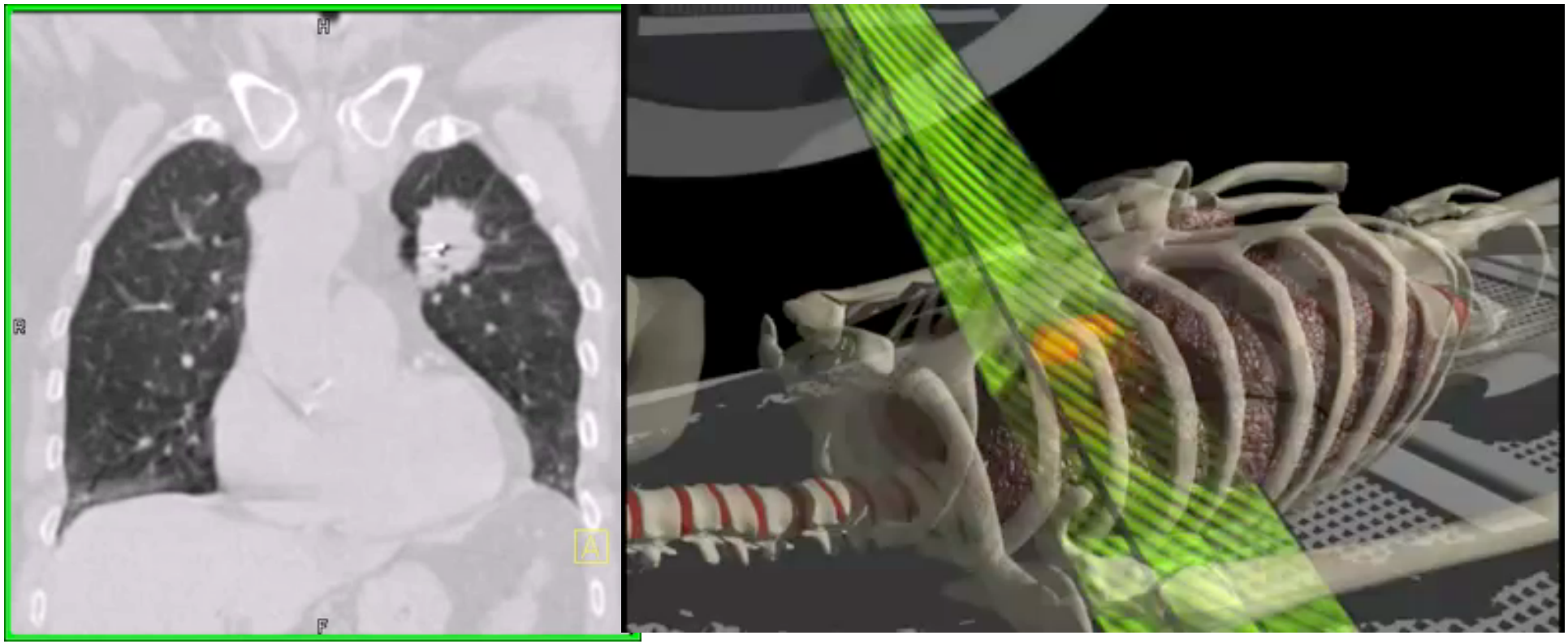
GATE Applications
Respiratory Motion in PET

Graeme O'Keefe
Centre for PET, Austin Health
School of Physics, University of Melbourne

Respiratory Motion

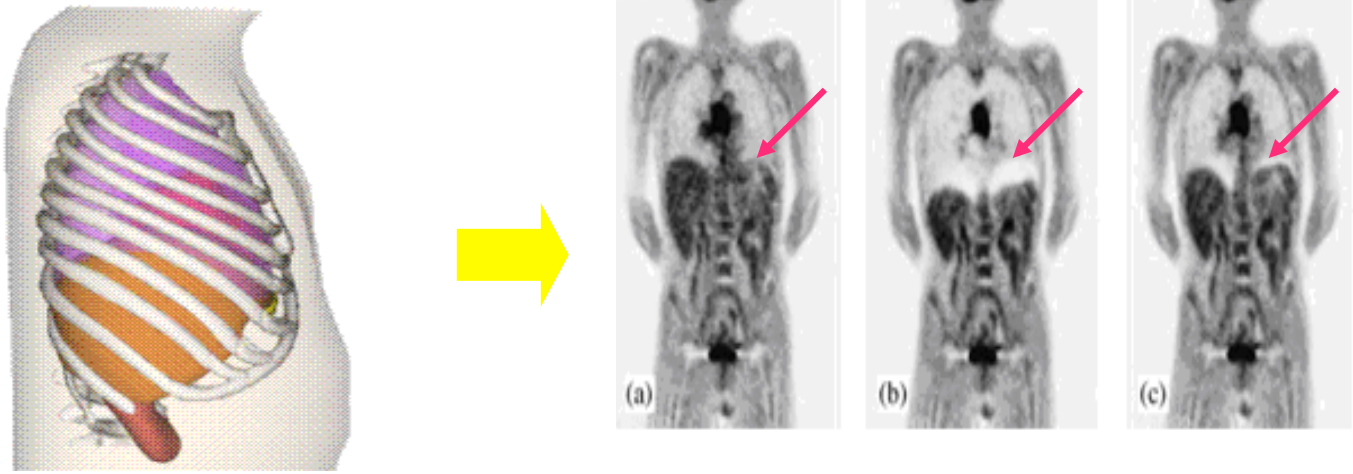


- Respiratory motion in PET
  - In lung, up to 20 mm

Respiratory Motion

Attenuation Correction Artifact

- Respiratory motion issue
  - Free breathing cycles during PET acquisition data cause blurring images
  - Attenuation correction artifact

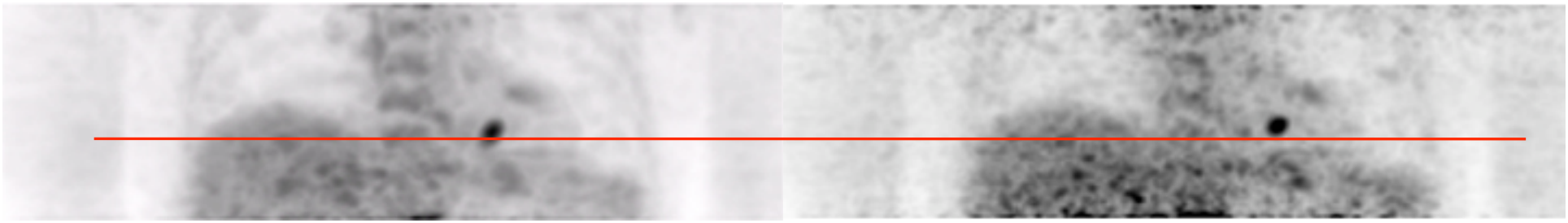


Nuclear Instruments & Methods in Physics Research A 569 2006, 453-457

Respiratory Motion

Lesion Localisation

- Effect of Respiratory Motion on Tumour



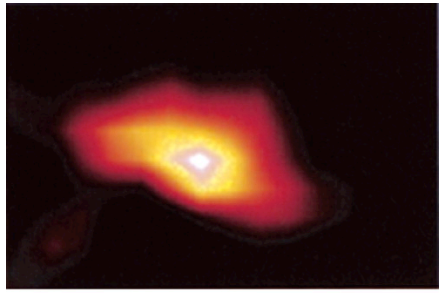
Average over all respiratory phase.

Exhalation phase.

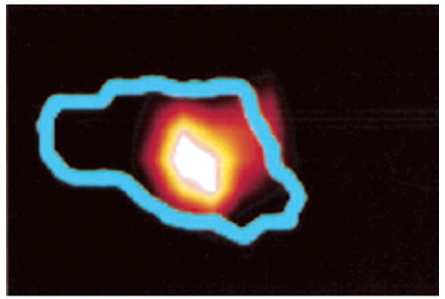
www.fzd.de : Forschungszentrum Dresden / Rossendorf

Respiratory Motion

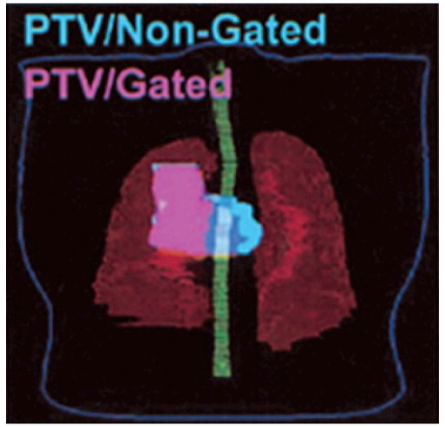
Tumour Volume Estimation



(a)



(b)



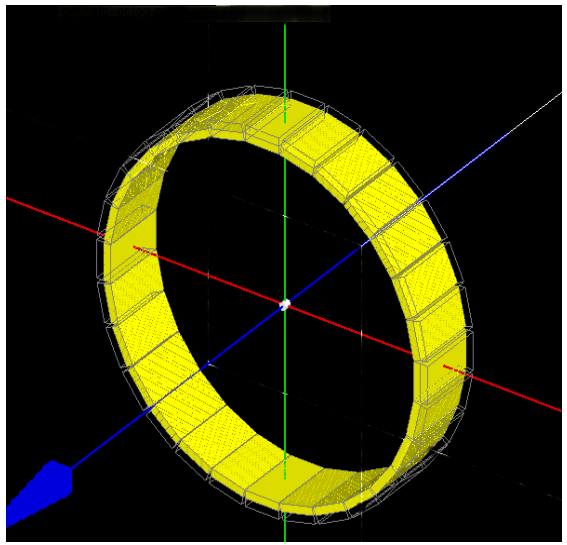
(c)

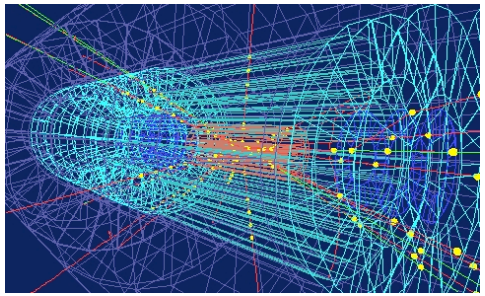
- Transaxial ^{18}F-FDG PET Image
  a) Non-gated Mode
  b) Gated mode
  c) Planning target volume in non-gated (light blue) and gated (pink)

Nehmeh S, Erdi Y, Ling CC, et al.
Effect of respiratory gating on quantifying PET images of lung cancer.
J Nucl Med 2002;43:876–81

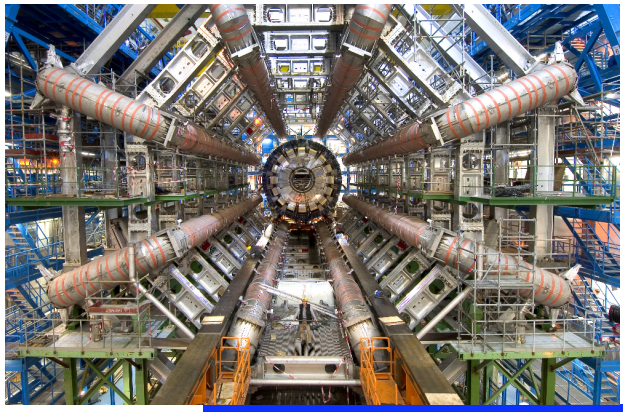
Method and Materials

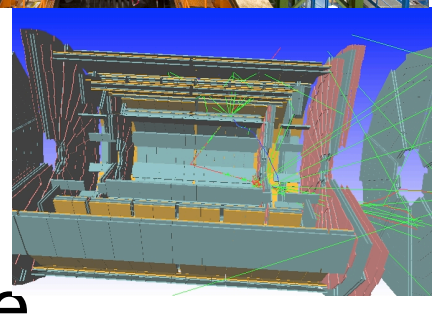
- GEANT4
- GATE



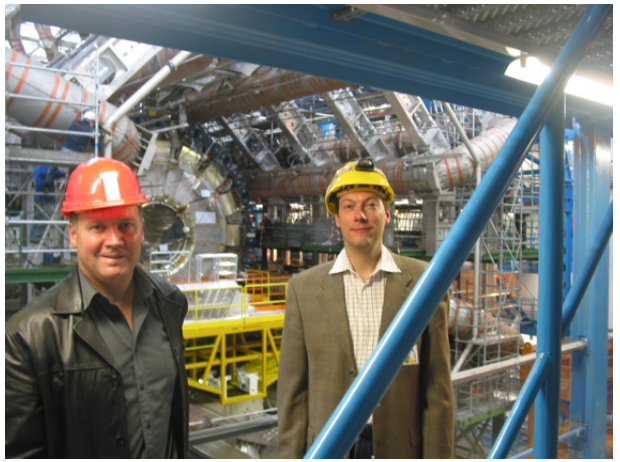


Geant4/GATE





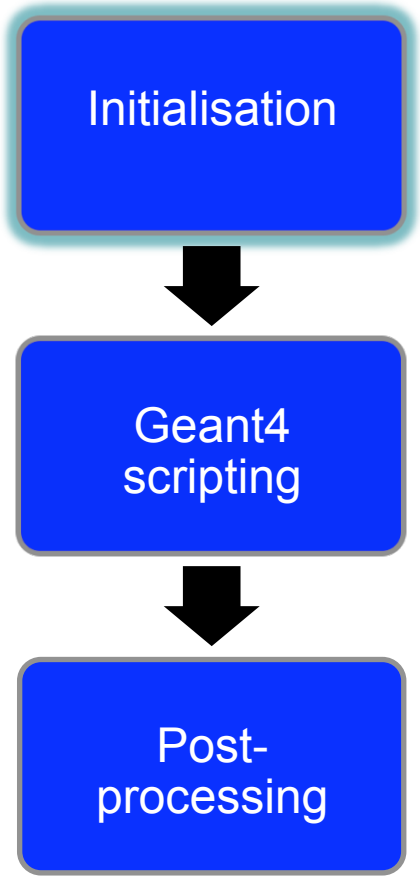
- GEANT
  - **GE**ometry **AN**d **T**racking
  - 1974 Project Initiation
  - 3.21 / 2000 – last FORTRAN release
- Geant4
  - 1994 Project Initiation
    - C++ – Object Oriented Design
  - 1998 – 0.0 release
  - 2008 – 9.1 release

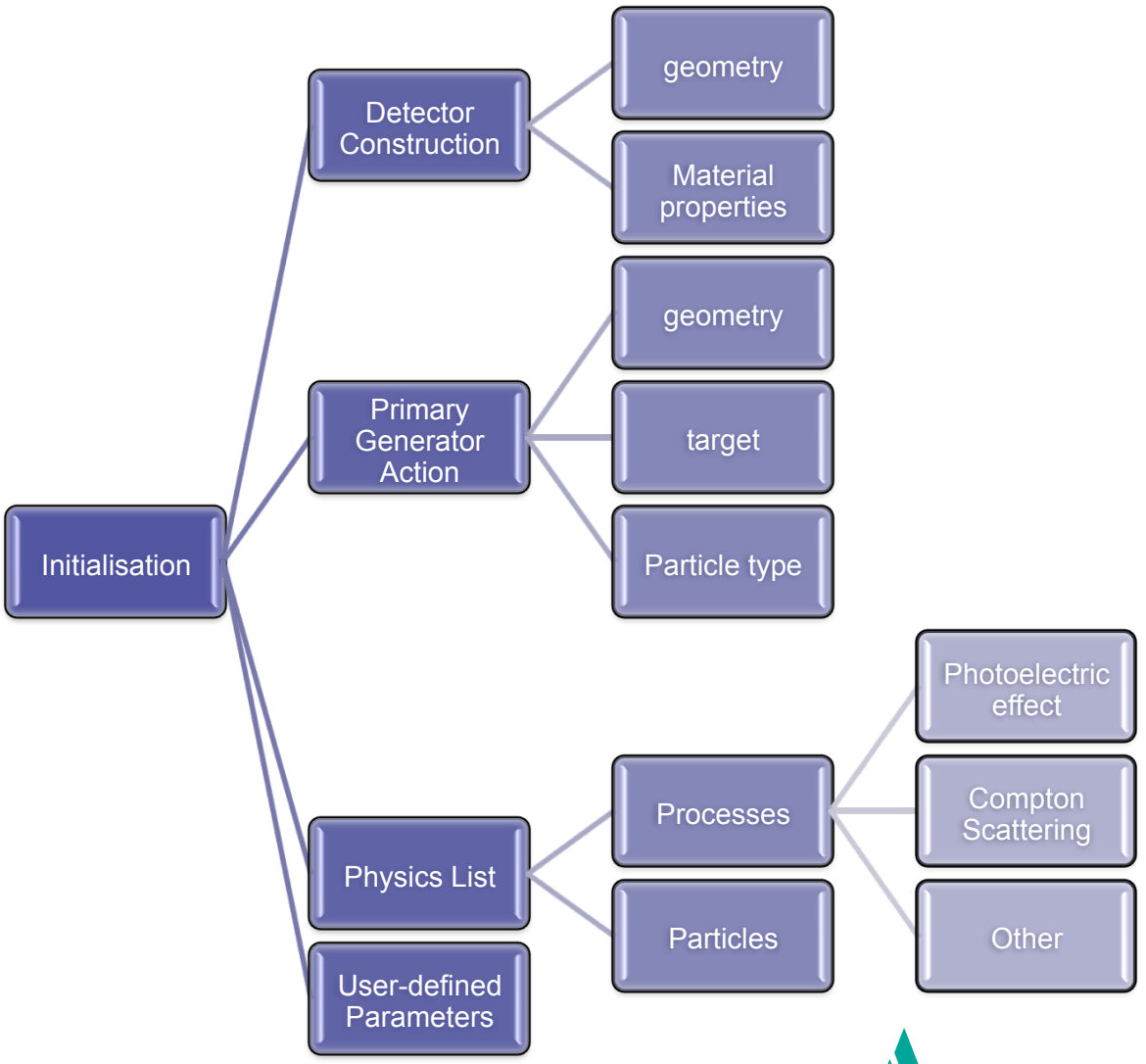


Geant4

ATLAS Detector

Geant4 object model





GATE

Geant4 **A**pplication **T**omographie **E**mission

- 2001 – Project Initiation
  - Irene Buvat
- 2002 – 1.0.0
- 2004 – 1.0.1
- 2005 – 1.1.0-**2.2.0** / 6.2.p02 – **6.9.p02**
- 2006 – 3.0.0 / 8.1.p02
- 2008 – 4.0.0 / 9.1.p03

