Tools for Simulating CT Scanners

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Conclusions

- Scanner access is limited
- Access to raw data even more difficult
- Simulations provide alternative and common source of data for algorithm development
- Medical imaging community uses standardized software phantoms for algorithm validation
- Standardized phantoms and increased access to simulation tools required for security applications

Why simulations?

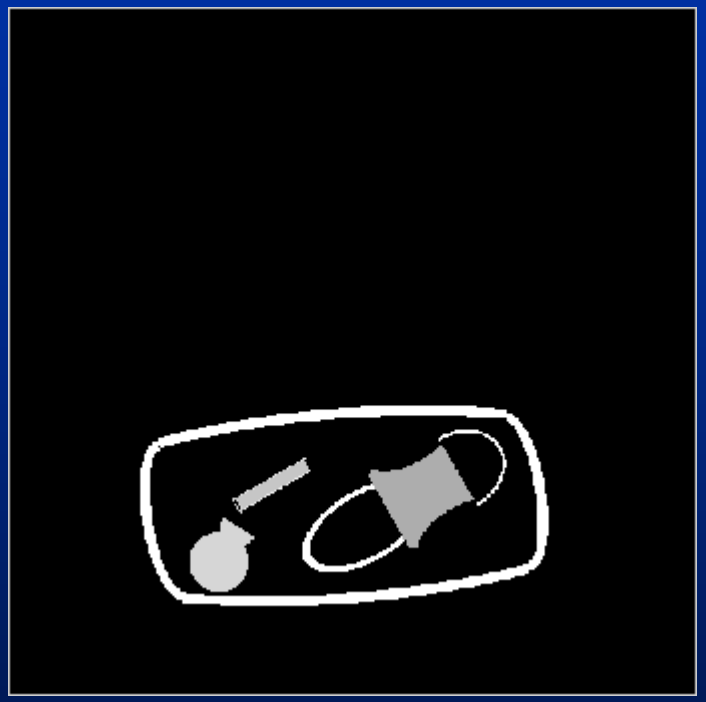
- Accessible, inexpensive data source
- Easy to modify scan/object parameters
- Enables modeling novel scanner designs
- Can establish standard software phantoms for algorithm development and validation
- Ground truth
- Can compare algorithms in literature using common images/data
- Not perfect, requires experimental validation

Goal for security research

- Define standard test bags and objects
  - repeatable across groups and sites
- Develop packing software
- Develop simulation software that models realistic scanner effects

Goal: Define Standard Objects

- Relevant test objects from basic shapes: ellipsoids, elliptic cylinders, cones, blocks, planes
- Material and density defined for each object
- Preliminary work by Seemeen Karimi: sausage, curvy magazine, water bottle, etc.



Courtesy of Seemeen Karimi, UCSD

Goal: Packing Software

- Randomly select from the list of defined objects
- Randomly select position and orientation of each object
- Adjust positions to prevent overlap
- Packing algorithm outputs bag definition in standard formatted text file

