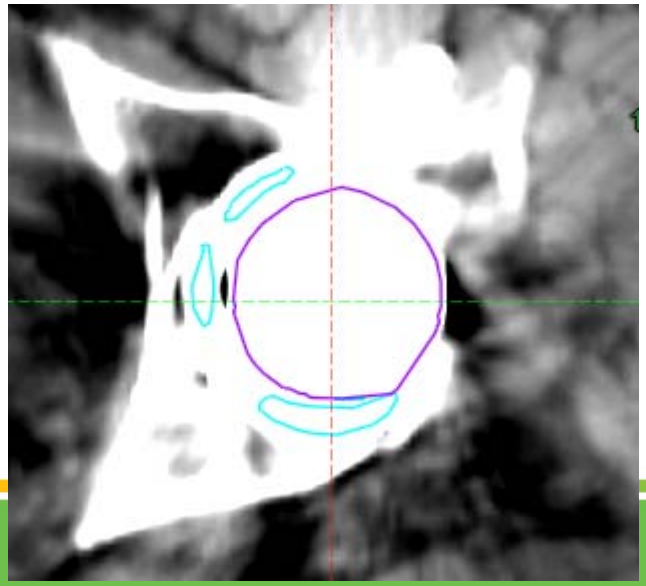
MAR

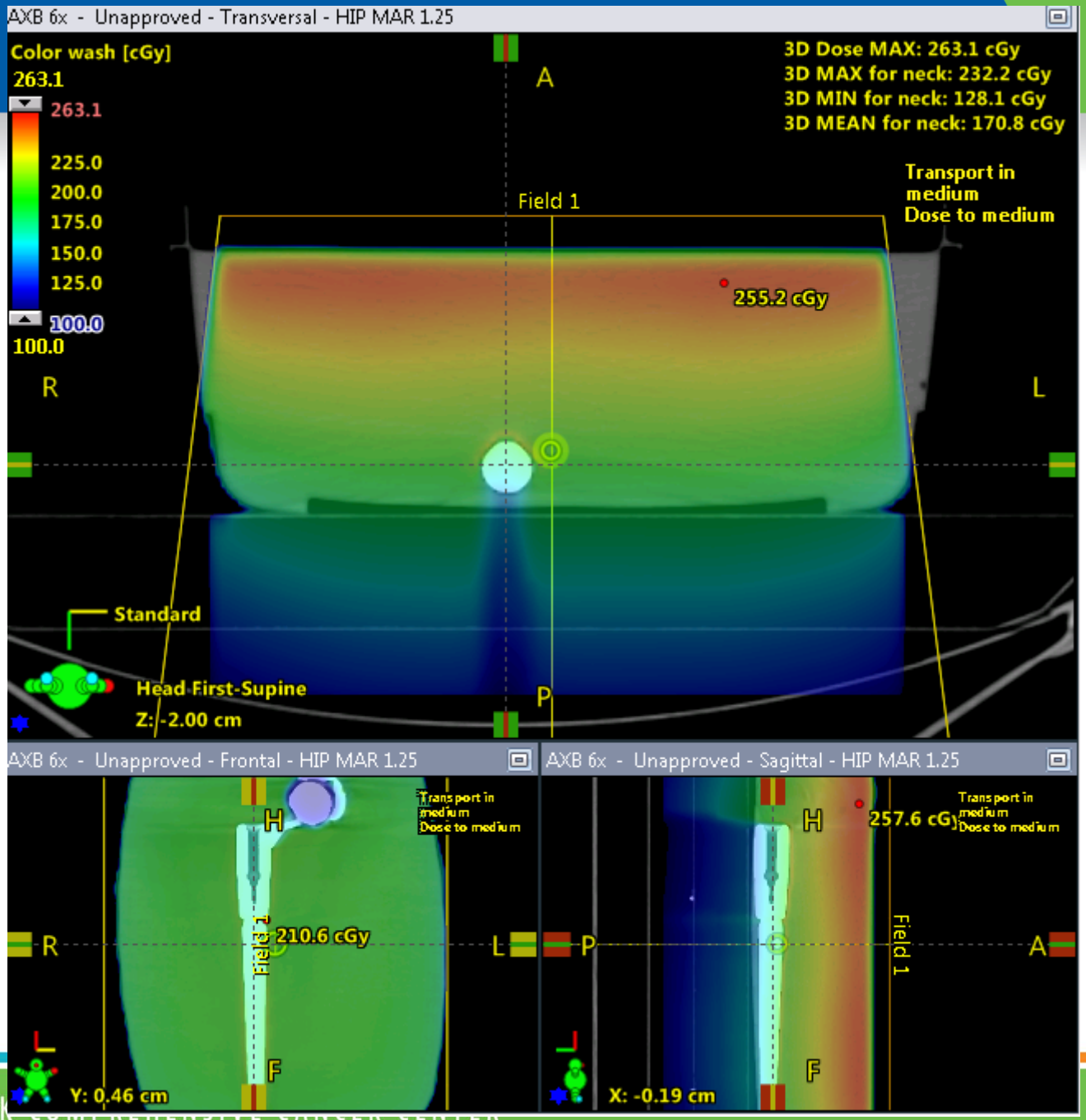


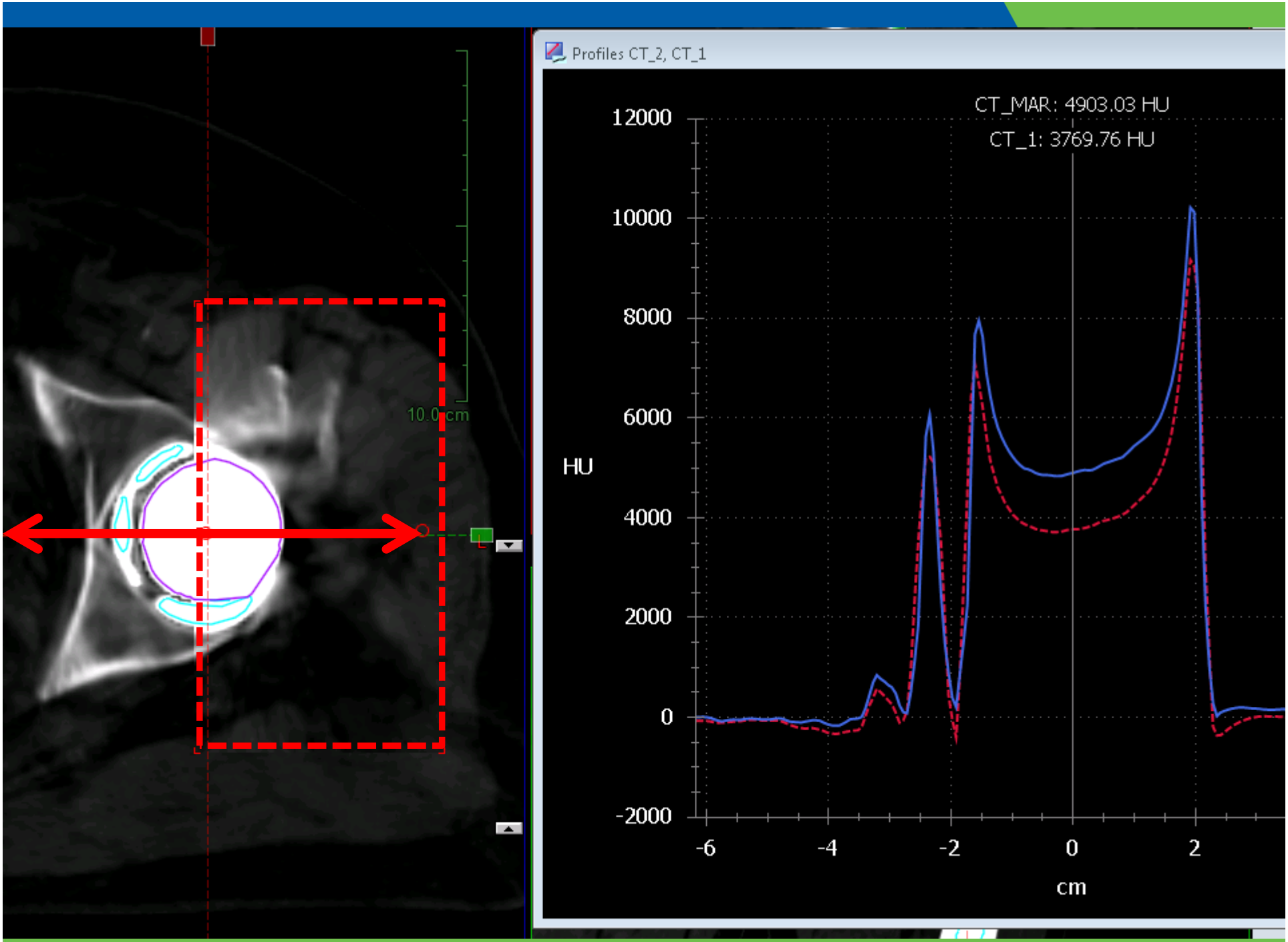


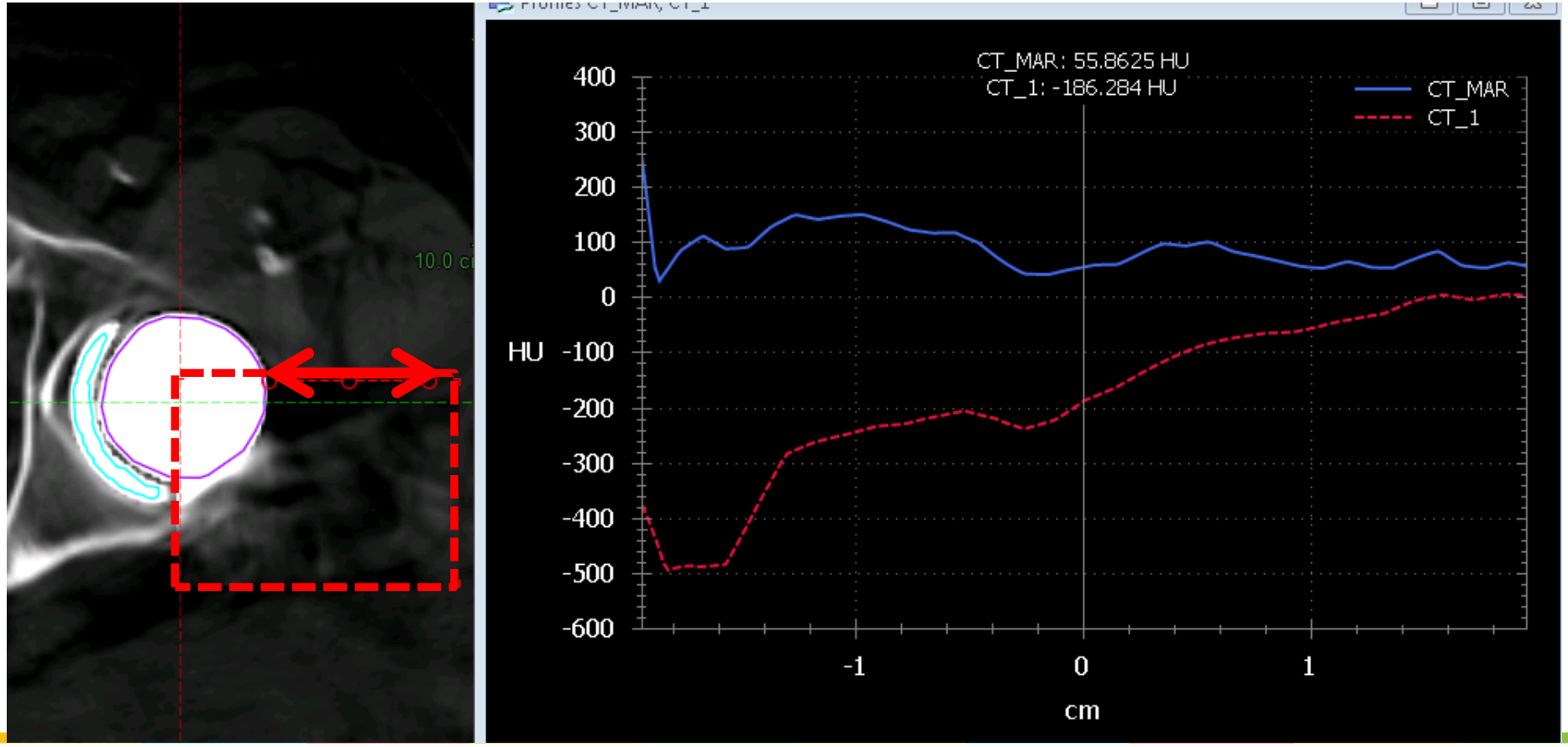
Non-MAR






AXB 6x - Unapproved - Transversal - HIP MAR 1.25
Color wash [cGy]
263.1
263.1
225.0
200.0
175.0
150.0
125.0
100.0
100.0
3D Dose MAX: 263.1 cGy
3D MAX for neck: 232.2 cGy
3D MIN for neck: 128.1 cGy
3D MEAN for neck: 170.8 cGy
Transport in medium
Dose to medium
A
Field 1
255.2 cGy
R
L
P
Standard
Head First-Supine
Z: -2.00 cm
AXB 6x - Unapproved - Frontal - HIP MAR 1.25
Transport in medium
Dose to medium
H
210.6 cGy
Field 1
R
L
F
Y: 0.46 cm
AXB 6x - Unapproved - Sagittal - HIP MAR 1.25
Transport in medium
Dose to medium
H
257.6 cGy
Field 1
P
A
F
X: -0.19 cm

