VCU

The Department of
Radiation Oncology

Virginia Commonwealth University

Application of Monte Carlo to four-dimensional radiotherapy

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Acknowledgements

- Virginia Commonwealth University
- National Cancer Institute
- American Cancer Society
- Varian Medical Systems
- Philips Medical Systems
- Standard Imaging

Application of Monte Carlo to 4D radiotherapy

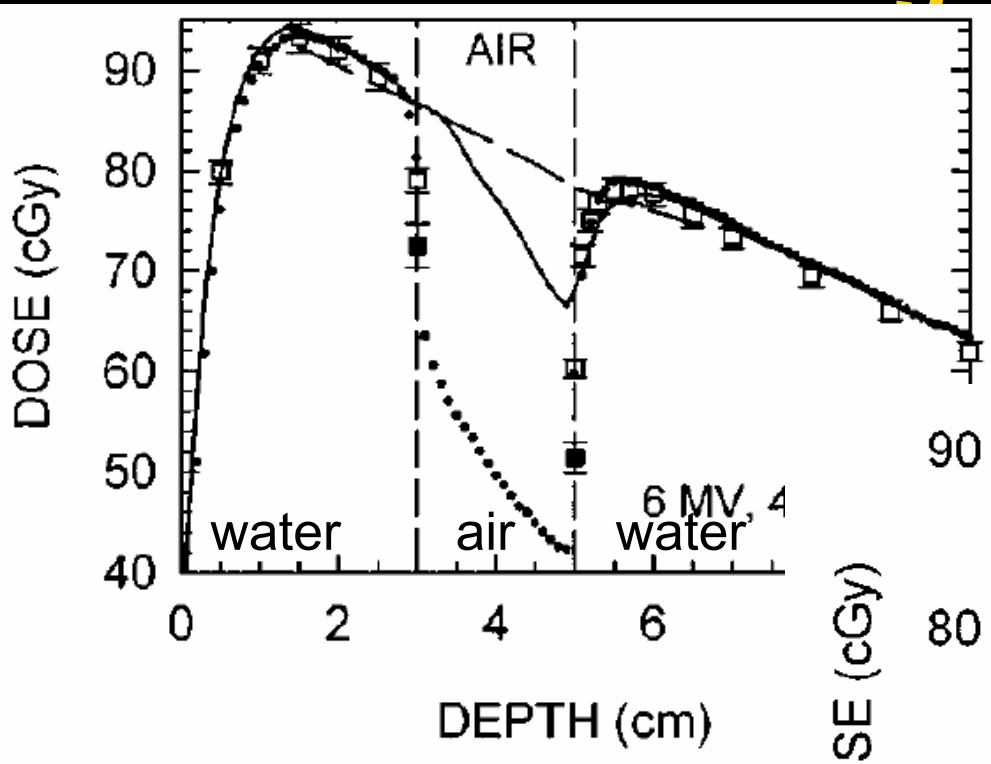
Outline

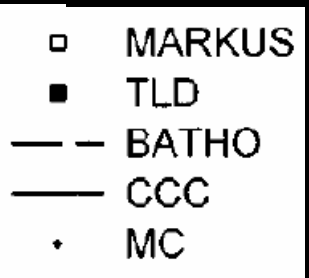
- Why
  - Lung tumours
  - Monte Carlo
  - 4D radiation therapy
- How
  - 4D and MC
- Results

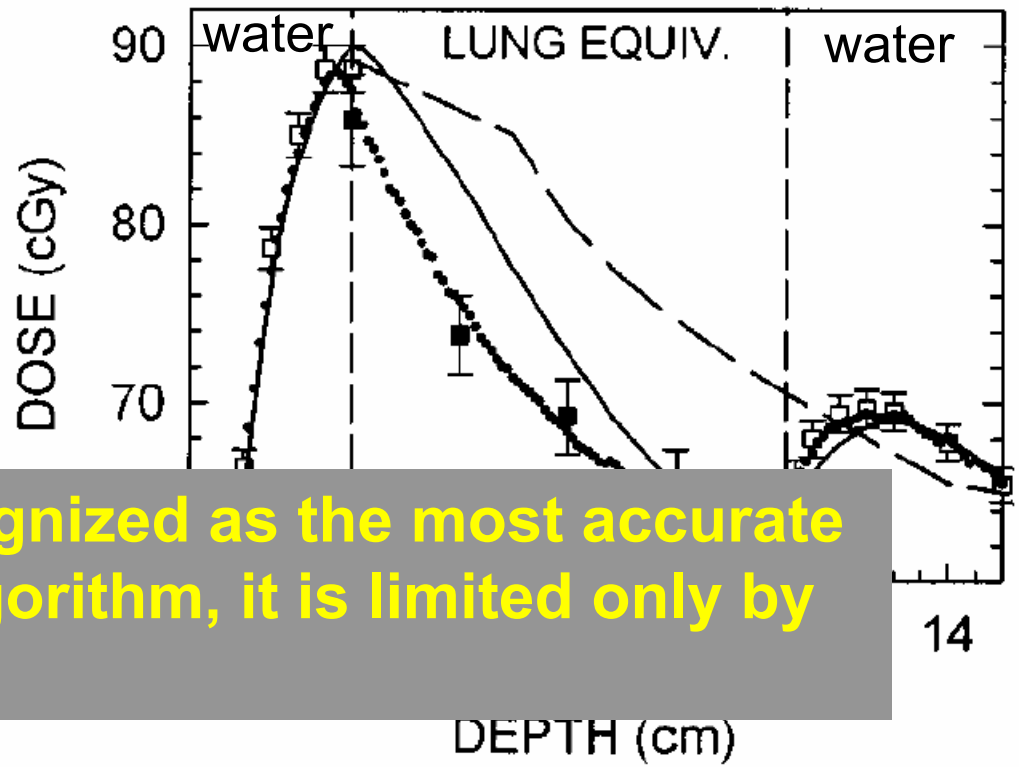
Why Lung Tumours?

- 15% 5-year survival
- Lung complications correlated with mean lung dose
  - Reduce lung mean dose, reduce complications
- Dose escalation predicted to benefit (>85 Gy)
  - Increase dose, expect increase cures

Problem I
Effect of Heterogeneities on Dose

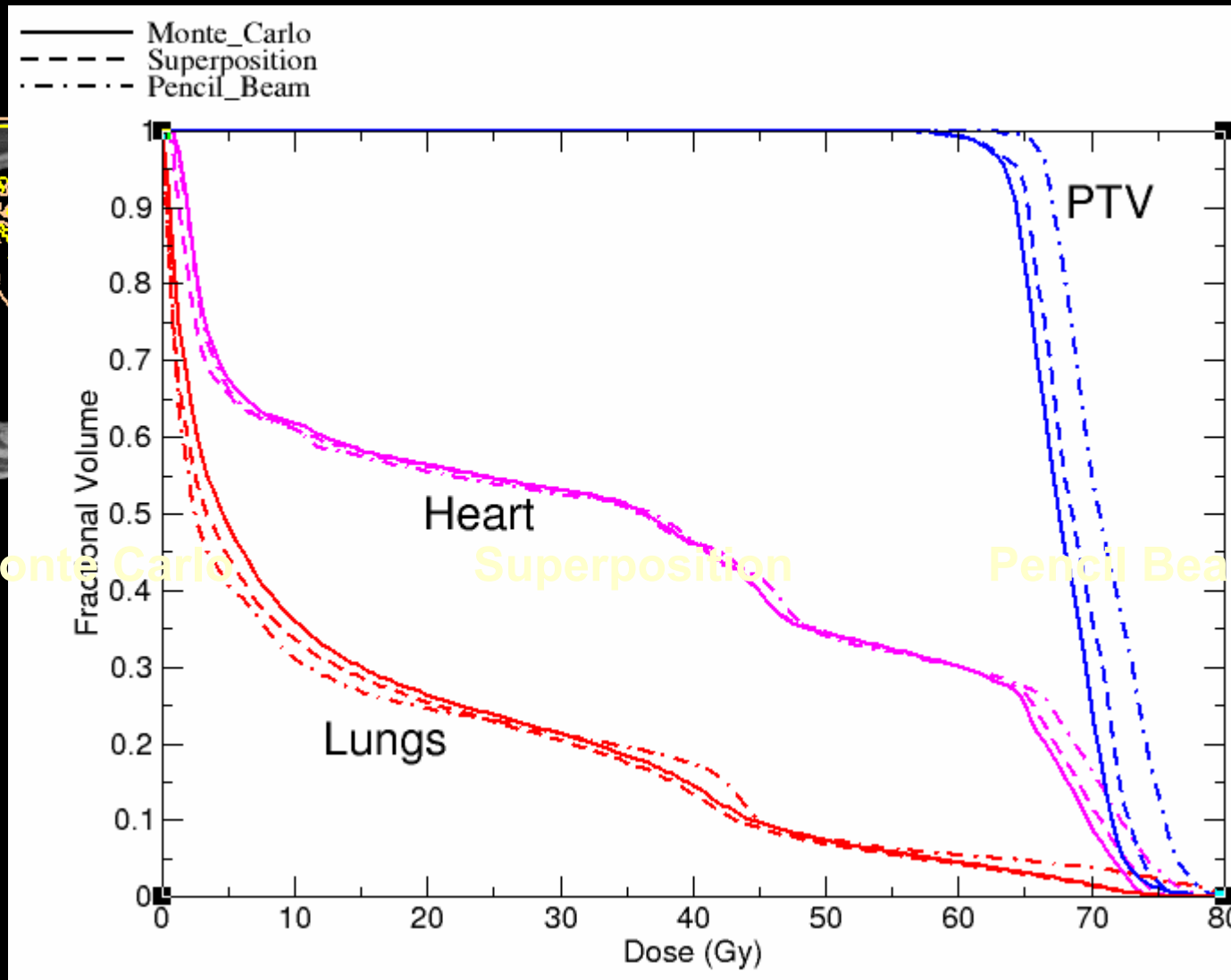






Monte Carlo is recognized as the most accurate dose calculation algorithm, it is limited only by accuracy of inputs.