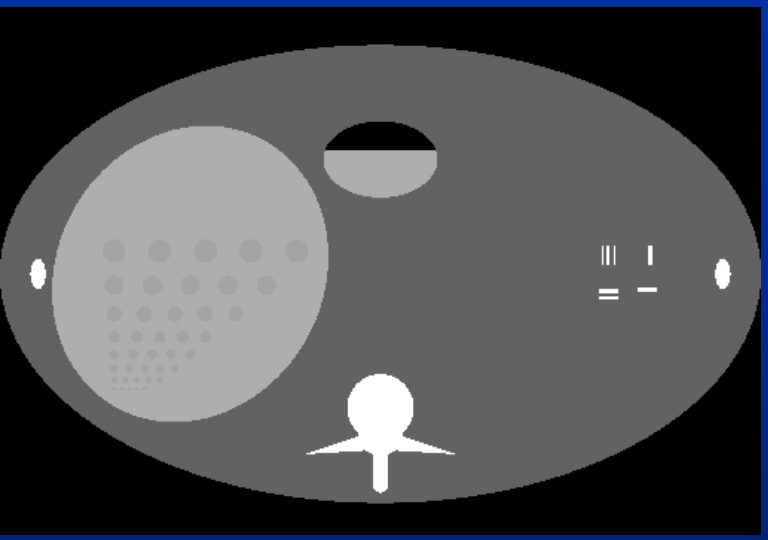
Goal: Simulation Software

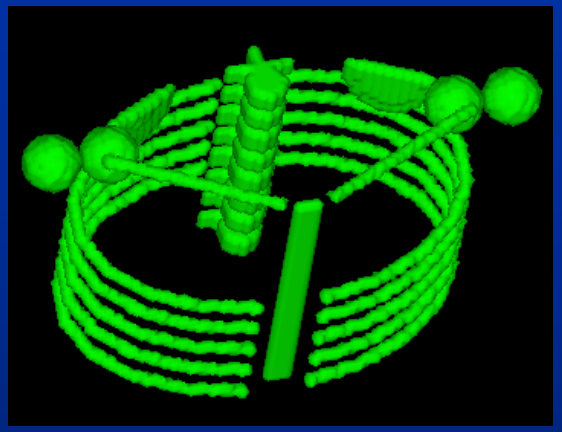
- Public Domain
- Easy to use
- Flexible scanner configuration
- Realistic scanner effects
- Validated

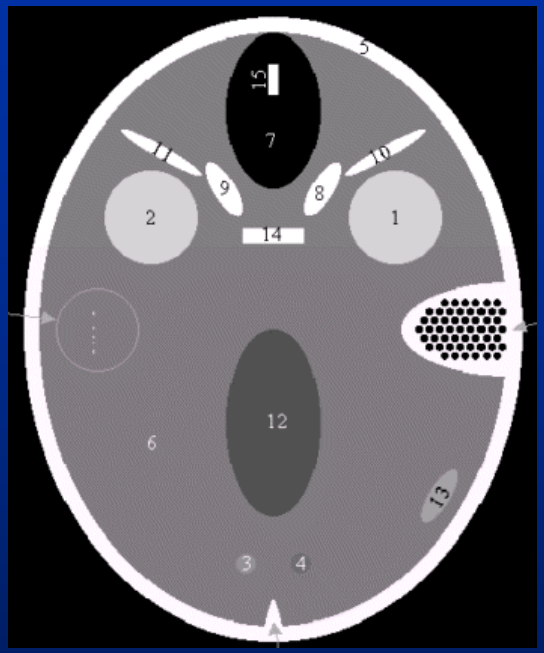
Outline

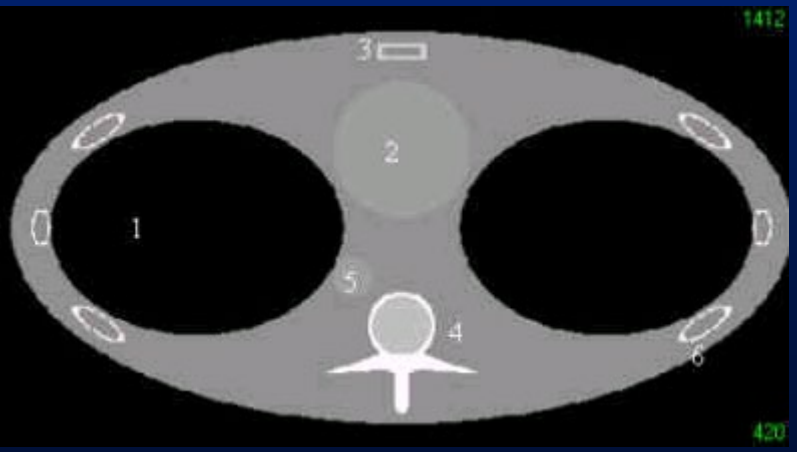
- What we can learn from the medical imaging community
- Simulation methods and tools

FORBILD Phantoms









http://www.imp.uni-erlangen.de/phantoms

Gold-standard phantoms

FORBILD Phantoms

- Collaboration between the University of Erlangen and Siemens Medical Solutions
- Gold standard 3D phantom definitions for specific applications
  - abdomen, head, hip, jaw, lung, thorax
  - artifact, high-contrast, low-contrast

http://www.imp.uni-erlangen.de/phantoms

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forbild phantom

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About 2,090 results (0.08 seconds)

2090 hits

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Images
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Videos
News
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More

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Change location

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Phantomgruppe
www.imp.uni-erlangen.de/**phantoms**/
Phantom group - Introduction. It is obvious that all sub-projects within the first major part of the **FORBILD** fund, as they deal with the improvement of CT imaging, ...