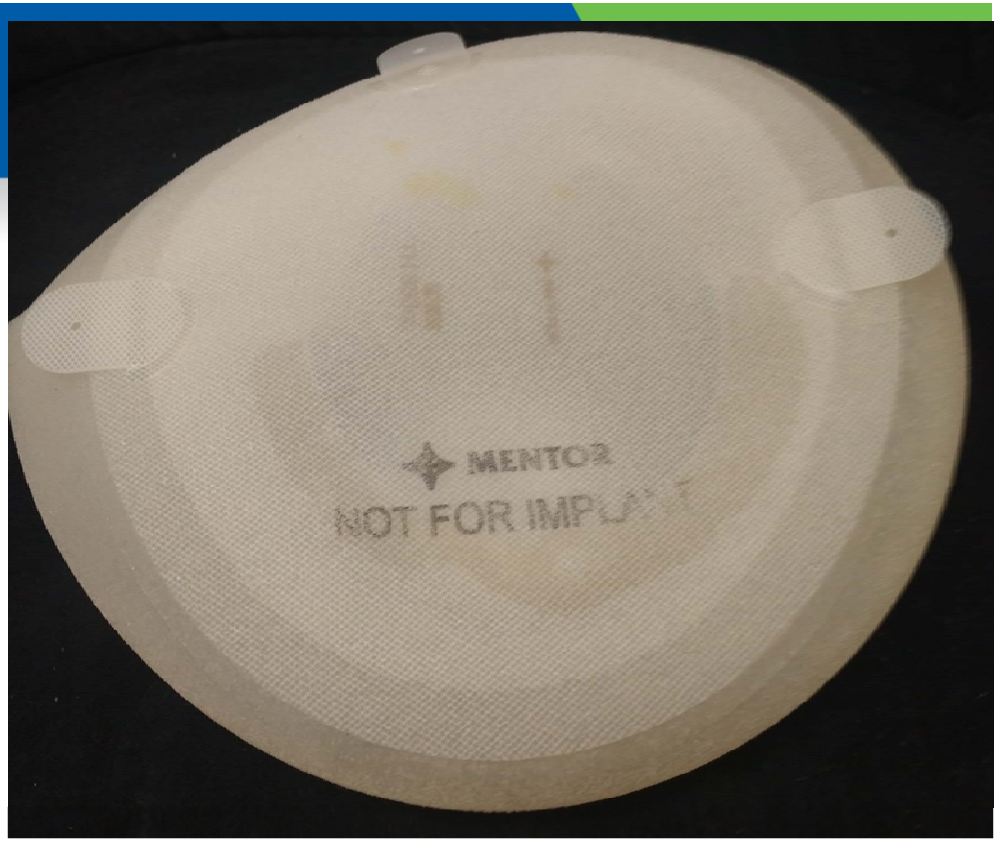

10.0 cm
Profiles CT_2, CT_1
CT_MAR: 4903.03 HU
CT_1: 3769.76 HU
12000
10000
8000
6000
4000
2000
0
-2000
HU
-6
-4
-2
0
2
cm


CT_MAR: 55.8625 HU
CT_1: -186.284 HU
CT_MAR
CT_1
400
300
200
100
0
-100
-200
-300
-400
-500
-600
HU
-1
0
1
cm

What is your centers most common method for treating VMAT prostate with a hip prosthesis?

A. Avoid entering through the prosthesis
B. Avoid entering and exiting through the prosthesis
C. Perform density correction using the measured HU
D. Assign a bulk density to the prosthesis

Breast Expanders



- neodymium magnet
  - height of 4.7 mm
  - diameter of 12.7 mm
- encased in stainless steel
  - 0.25 mm thick
- overall external dimensions are approximately
  - 36.5 mm inches in diameter and 10 mm in height

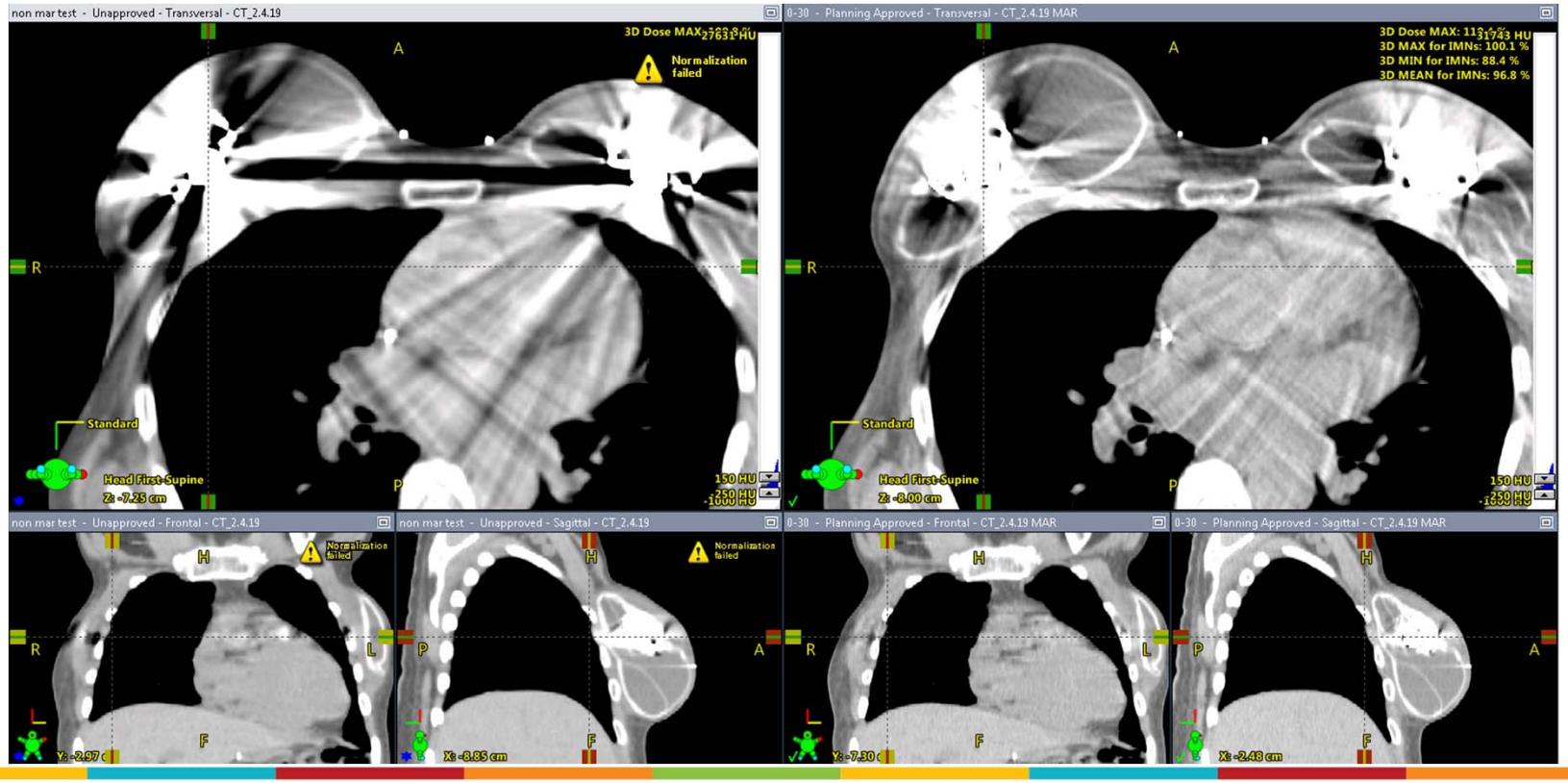
Breast tissue expander

Radiation Therapy

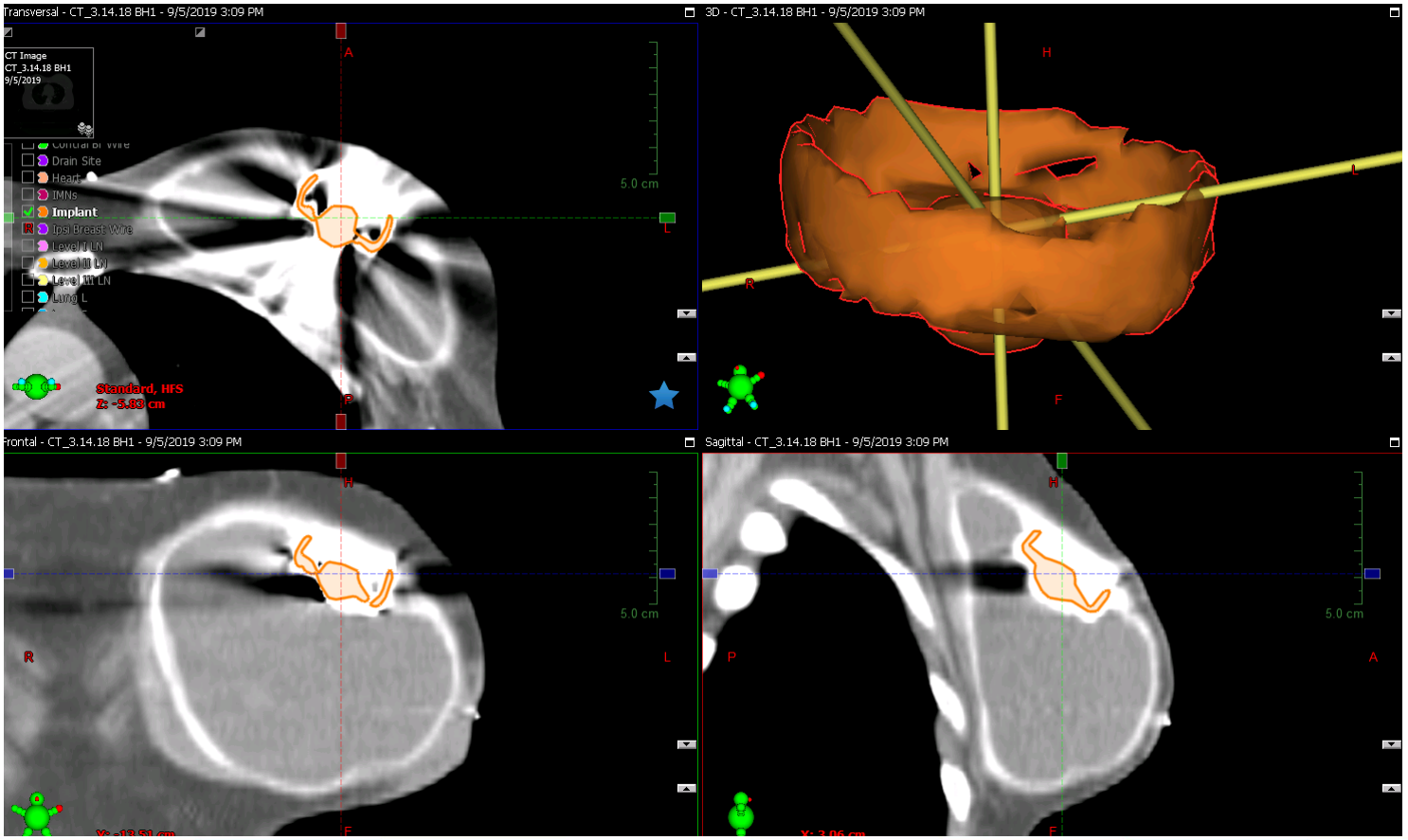
Mentor has not tested the *in-vivo* effects of radiation therapy with these devices and cannot warrant the safety of such use. The decision regarding the use of these devices in patients about to undergo radiation therapy should be made by the surgeon and the radiation oncologist.