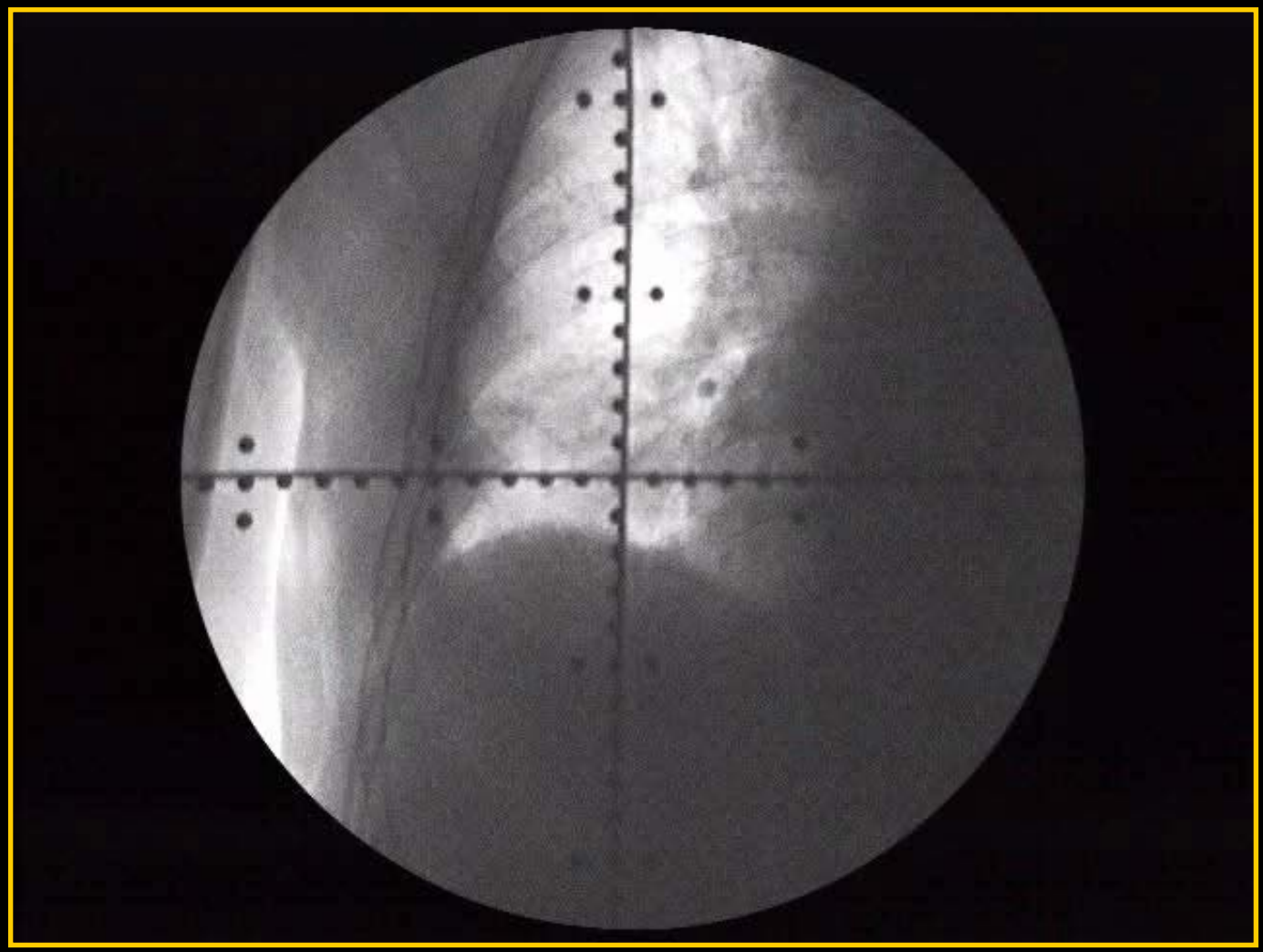
Lung Patient
Algorithm Comparison



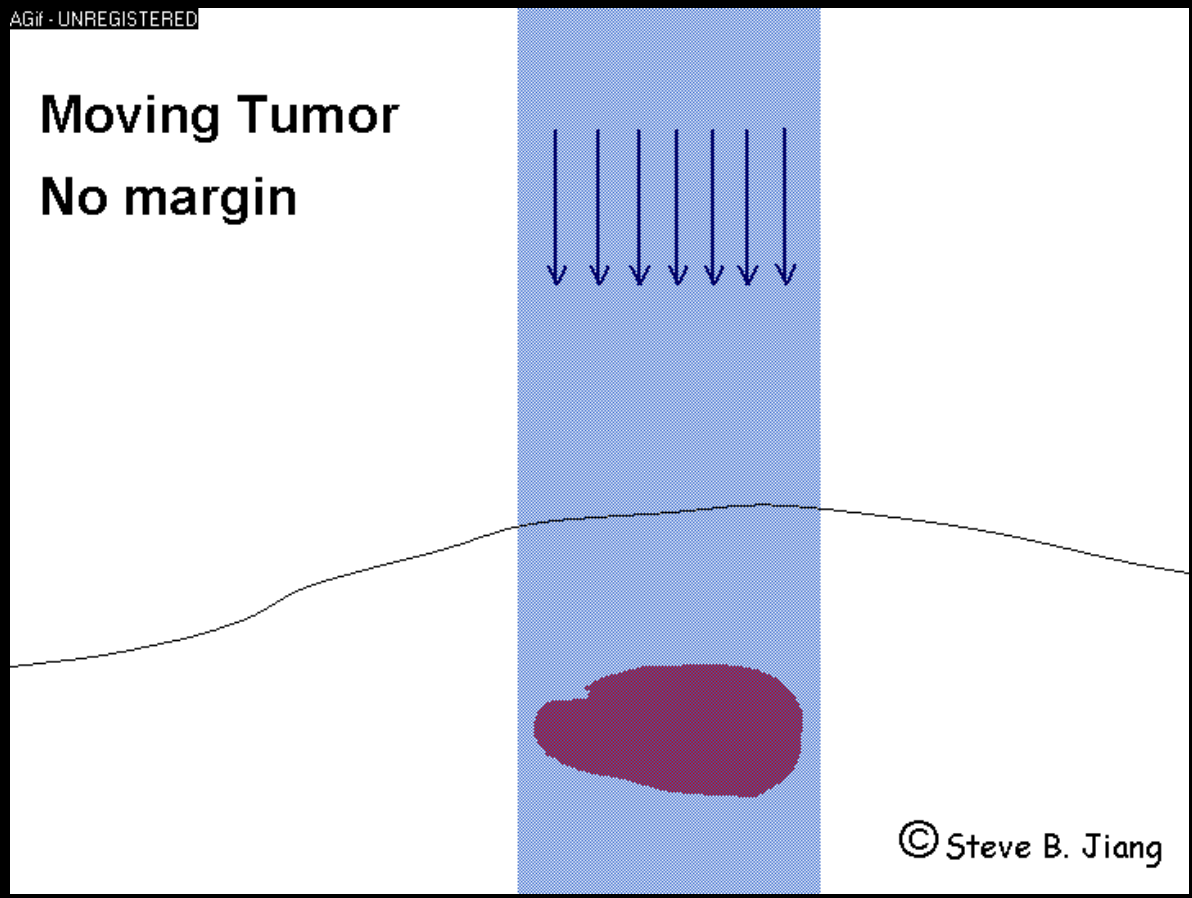
Monte Carlo Superposition Pencil Beam

Problem II

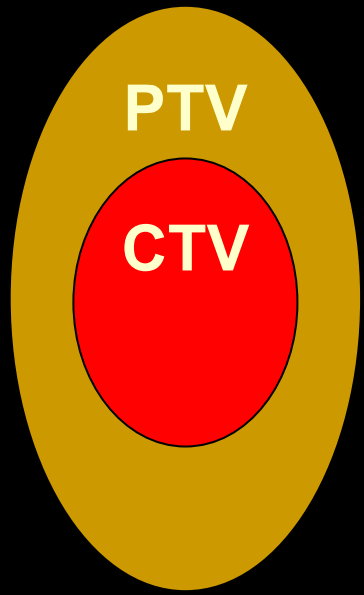
The tumour moves with time



Problem II
Respiratory Motion



Conventional Solution
Use large margins to ensure coverage

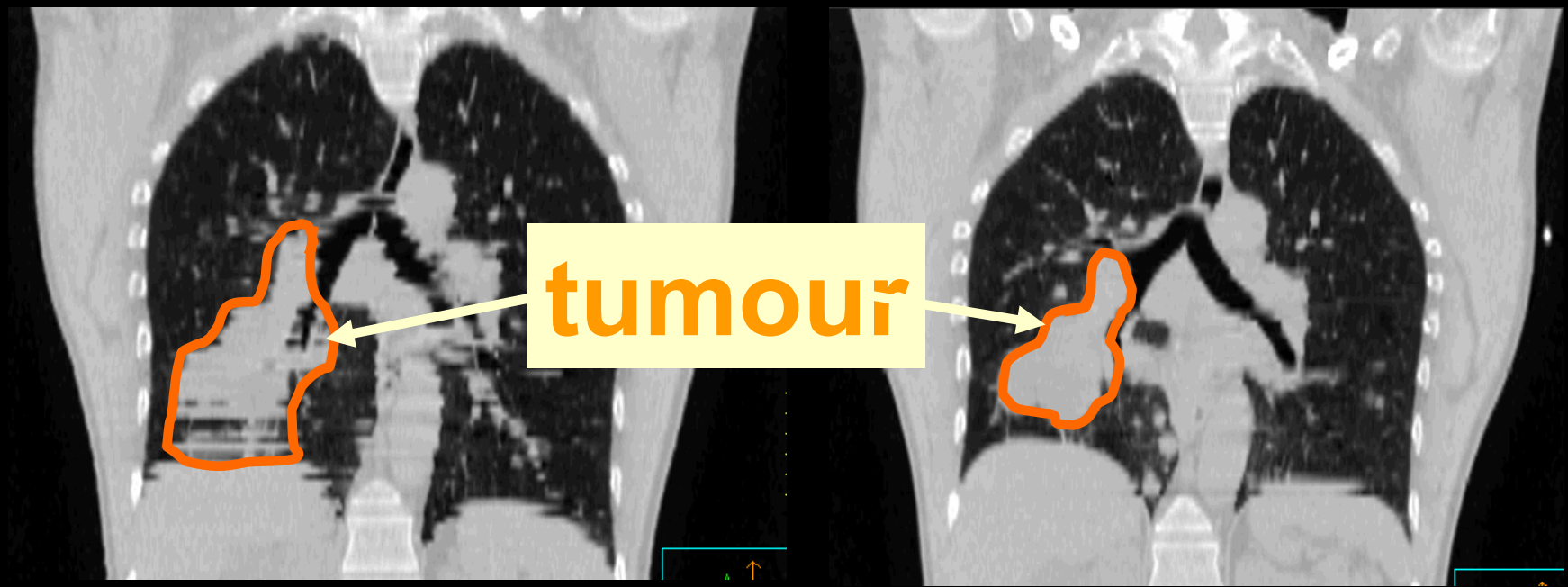


Conventional

- Results in large normal tissue dose
- Limits target dose (complications)

Problem III

Distorted images, incorrect anatomical positions, volumes or shapes

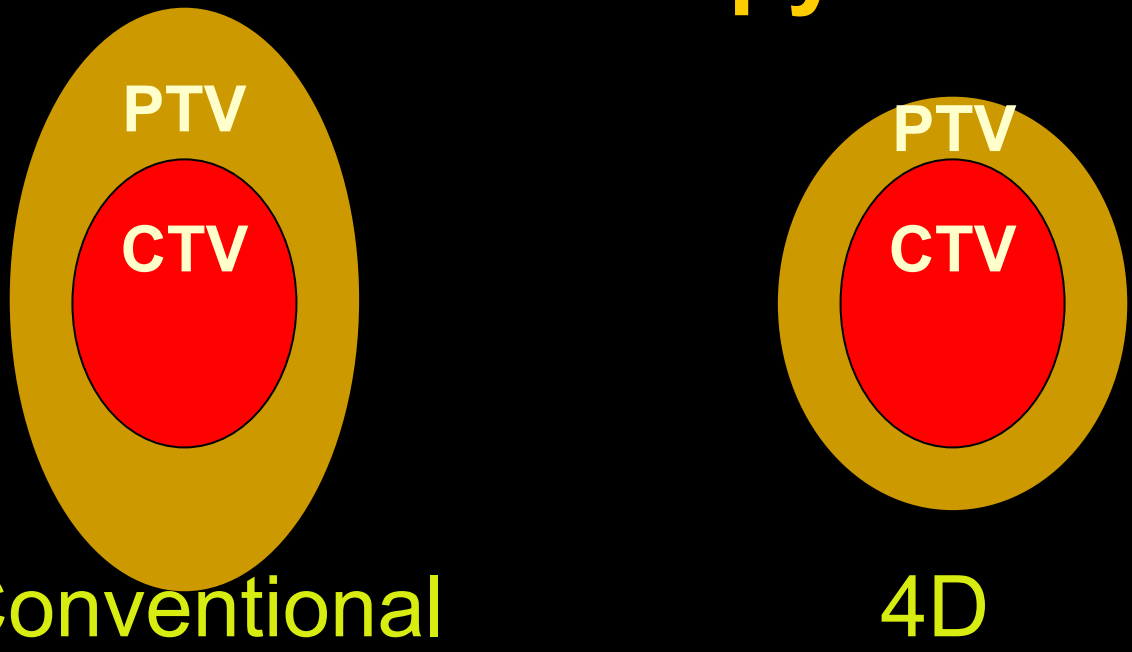


Conventional

With 4D imaging

Alternative Solution

Track tumour motion with 4D imaging and therapy



- Reduces volume of normal tissue irradiated
- Should allow dose escalation

The 4D radiotherapy process

4D Radiotherapy

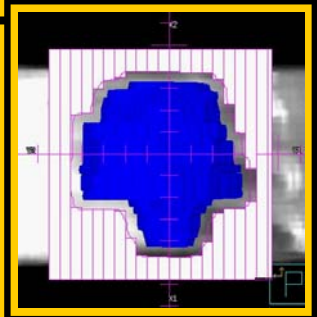
The explicit inclusion of the temporal changes in anatomy during the imaging, planning and delivery of radiotherapy

4D CT Imaging

Acquisition of a sequence of CT image sets over consecutive phases of a breathing cycle

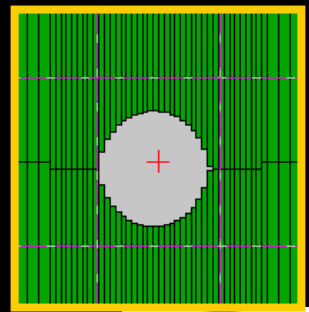
4D Treatment Planning

Designing treatment plans on CT image sets obtained for each phase of the breathing cycle



4D Treatment Delivery

Continuous delivery of the 4D treatment plans throughout the breathing cycle

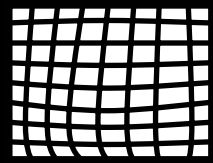


Aims

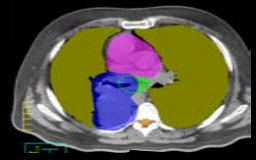
1. Develop 4D Monte Carlo methodology
2. Apply this technique to a 4D treatment plan
3. Evaluate implications of 4D Monte Carlo