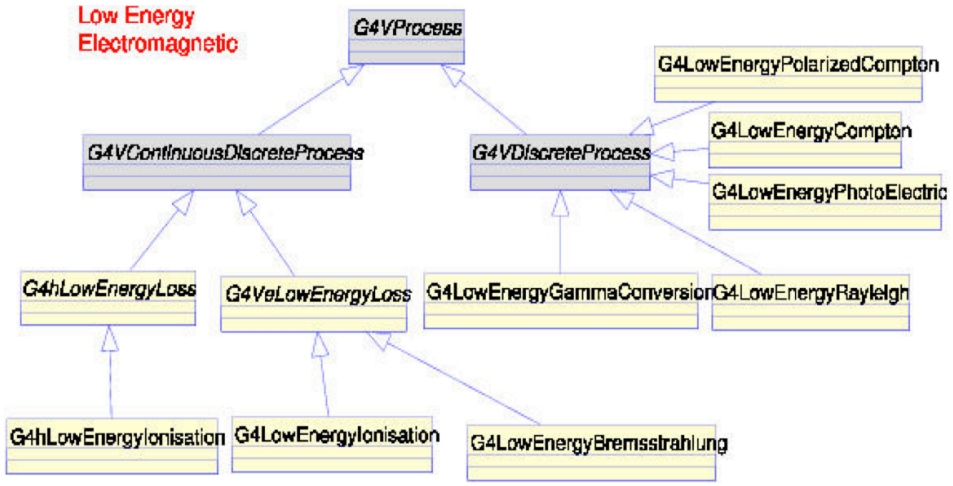
GATE
Installation

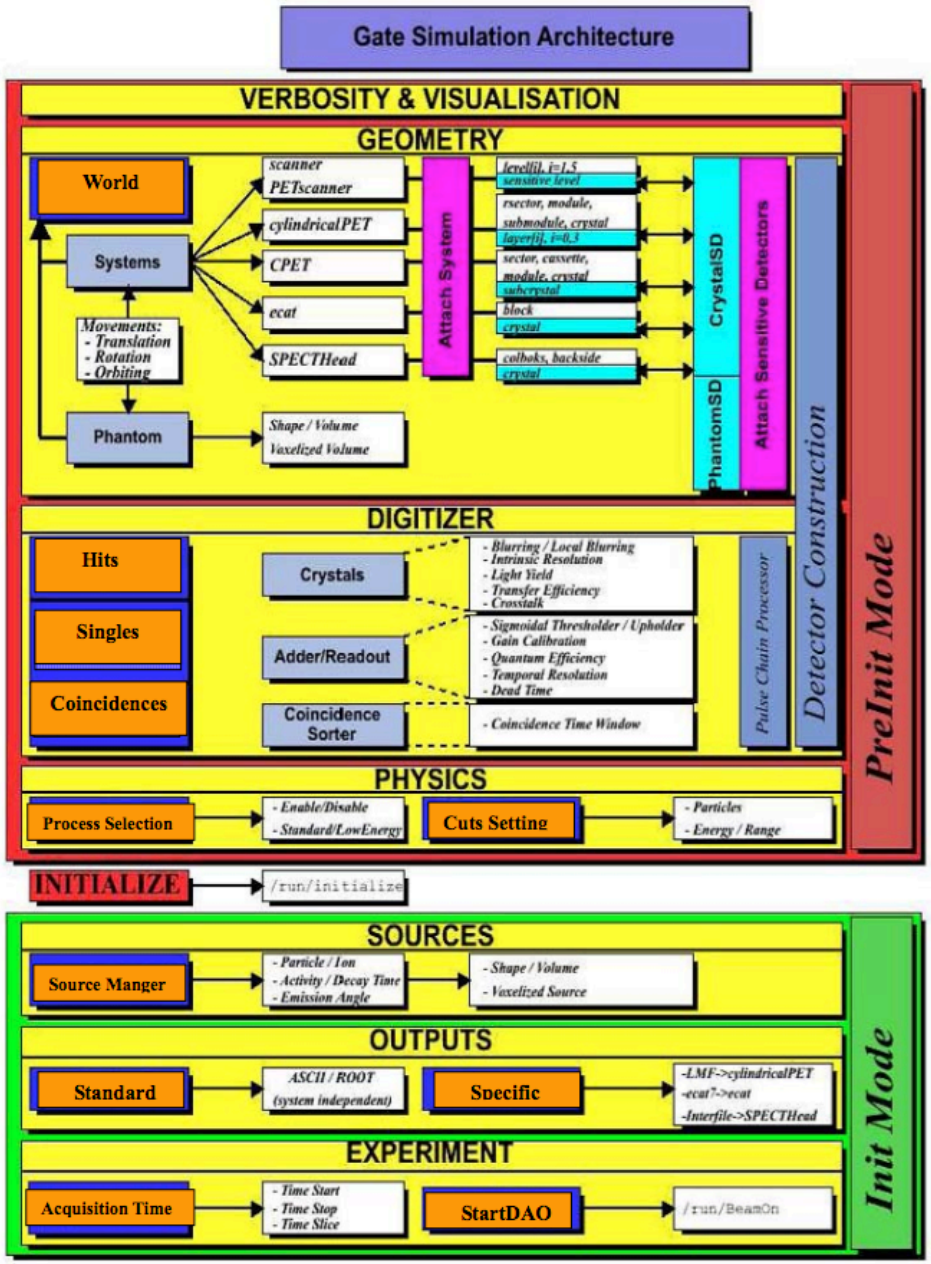
- Platforms
  - Linux, OS X, Unices, Windows/CygWin
- Requirements / Dependencies
  - gcc 4.x
  - Xwindows
  - CLHEP
  - Geant4 + G4EMLOW data
  - ROOT
  - LMF
  - ECAT
  - ***Lots of Patience!***

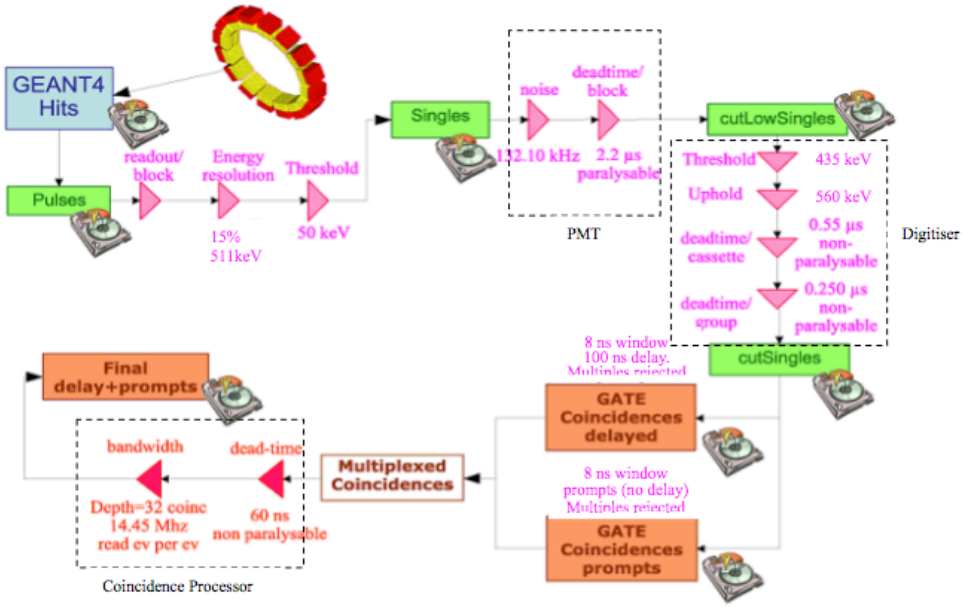
Geant4

Data Files

- G4ABLA.3.0
  - Nuclear Shell Effects
- G4EMLOW.5.1
  - Low Energy Electromagnetic Processes (250 eV to 10 GeV)
    - Rayleigh Scattering
    - Compton Scattering
    - Photo-electric
    - Pair-production
- Neutron Processes
  - G4NDL.0.2
    - without thermal neutron reaction channels
  - G4NDL.3.12
    - with thermal neutron reaction channels
- G4RadioactiveDecay.3.2
    - Hadronic radioactive decay processes
- PhotonEvaporation.2.0
    - Photon Evaporation Reaction Channels



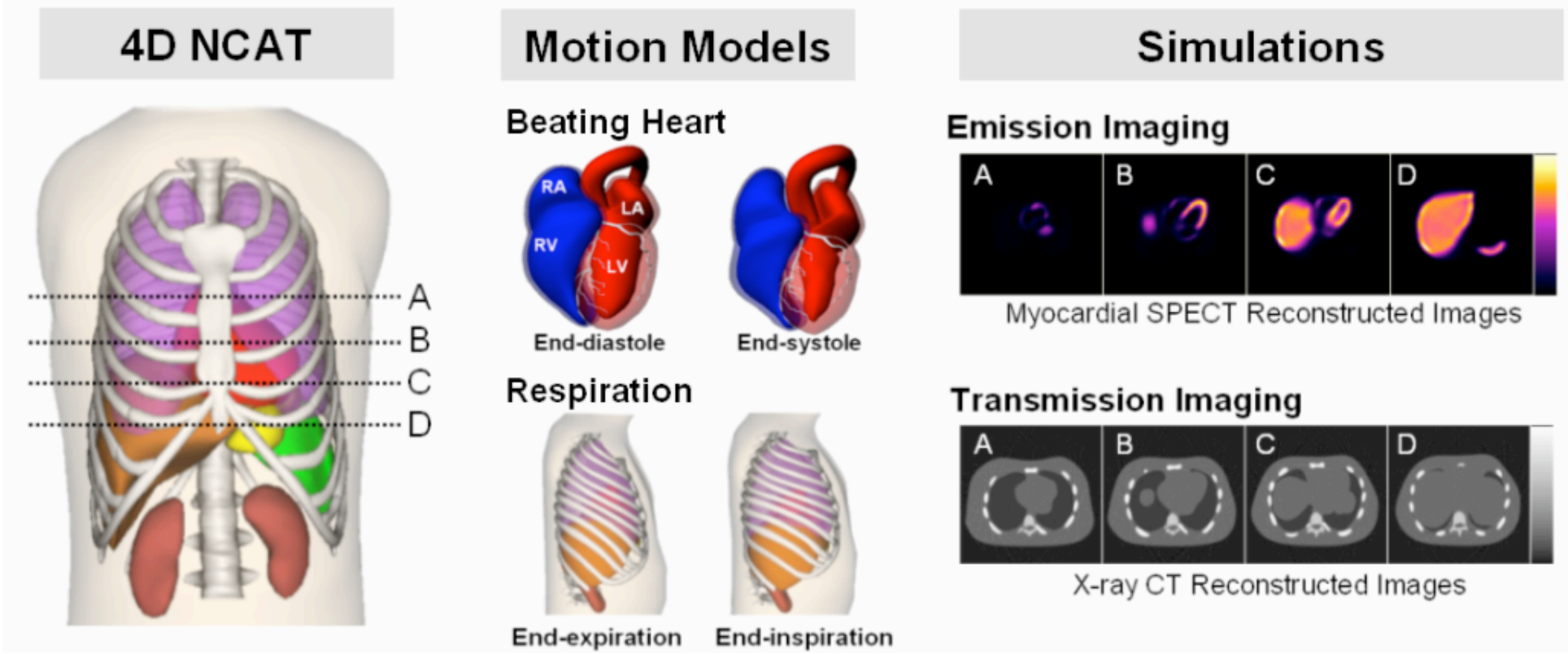

Gate Simulation Architecture
VERBOSITY & VISUALISATION
GEOMETRY
World
Systems
Movements:
- Translation
- Rotation
- Orbiting
Phantom
scanner
PETscanner
cylindricalPET
CPET
ecat
SPECTHead
Shape / Volume
Voxelized Volume
Attach System
levelfil, i=1,5
sensitive level
rsector, module, submodule, crystal
layerfil, i=0,3
sector, cassette, module, crystal
subcrystal
block
crystal
colboks, backside
crystal
CrystalSD
PhantomSD
Attach Sensitive Detectors
Detector Construction
DIGITIZER
Hits
Singles
Coincidences
Crystals
Adder/Readout
Coincidence Sorter
- Blurring / Local Blurring
- Intrinsic Resolution
- Light Yield
- Transfer Efficiency
- Crosstalk
- Sigmoidal Thresholder / Upholder
- Gain Calibration
- Quantum Efficiency
- Temporal Resolution
- Dead Time
- Coincidence Time Window
Pulse Chain Processor
PHYSICS
Process Selection
- Enable/Disable
- Standard/LowEnergy
Cuts Setting
- Particles
- Energy / Range
PreInit Mode
INITIALIZE
/run/initialize
SOURCES
Source Manger
- Particle / Ion
- Activity / Decay Time
- Emission Angle
- Shape / Volume
- Voxelized Source
OUTPUTS
Standard
ASCII / ROOT
(system independent)
Specific
-LMF->cylindricalPET
-ecat7->ecat
-Interfile->SPECTHead
EXPERIMENT
Acquisition Time
- Time Start
- Time Stop
- Time Slice
StartDAO
/run/BeamOn
Init Mode


GEANT4 Hits
Pulses
readout/ block
Energy resolution
15% 511keV
Threshold
50 keV
Singles
noise
122.10 kHz
deadtime/ block
2.2 µs paralysable
PMT
cutLowSingles
Threshold
435 keV
Uphold
560 keV
deadtime/ cassette
0.55 µs non-paralysable
deadtime/ group
0.250 µs non-paralysable
Digitiser
8 ns window
100 ns delay.
cutSingles
GATE Coincidences delayed
8 ns window
prompts (no delay)
GATE Coincidences prompts
Multiplexed Coincidences
Final delay+prompts
bandwidth
dead-time
Depth=32 coinc
14.45 Mhz
read ev per ev
60 ns
non paralysable
Coincidence Processor

Respiratory Motion

- Scanner specification
  - Allegro / Gemini
- Validation
  - Physical Phantoms
- Phantom specification
  - Geometric (gate) objects
  - Voxelised 4D-NCAT

4D NCAT



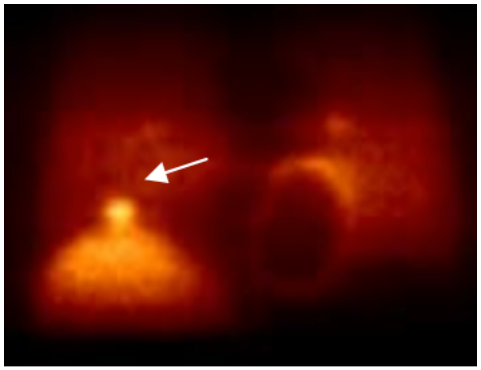
- http://dmip.rad.jhmi.edu/people/faculty/Paul/Segars_research.htm

4D NCAT

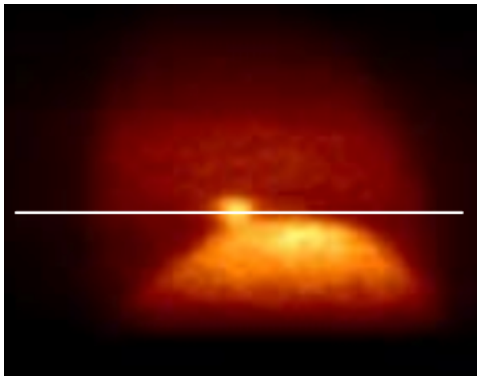
- Developed by Segars
  - 3D surfaces of torso structures
    - MRI & hi-res respiratory-gated CT
  - Heart motion
    - 4D cubic NURBS
      - Non Uniform Rational B-Splines
  - Respiratory Motion
    - Modelled on Normal Tidal Breathing
  - Compressible motions
    - Lung, Liver, Heart

4D NCAT

- Lesion models
  - resp_lesn_bin : lesion generator
- Dynamic output
  - User defined times
  - Output as binary
    - Converted to Interfile for GATE



Coronal view: heart/lung/liver/lesion



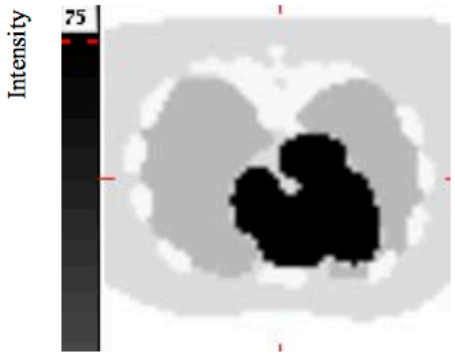
Sagittal view: liver/lung/lesion

GATE

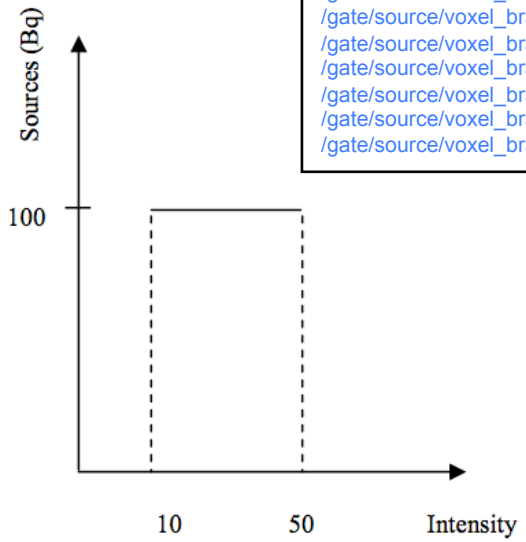
Voxelised Phantoms

- Translation tables
  - Source
  - Attenuation

```
#VOXEL SOURCE BASED ON THE NCAT PHANTOM
/gate/source/addSource voxel_brain voxel
 ########## Range translator
/gate/source/voxel_brain/reader/insert interfile

##########  Linear translator: All numbers directly #into activities
/gate/source/voxel_brain/interfileReader/translator/insert linear
/gate/source/voxel_brain/interfileReader/linearTranslator/setScale 10.50 Bq

/gate/source/voxel_brain/interfileReader/readFile lung_lesn.h33

/gate/source/voxel_brain/setType backtoback
/gate/source/voxel_brain/gps/particle gamma
/gate/source/voxel_brain/setForcedUnstableFlag true
/gate/source/voxel_brain/setForcedHalfLife 6586.2 s
/gate/source/voxel_brain/gps/energytype Mono
/gate/source/voxel_brain/gps/monoenergy 0.511 MeV
/gate/source/voxel_brain/setPosition -160. -160. -160.mm   # 64*64*64;0.5mm
/gate/source/voxel_brain/gps/confine NULL
/gate/source/voxel_brain/gps/angtype iso
/gate/source/voxel_brain/dump 1
```