Breast expander

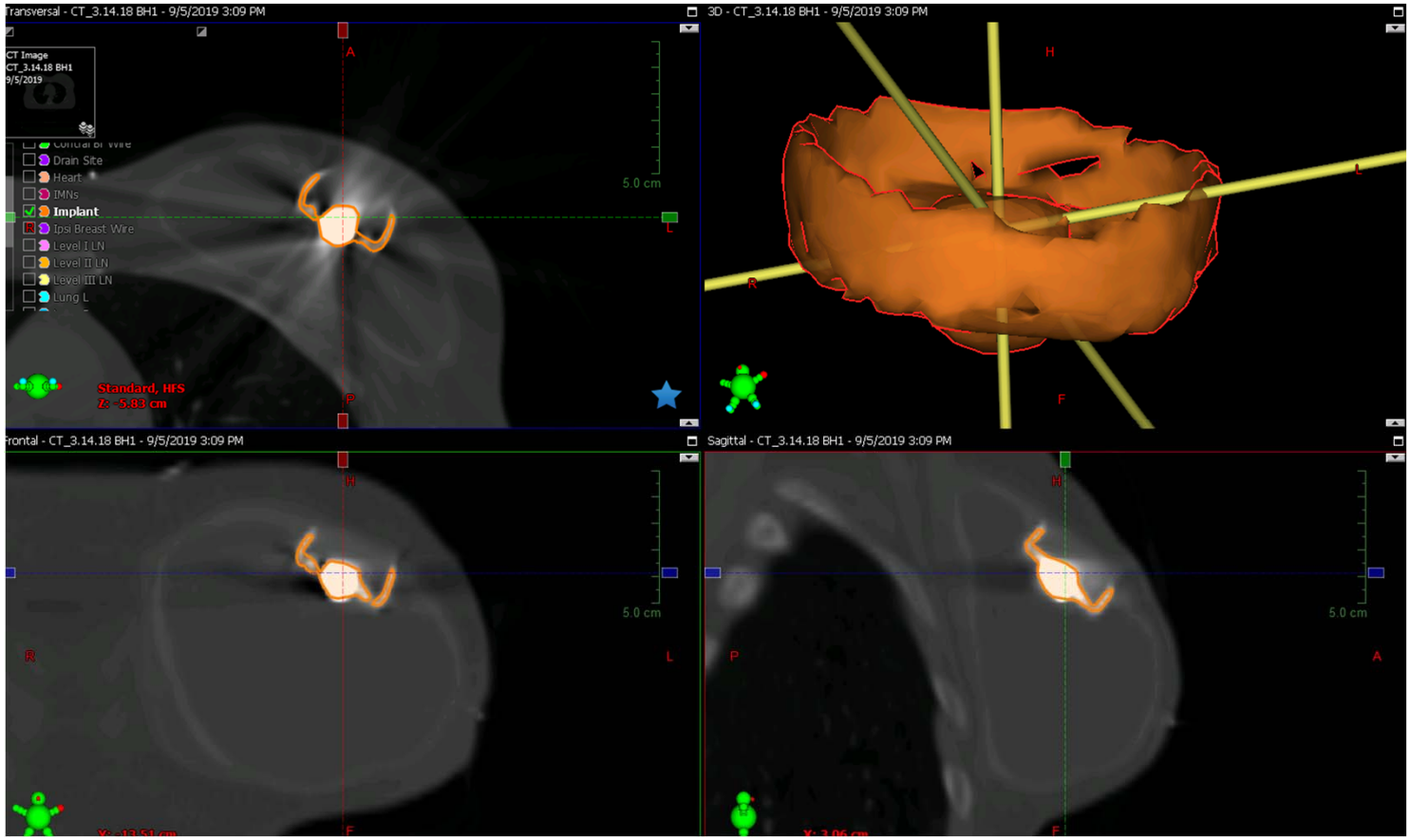
Non MAR **MAR**



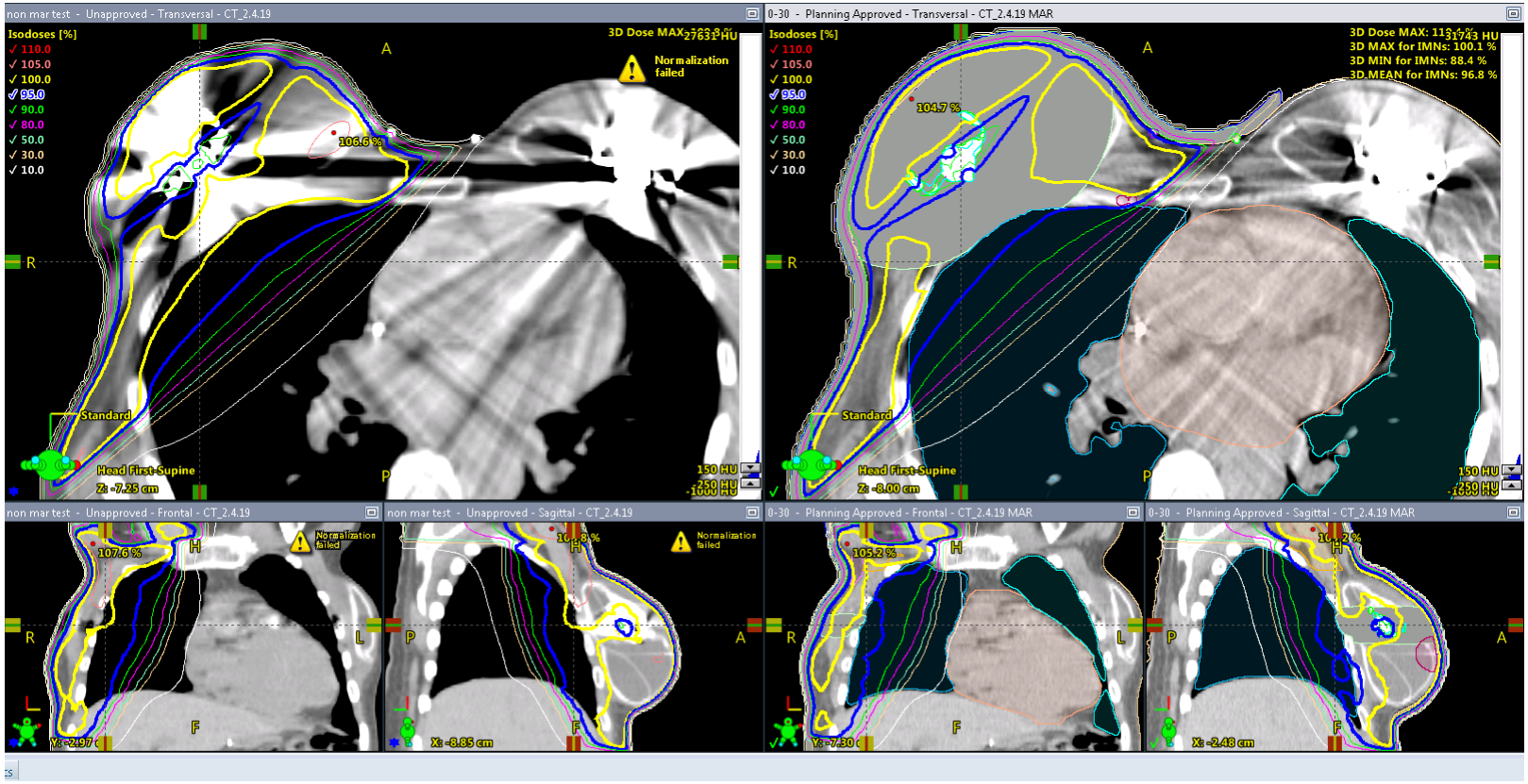
Non- MAR extended HU – breast W/L



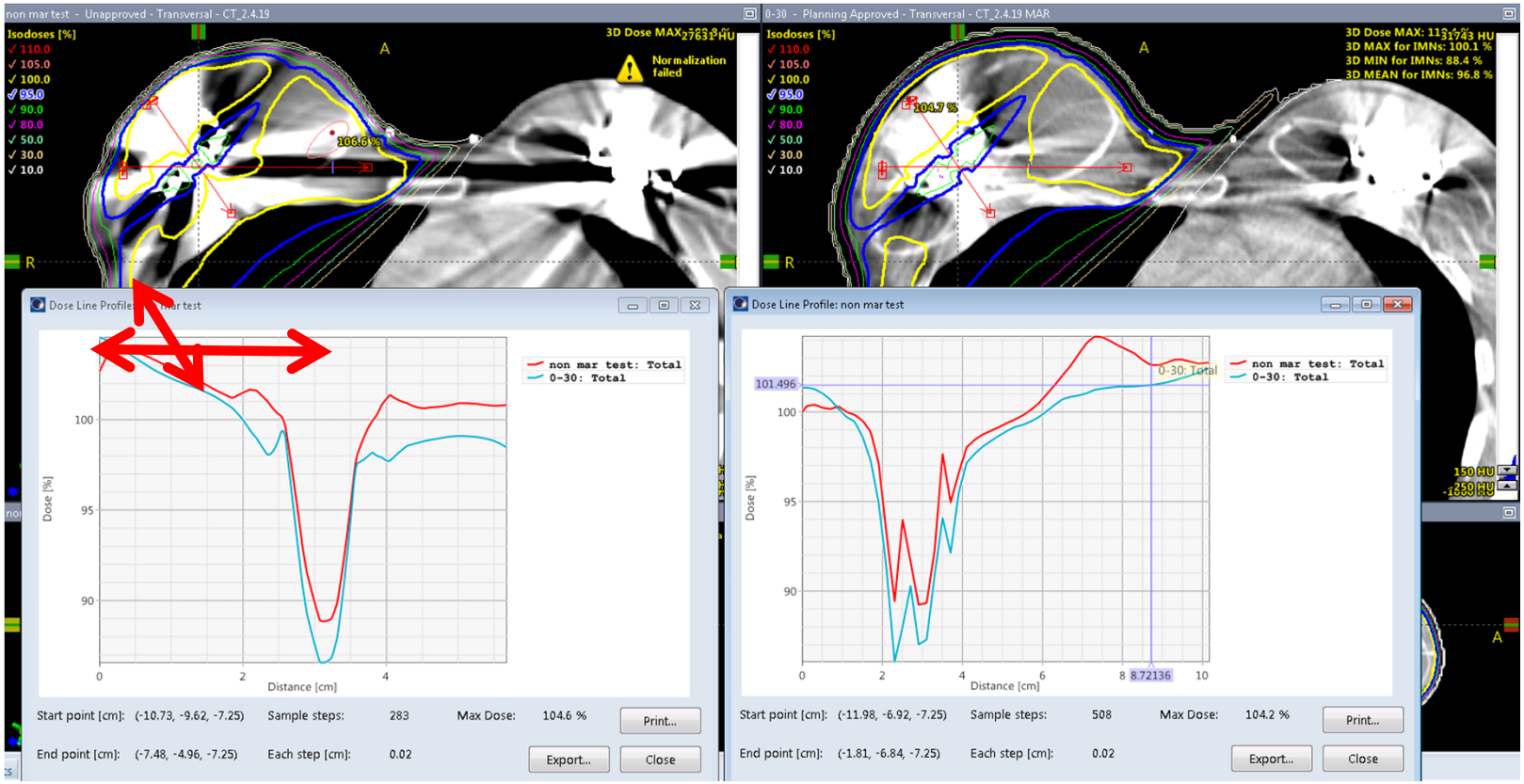
MAR extended HU



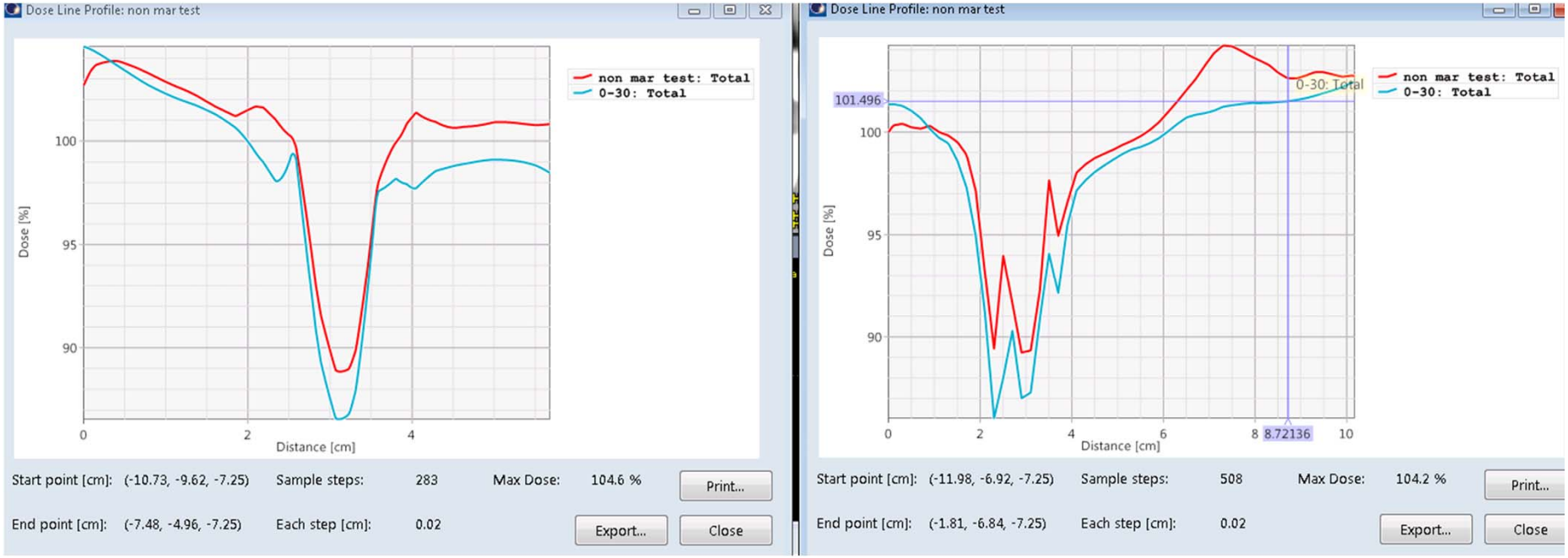
Bulk density on MAR image



Dose profiles through expander

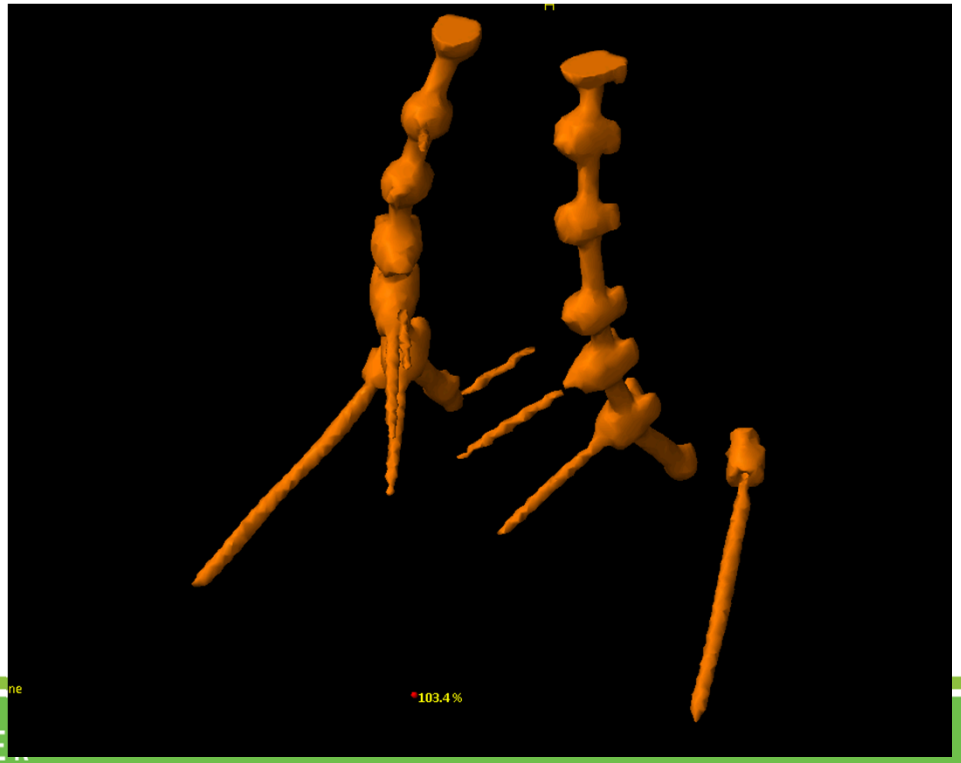


Dose profiles through breast expander

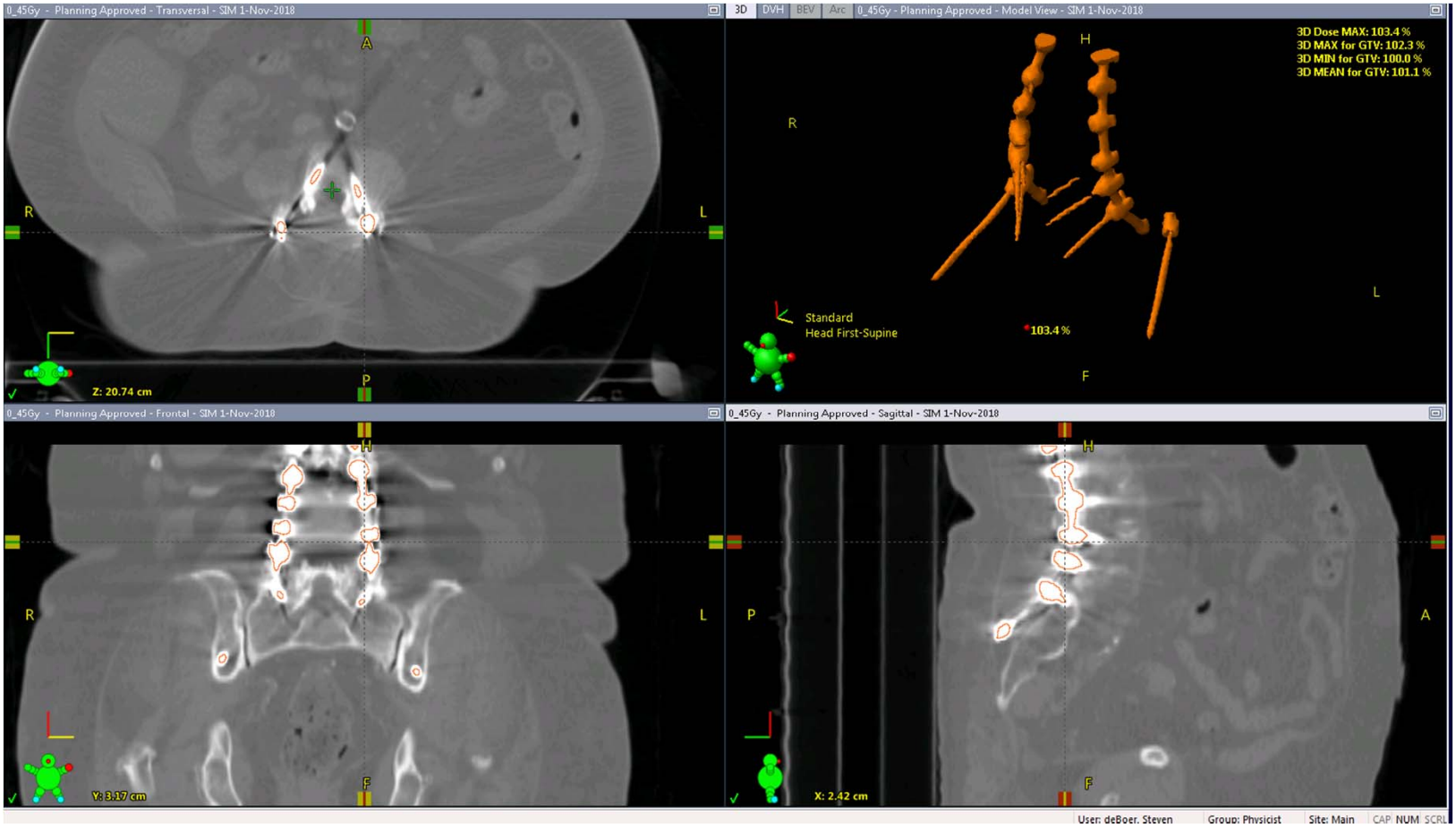


Spinal fixation