Method and Materials

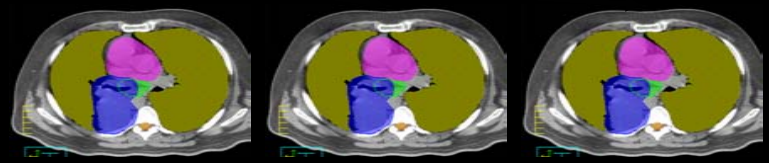
1. Create deformation fields



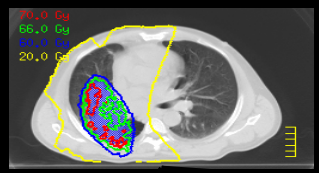
2. Define anatomy on reference CT



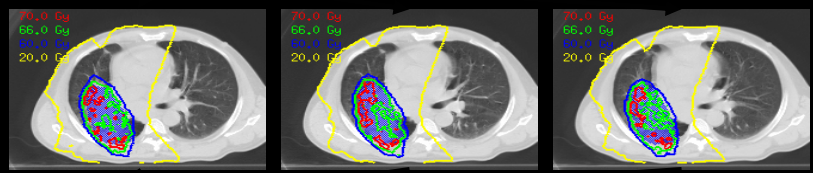
3. Map anatomy to all CT sets



4. Create Monte Carlo treatment plan on reference CT



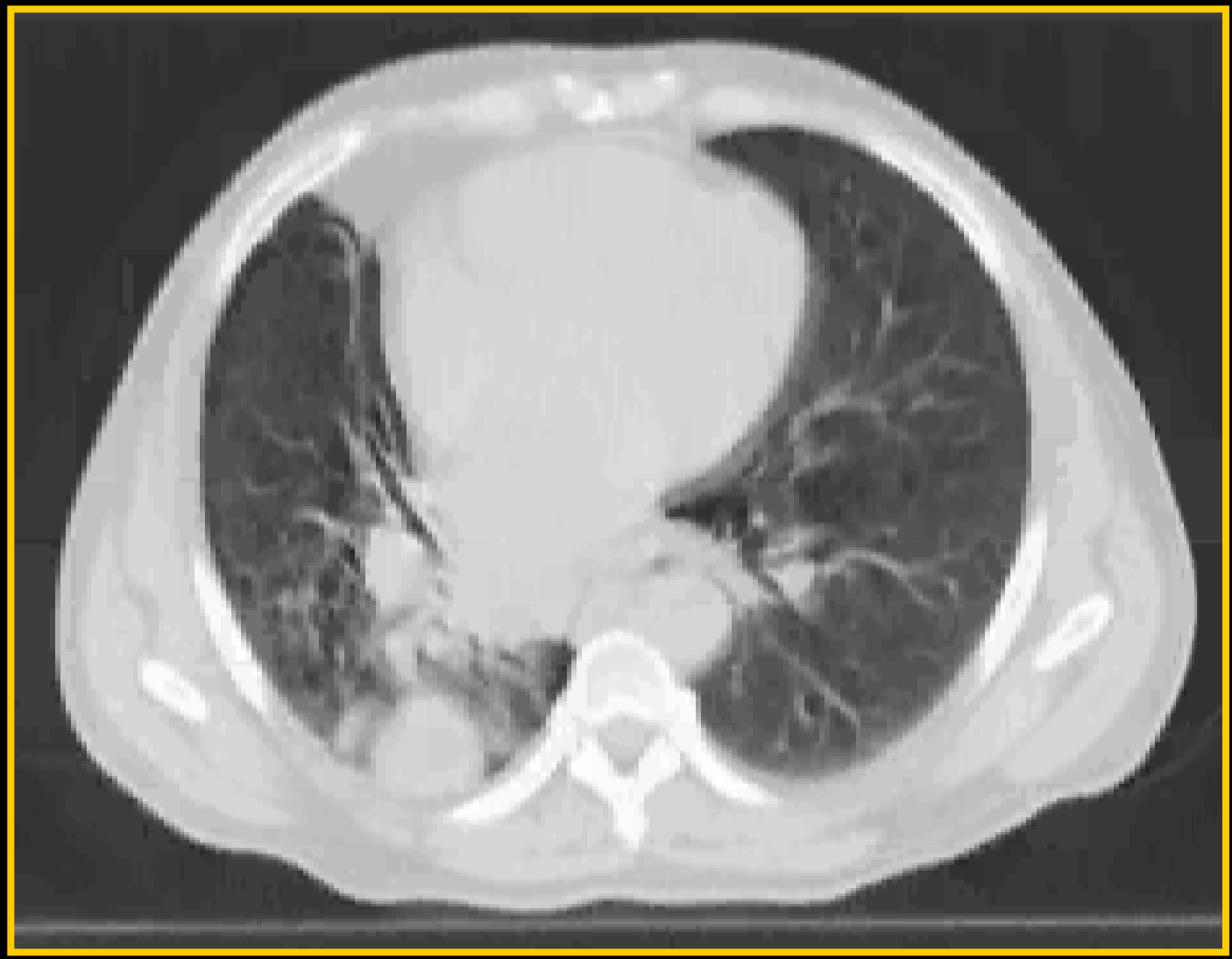
5. Create treatment plan on all CT sets



6. Combine dose distributions and display on reference CT

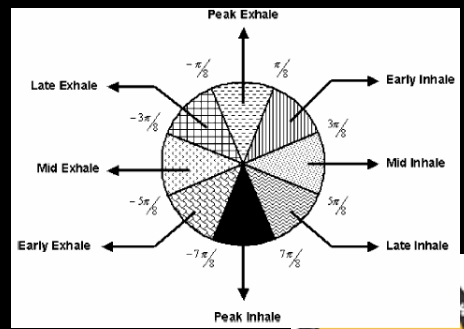
CT Image Acquisition

4D CT images



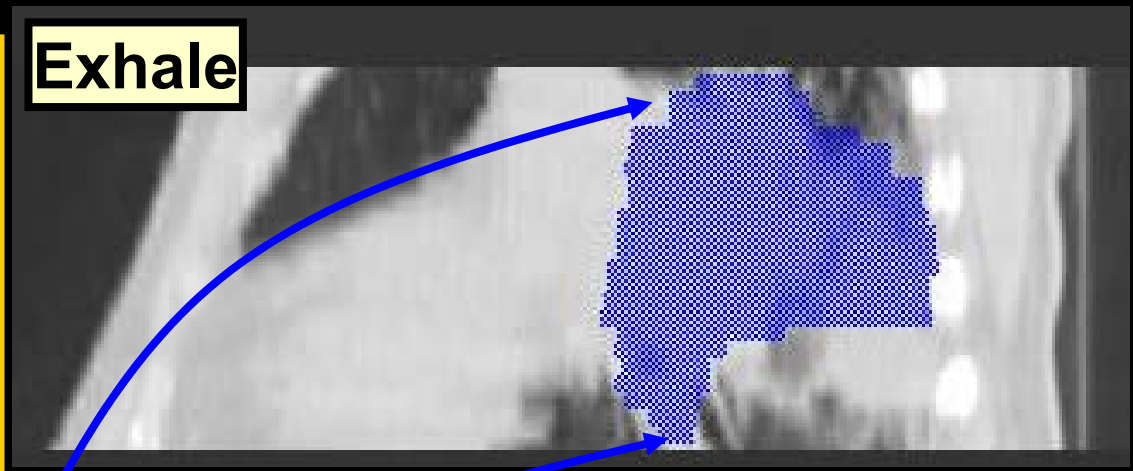
Vedam *et al* PMB 2003 48:45-62

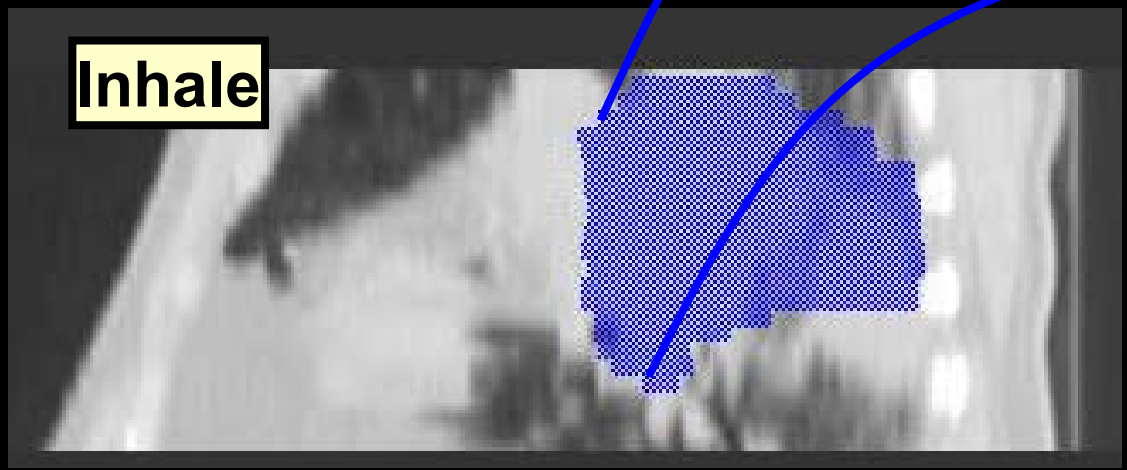
8 respiratory phases
- Peak inhale
- Early inhale
- Mid inhale
- End inhale
- Peak exhale
- Early exhale
- Mid exhale
- Late exhale



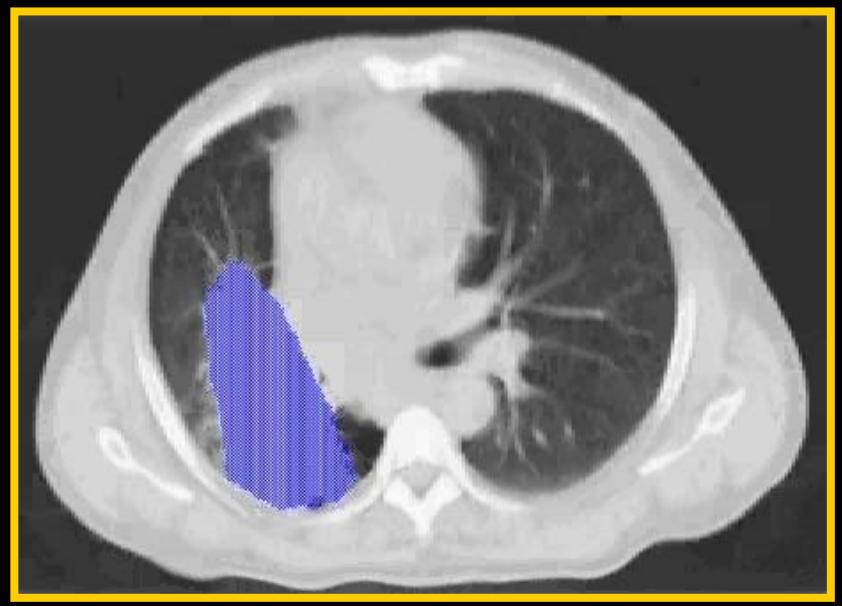
Contouring and deformations
Determine anatomical deformations

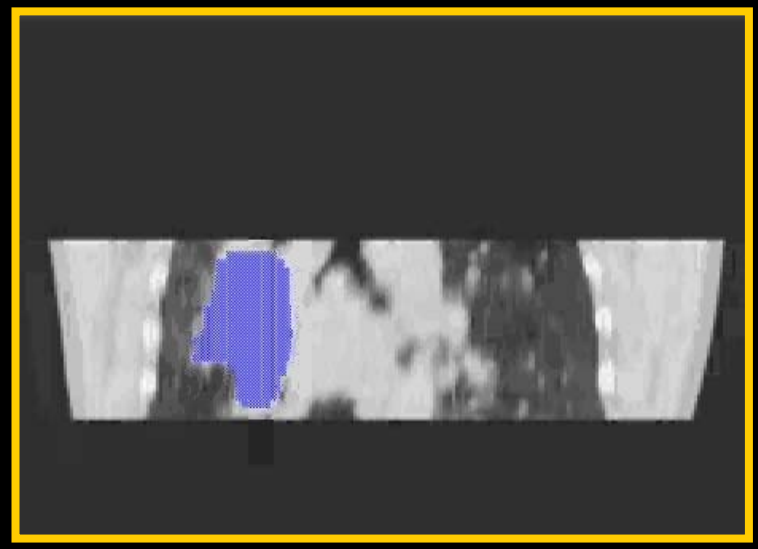
Large deformation diffeomorphic image warping
- Christensen *et al* PMB 1994 39: 209-618
- Christensen *et al* IEEE Trans Med Imag 1997 16:864-877
- Miller *et al* in Toga (Ed.) Brain Warping, Academic Press