(a). Intensity value = 10 ~ 50 in the voxelised phantom



(b). Intensity value = 10 ~ 50 converted to source activity = 100 Bq

GATE Configuration

Scanner Descriptor Macro

- Physics
  - Photo-electric + Compton
- Detectors
  - Geometry
  - Materials
- Sources
  - Geometry
  - Energy

GATE Configuration

Jazczack **Source** Descriptor Macro

```
/gate/source/addSource F18PointA
/gate/source/F18PointA/setActivity 5640000. Bq
/gate/source/F18PointA/gps/particle e+
/gate/source/F18PointA/setForcedUnstableFlag true
/gate/source/F18PointA/setForcedHalfLife 6586 s
/gate/source/F18PointA/gps/energytype Fluor18
/gate/source/F18PointA/gps/angtype iso
/gate/source/F18PointA/gps/type Volume
/gate/source/F18PointA/gps/shape Sphere
/gate/source/F18PointA/gps/radius 12.5 mm
/gate/source/F18PointA/gps/centre 0.85 0.85 0.85 cm

/gate/source/addSource F18PointB
/gate/source/F18PointB/setActivity 2030000. Bq
/gate/source/F18PointB/gps/particle e+
/gate/source/F18PointB/setForcedUnstableFlag true
/gate/source/F18PointB/setForcedHalfLife 6586 s
/gate/source/F18PointB/gps/energytype Fluor18
/gate/source/F18PointB/gps/angtype iso
/gate/source/F18PointB/gps/type Volume
/gate/source/F18PointB/gps/shape Sphere
/gate/source/F18PointB/gps/radius 9. mm
/gate/source/F18PointB/gps/centre 0.85 -0.85 -0.85 cm
```

```
/gate/source/addSource F18PointC
/gate/source/F18PointC/setActivity 1160000. Bq
/gate/source/F18PointC/gps/particle e+
/gate/source/F18PointC/setForcedUnstableFlag true
/gate/source/F18PointC/setForcedHalfLife 6586 s
/gate/source/F18PointC/gps/energytype Fluor18
/gate/source/F18PointC/gps/angtype iso
/gate/source/F18PointC/gps/type Volume
/gate/source/F18PointC/gps/shape Sphere
/gate/source/F18PointC/gps/radius 8. mm
/gate/source/F18PointC/gps/centre -0.85 -0.85 0.85 cm

/gate/source/addSource F18PointD
/gate/source/F18PointD/setActivity 590000. Bq
/gate/source/F18PointD/gps/particle e+
/gate/source/F18PointD/setForcedUnstableFlag true
/gate/source/F18PointD/setForcedHalfLife 6586 s
/gate/source/F18PointD/gps/energytype Fluor18
/gate/source/F18PointD/gps/angtype iso
/gate/source/F18PointD/gps/type Volume
/gate/source/F18PointD/gps/shape Sphere
/gate/source/F18PointD/gps/radius 6.5  mm
/gate/source/F18PointD/gps/centre -0.85 0.85 -0.85 cm

/gate/source/list
```

GATE Configuration

Physics Descriptor Macro

```
#     EM PROCESS
/gate/physics/gamma/selectRayleigh lowenergy
/gate/physics/gamma/selectPhotoelectric lowenergy
/gate/physics/gamma/selectCompton lowenergy

#     INACTIVE SECONDARY ELECTRONS
/gate/physics/setElectronCut 1. m

#     INACTIVE X-RAYS
/gate/physics/setXRayCut 1. GeV
/gate/physics/setDeltaRayCut 1. GeV
```

GATE Configuration

Jazczack **Phantom** Descriptor Macro

```
/gate/world/daughters/name phantomA
/gate/world/daughters/insert sphere
/gate/phantomA/setMaterial Water
#/gate/phantomA/vis/forceWireframe
/gate/phantomA/vis/setColor green
/gate/phantomA/geometry/setRmax   12.5 mm
/gate/phantomA/placement/setTranslation  0.85 0.85 0.85 cm
/gate/phantomA/attachPhantomSD

/gate/world/daughters/name phantomB
/gate/world/daughters/insert sphere
/gate/phantomB/setMaterial Water
#/gate/phantomB/vis/forceWireframe
/gate/phantomB/vis/setColor green
/gate/phantomB/geometry/setRmax   9. mm
/gate/phantomB/placement/setTranslation  0.85 -0.85 -0.85 cm
/gate/phantomB/attachPhantomSD

/gate/world/daughters/name phantomC
/gate/world/daughters/insert sphere
/gate/phantomC/setMaterial Water
#/gate/phantomC/vis/forceWireframe
/gate/phantomC/vis/setColor green
/gate/phantomC/geometry/setRmax   8. mm
/gate/phantomC/placement/setTranslation  -0.85 -0.85 0.85 cm
/gate/phantomC/attachPhantomSD
```

```
/gate/world/daughters/name phantomD
/gate/world/daughters/insert sphere
/gate/phantomD/setMaterial Water
#/gate/phantomD/vis/forceWireframe
/gate/phantomD/vis/setColor green
/gate/phantomD/geometry/setRmax   6.5  mm
/gate/phantomD/placement/setTranslation  -0.85 0.85 -0.85 cm
/gate/phantomD/attachPhantomSD
```

GATE Configuration

Scanner Descriptor Macro

```
/control/verbose 0

#    W O R L D
/gate/world/geometry/setXLength 2.0 m
/gate/world/geometry/setYLength 2.0 m
/gate/world/geometry/setZLength 2.0 m
/gate/world/setMaterial Air

#    D E T E C T O R
/gate/world/daughters/name cylindricalPET
/gate/world/daughters/insert cylinder
/gate/cylindricalPET/setMaterial Air
/gate/cylindricalPET/geometry/setRmax 52. cm
/gate/cylindricalPET/geometry/setRmin 28. cm
/gate/cylindricalPET/geometry/setHeight 24.02 cm
/gate/cylindricalPET/vis/forceWireframe

#    S H I E L D I N G
/gate/cylindricalPET/daughters/name Shielding
/gate/cylindricalPET/daughters/insert cylinder
/gate/Shielding/setMaterial Lead
/gate/Shielding/geometry/setRmax 46.132 cm
/gate/Shielding/geometry/setRmin 28. cm
/gate/Shielding/geometry/setHeight 2.86 cm
/gate/Shielding/vis/forceSolid
/gate/Shielding/vis/forceWireframe
/gate/Shielding/vis/setColor white


#    R E P E A T   S H I E L D I N G
/gate/Shielding/repeaters/insert linear
/gate/Shielding/linear/setRepeatNumber 2
/gate/Shielding/linear/setRepeatVector 0. 0. 21.16 cm

#    D E T E C T O R = R S E C T O R
/gate/cylindricalPET/daughters/name rsector
/gate/cylindricalPET/daughters/insert box
/gate/rsector/geometry/setXLength 40 mm
/gate/rsector/geometry/setYLength 94.5 mm
/gate/rsector/geometry/setZLength 18.3 cm
/gate/rsector/setMaterial Glass
/gate/rsector/placement/setTranslation  45.2 0 0 cm
/gate/rsector/vis/forceWireframe

#    C R Y S T A L
/gate/module/daughters/name crystal
/gate/module/daughters/insert box
/gate/crystal/geometry/setXLength 20. mm
/gate/crystal/geometry/setYLength 4 mm
/gate/crystal/geometry/setZLength 6 mm
/gate/crystal/setMaterial GSO
/gate/crystal/placement/setTranslation 0 0 0 mm

#    L A Y E R   G S O
/gate/crystal/daughters/name GSO
/gate/crystal/daughters/insert box
/gate/GSO/geometry/setXLength 20. mm
/gate/GSO/geometry/setYLength 4 mm
/gate/GSO/geometry/setZLength 6 mm
/gate/GSO/placement/setTranslation 0 0 0 mm
/gate/GSO/setMaterial GSO

# R E P E T I T I O N   C R I S T A L
/gate/crystal/repeaters/insert cubicArray
/gate/crystal/cubicArray/setRepeatNumberX 1
/gate/crystal/cubicArray/setRepeatNumberY 22
/gate/crystal/cubicArray/setRepeatNumberZ 29
/gate/crystal/cubicArray/setRepeatVector 0. 4.3 6.3 mm

# R E P E T I T I O N   R S E C T O R
/gate/rsector/repeaters/insert ring
/gate/rsector/ring/setRepeatNumber 28

# P H A N T O M
# The phantom must model the attenuation geometry
/gate/world/daughters/name phantom
/gate/world/daughters/insert cylinder
/gate/phantom/geometry/setRmax    25 cm
/gate/phantom/geometry/setHeight  18.5 cm
/gate/phantom/placement/setTranslation 0. 0. 0. cm
/gate/phantom/setMaterial Water

#                A T T A C H   S Y S T E M
/gate/systems/cylindricalPET/rsector/attach rsector
/gate/systems/cylindricalPET/module/attach module
/gate/systems/cylindricalPET/crystal/attach crystal
/gate/systems/cylindricalPET/layer0/attach GSO

#                A T T A C H   L A Y E R   S D
/gate/GSO/attachCrystalSD
/gate/rsector/attachPhantomSD
/gate/module/attachPhantomSD
/gate/phantom/attachPhantomSD
#/gate/Shielding/attachPhantomSD
```

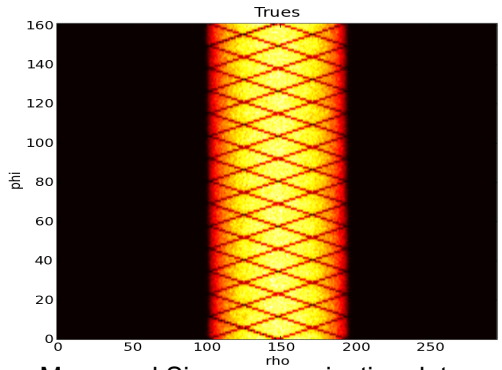
Methods

- 37 MBq in FOV
- Single CPU simulation
  - 1 second simulation
    - 1 day for geometric phantom
    - 3 day for voxelised phantom
- 5 second breathing cycle
  - 25 frames
  - 200 msec respiratory frames

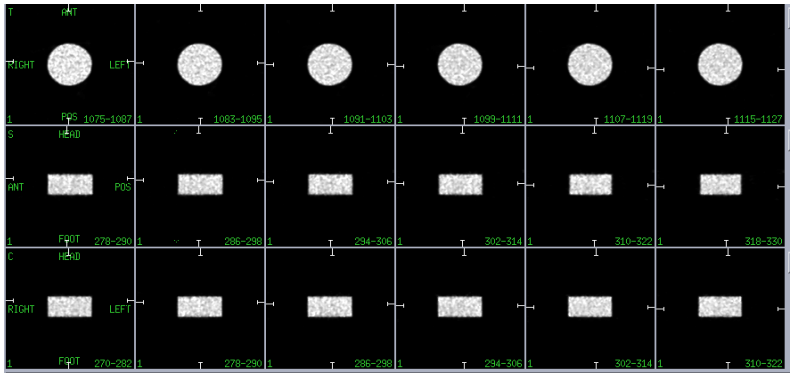
GATE Validation

Geometric phantoms

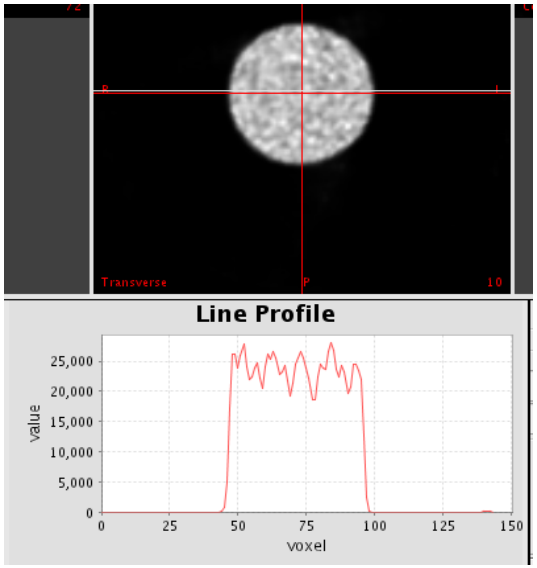
- Cylindrical phantom uniform simulation

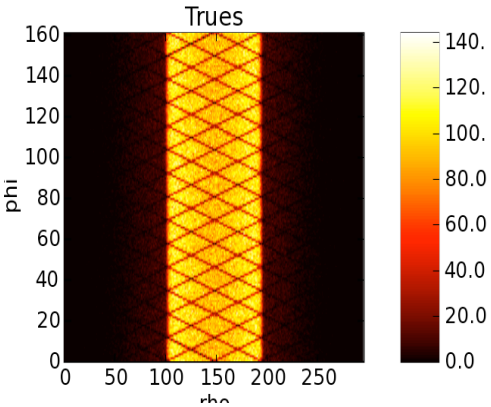


Measured Sinogram projection data

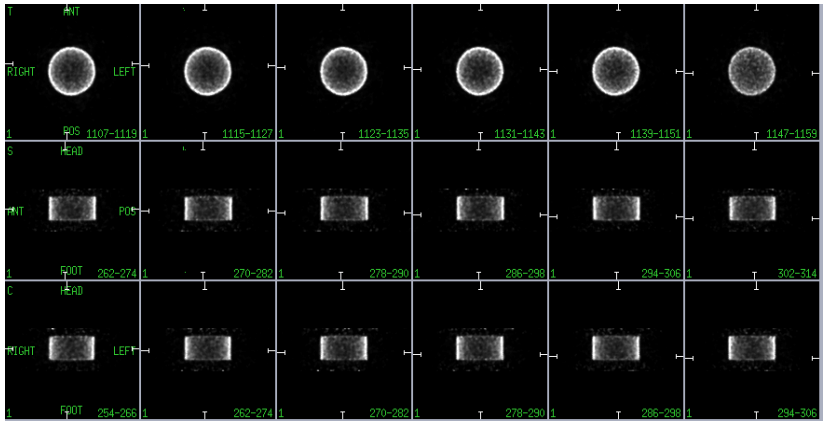


Cylindrical phantom : GATE / non-attenuation, 3.4 million LOR events

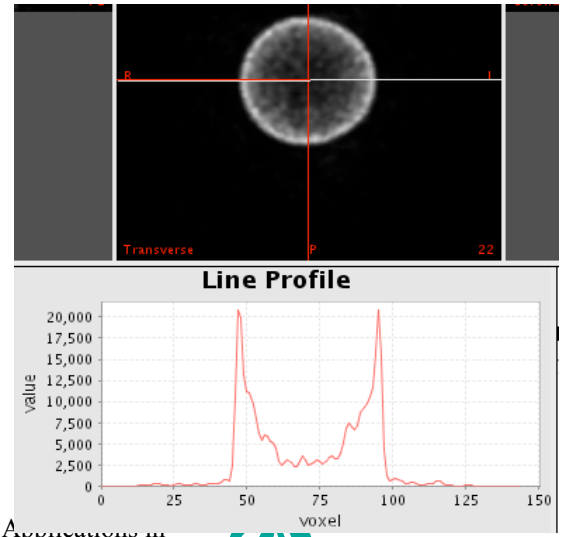




Simulated Sinogram projection data



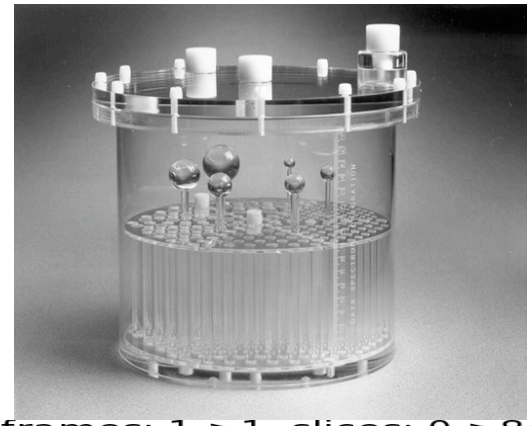
Cylindrical phantom : GATE / attenuation, 1.9 million LOR events