- Rods typically titanium alloy
- Screws may be stainless steel



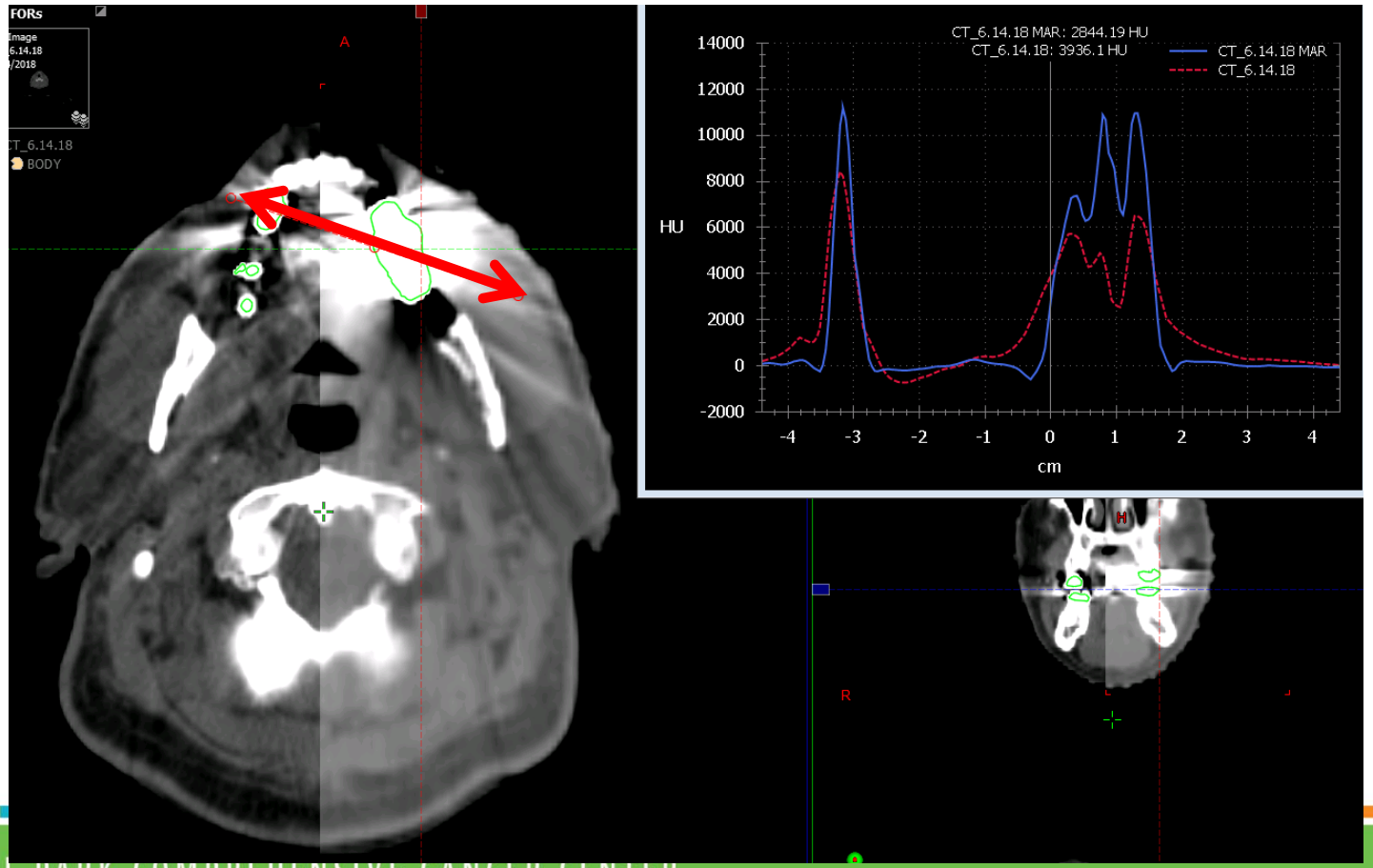
Spinal fixation



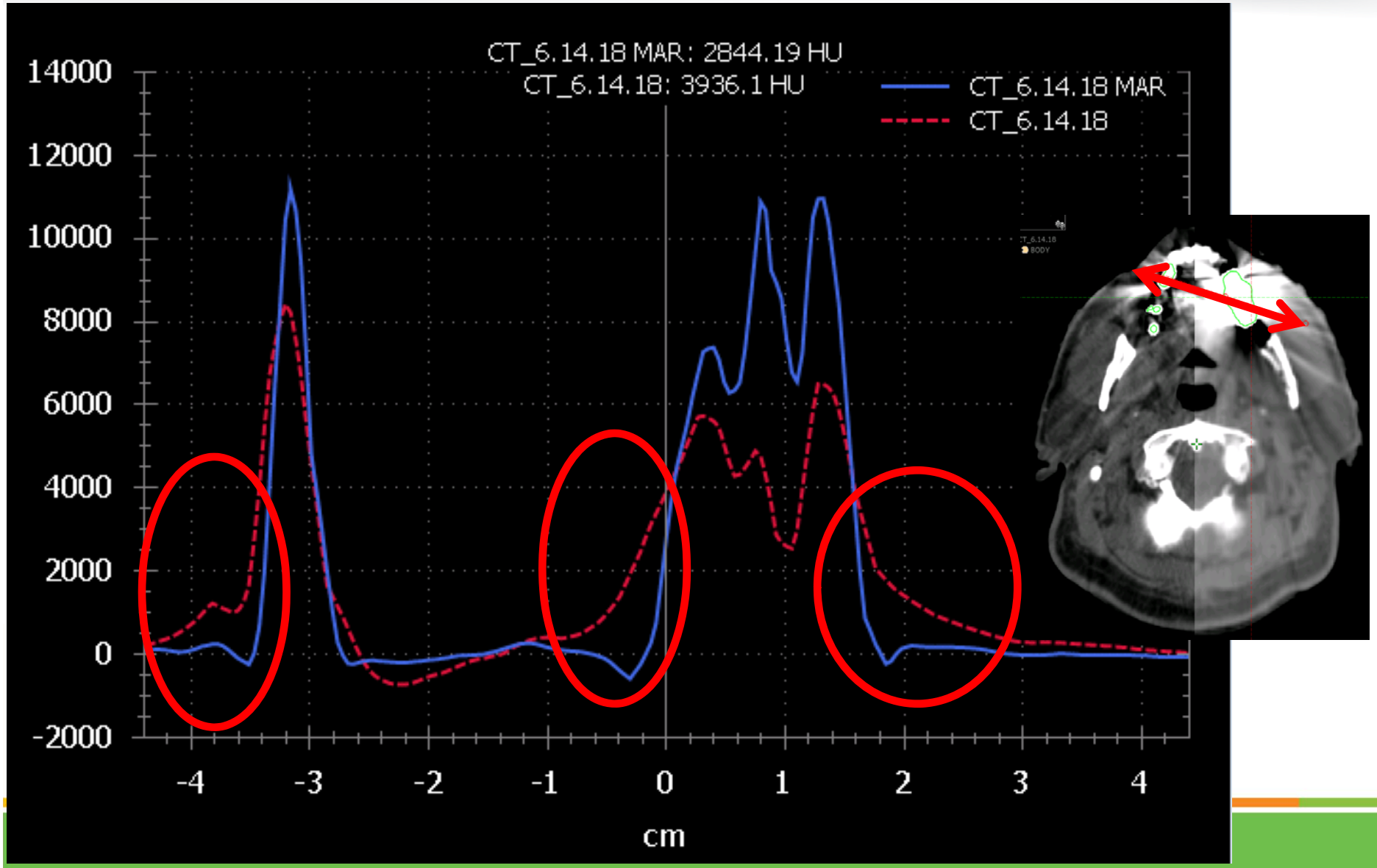
Dental Fillings

- Historically silver amalgam (silver, mercury…)
- Density 14-16 g/cc
- Not currently commonly used but very common is current and near future patient population
- Large artifacts, very hard to contour
  - (should it be teeth, lips, air…?)
- MAR and extended HU very helpful