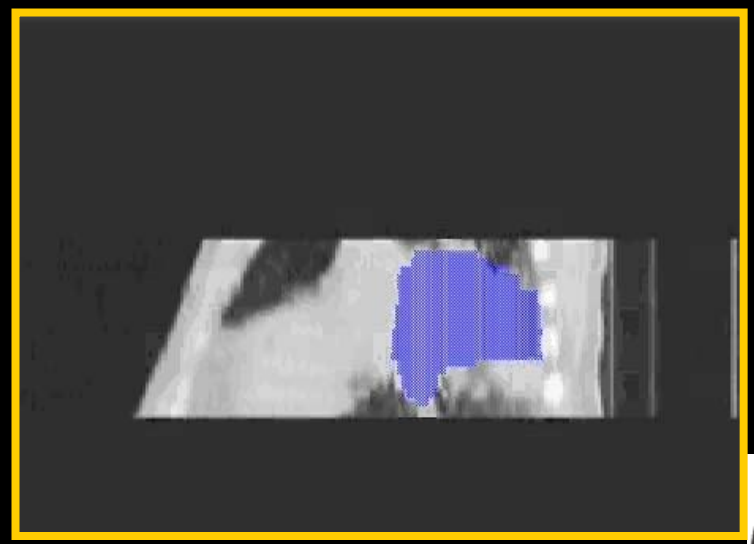




4D PTVs

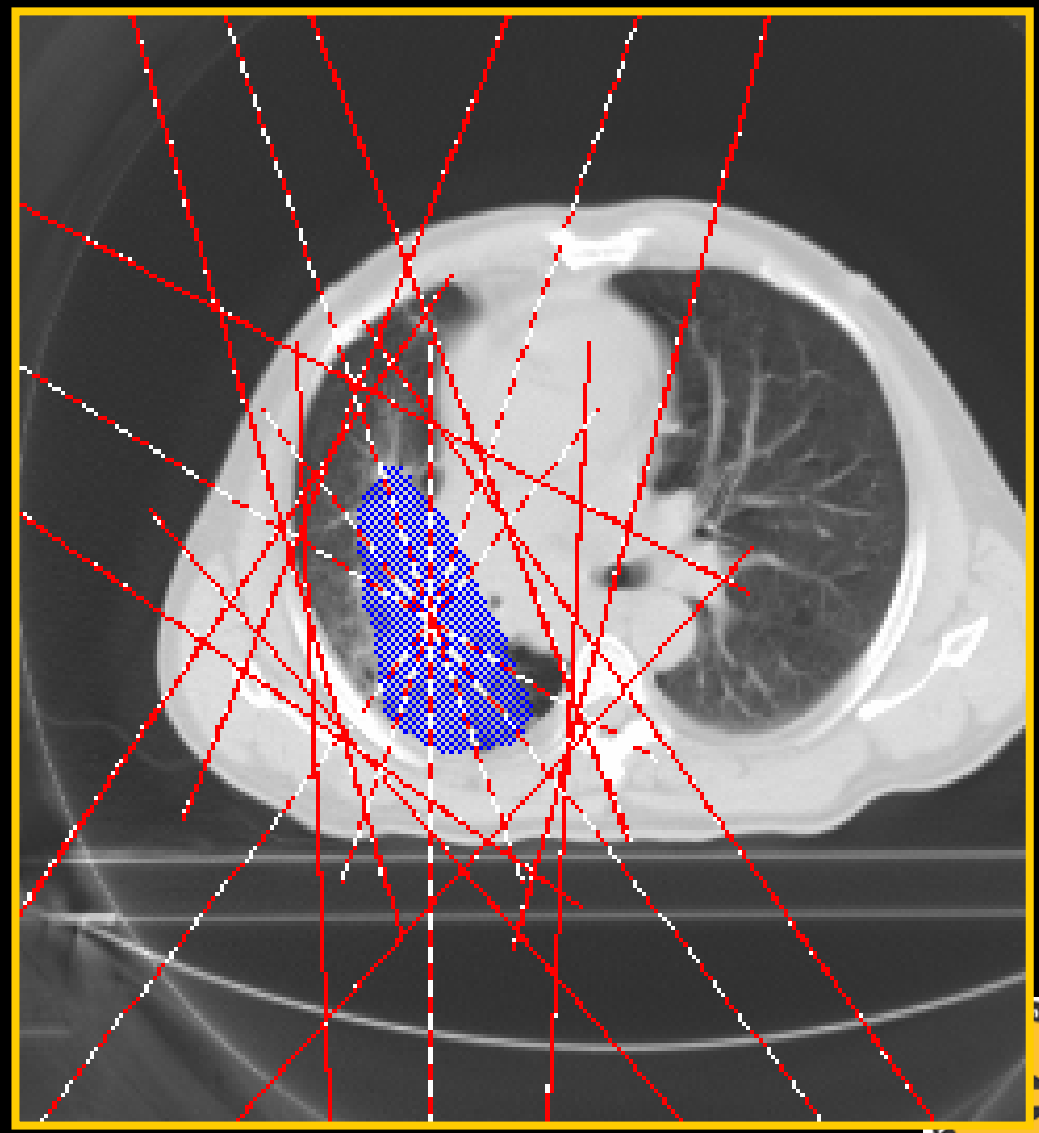




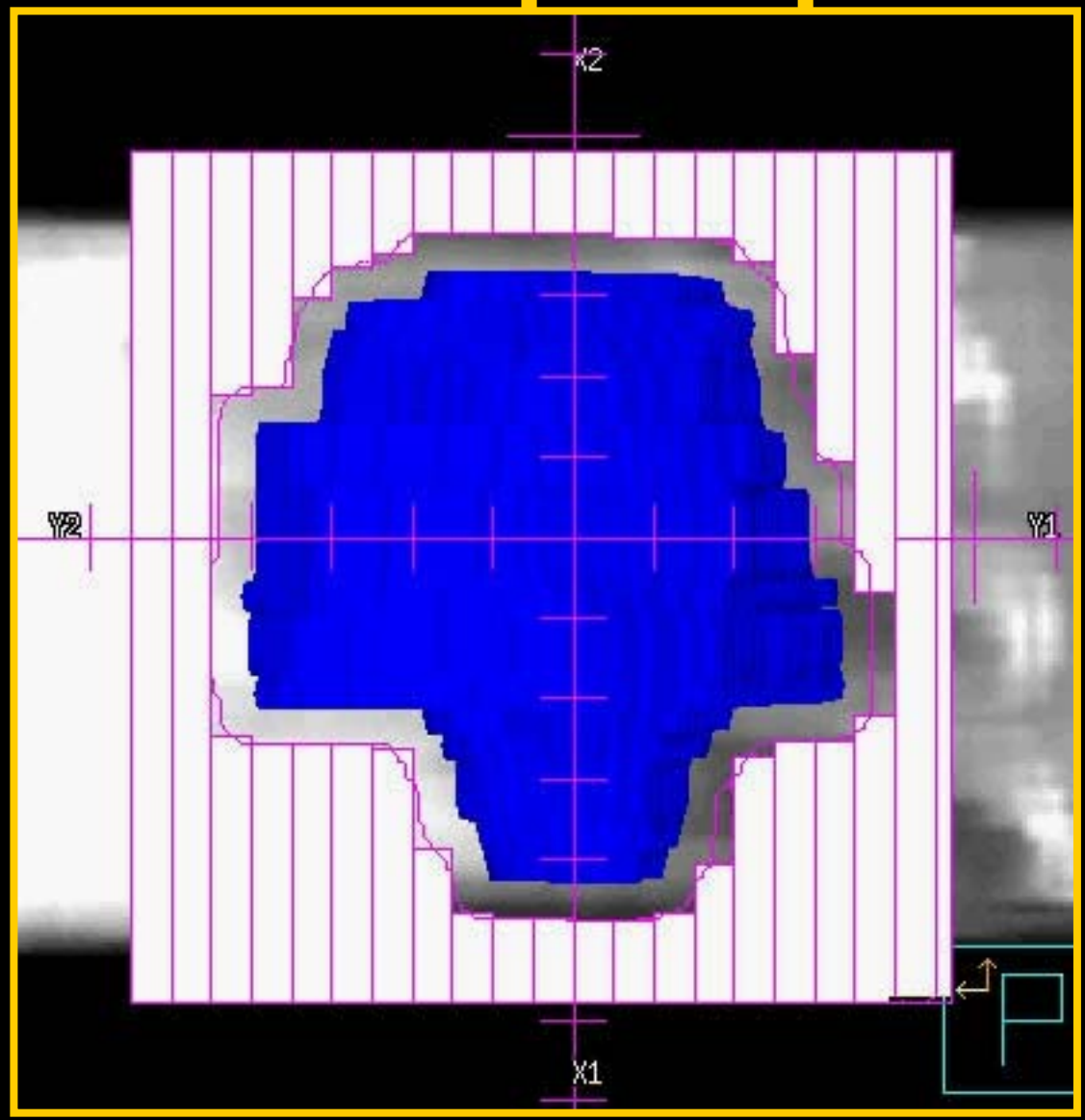


Define Field Arrangement

- 6 fields
- Non-opposed
- Coplanar
- 6 MV
- Autoblock PTV + 0.5 cm



Develop 4D plan



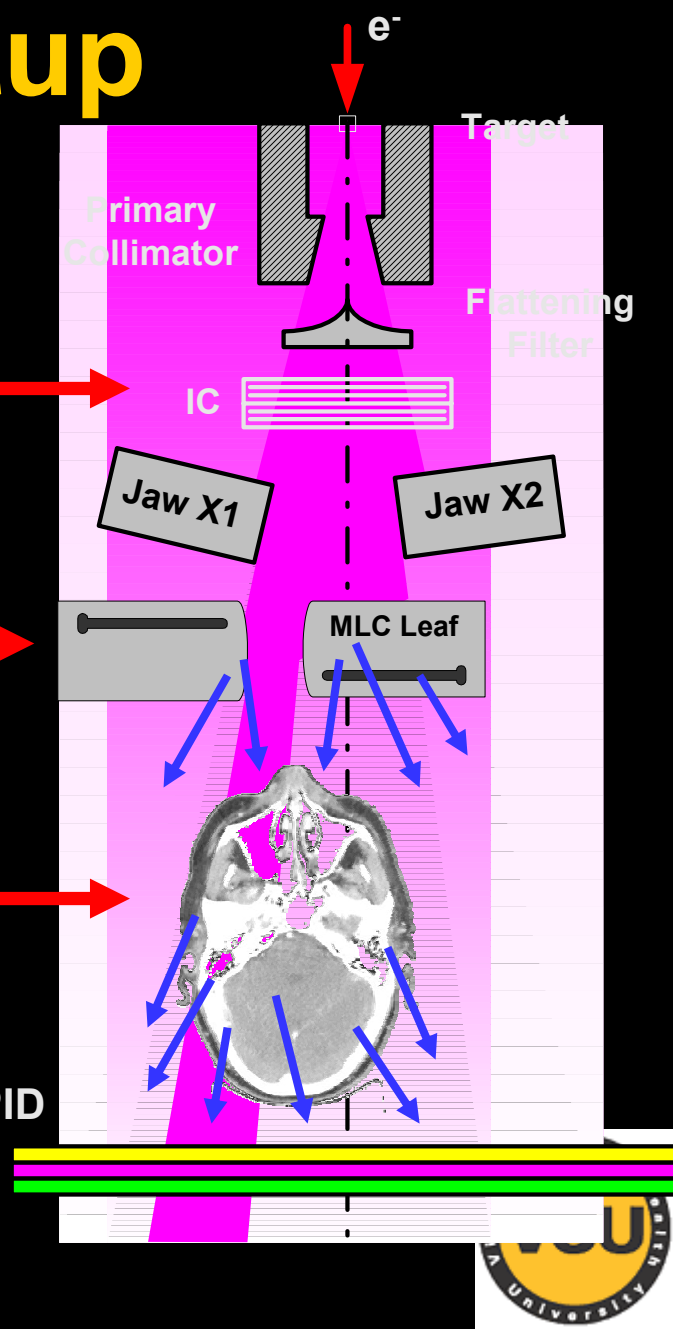
Monte Carlo setup

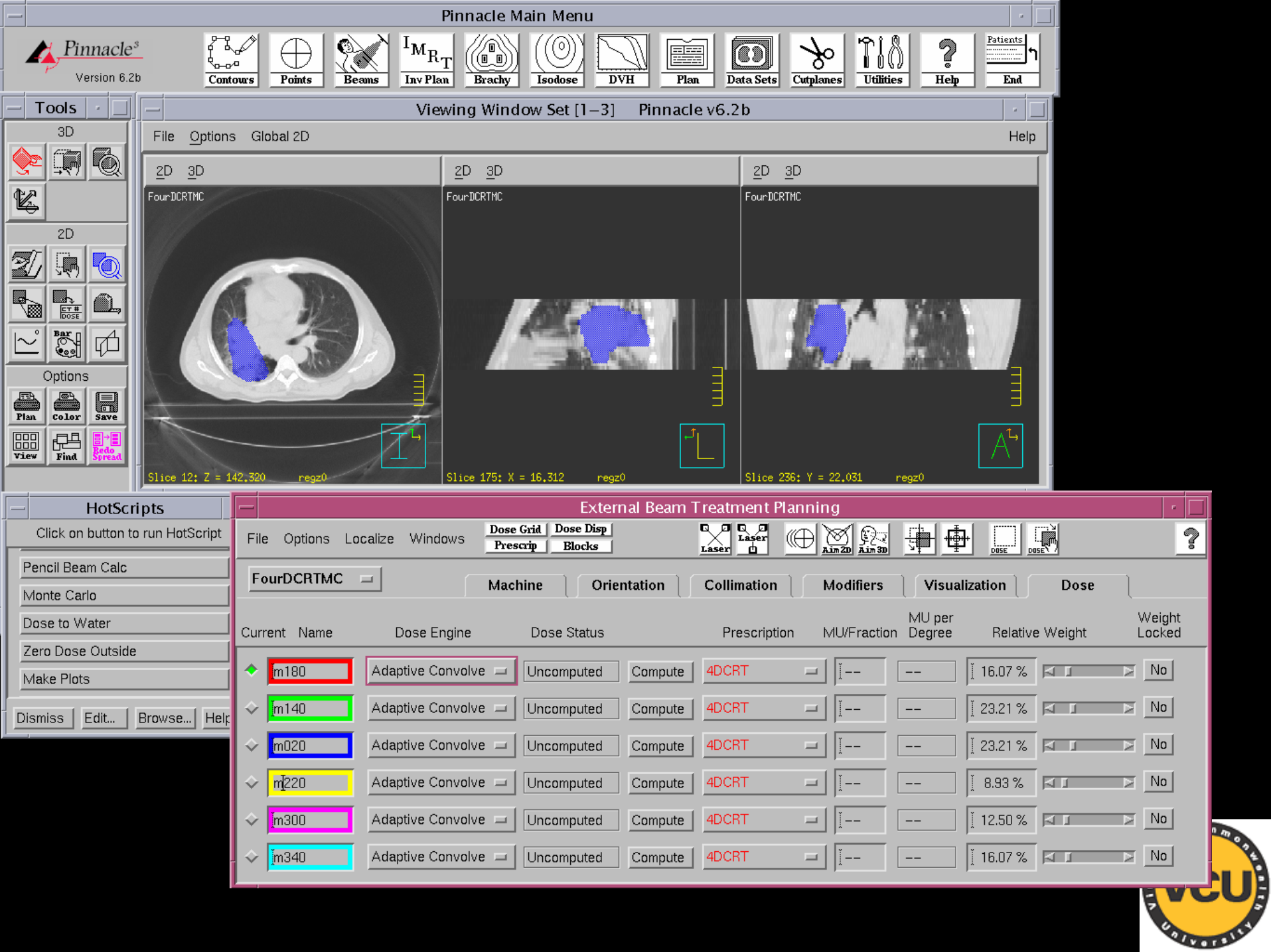
Treatment head: EGS4/BEAM

DMLC: VCUDMLC

Patient: EGS4/DOSXYZ

EPID: EGSnrc




Pinnacle Main Menu
Pinnacle³
Version 6.2b
Contours
Points
Beams
IMRT
Inv Plan
Brachy
Isodose
DVH
Plan
Data Sets
Cutplanes
Utilities
Help
Patients
End
Tools
3D
2D
Options
Plan
Color
Save
View
Find
Redo Spread
Viewing Window Set [1–3] Pinnacle v6.2b
File Options Global 2D Help
2D 3D
FourDCRTMC
Slice 12: Z = 142.320 regz0
Slice 175: X = 16.312 regz0
Slice 236: Y = 22.031 regz0
HotScripts
Click on button to run HotScript
Pencil Beam Calc
Monte Carlo
Dose to Water
Zero Dose Outside
Make Plots
Dismiss
Edit...
Browse...
Help
External Beam Treatment Planning
File Options Localize Windows
Dose Grid
Dose Disp
Prescrip
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Aim 2D
Aim 3D
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Modifiers
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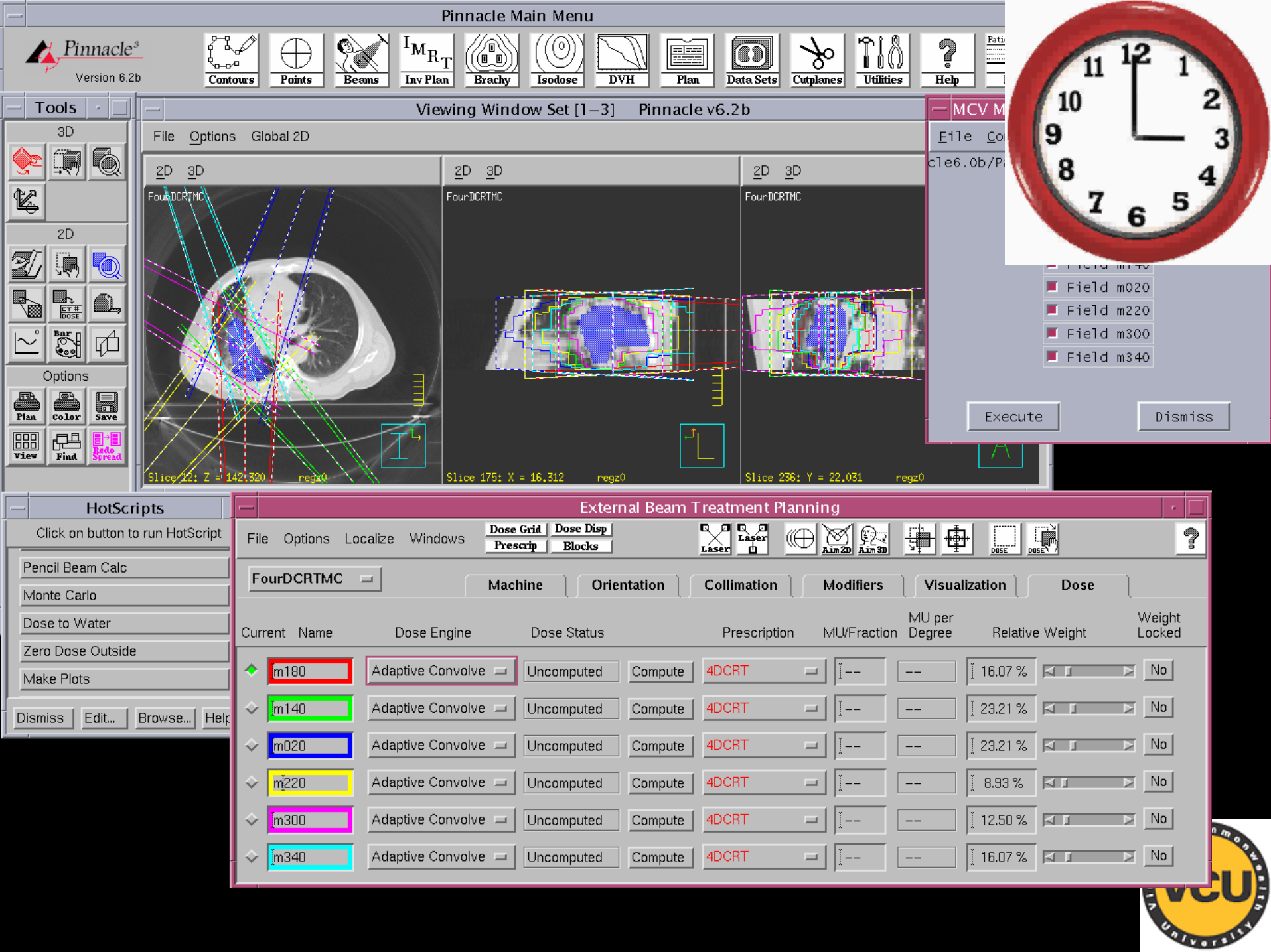
m180 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 16.07 % No
m140 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 23.21 % No
m020 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 23.21 % No