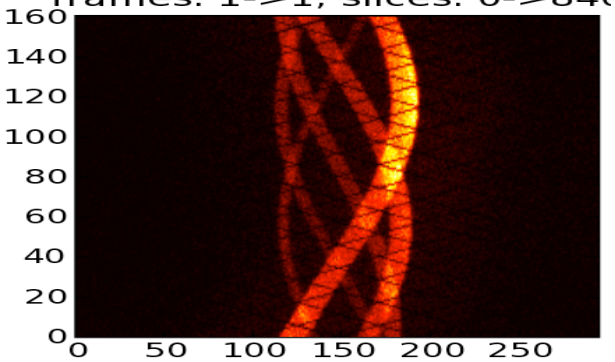


GATE Validation

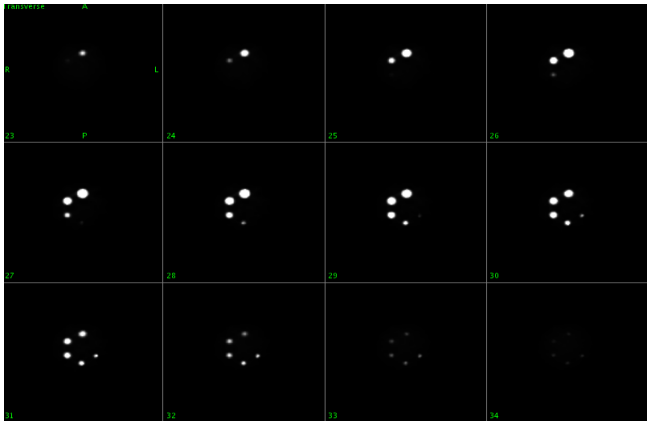
Geometric Phantoms

- Five sphere sources in Jazczack phantom simulation

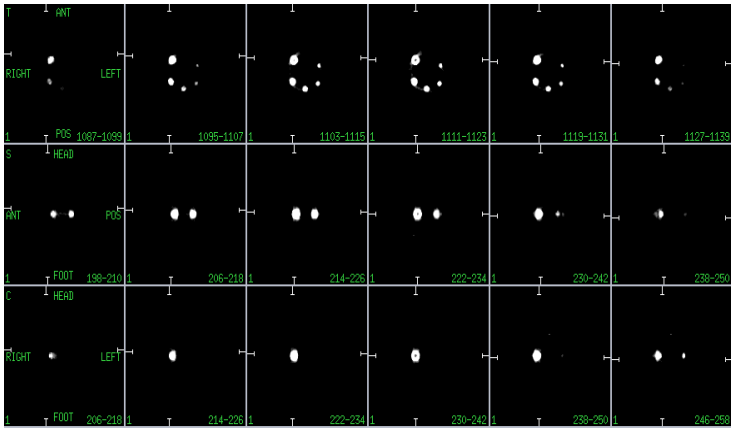




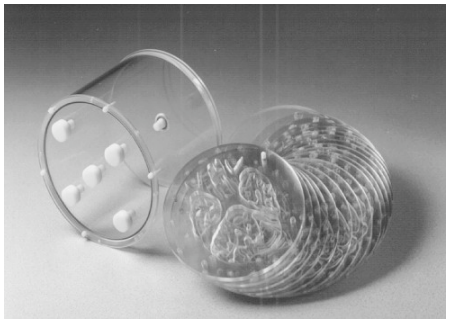
UGM sinogram from GATE projection data



Jaszczack phantom measurement by Allegro PET with 300 million line of response (LOR) events

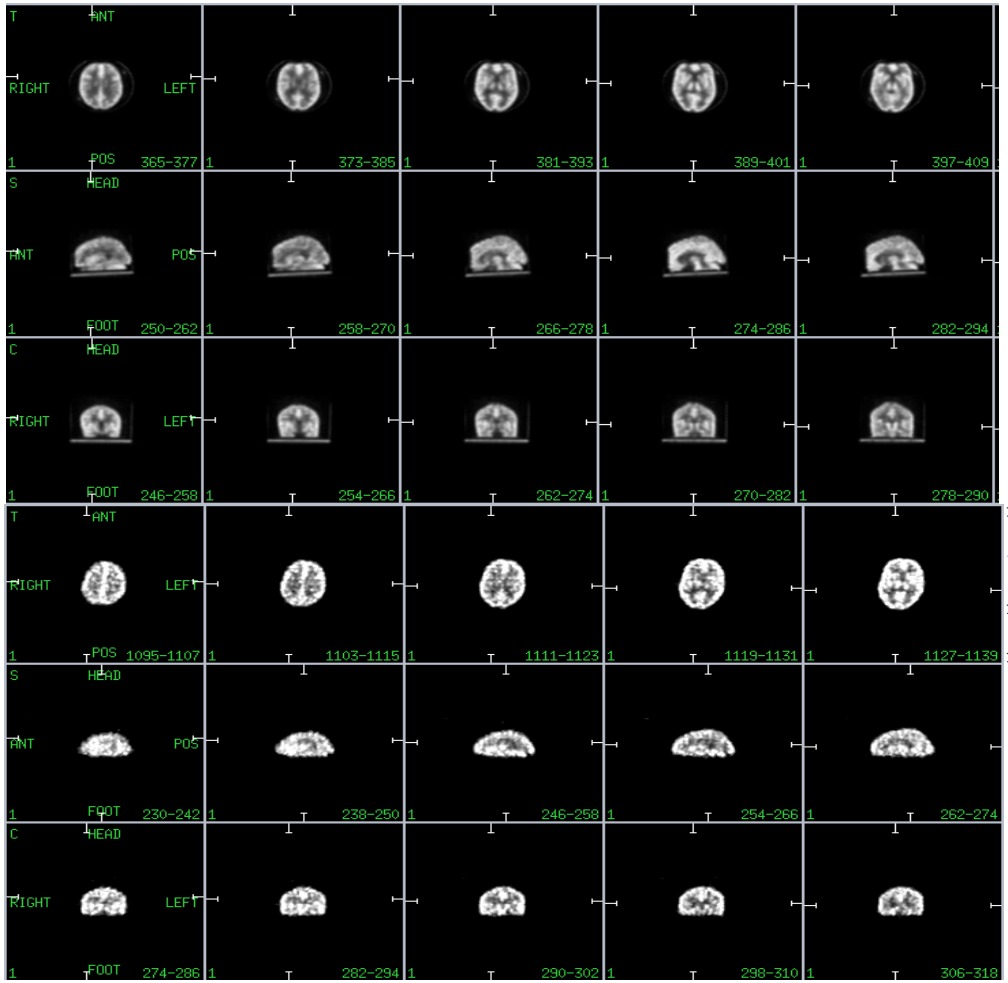


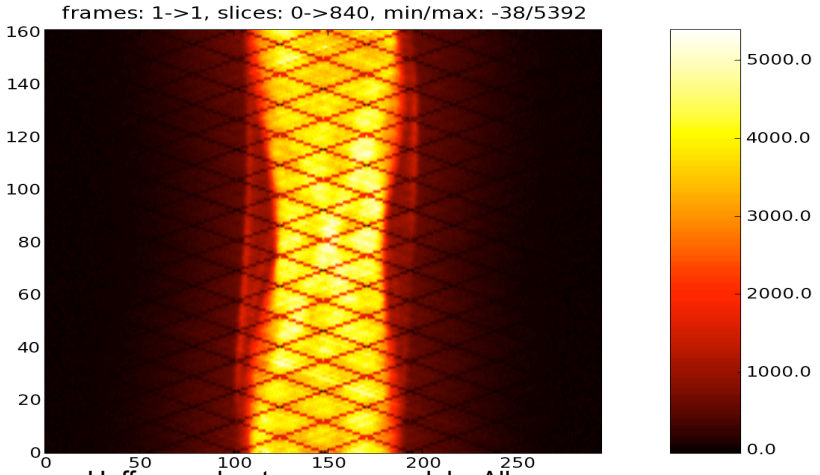
Simulation reconstructed image with 3 million LOR events



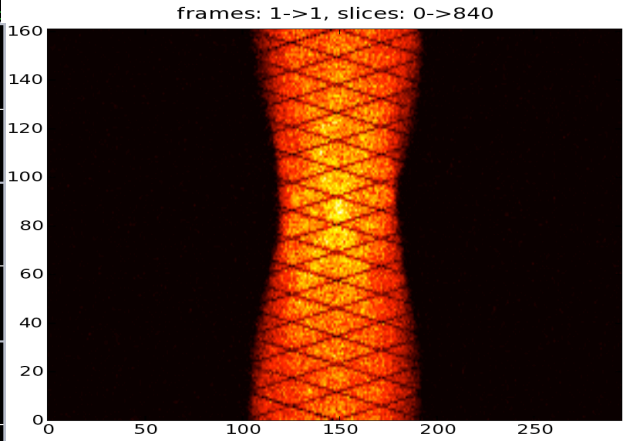
GATE Validation

Voxelised Hoffman Phantom

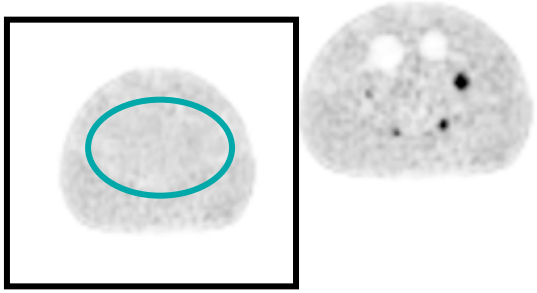




Hoffman phantom measured by Allegro
51 million LOR events

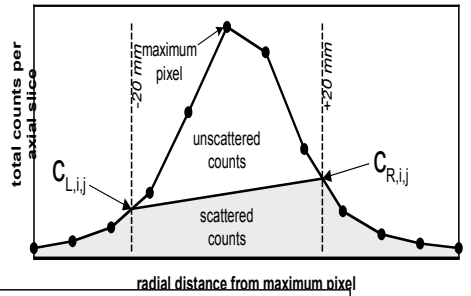


Hoffman phantom simulated by GATE w/o attenuation
0.89 million LOR events

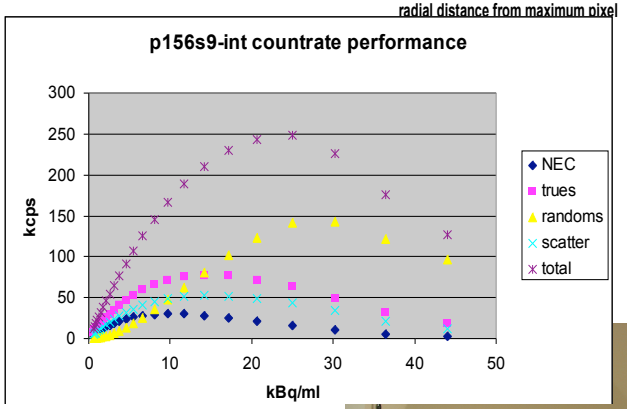


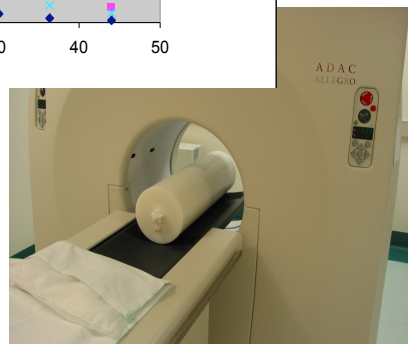
NEMA-NU2

Acceptance Testing



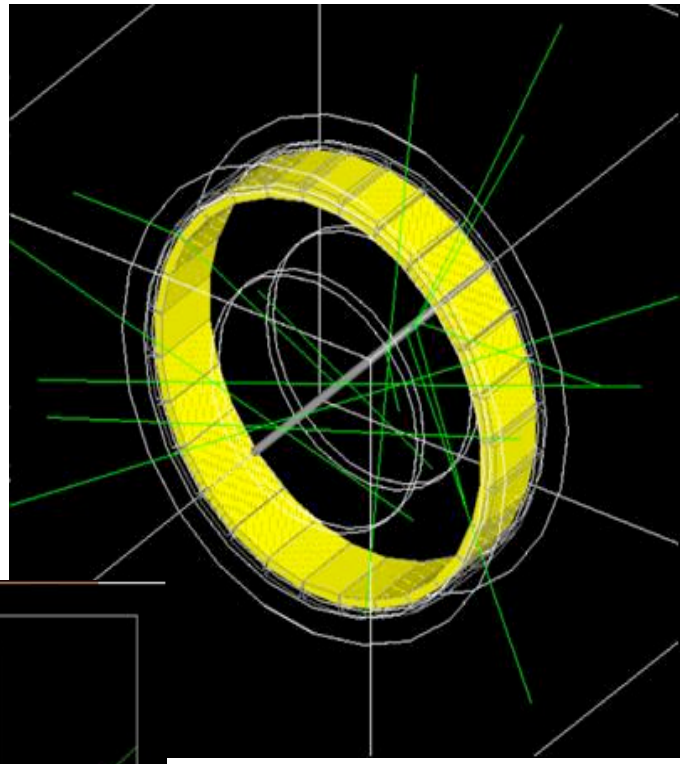
- Spatial Resolution
- Scatter Fraction
- Countrate Losses
- Randoms Measurement
- Sensitivity
- Corrections
- Image Quality
- Accuracy of Attenuation/Scatter corrections

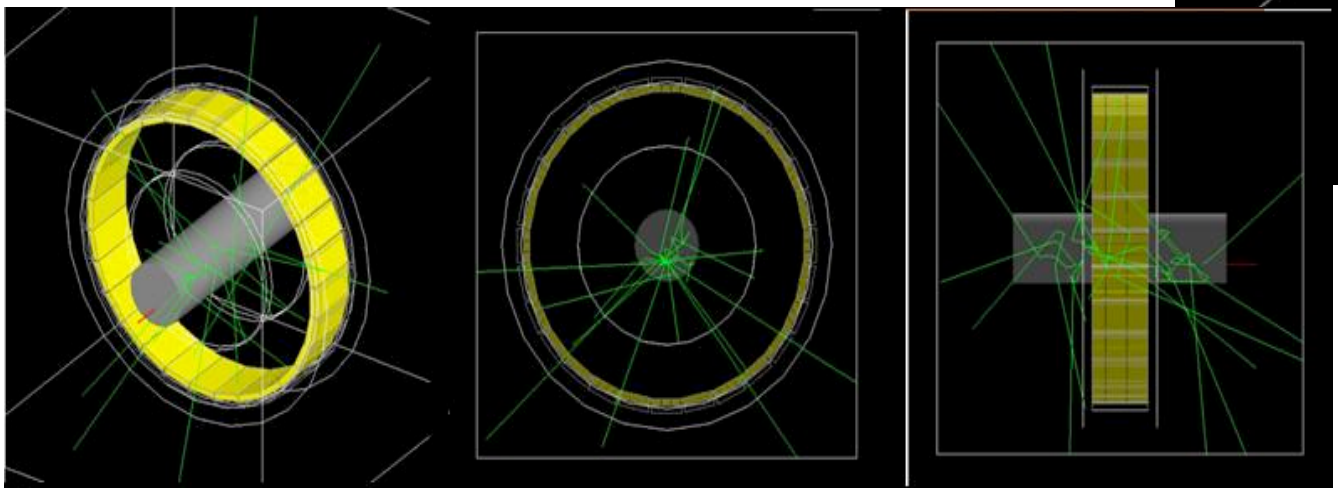




NEMA-NU2
Software Validation

- Phantom specification
  - Sensitivity
  - Countloss
  - Image Quality





Respiratory Motion

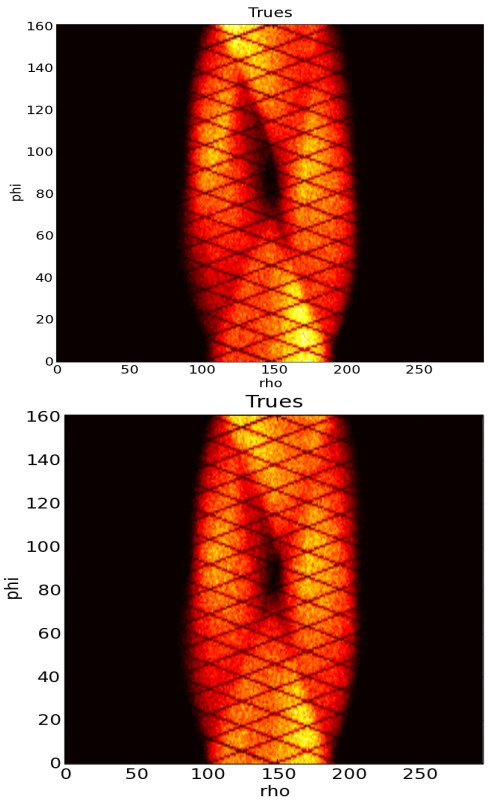
- Simulate respiratory motion in PET
  - Develop data-driven motion detection schemes
  - Validate motion correction schemes
- GATE 2.2.0
  - GEANT4 Application for Tomographie Emission
- Phantoms
  - Geometric phantom validation
  - Voxelised phantom validation
    - NCAT: NURBS Based Cardiac Torso

Respiratory Motion

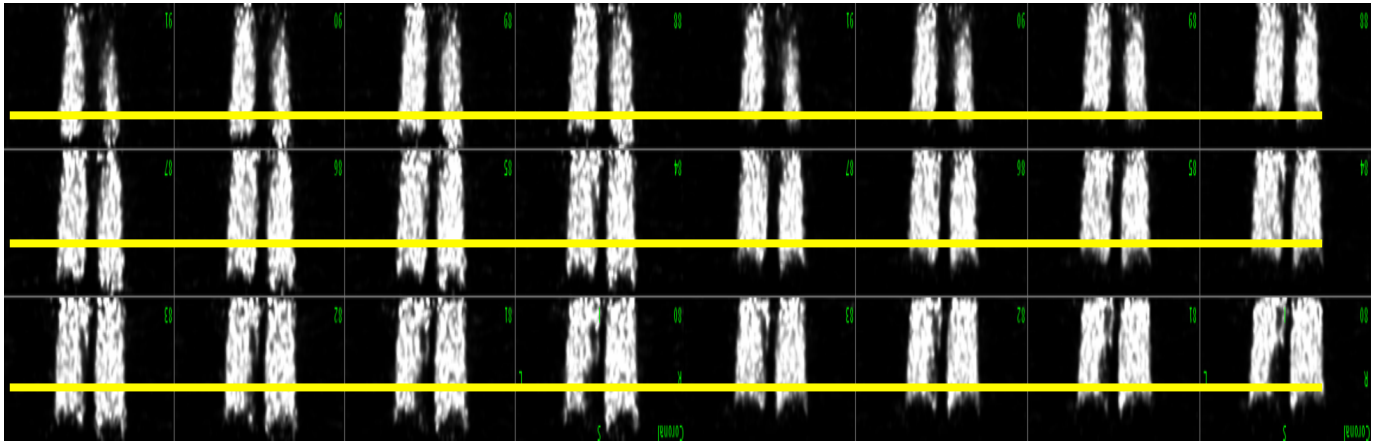
Voxelised Phantom

- **Simulation**
  - GATE & 4D-NCAT

Lung Activity
w/o attenuation

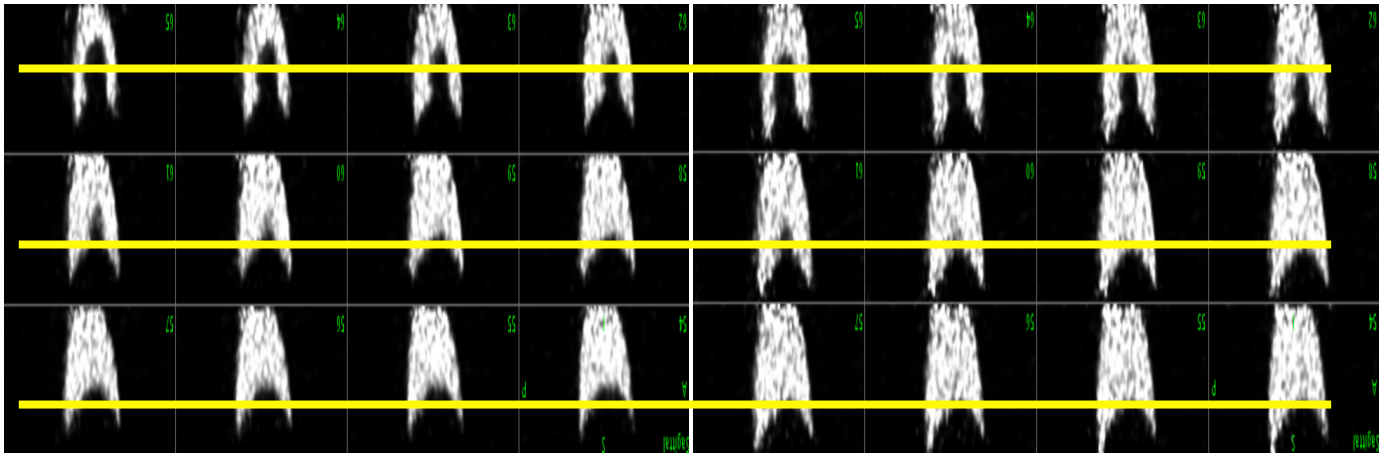


1st and 12th Sinogram frame



1st frame coronal image

12th frame coronal image



1st frame sagittal image

12th frame sagittal image

1st frame for expiration with non-attenuation modelled, 1 million LOR events and comparison with the 12th inspiration frame