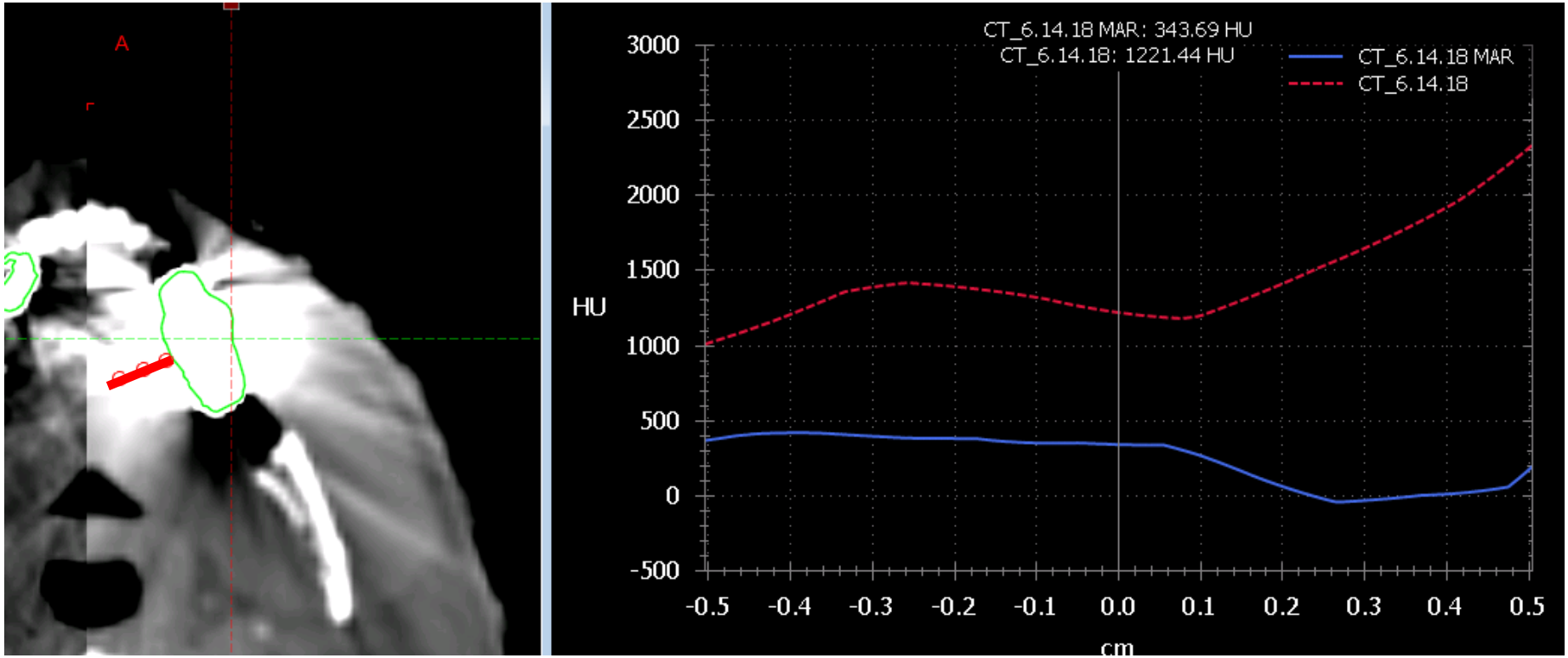
HU profile through dental amalgam



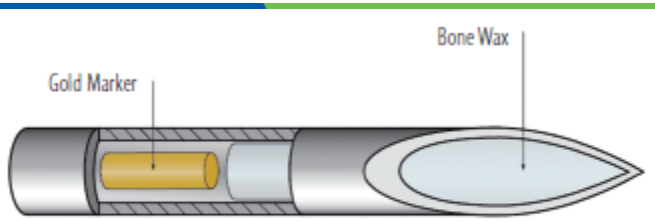
HU profile through dental amalgam



HU profile in dental artifact

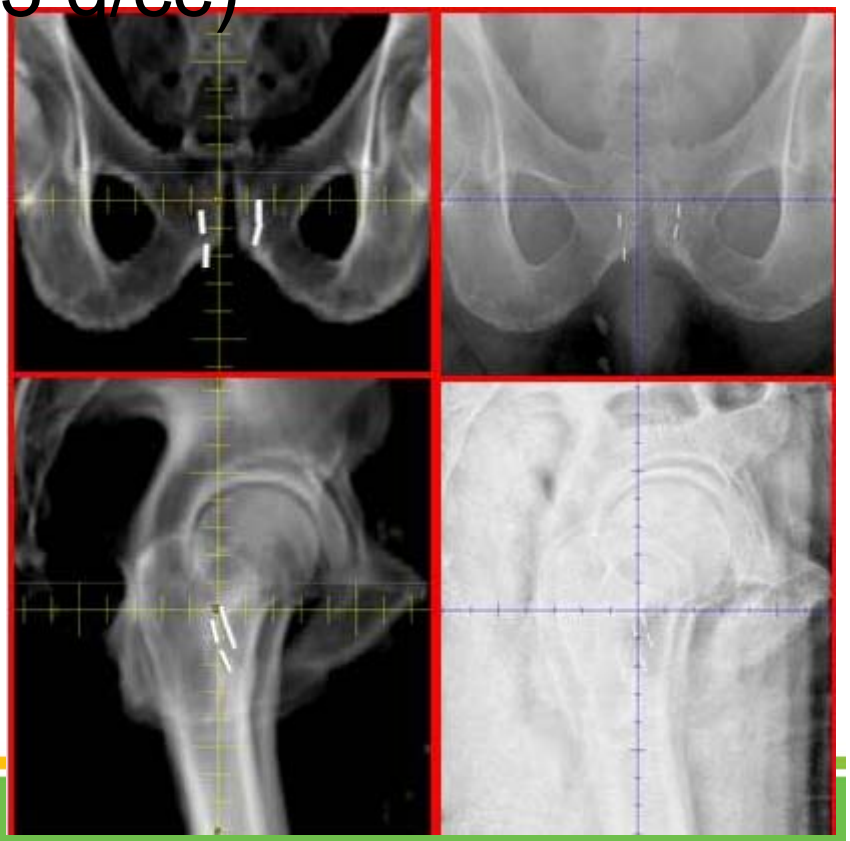


Gold seeds



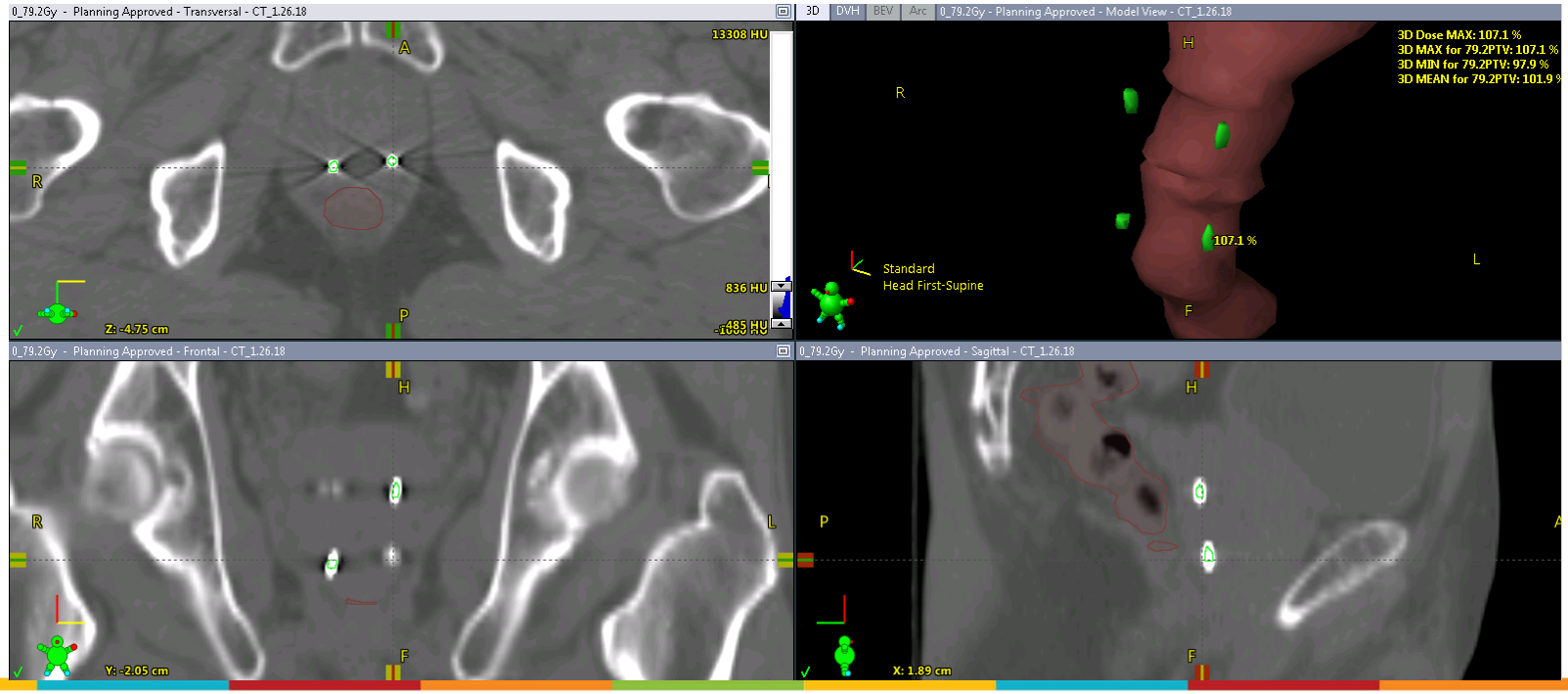
Mick® Gold Fiduciary Markers are each individually preloaded in a pre-waxed needle

- Used for matching prostate location with orthogonal kV imaging
- (Pure gold (z=79, ρ = 19.3 g/cc)
- 0.08 to 0.12 cm diameter
- 0.3 to 0.5 cm long



Gold seeds: Challenges for dose calculation

- Contoured diameter about 0.25 but actual diameter is 0.08 cm
- Volume is over estimated by a factor of 5 to 10 times



Gold seeds: dose grid limit

- The actual size of the seeds (0.08 cm) is smaller than the 0.1 cm dose grid.
- Calculations at this level are not expected to be accurate.
- Experiments with 6 cm long by 0.08 cm diameter seeds placed 0.25cm apart demonstrated that the shadowing of the gold seeds was not seen for every seed using a single direct field.

Gold seeds: HU and artifacts

- Gold HU can be underestimated due to small size.
- The dose calculation is affected by both high and low density artifacts
- Artifacts may not be consistent between different seeds, seed location, seed orientation, kVp used or patient.

Experiment 2

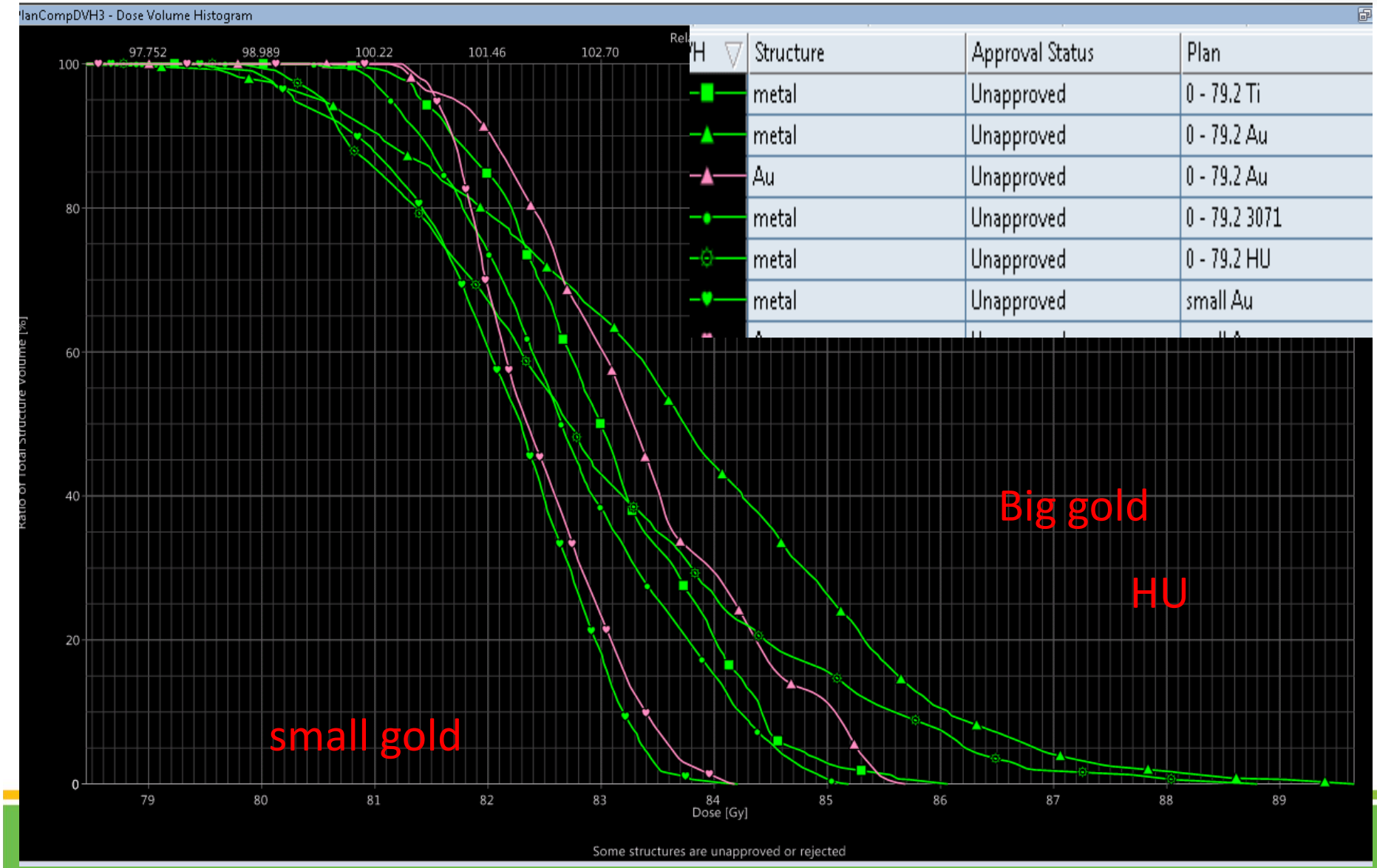
- VMAT prostate
- Define seeds with
  - different HU (density)
  - different volume (actual versus imaged)
- Calculate dose