m220 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 8.93 % No
m300 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 12.50 % No
m340 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 16.07 % No


Pinnacle Main Menu
Pinnacle³
Version 6.2b
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Slice 175: X = 16.312 regz0
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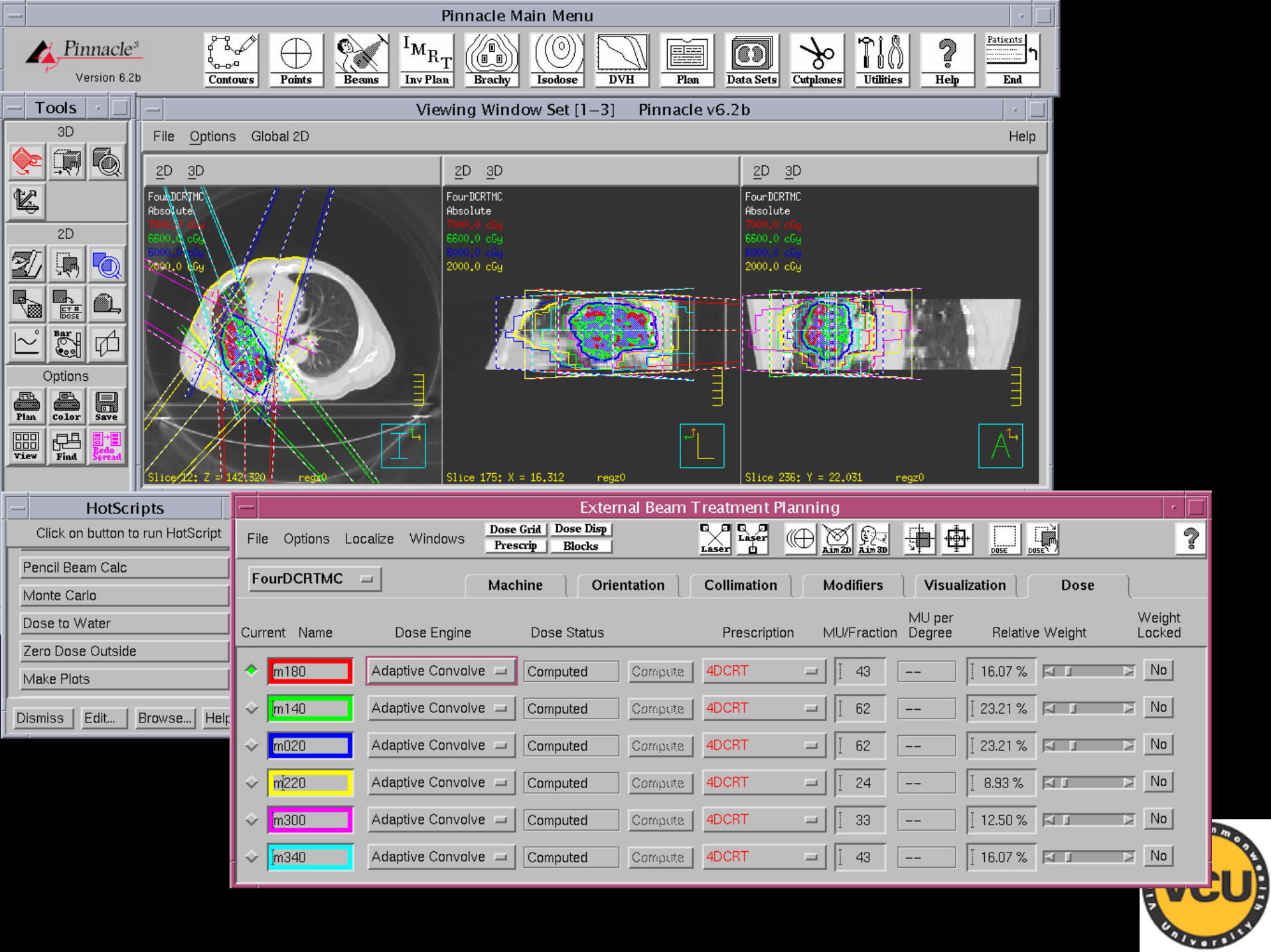
m340 Adaptive Convolve Uncomputed Compute 4DCRT -- -- 16.07 % No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Viewing Window Set [1–3] Pinnacle v6.2b
File Options Global 2D
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2D 3D
FourDCRTMC
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Slice 175: X = 16.312 regz0
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m180 Adaptive Convolve Computed Compute 4DCRT 43 -- 16.07 % No
m140 Adaptive Convolve Computed Compute 4DCRT 62 -- 23.21 % No
m020 Adaptive Convolve Computed Compute 4DCRT 62 -- 23.21 % No
m220 Adaptive Convolve Computed Compute 4DCRT 24 -- 8.93 % No
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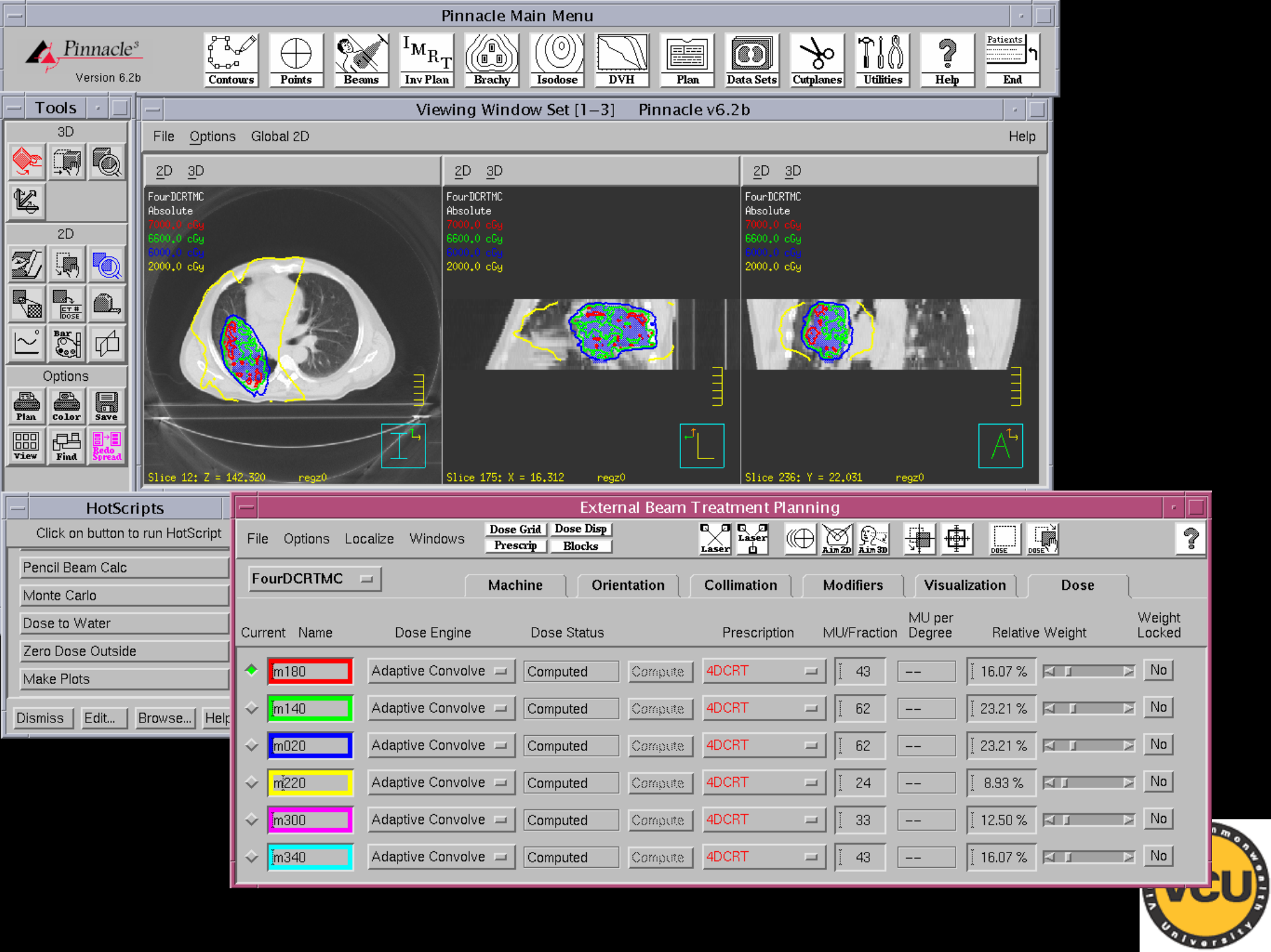
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MU/Fraction
MU per Degree
Relative Weight
Weight Locked
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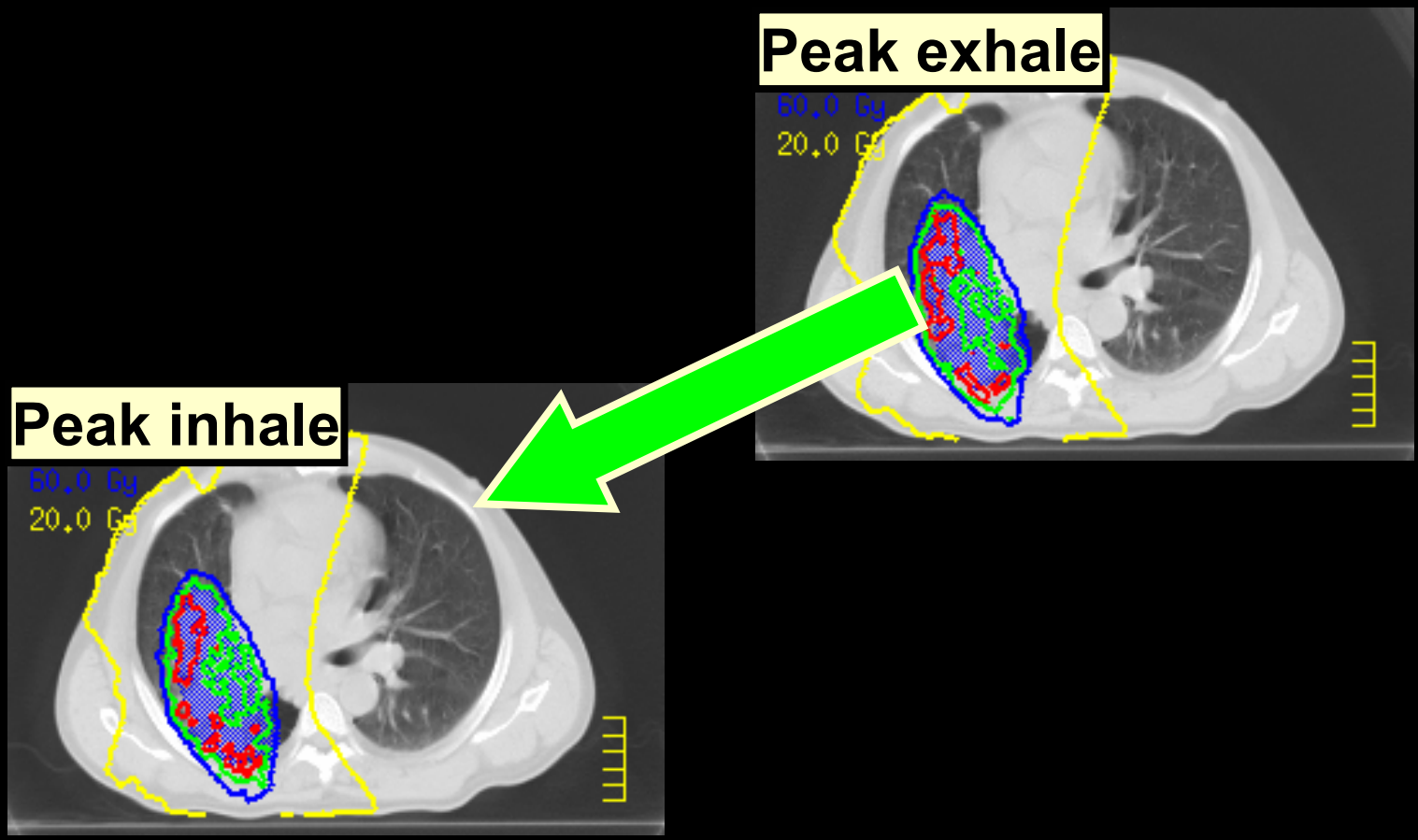
m220 Adaptive Convolve Computed Compute 4DCRT 24 -- 8.93 % No
m300 Adaptive Convolve Computed Compute 4DCRT 33 -- 12.50 % No
m340 Adaptive Convolve Computed Compute 4DCRT 43 -- 16.07 % No