Austin Health

Respiratory Motion

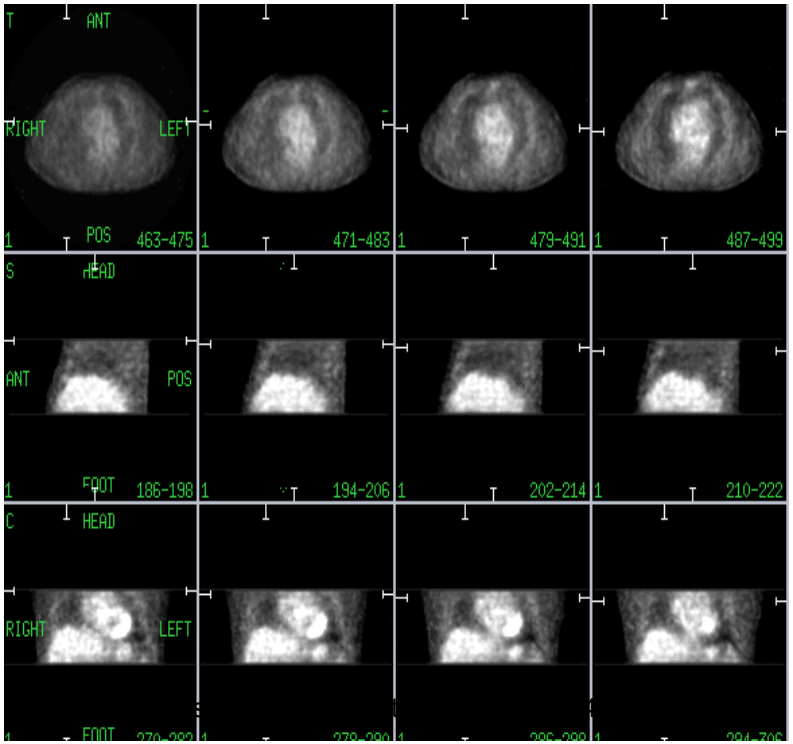
Voxelised Phantom

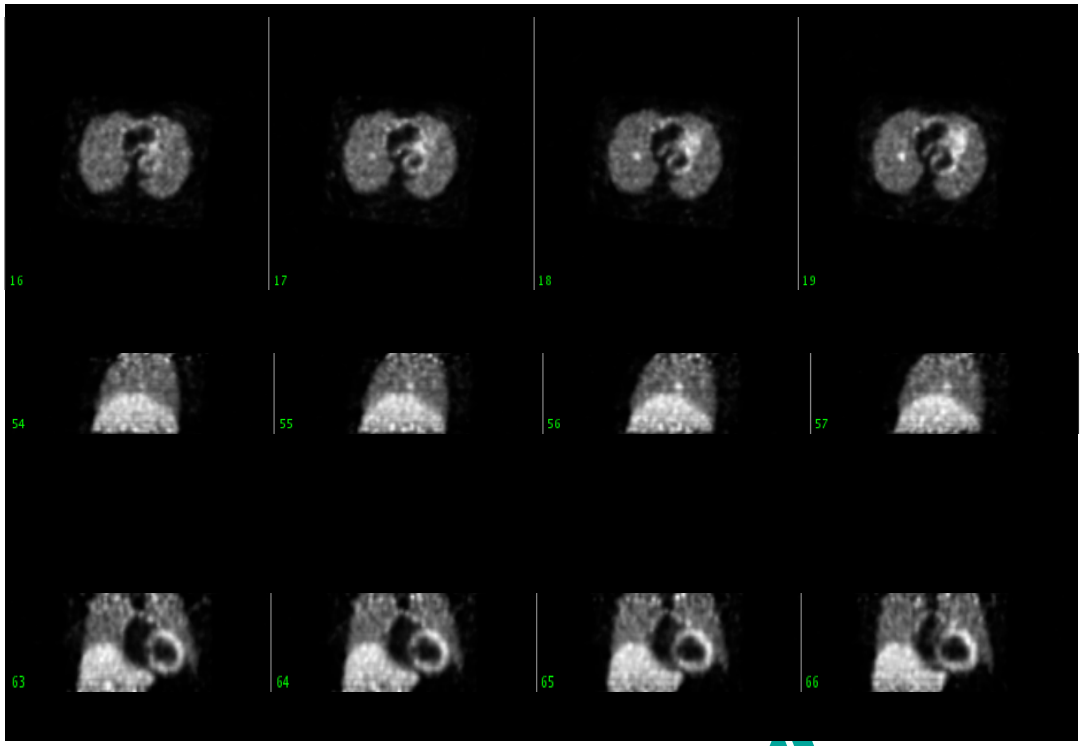
- **Simulation**
  - GATE & 4D-NCAT

    Clinically Realistic Activities (no mediastinum)

    Lung Lesion

    w/o Attenuation Modelling





Simulation reconstructed image, 8.8 millions LORs

Austin Health

Respiratory Motion

Simulation times (2.2.0)

Summary of simulations			Coincident Rate (kcps)	Computational / Measurement Times		
Classification	**phantoms**	**Simulations / Measurements**		**Measured**	**Compute**	**LOR events**
Geometric phantom & source	Jaszczsak	Measurement with attenuation by Allegro	166	30 minus	n/a	Non Attenuation: 1 million/4 hrs
		Simulation with attenuation	517	5.8 sec	4.4 days	
	Cylinder	Simulation without attenuation	106	3.2 sec	1 day	
		Simulation with attenuation	311	6.1 sec	3 days	Attenuation: 1 million/5 days
Voxelised phantom & source	Hoffman	Measurement with attenuation by Allegro	170	30 sec	n/a	Non Attenuation: 1 million/4hrs
		Simulation without attenuation	262	6.1 sec	10 hours	
		Simulation with attenuation	262	6.1 sec	12 days	Attenuation: 1 million/8 days
	NCAT	Measurement with attenuation by Allegro	113	5 mins	n/a	Non Attenuation: 1 million/5 hrs
		Simulation with attenuation, heart, liver	120	10 sec	24 days	
		1st frame simulation without attenuation	227	4.4 sec	2 days	
		12th frame simulation without attenuation	302	2.9 sec	2 days	
		Average frame simulation without attenuation	270	3.7 sec	2 days	Attenuation: 1 million/24 days
		1st frame simulation with attenuation	264	2.27 sec	24 days	
		1st frame simulation with a lesion	733	12 sec	2 days	

Respiratory Motion

Simulation Evaluation Summary

- Voxelised vs Geometric
  - Up to a factor of 5 slower
  - Dependent on size of voxelised phantom
- Attenuation vs Non-Attenuation modelling
  - Up to a factor of 50 slower
- Supercomputing facilities
  - VPAC (Brecca: 180 CPU Linux Cluster)
  - Spawn individual frames

GATE and 4D-NCAT are able to provide practical phantom listmode data and lung voxelised phantom respectively.

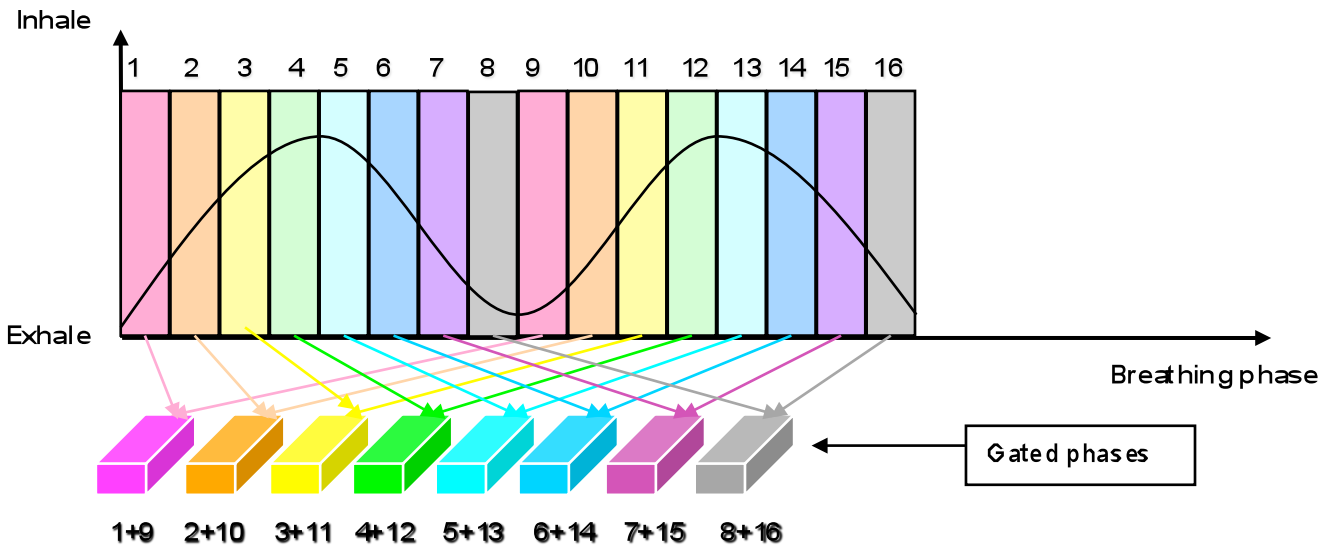
Simulations provide a valuable tool for the modelling of respiratory motion.

Respiratory Gating

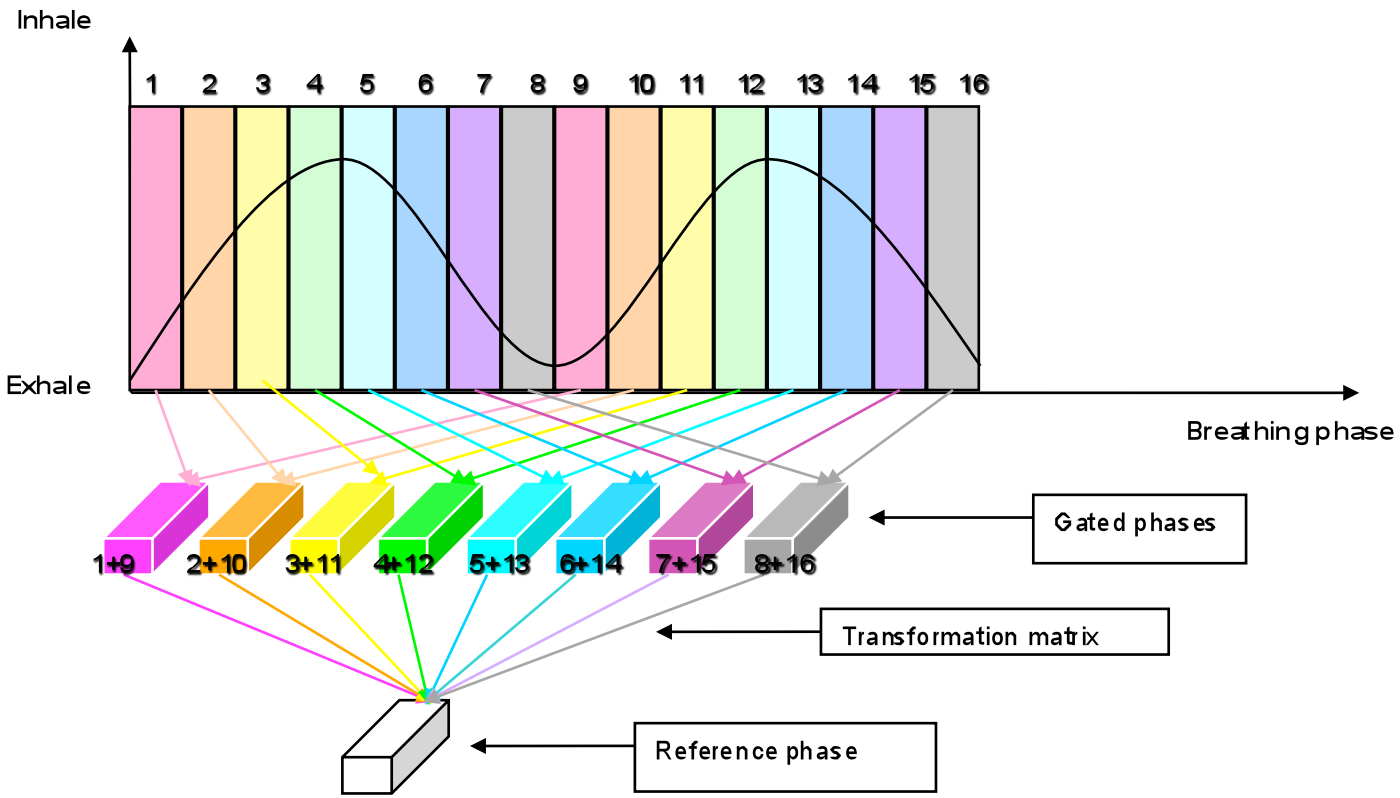
- Gating techniques
  - Detect Phase of Motion
    - Hardware, Data-driven
  - Image at nominated Phase
- Correction techniques
  - Gated images translated reference phase

Respiratory Gating

Two breathing cycles for gating procedure. These two breathing cycles can be gated into 8 phases.



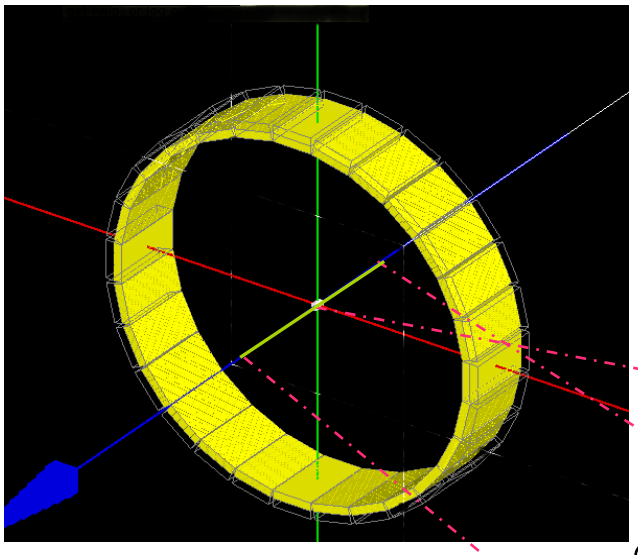
Respiratory Correction



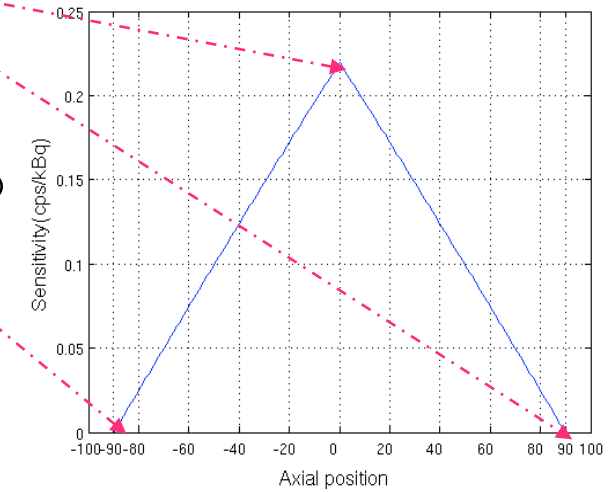
Two breathing cycles are gated into 8 breathing phases, which can be translated into the reference phase with transformation matrix.

Austin Health

Motion Detection



Philips Allegro Scanner, the geometric sensitivity of 3D PET cylindrical scanner varies with the axial position. The sensitivity value is the highest at the centre of FOV while the sensitivity value at the edge of FOV is close zero.