Effects of seed size defined by CT and assigned density of gold

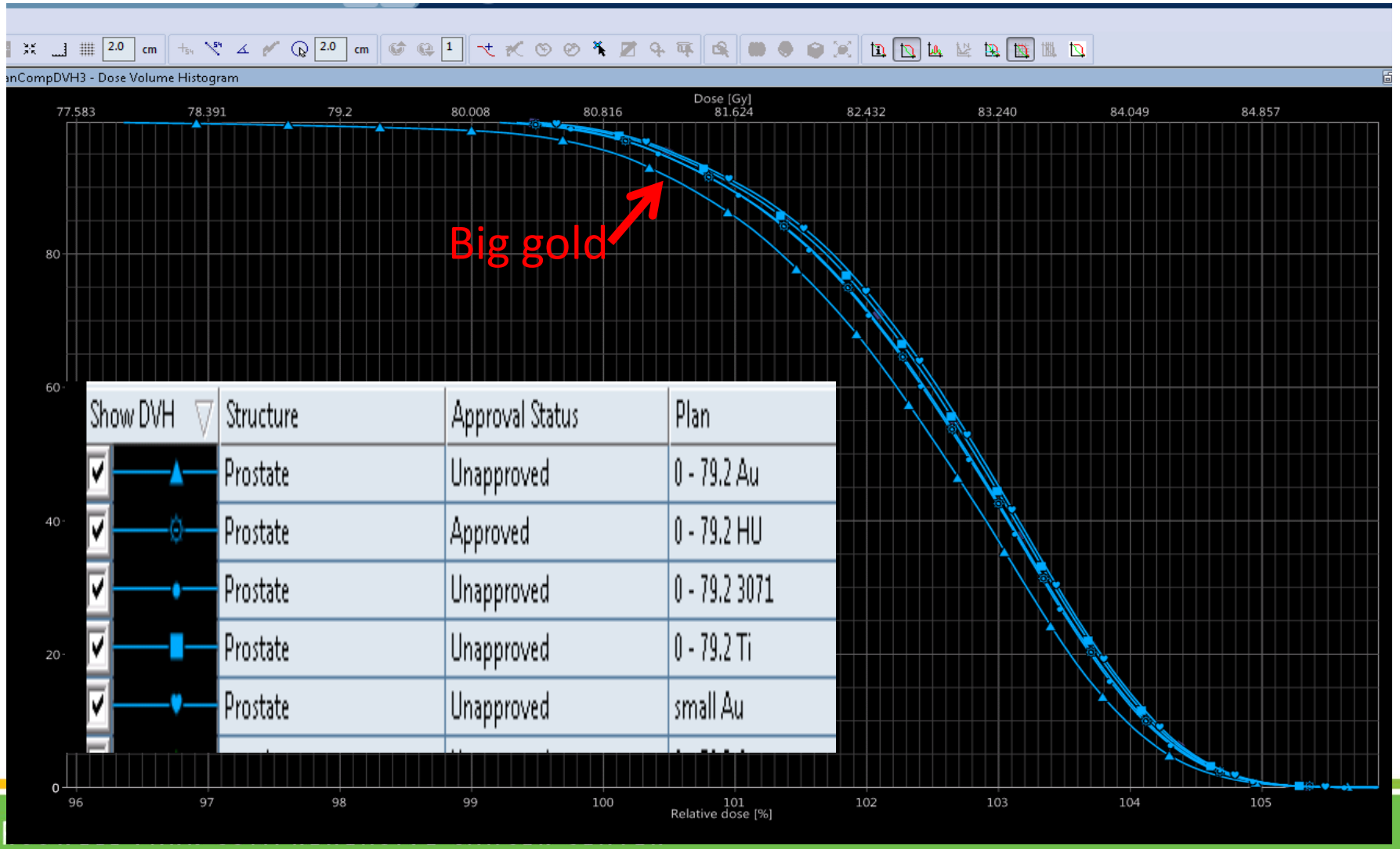
- Prostate:
- There is a small but significant volume of the prostate being under dose with the definition of gold to the 0.25 cm seed delineation.
- The maximum dose to the prostate is significantly higher (very small volume) when the 0.25 cm seed is defined as gold or if the CT HU are used.
- Nearly all of the high doses occur within the seeds.

VMAT seed and prostate dose with different contours and densities

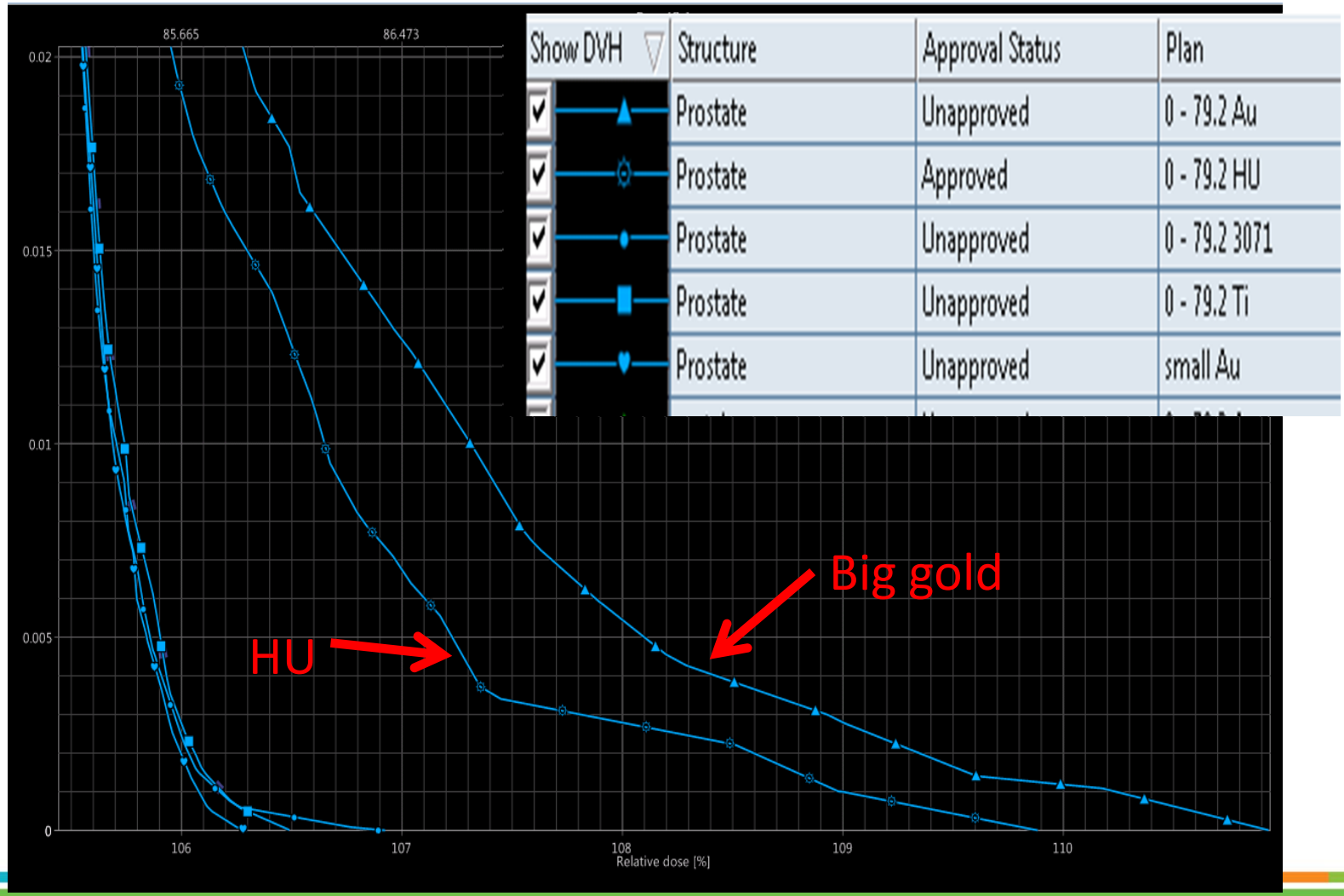
Seed Definition	Seed size (cm)	Seed HU	Artifact HU	Seed dose (%)			Prostate dose (%)		
				min	max	mean	min	max	mean
3071	0.25	3071	0	99.5	105.4	102.4	97.9	106.9	102.6
CT HU	0.25	<4306> 1415 to 10748	NA	98.7	109.9	102.7	96.8	109.9	102.6
Ti	0.25	4304	0	99.6	106.5	102.8	**98.5**	**106.5**	**102.7**
Au	0.25	14869	0	96.6	110.9	103.6	92.6	110.9	102.4
Au small	0.08	14869	0	100.5	104.2	102.0	98.3	106.3	102.7


lanCompDVH3 - Dose Volume Histogram
97.752
98.989
100.22
101.46
102.70
100
80
60
40
20
0
79
80
81
82
83
84
85
86
87
88
89
Dose [Gy]
Some structures are unapproved or rejected
Structure
Approval Status
Plan
metal
Unapproved
0 - 79.2 Ti
metal
Unapproved
0 - 79.2 Au
Au
Unapproved
0 - 79.2 Au
metal
Unapproved
0 - 79.2 3071
metal
Unapproved
0 - 79.2 HU
metal
Unapproved
small Au
small gold
Big gold
HU

VMAT prostate dose with Au fiducials



Prostate D_{max} with Au seeds



Gold seeds: Conclusion/recommendations

1. Defining the seed as 0.25 cm and assigning gold is an over estimation of the material in the prostate and should not be used. It would lead to erroneously reported maximum and minimum doses.
2. Allowing the CT to define the HU will be highly variable and should not be used.
3. Defining seeds as the actual size of 0.08 cm is extremely time consuming and not accurate or practical.
4. **The seeds should be defined as the 0.25 cm diameter and assigned a density of titanium.**
5. **For VMAT cases, defining the seeds and artifact as water will have minimal effect on the prostate reported dose (except hot spot)**

- While recommendation 4 does not have strong evidence that it is the most accurate, it does fall between the extremes which have strong argument to be inaccurate. Furthermore, published papers using monte carlo showed that the dose shadow effect is minimal (< 5%) for a parallel opposed beam set so it is expected the effect would be even smaller for a VMAT plan. The backscatter dose enhancement is still present to an extremely sm volume but it is impractical to attempt to calculate this accurately with our current sy

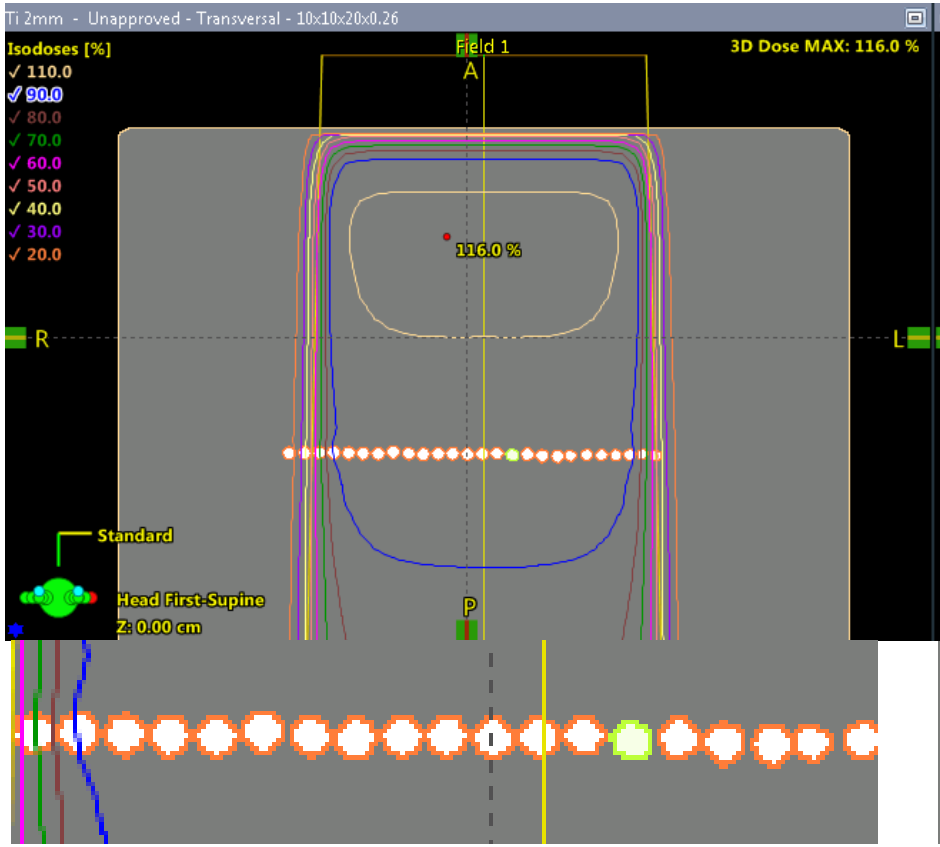
Other investigations: gold seeds

From Pontoriero et al

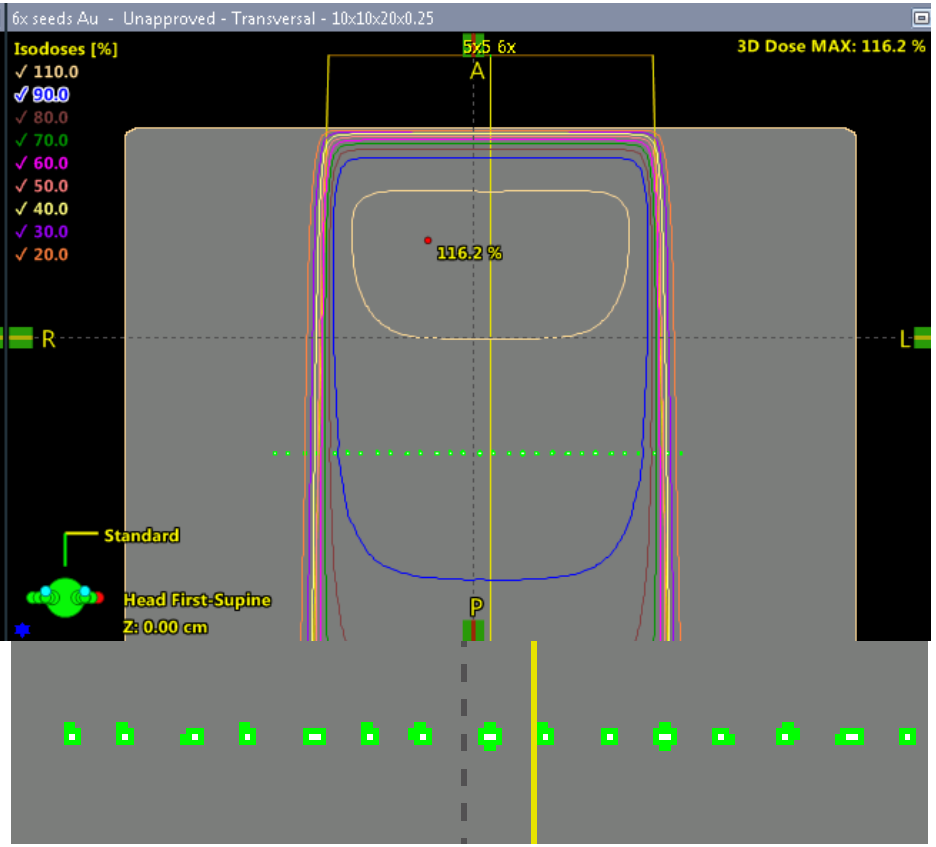
- less relevant when more beams are delivered.
- dose reduction was within 5% at 6 MV and 2% at 18 MV, when using two parallel and opposed beams. *Vassiliev et al.*
- 5 fields 17% hotspot at fiducial