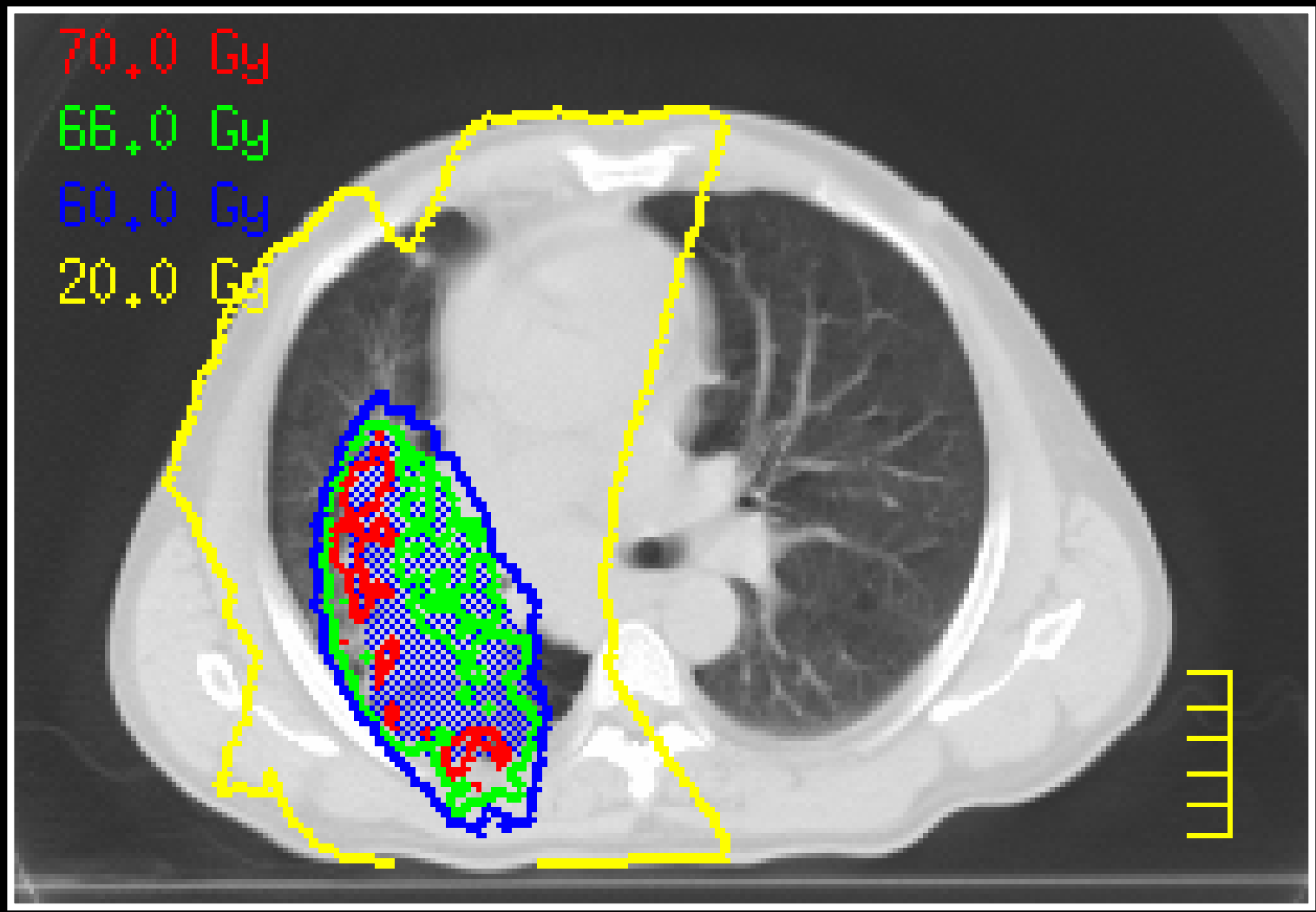
Data Merging

Map dose distributions from each of n 3D CT set onto a 'reference' CT set for visualization and analysis