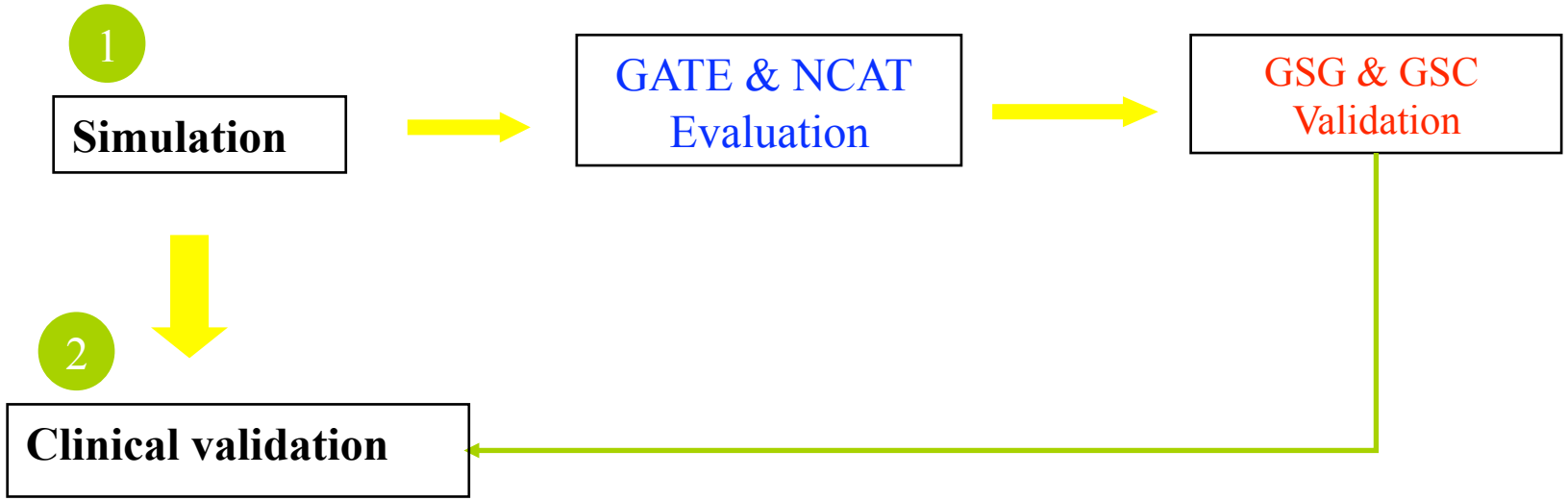


Respiratory motion compensation in PET imaging could be implemented in terms of the geometric sensitivity along axis of the scanner.

Austin Health

Respiratory Motion

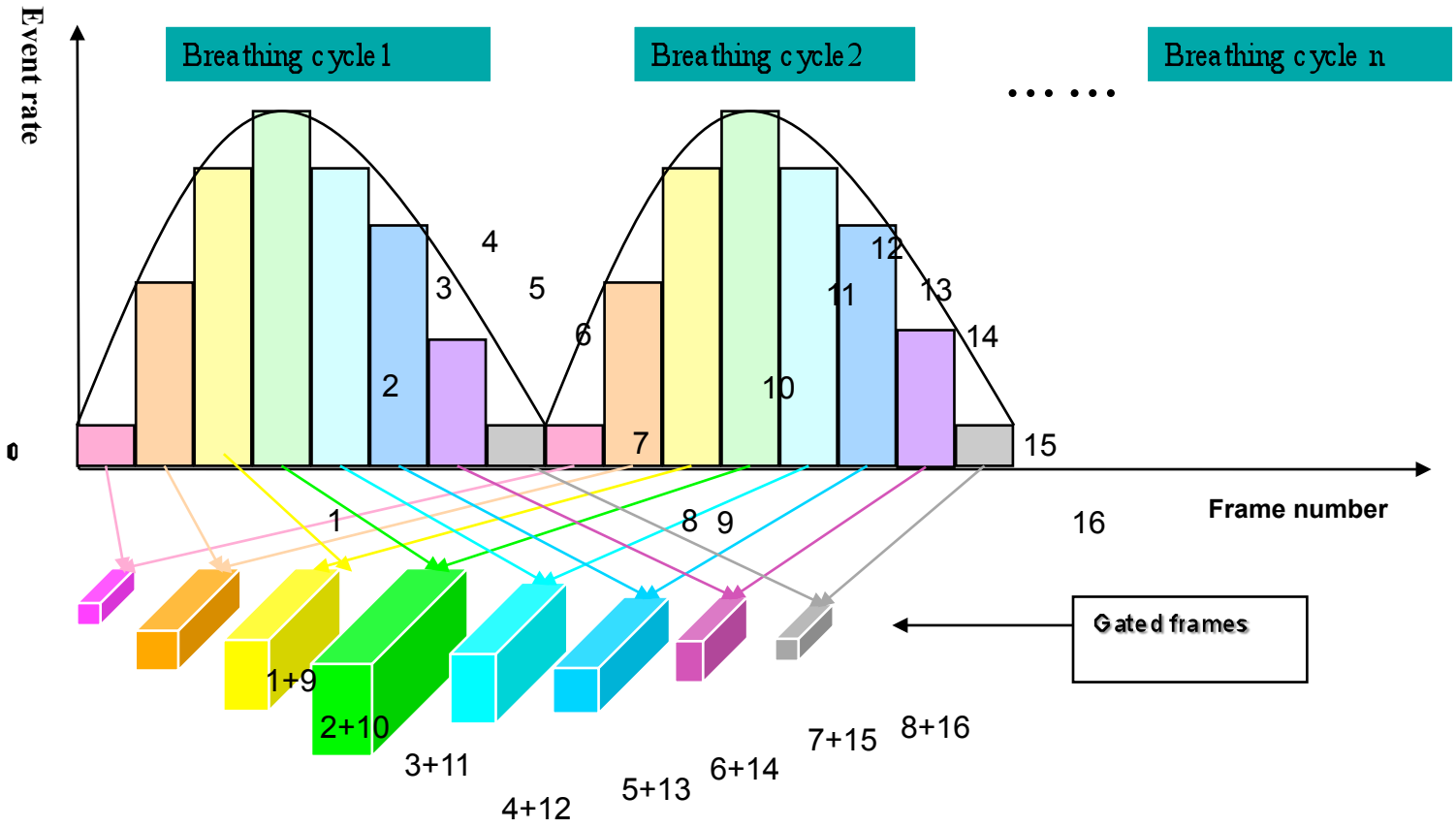
Geometric Sensitivity



GSG: Geometric Sensitivity Gating
GSC: Geometric Sensitivity Correction

Respiratory Motion

Geometric Sensitivity Gating

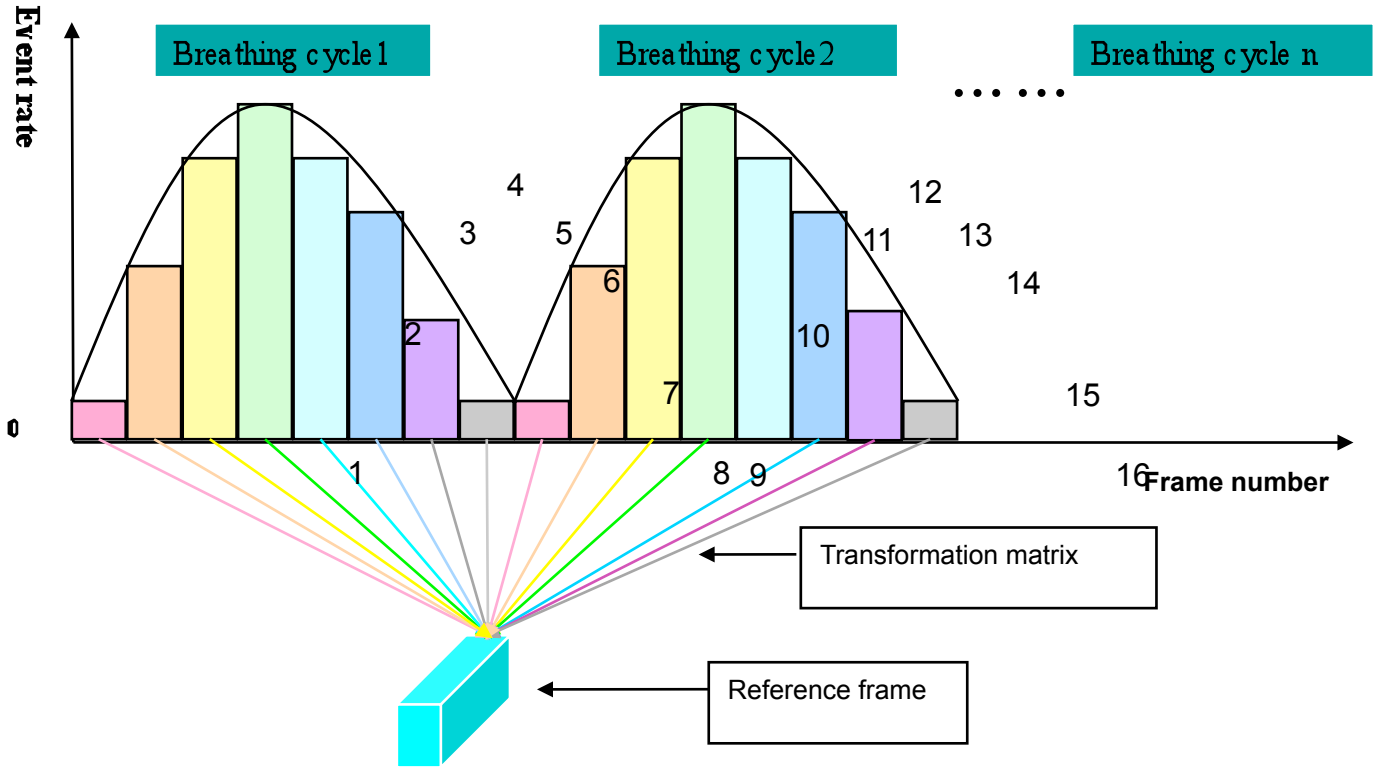


The cyclic change in event-rate with respect to frames illustrating the respiratory breathing cycle. The count-rate in two breathing cycles is used to determine gating-phases. Each cycle is 5 seconds and 8 frames motion along axis.

Austin Health

Respiratory Motion

Geometric Sensitivity Gating



The change in event-rate with respect to frames illustrating the respiratory motion displacements. The count-rate in two breathing cycles is used to determine transformation matrix. Each frame is directly moved to the reference frame. Each cycle is 5 seconds with 8 frames motion along axis.

Austin Health

Respiratory Motion

Geometric Sensitivity Correction

Displacements transformation matrix calculation for GSC:

$$M(i) = \frac{A}{\max(\arcsin(\frac{f_{\max} - f(i)}{f_{\max}}))} * \arcsin(\frac{f_{\max} - f(i)}{f_{\max}})$$

$$(i = 1,2,3,.....n)$$

$M(i)$: Transformation matrix

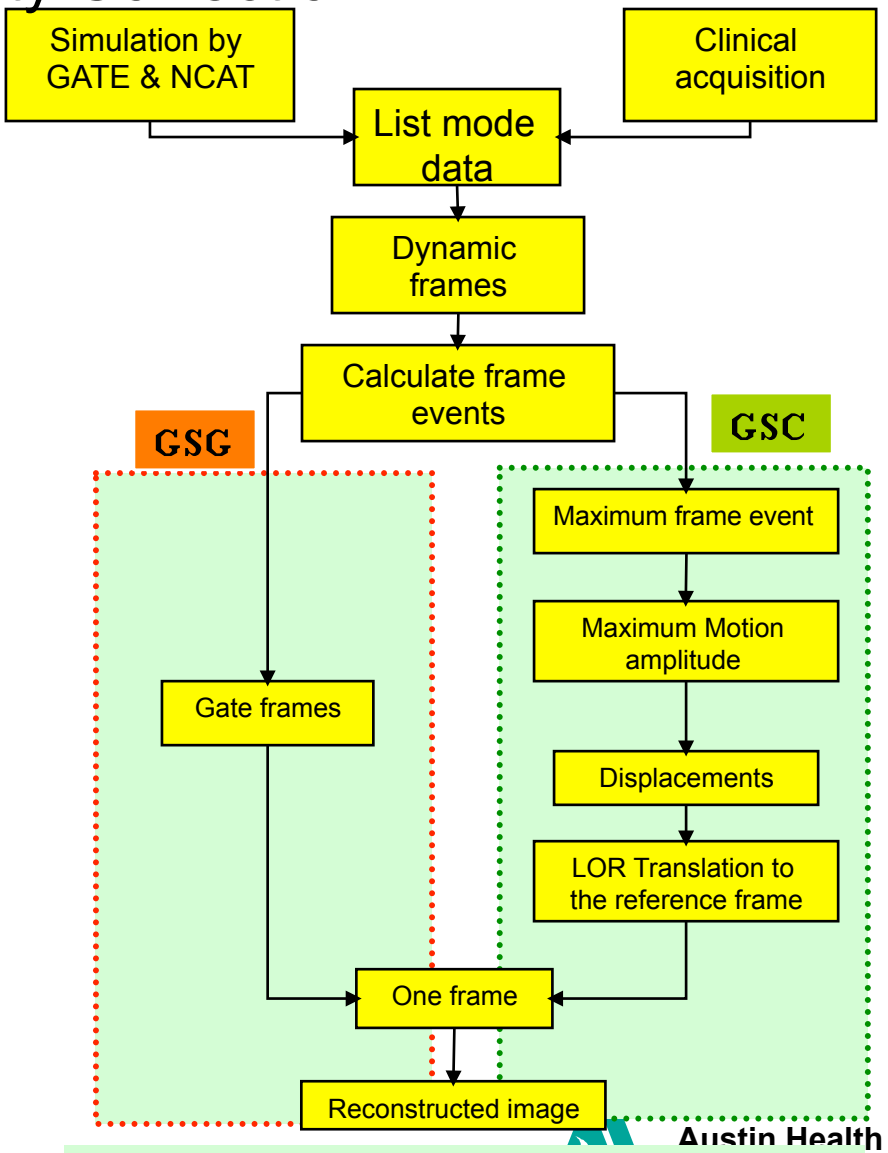
i : Frame number

A : Maximum motion amplitude

$f_{\max}$: Maximum frame events

$f(i)$: Each frame events

8th December, 2008

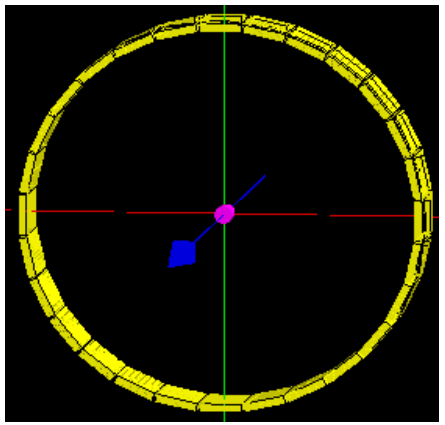


The summary of implementing Geometrical Sensitivity Gating (GSG) and Geometrical Sensitivity Correction (GSC).

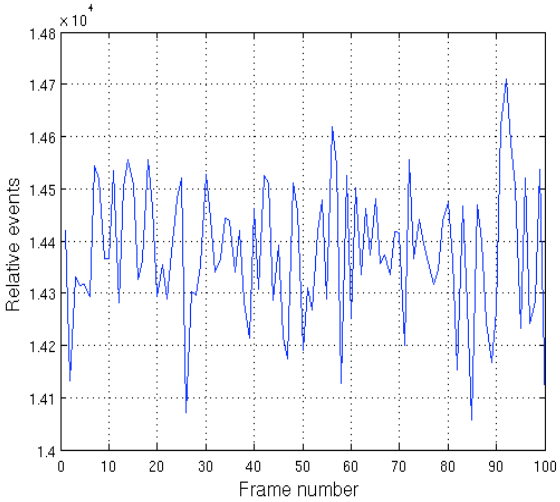
Respiratory Motion

Geometric Sensitivity Gating Simulation

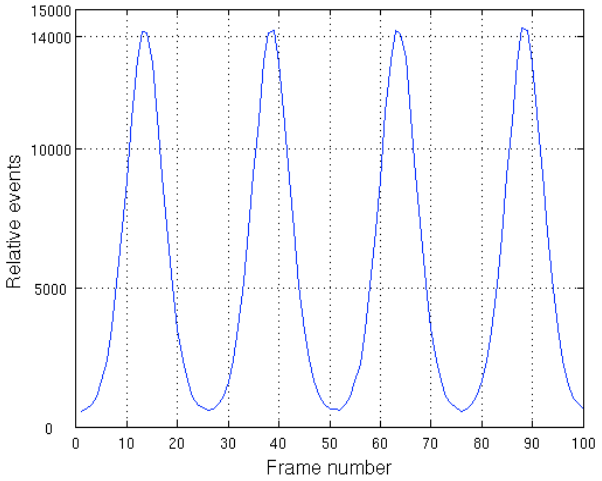
- Geometric Source
  - Cylindrical Object
    - GATE defined cylindrical phantom
    - 100 frames were generated
    - 2 oscillation cycles over 10sec.



Static simulation : 4% variation in event-rate.



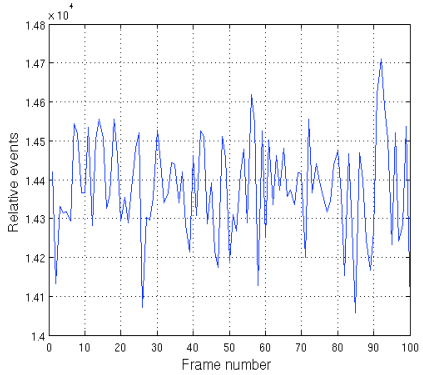
Motion simulation : sinusoid nature 96% change

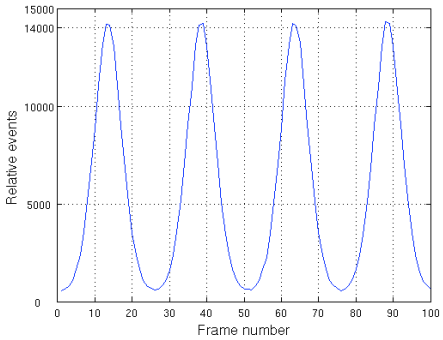


Respiratory Motion

Geometric Sensitivity Gating

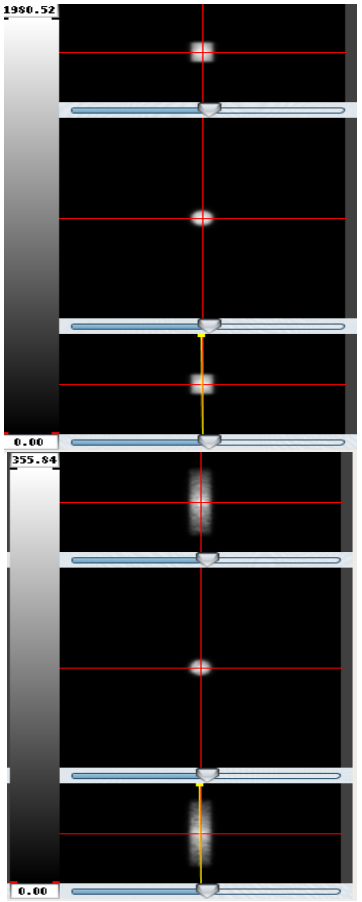
- GATE defined cylindrical phantom
- 100 frames generated
- 2 oscillation cycles over 10sec.