Contoured seed size and assigned density

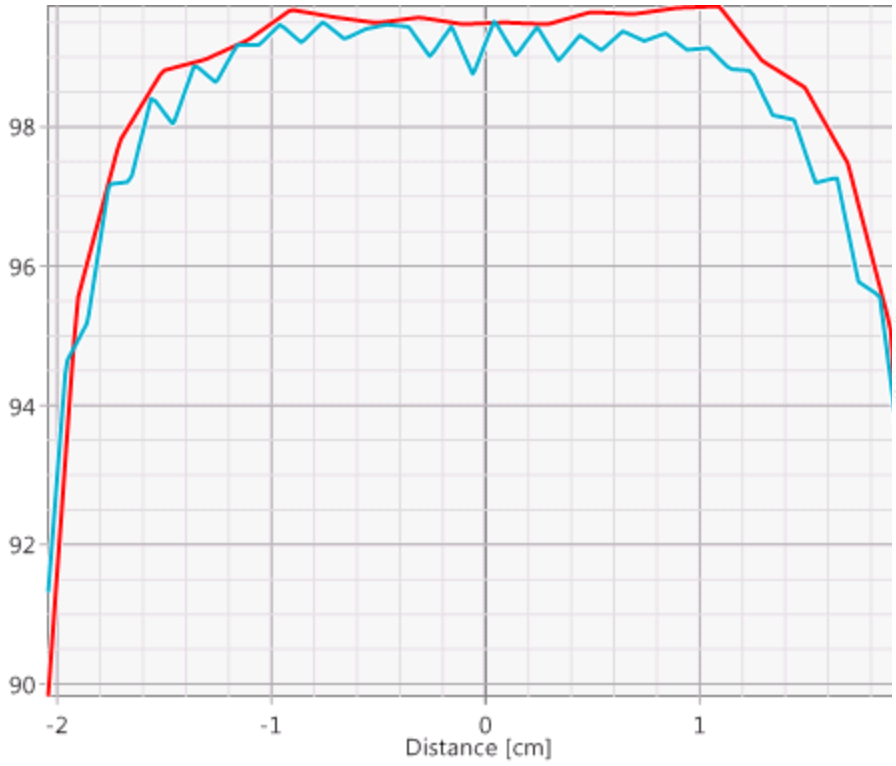
2.5 mm titanium



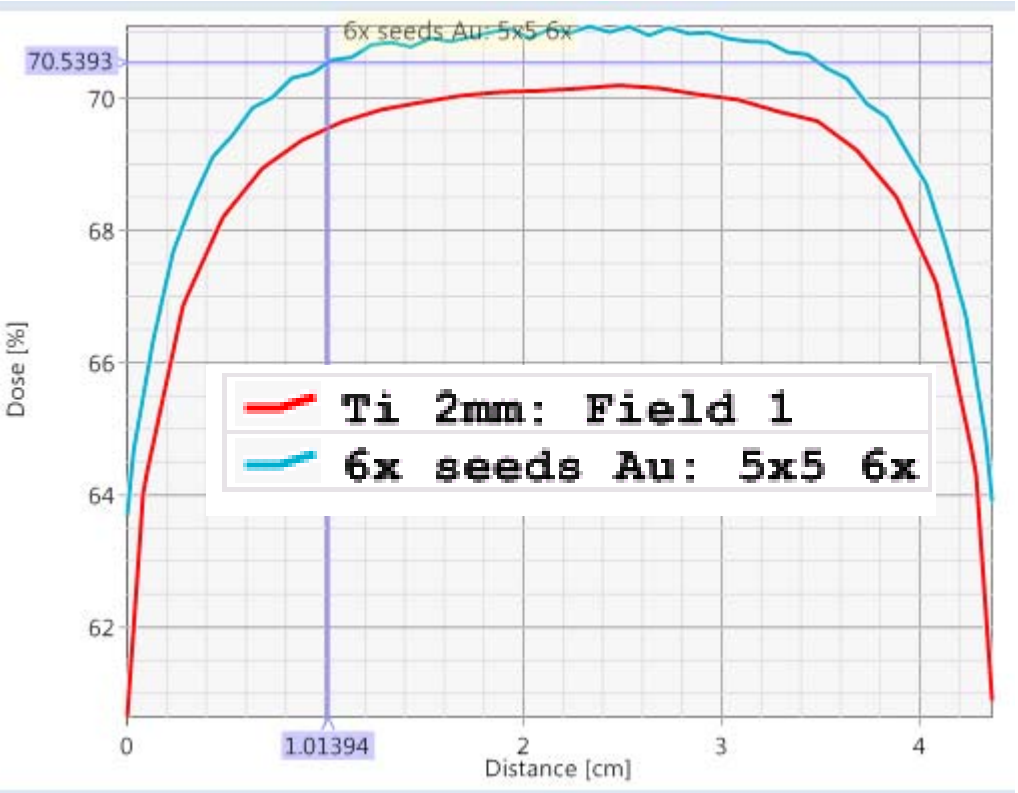
0.8 mm gold



Just beyond seeds



4 cm beyond seeds

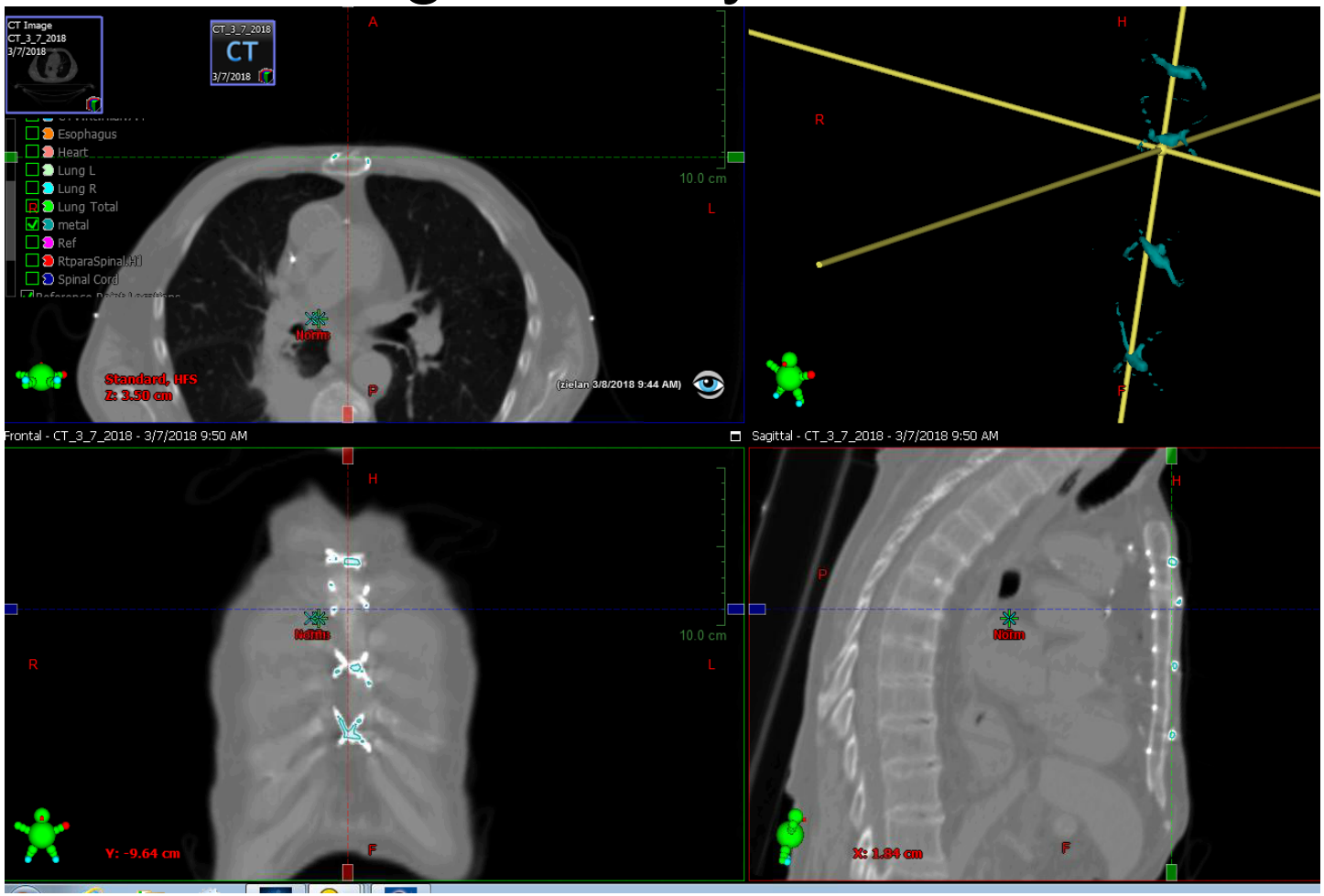


Surgical wires

- Typically used for sternal chest closure
- Wires about 1 mm thick, wound in helical pattern
- Stainless steel
- Large image artifact
- Small shadow

Surgical wire

- Stainless steel, high density, small shadow

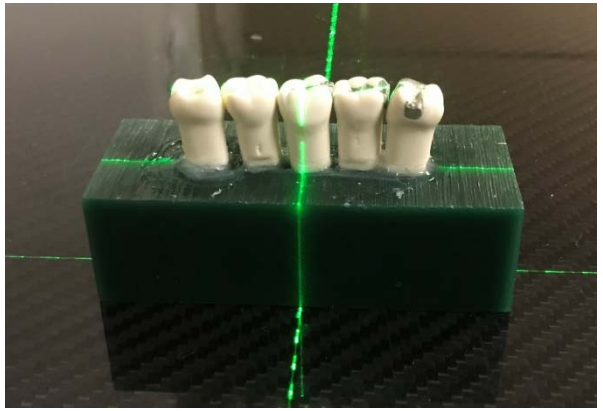


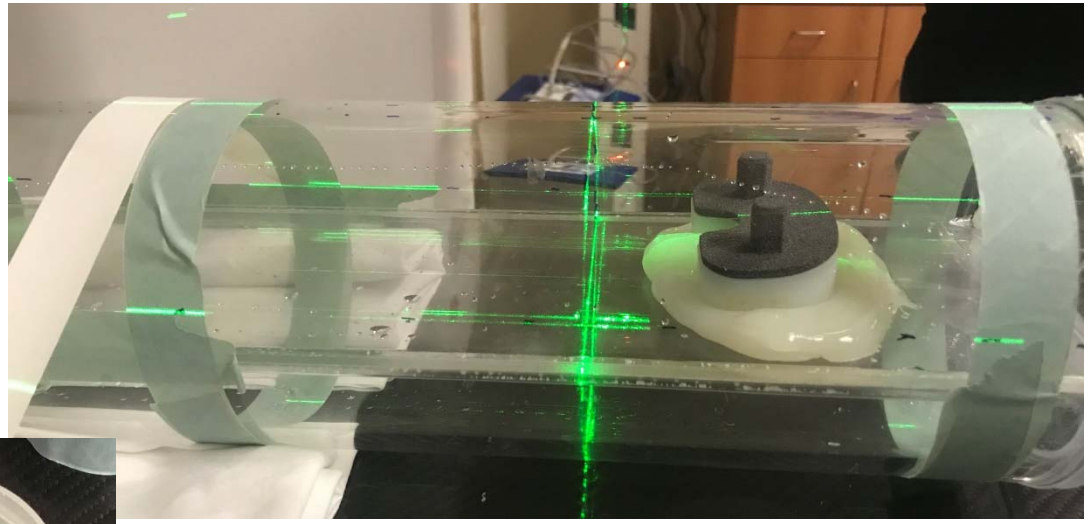
Conclusions / Recommendation

- Assign densities to metals and artifacts
- Extended HU can help differentiate metals and in delineating the objects
- Artifacts should be overridden
- Thin metals (Au seeds, surgical wire) only have local effect
  - Do not over contour
- MAR can
  - Yield more accurate HU
  - Help in metal delineation
  - Reduce streaking artifact