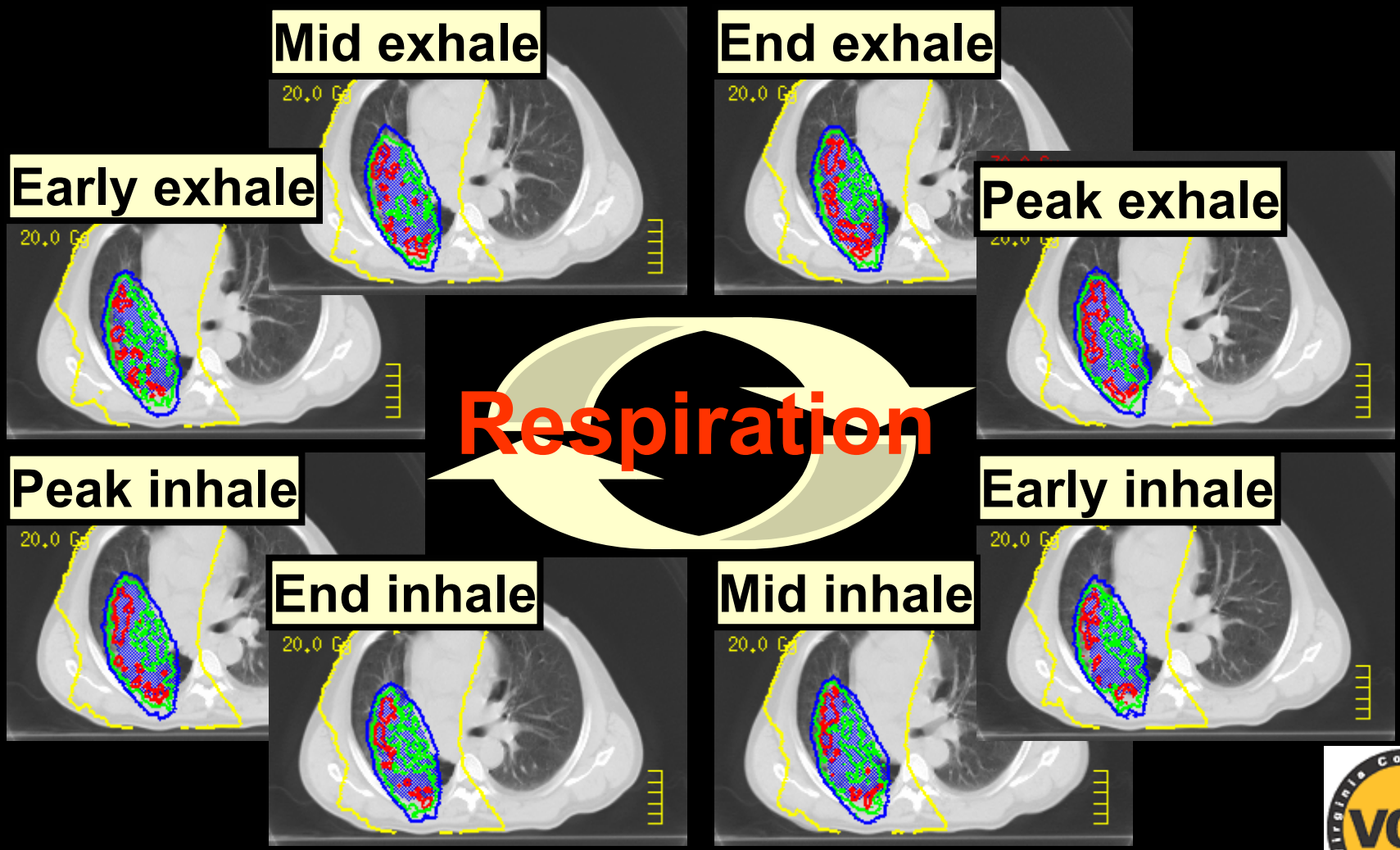


Results

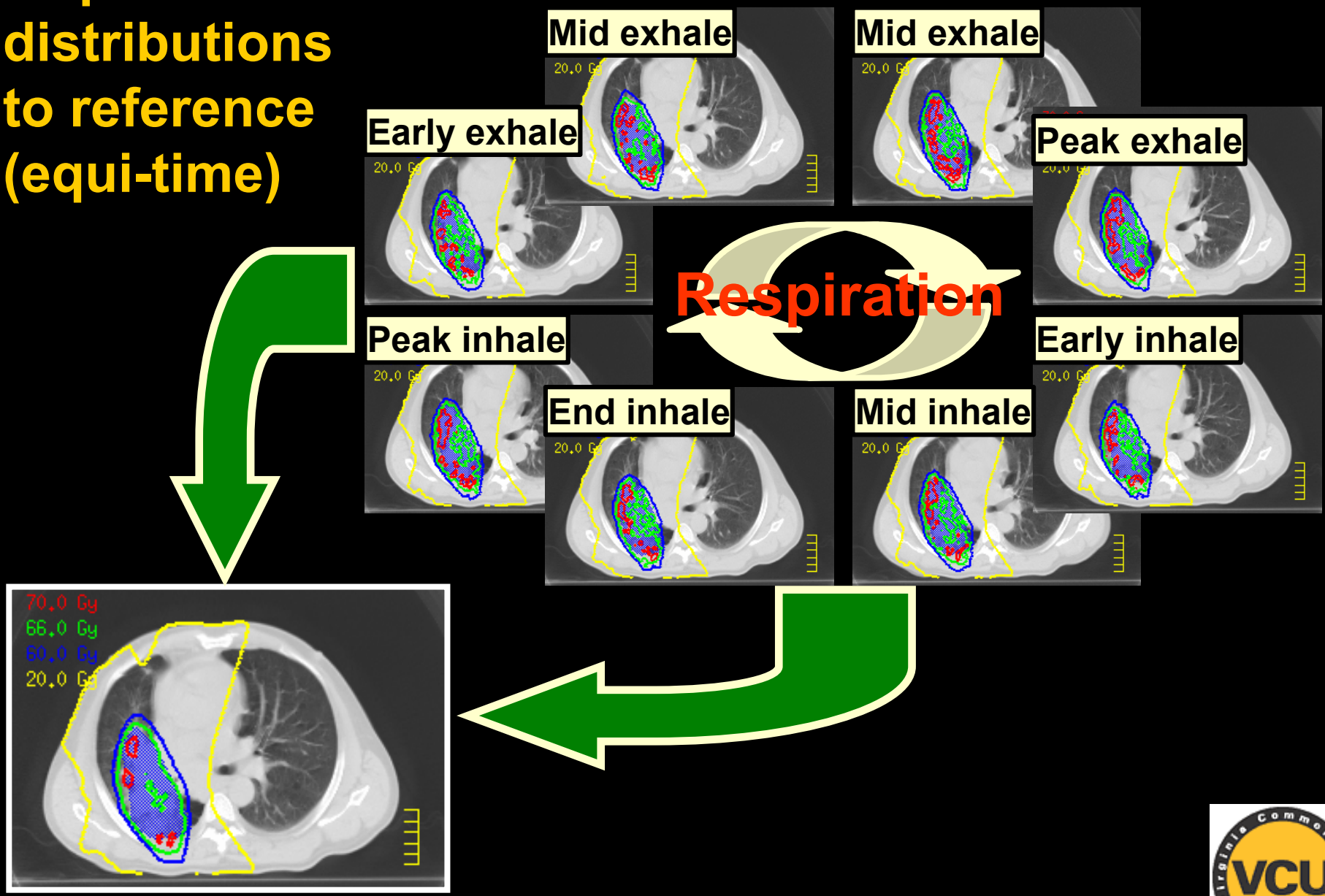
Isodoses from 6% uncertainty calculation per beam at peak inhale



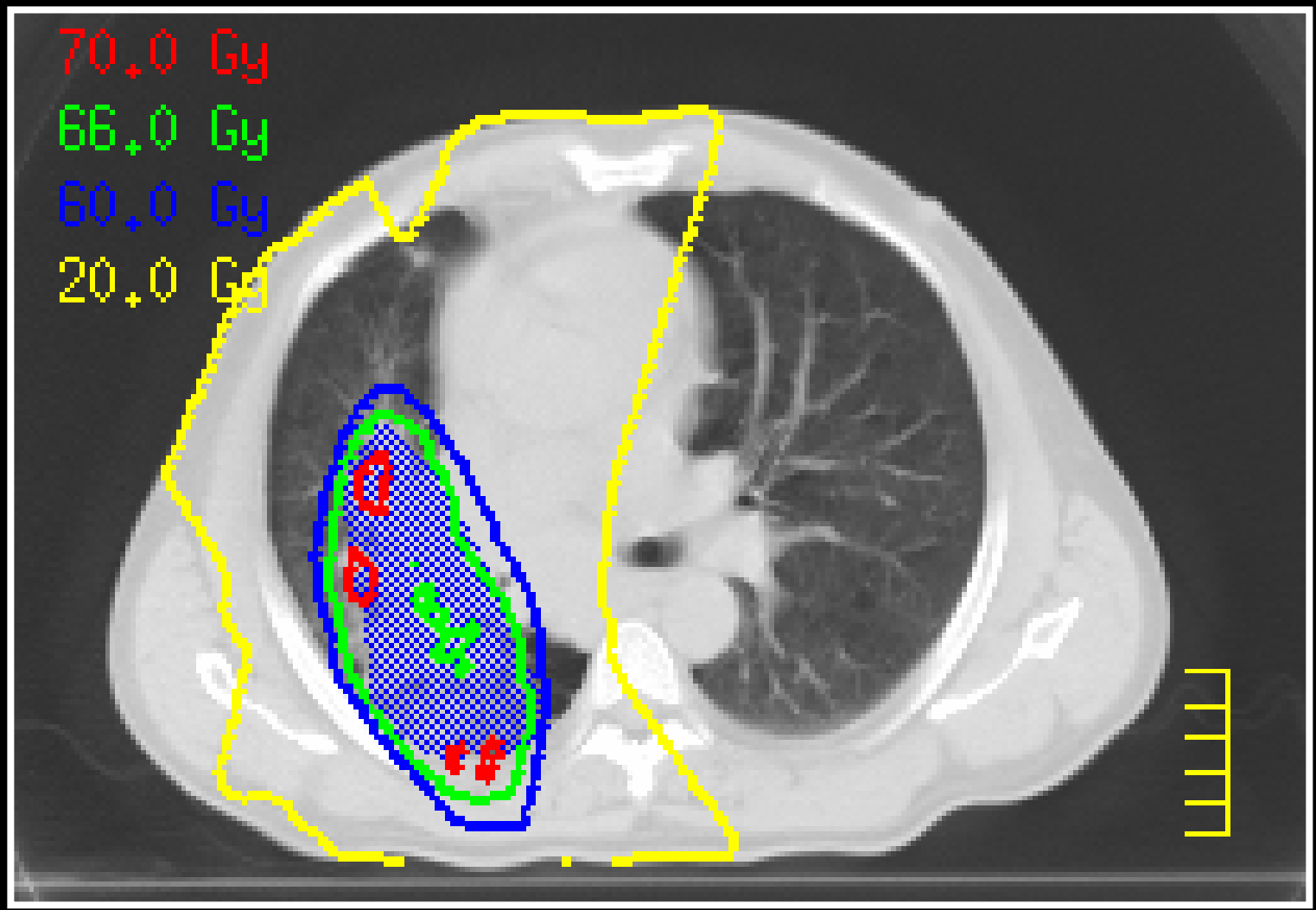
Isodoses from 6% uncertainty calculation per beam for all phases



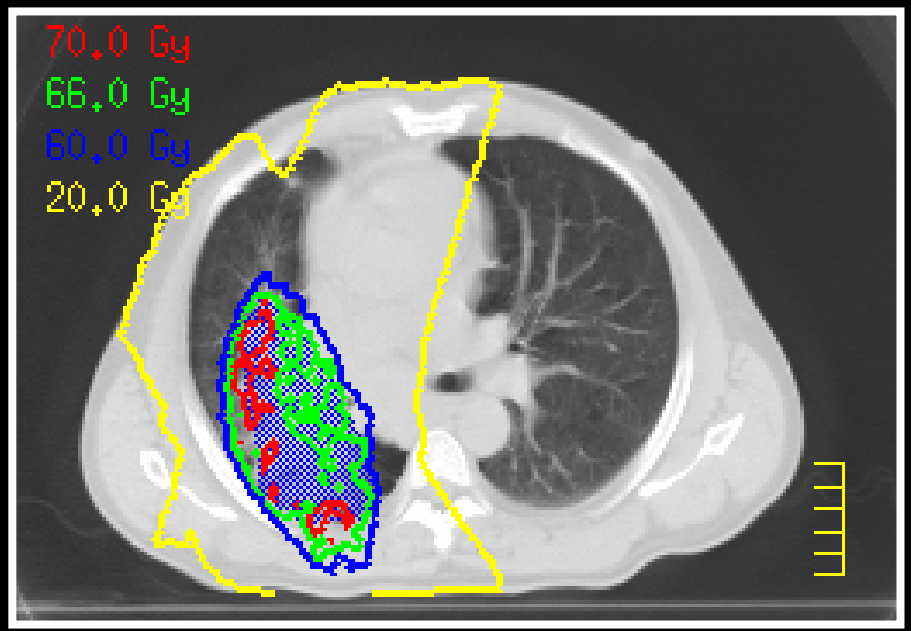
Map dose distributions to reference (equi-time)



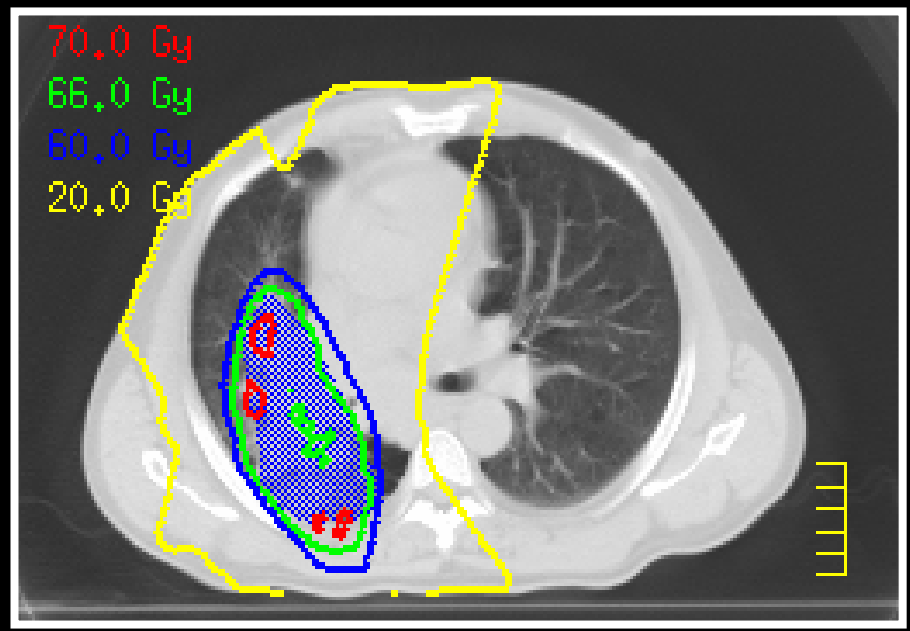
Isodoses from all phases deformed to peak inhale