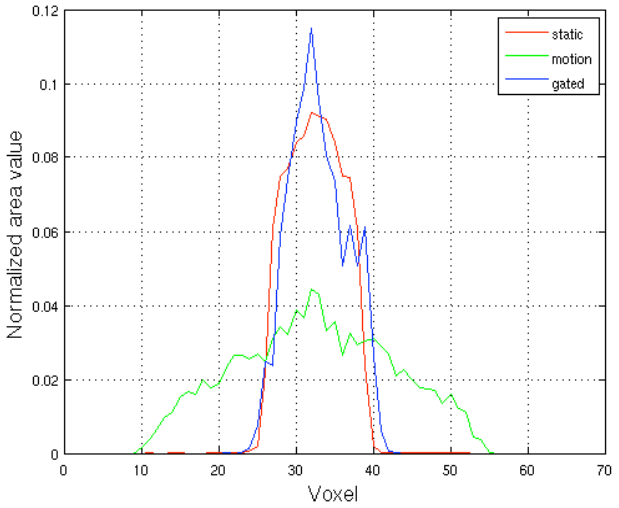




Static

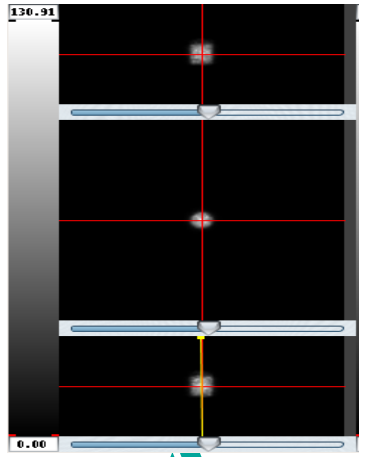
Motion





Line profile comparison of static, motion and gated.

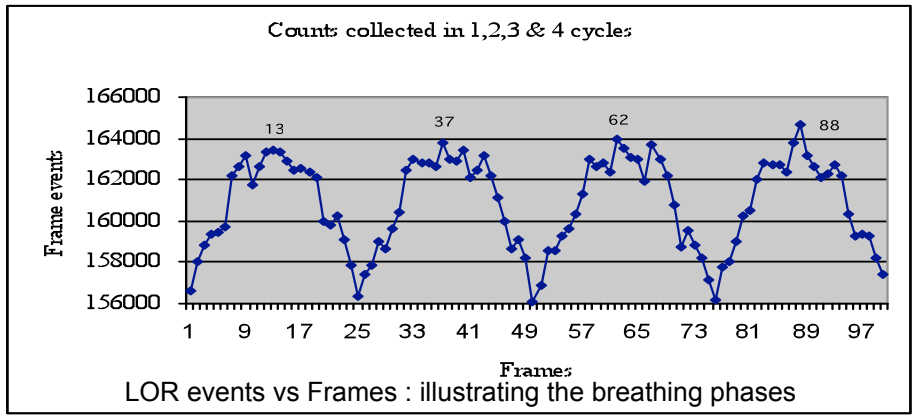
Gated



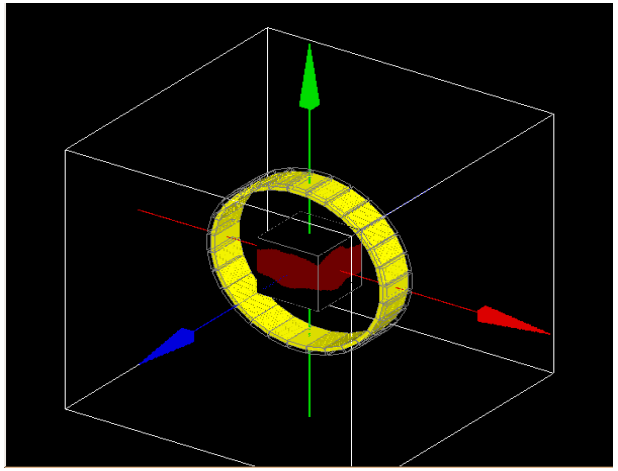
Respiratory Motion

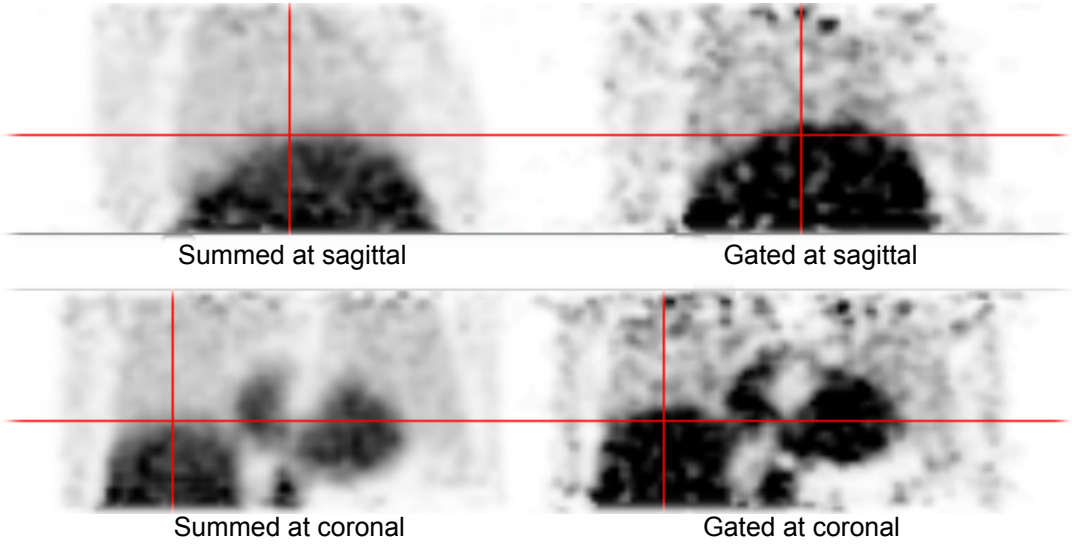
Geometric Sensitivity Gating Simulation

- Voxelised Source
  - 4D NCAT
    - No Attenuation Modelling
    - 250 frames were generated
    - 10 breathing cycles over 50 sec.



LOR events vs Frames : illustrating the breathing phases


64x64x64 matrix of frame with 320mm length was centered in the FOV with 180mm length along Z axis.


Summed at sagittal

Gated at sagittal

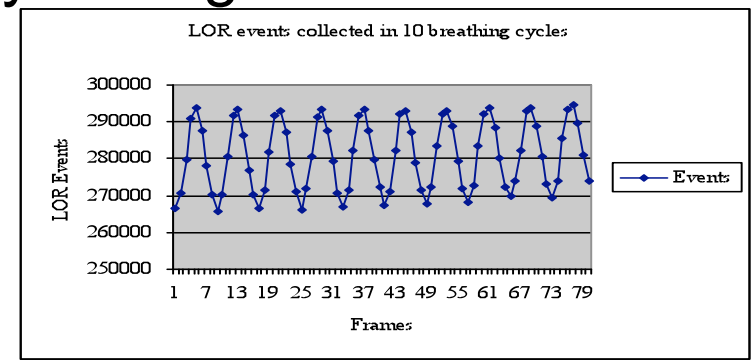
Summed at coronal

Gated at coronal

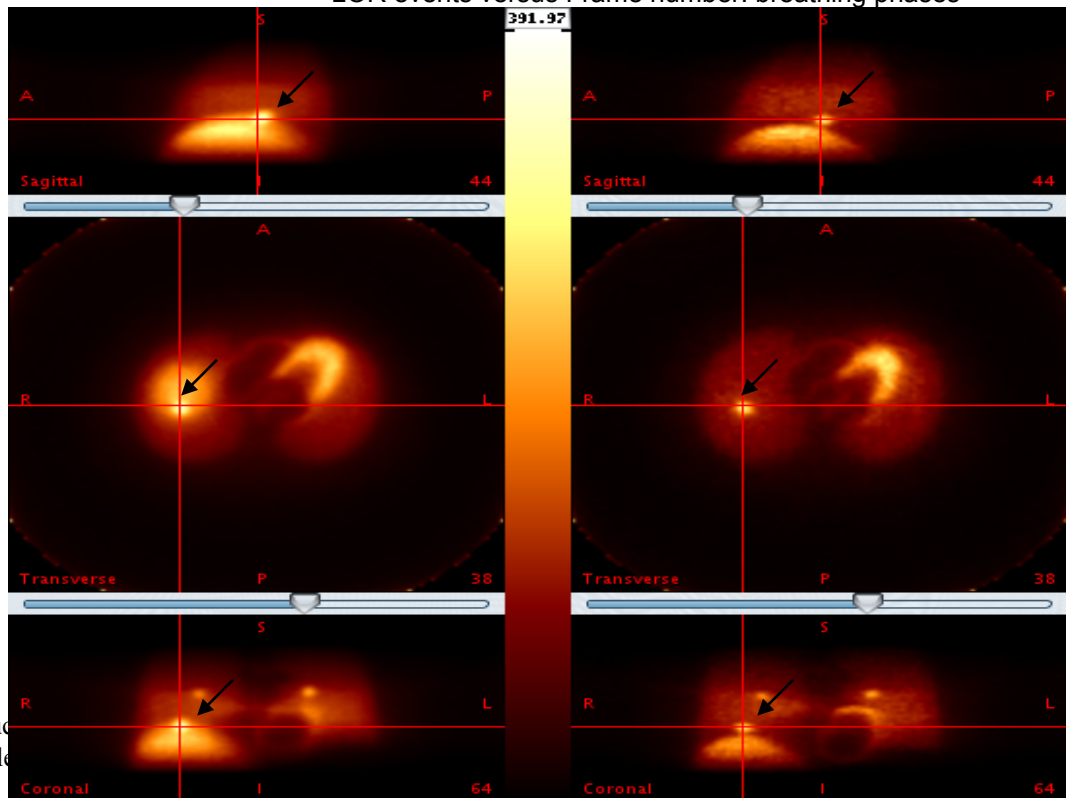
Respiratory Motion

Geometric Sensitivity Gating

- Voxelised Source
  - 4D NCAT
    - No Attenuation Modeling
    - Lesion
    - 80 frames / 10 cycles
    - 7.1×10^7 total
    - 3.3×10^7 gated



LOR events versus Frame number: breathing phases

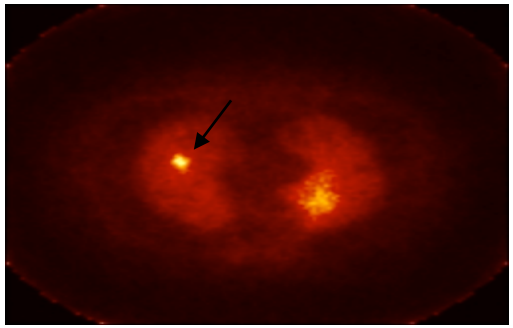


Respiratory Motion

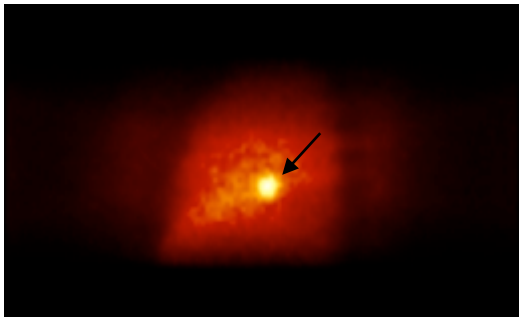
Geometric Sensitivity Gating

- Voxelised Source
  - 4D NCAT
    - Attenuation Modeling
    - Lesion
    - 80 frames / 10 cycles

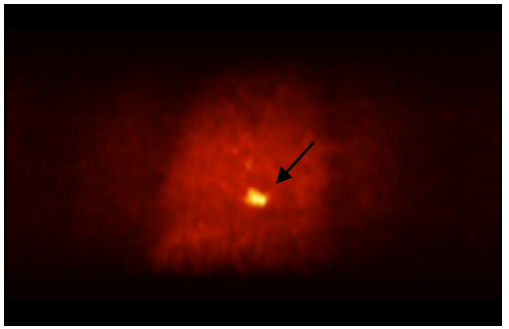
Summed: transaxial



Gated: transaxial



Summed: sagittal

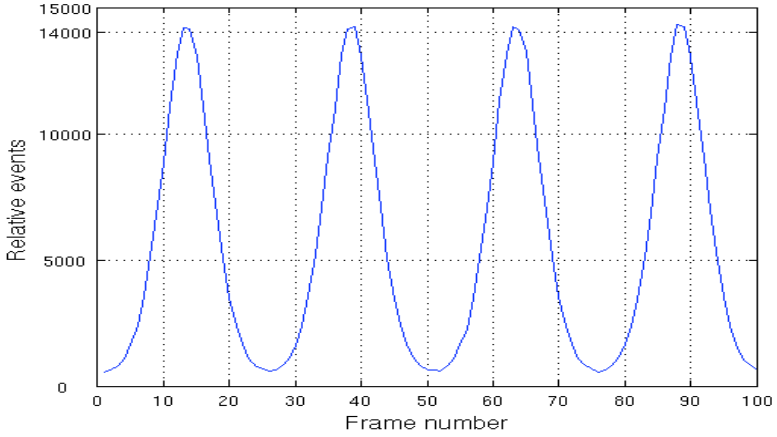


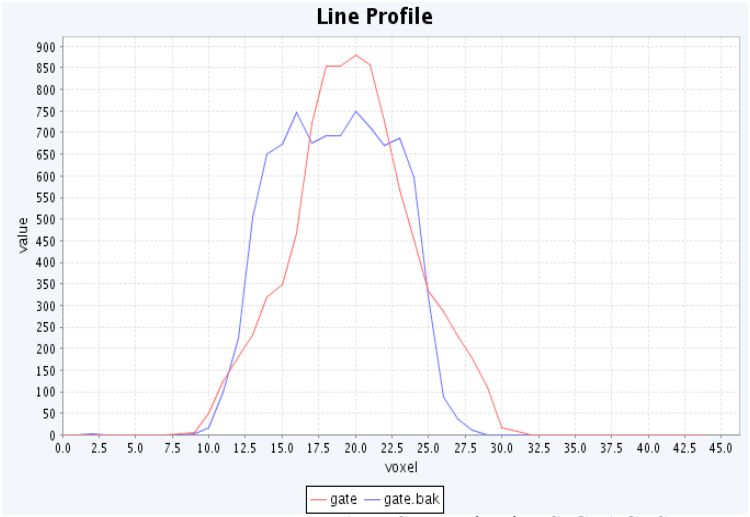
Gated: sagittal

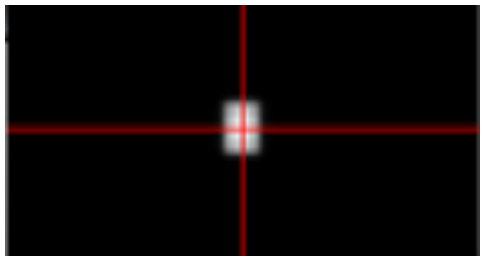
Respiratory Motion

Geometric Sensitivity Correction

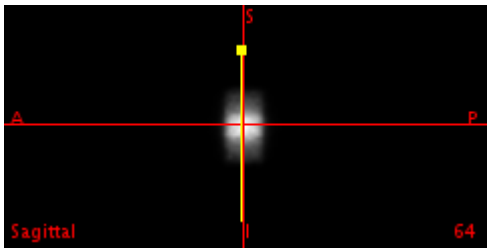
- Geometric Source
  - Cylindrical Object
    - GATE defined cylindrical phantom
    - 5 cm amplitude motion
    - 100 frames, 2 cycles over 10 sec
    - Corrected by
      - Centre of Mass (COM)
      - GSG respectively.