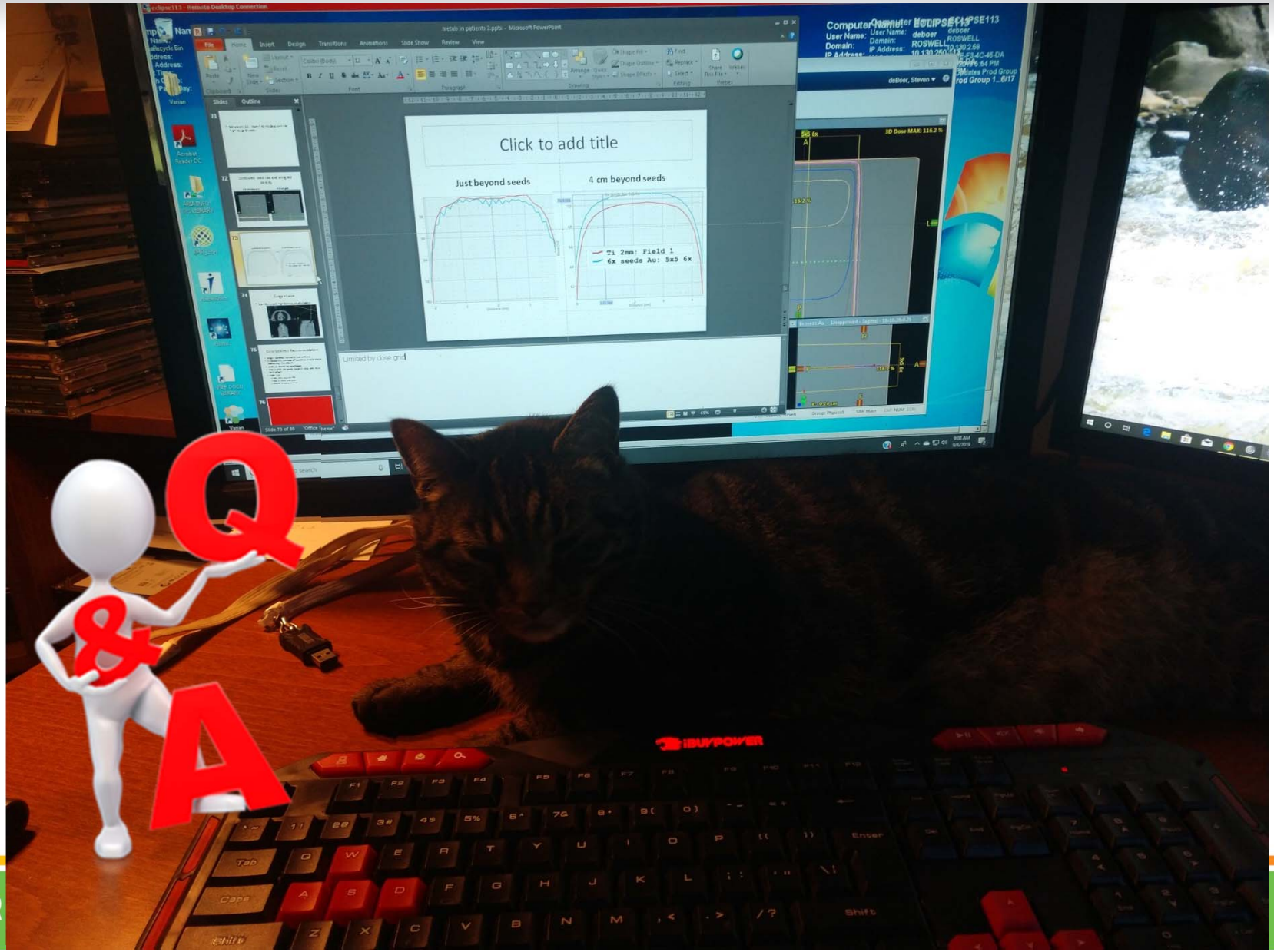
Future work

- Confirm with dose measurements



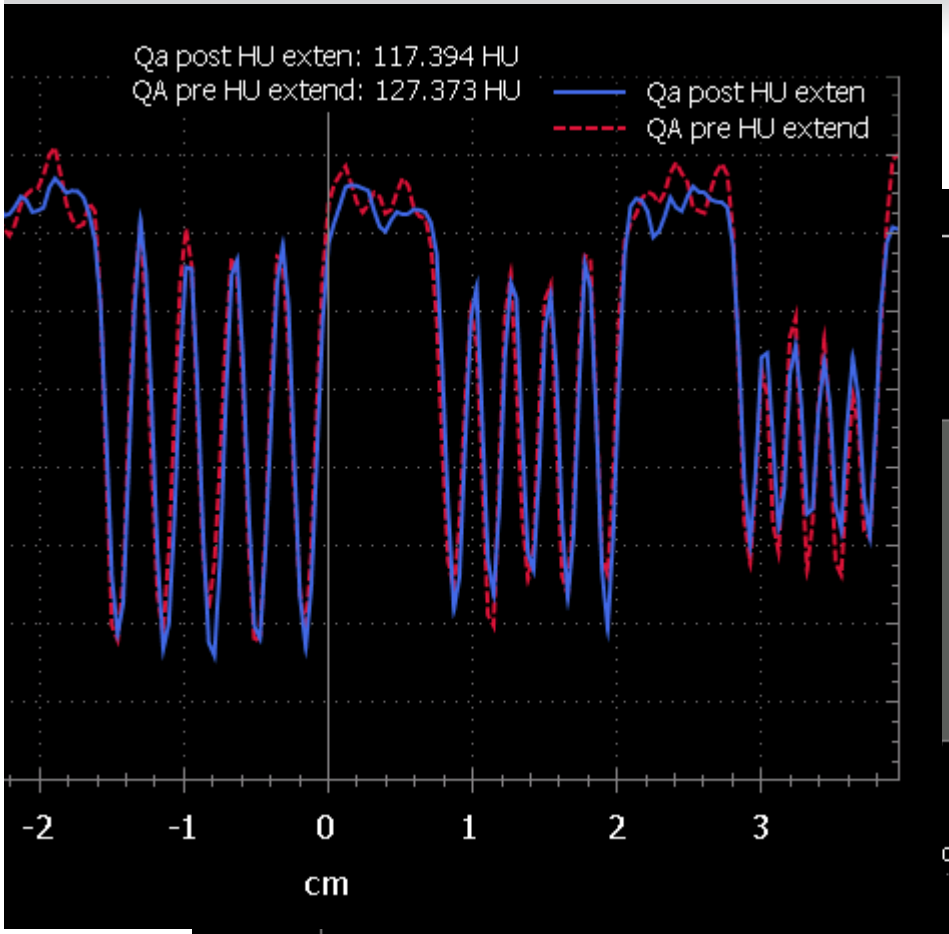


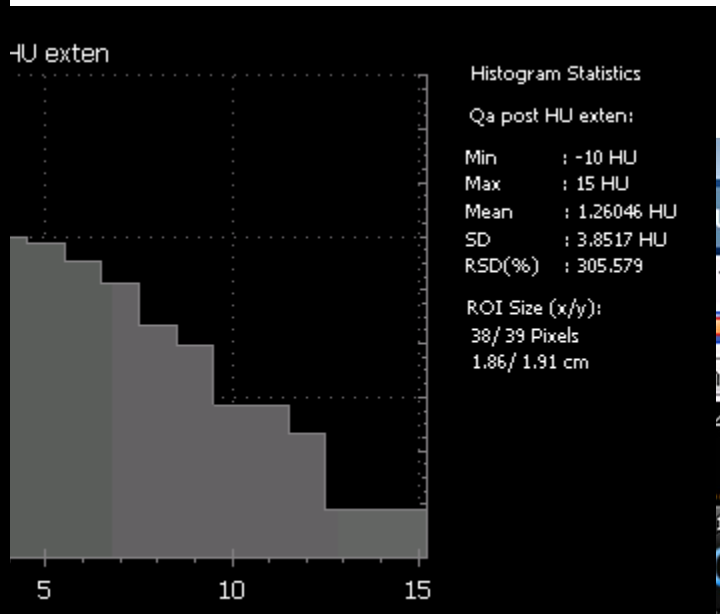
Thanks !

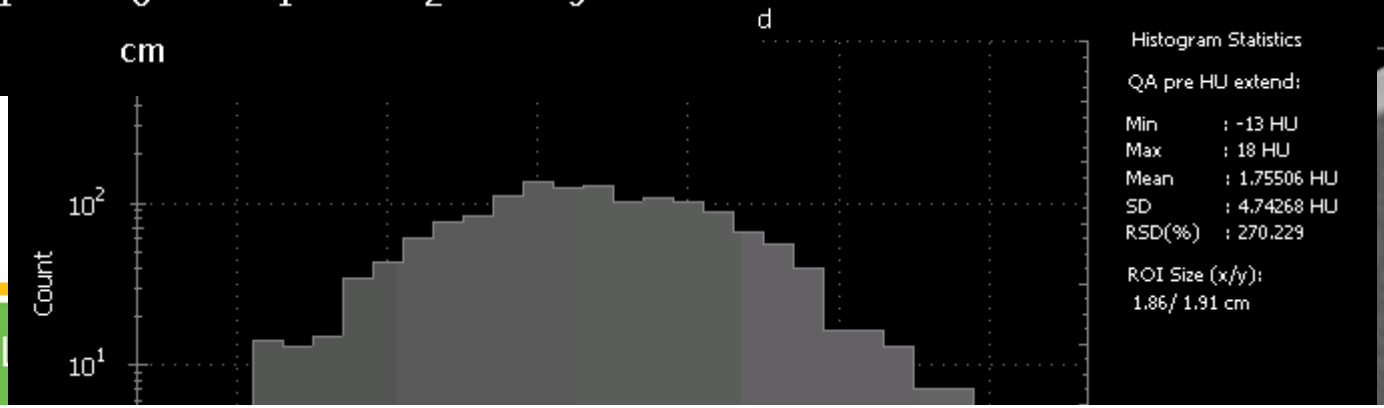

Click to add title
Just beyond seeds
4 cm beyond seeds
Ti 2mm: Field 1
6x seeds Au: 5x5 6x
Limited by dose grid
Q
&
A

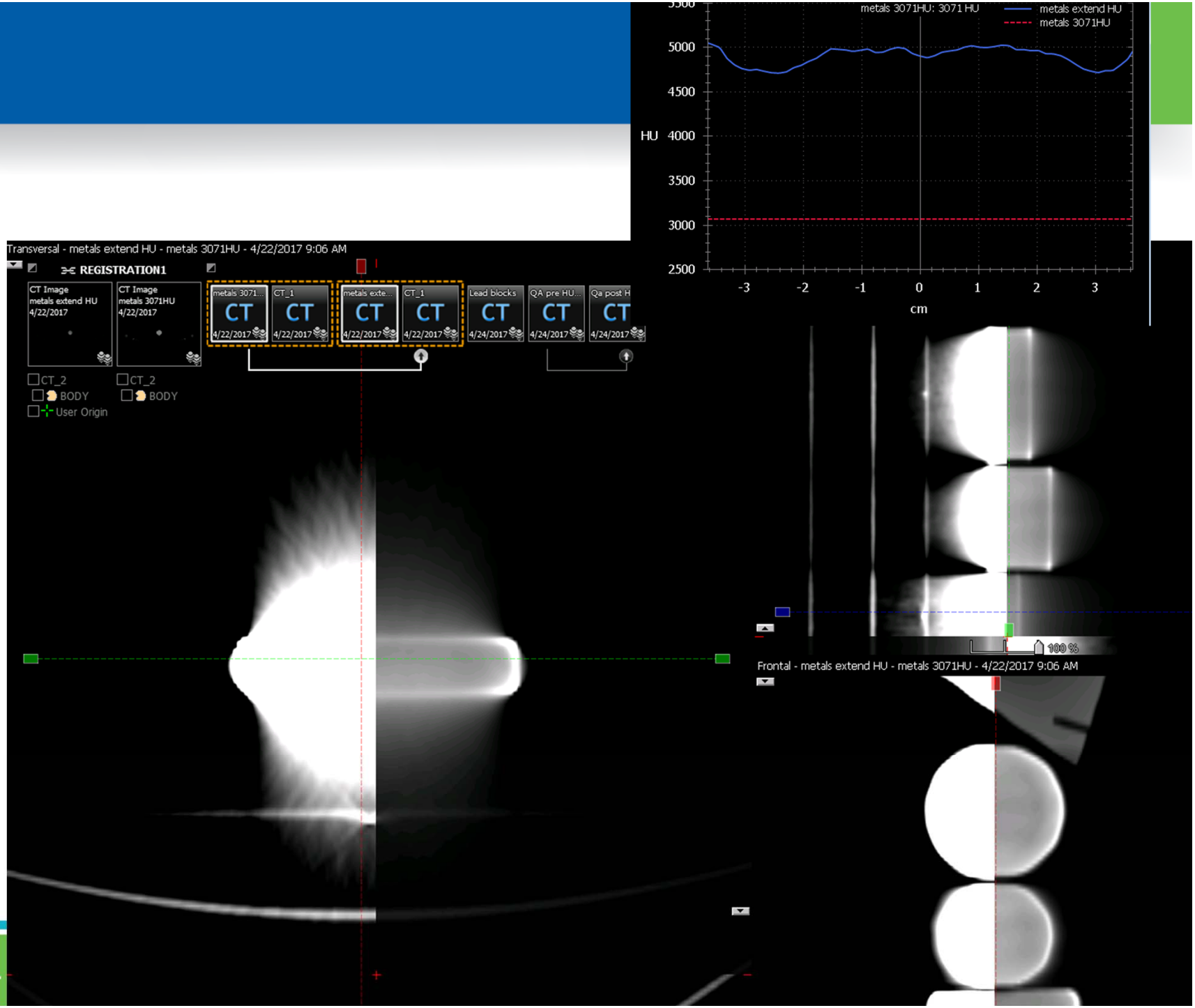

B
Q
&
A
?
ROSWELL PARK COMPREHENSIVE CANCER CENTER

Extended HU range – HU 0 to 200








metals 3071HU: 3071 HU
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ROSWELL

Breast Expanders

- "*The magnet is a N42SH neodymium magnet with a height of 0.187 inches and a diameter of 0.500 inches. The magnet is encased in 0.010 inches thick 316L Stainless Steel, which comprises the distal end of the needle guard. The proximal end of the needle guard is hollow to allow entry of the needle into the port, but the overall external dimensions are approximately 1.437 inches in diameter and .392 inches in height*"

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Radiation Therapy
Mentor has not tested the *in-vivo* effects of radiation therapy with these devices and cannot warrant the safety of such use. The decision regarding the use of these devices in patients about to undergo radiation therapy should be made by the surgeon and the radiation oncologist.

- *From Pontoriero et al*
- *“The dose perturbation near the metal fiducial becomes less relevant when more beams are delivered. Indeed, Vassiliev et al. [9] observed that the dose reduction was within 5% at 6 MV and 2% at 18 MV, when using two parallel and opposed beams.*
- *At the best of our knowledge, the present study is the first report on dose perturbation using a common clinical beam setup (five beams) and confirms a dose increment around a gold fiducial which increases with photon energy, while a 17% average dose increment is observed around a steel fiducial, irrespective of photon energy. However, it is to be pointed out explicitly that steel fiducials are contraindicated when MRI is required.*
- *Dose increment around both steel and gold markers may cause undesirable dose “hot spots” into the treated volume. Theoretically, when fiducials are into the GTV (gross tumor volume) this increment could be desirable.*
- *In general, a dose “hot spot” should be considered significant, following the approach proposed in the ICRU Report Nr. 50 [23], when the diameter exceeds 1.5 cm, i.e. spherical volumes greater than 1.8 cm3. However, when small organs at risk have to be taken into account, Ref. [23] points out the need to take care of dose inhomogeneities at smaller scales.*
- *Therefore, even if, generally, the hot spot around a fiducial irradiated by five fields is not significant due to its small dimension (about 6 mm of diameter), such a perturbation can become significant near small organs at risk, as the urethra in the case of prostate treatments.”*