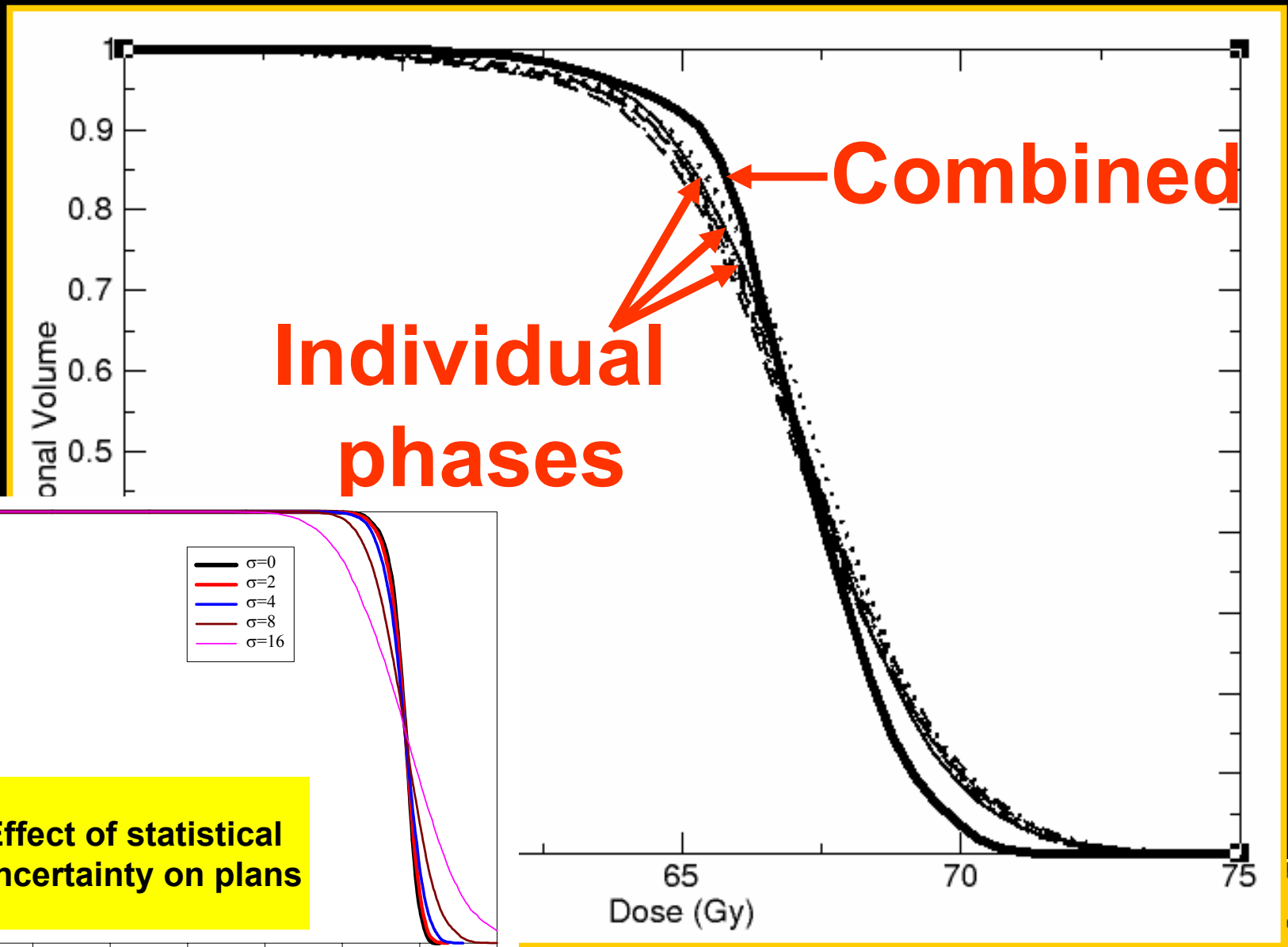
6% uncertainty per beam



Combined 8 phases

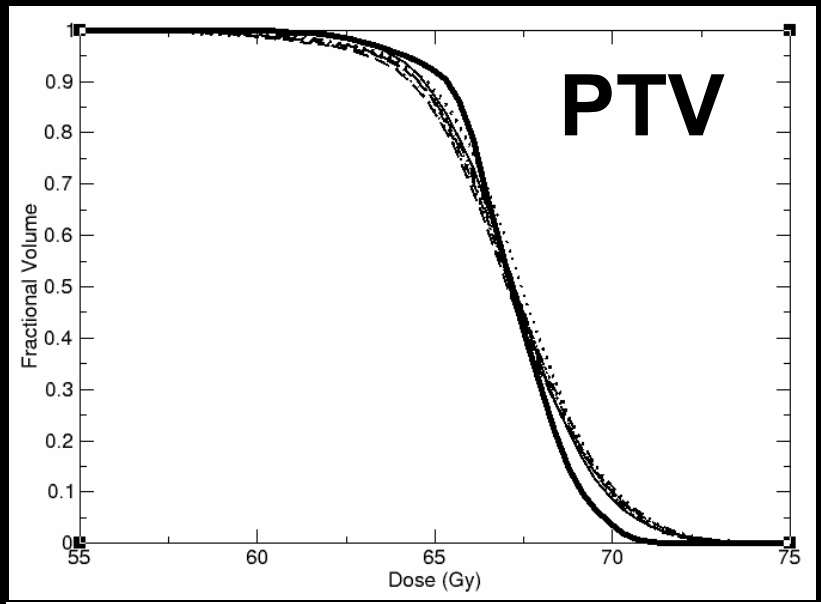


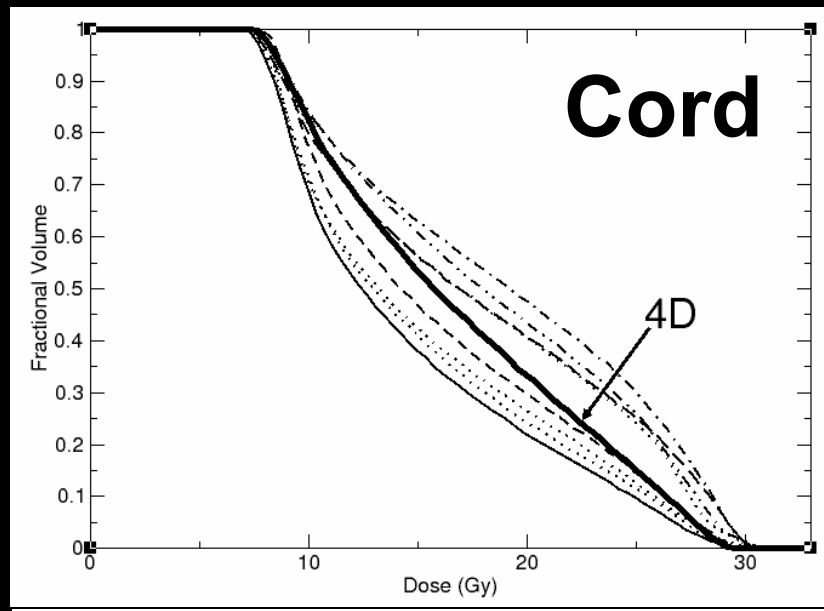
PTV DVHs

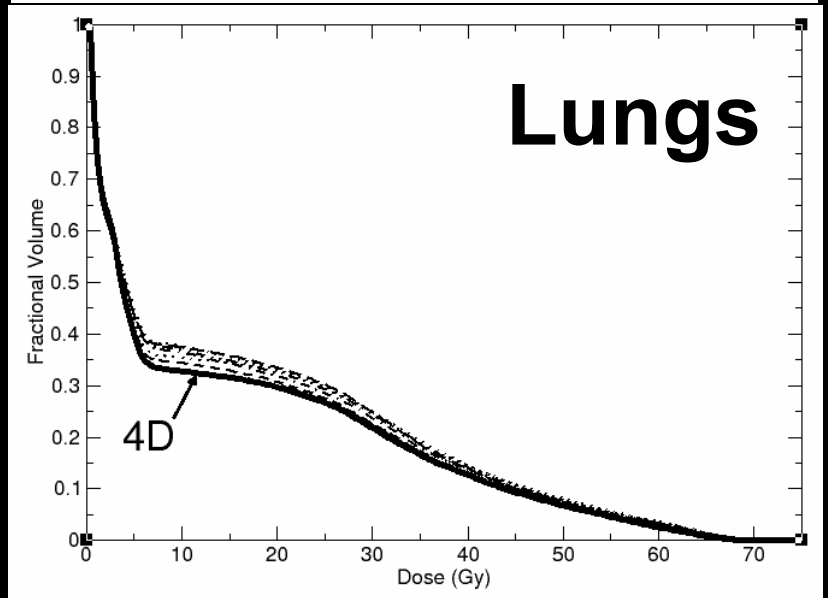

Combined
Individual phases
1
0.9
0.8
0.7
0.6
0.5
onal Volume
65
70
75
Dose (Gy)

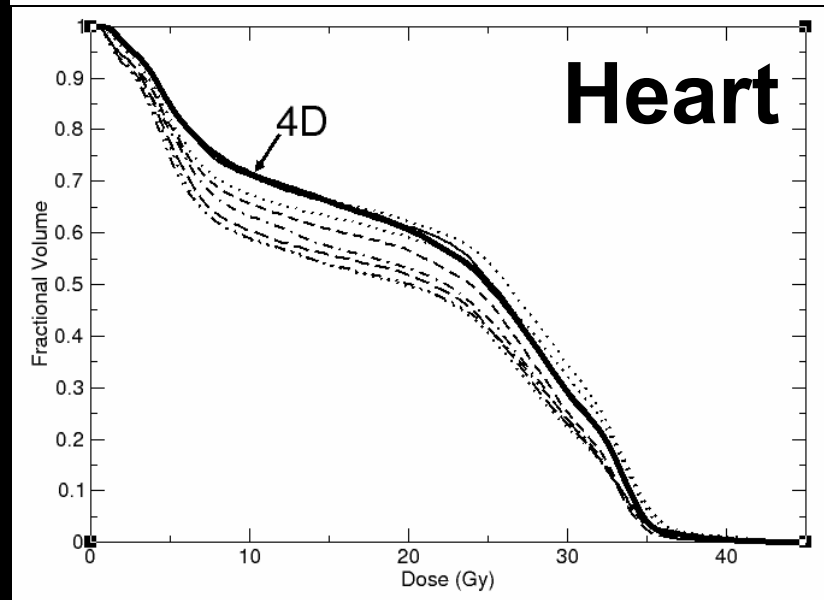
σ=0
σ=2
σ=4
σ=8
σ=16
Volume (%)
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
Dose (cGy)
Effect of statistical uncertainty on plans

Dose Volume Histograms





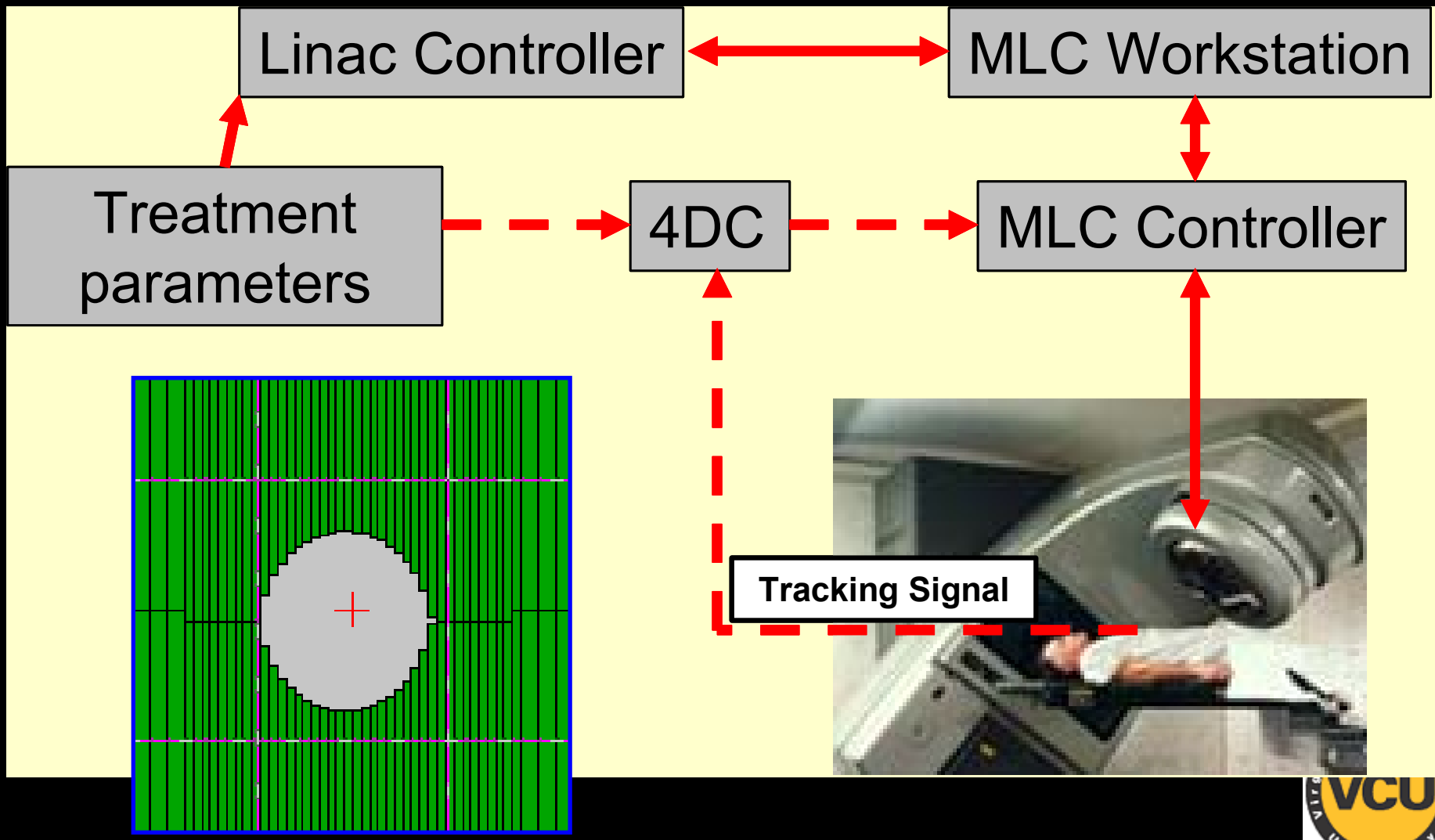


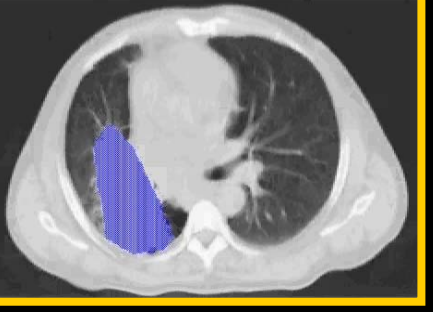


Future Work

- Imaging
  - Acquire complete 4D image sets
  - Quantify deformation maps
- Planning
  - Margin reduction allowed by 4D
  - Potential toxicity reduction for 4D
  - Potential dose escalation for 4D
  - Potential benefits of MC for 4D
    - Dose accuracy
    - Dose calculation speed
- …

Future
4D Radiotherapy Delivery





Conclusion

- Methodology for 4D Monte Carlo radiotherapy calculations has been developed
- 4D radiotherapy planning with Monte Carlo has two advantages
  - (1) higher accuracy for calculation in electronic disequilibrium conditions such as those encountered during lung radiotherapy
  - (2) if deformable image registration is used, the calculation time for Monte Carlo is ≈independent of the number of 3D CT image sets constituting a 4D CT (same time for 4D and 3D calculation)


Thank you