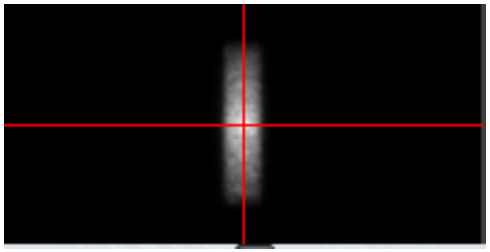




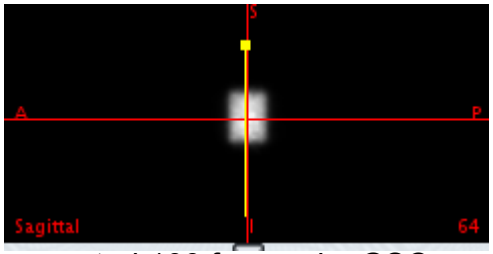
Static



Corrected 100 frames by COM



Motion

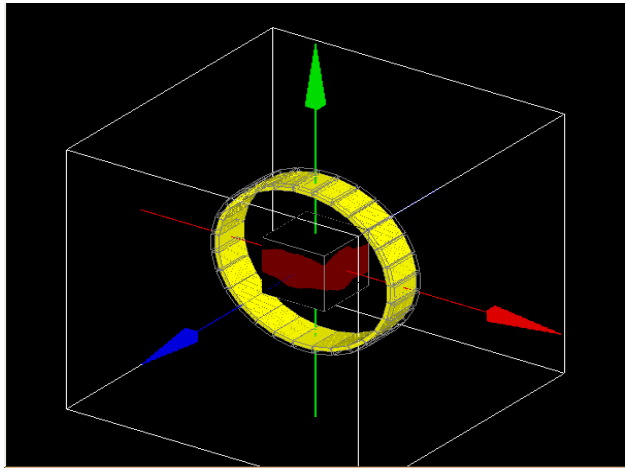


corrected 100 frames by GSC

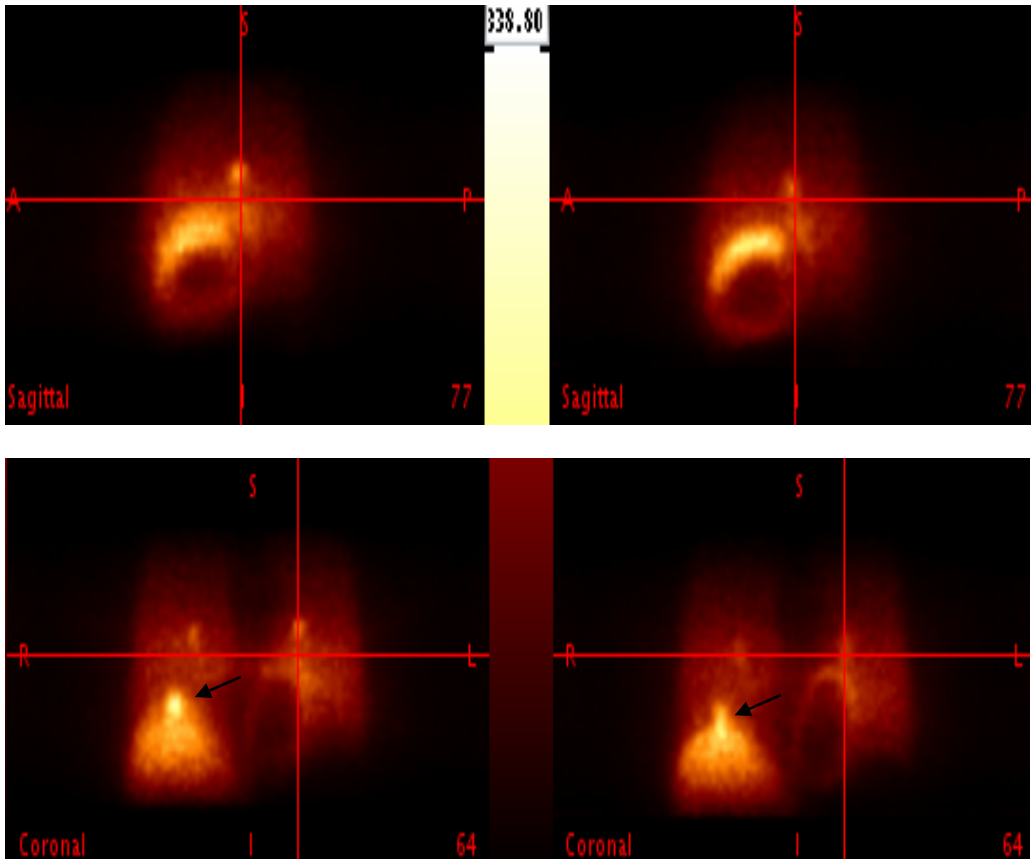
Respiratory Motion

Geometric Sensitivity Correction

- Voxelised Source
  - 4D NCAT
    - Attenuation Modeling
    - Lesion
    - 80 frames / 10 cycles



128x128x55 matrix of frame with 320mm length was centered in the FOV with 180mm length along Z axis.



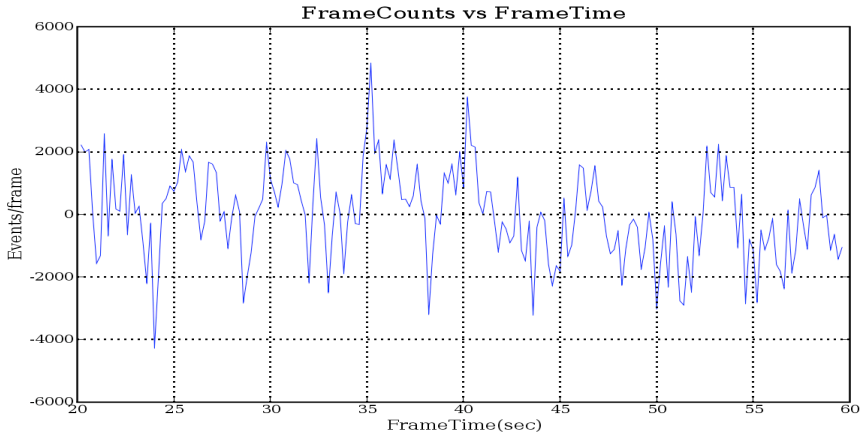
Summed frames 1-8

Corrected frames 1-8

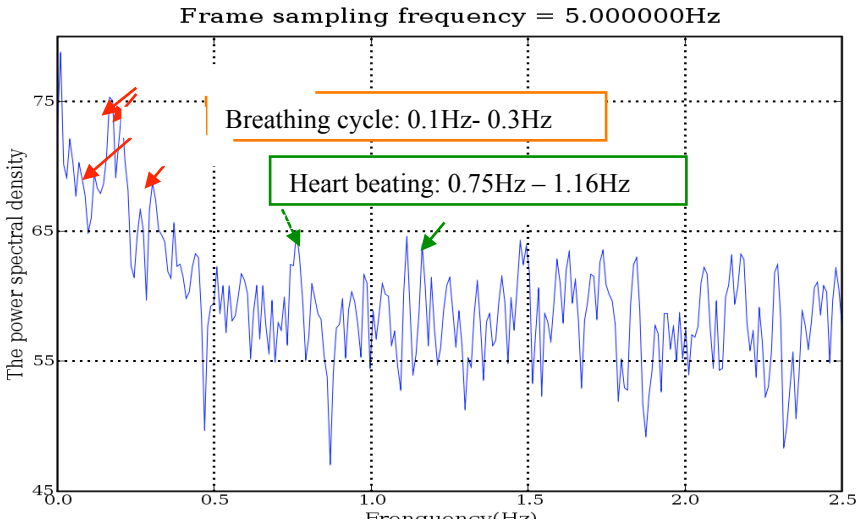
Respiratory Motion

Geometric Sensitivity Correction

- **Clinical**
  - Patient **P3969**
    - NSCL cancer
    - Philips Allegro PET scanner
    - 381.5 MBq ^{18}F-FDG
    - Listmode acquisition
    - coincidence rate is 226 kcps
    - 57 million prompt events
    - 300 seconds acquisition
    - 2 million gated events.



LOR events (mean corrected) of the measured raw frames per 0.2sec from list-mode data. Baseline drift over 60 seconds is evident. The count-rate variation illustrating = the respiratory cycle.

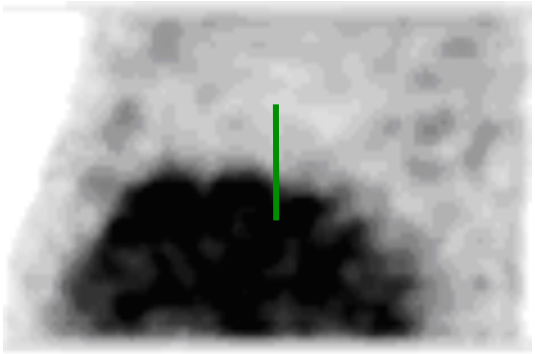


The Power Spectral Distribution of Event Rate demonstrates several distinct frequencies; Respiratory/Cardiac features are indicated by red and green arrows respectively.

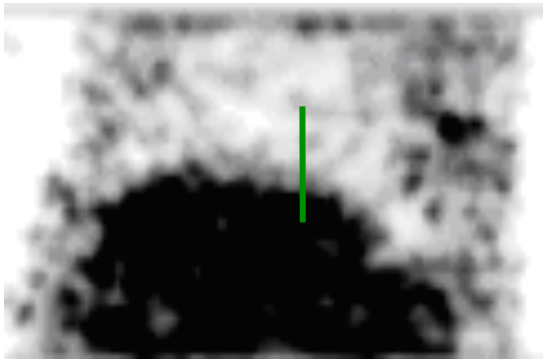
Respiratory Motion

Geometric Sensitivity Correction

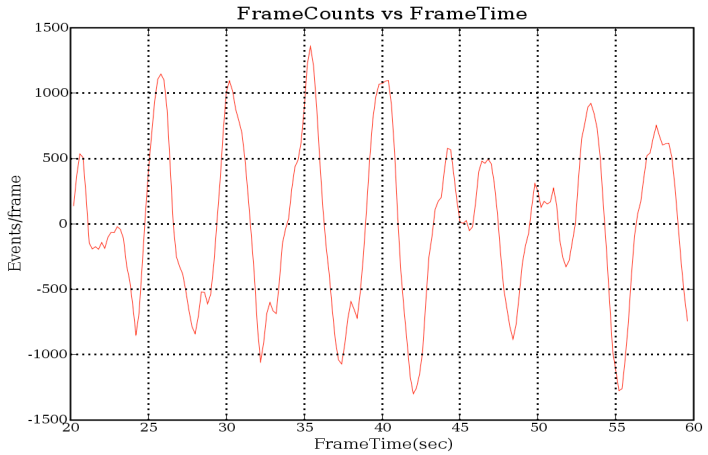
- **Clinical**
  - Patient **P3969**
    - NSCL cancer
    - Philips Allegro PET scanner
    - 381.5 MBq ^{18}F-FDG
    - Listmode acquisition
    - coincidence rate is 226 kcps
    - 57 million prompt events
    - 300 seconds acquisition
    - 2 million gated events.



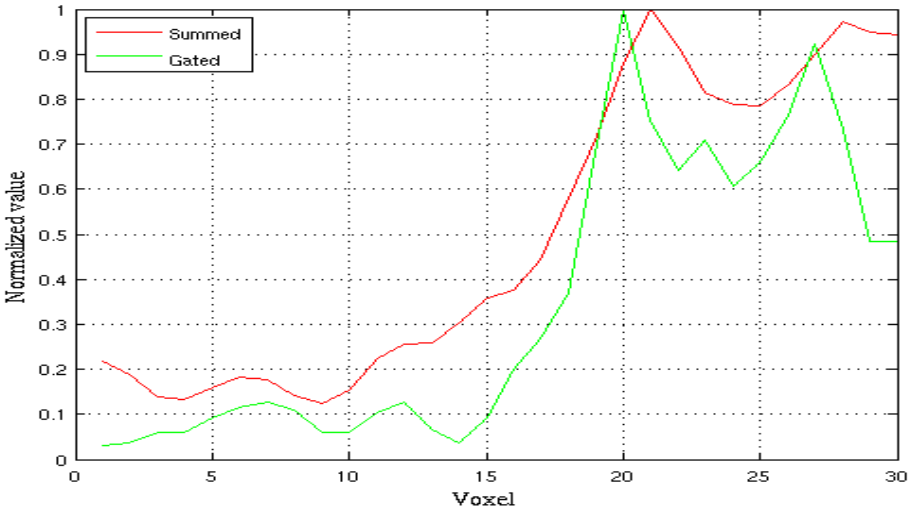
Reconstructed sum image: 1500 frames at sagital



Reconstructed gated image: 46 frames at sagital



Band pass filter frame events (0.1 Hz – 0.3 Hz)

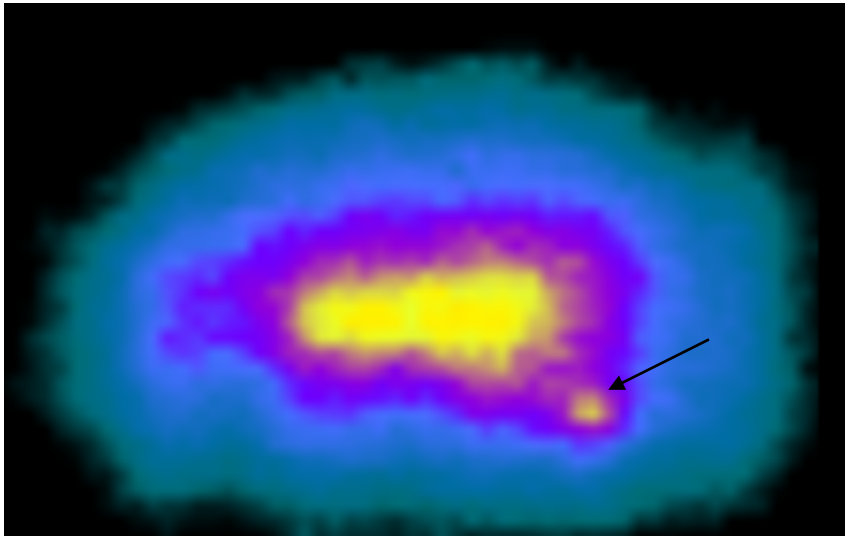


Comparison of line profile from the summed and gated reconstructed images at sagittal. The gated profile demonstrates an improved spatial contrast

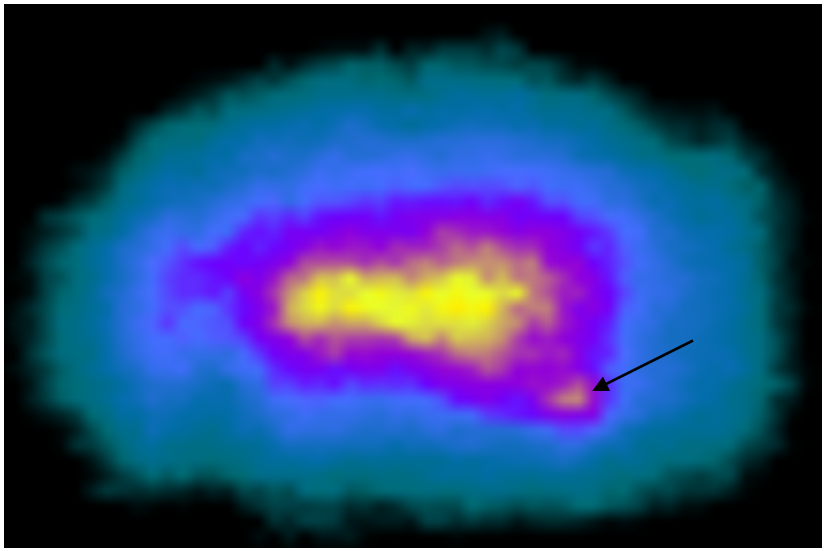
Respiratory Motion

Geometric Sensitivity Correction

- Clinical
  - Patient **P107529**
    - NSCL Cancer
    - Philips Gemini PET scanner
    - ~370 MBq ^{18}F-FDG
    - Listmode acquisition
    - 180 seconds acquisition



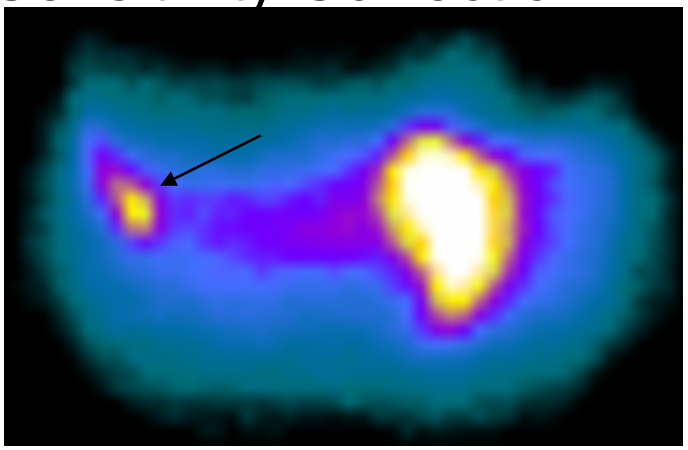
Summed 296 frames transaxial



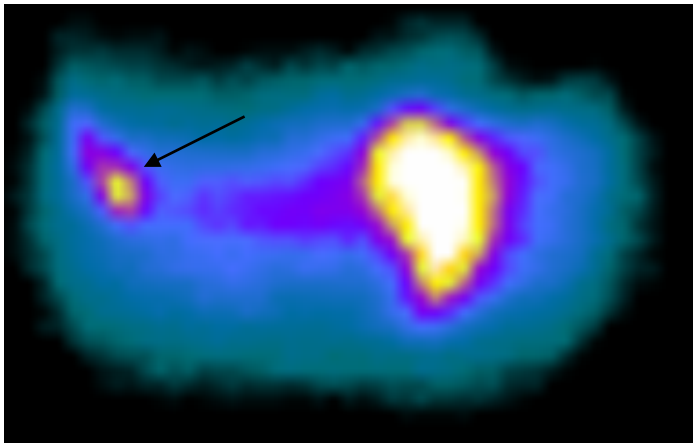
Respiratory Motion

Geometric Sensitivity Correction

- Clinical
  - Patient **P107909**
    - NSCL Cancer
    - Philips Gemini PET scanner
    - ~370 MBq ^{18}F-FDG
    - Listmode acquisition
    - 180 seconds acquisition



Summed 360 frames at coronal



Corrected 360 frames, 0.5s per frame, 12mm amplitude at coronal

Summary

1. Simulation

GATE & NCAT Evaluation
- Geometric Phantom
- Voxelized Phantom

GSG & GSC Validation

- GSG
  - Geometric Phantom
  - Voxelized Phantom
- GSC
  - Geometric Phantom
  - Voxelized Phantom

2. Clinical

- GSG
  - One clinical data with non tumor
- GSC
  - Two clinical data with tumor

Austin Health

Conclusion

Respiratory motion gating and correction

- Utilising the geometric sensitivity properties of 3D PET.
- Data-driven method is intrinsic to acquired list-mode.
- Does not involve hardware monitoring.

All simulations and clinical studies demonstrate that the proposed GSG & GSC method is able to compensate respiratory motion.

Austin Health

Acknowledgements

- Department Nuclear Medicine & Centre for PET, Austin Health
  - Dr Jianfeng He
  - Dr. Sylvia J. Gong
  - Tim Saunder
  - Gareth Jones
  - Prof. Andrew M. Scott

- School of Medical Sciences, RMIT
  - A/Prof. Moshi Geso
  - Trevor Ackerly

- Philips Research Division, Aachen, Germany
  - Dr. Ralph Brinks