Head Phantom
www.imp.uni-erlangen.de/**forbild**/deutsch/results/head/head.html
The head **phantom** is a 3-D extension of the well-known 2-D head **phantom** which is used for evaluation of image quality since a long time. The 2-D geometry of ...

Thorax Phantom
www.imp.uni-erlangen.de/**phantoms**/thorax/thorax.htm
A modification of the thorax FORBILD phantom for 4D imaging by Frank Bergner, Marc Kachelrieß is available here. Figure 1: Representation of the bones of the ...

Realistic CT simulation using the 4D XCAT phantom
www.ncbi.nlm.nih.gov › Journal List › Med Phys
by WP Segars - 2008 - Cited by 48 - Related articles
Jul 24, 2008 – Each **phantom** is modeling the same amount of structures for comparison. Images of the **FORBILD** and superquadric **phantom** are from Ref.

SpringerImages - Simulated images of the FORBILD head phantom ...
www.springerimages.com/Images/.../1-10.1007_s00330-005-0118-9...
SpringerImages - Simulated images of the **FORBILD** head **phantom** without and with z-flying focal spot (zFFS). Windmill artifacts are largely suppressed in the ...

FORBILD Phantoms

- Defined as a list of 3D shapes
- Each shape defined by parameters, position, orientation, material
- Text files available for the definition of each specific phantom

	Object	Center	Axis	Parameters	Clip plane	Density
Thorax	Cylinder	[0, 0, 0]	[0, 0, 1]	L=50 ax=20 ay=10		1.000
Shoulder blade L	Ellipsoid _free Ellipsoid _free	[-12 ,-5, 15] [-12 ,-5, 15]	Ax[2,-1, 0]Ay[1, 2, 0] Ax[2,-1, 0] Ay[1, 2, 0]	ax=4.5 ay=0.5 az=6 ax=4 ay=0.4 az=5.5	Z<15	1.46 0.98

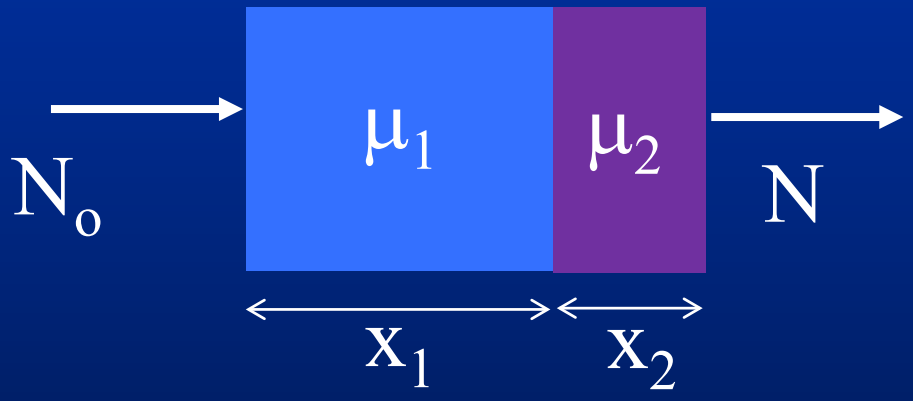
```
#define CTMAT(x) formel=H2O dichte=x
#define LEN   100

Phantom
/* ++++ Body ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++ */
{ "A1" [Elipt_Cyl_z: dx=20 dy=12 l=100 ]       CTMAT(WATER)    REL     }

/* ++++ Liver +++++++++++++++++++++++++++++++++++++++++++++++++++++++++ */
{ "B2" [Ellipsoid_free: x=-10 y=0 dx=8 dy=7 dz=10
                      a_x(cos(60), sin(60),0) a_z(0,0,1) ]
                                              CTMAT(1.06)             REL     }

/* ++++ Vertebrae +++++++++++++++++++++++++++++++++++++++++++++++++++++++ */
Wirbelkoerper(0, -7,-10, KORTIKALIS, SPONGIOSA, 4)
Wirbelkoerper(0, -7, -5, KORTIKALIS, SPONGIOSA, 4)
Wirbelkoerper(0, -7,  0, KORTIKALIS, SPONGIOSA, 4)
Wirbelkoerper(0, -7,  5, KORTIKALIS, SPONGIOSA, 4)
Wirbelkoerper(0, -7, 10, KORTIKALIS, SPONGIOSA, 4)

/* ++++ Lesions at z=0 ++++++++++++++++++++++++++++++++++++++++++++++++ */
{ "C11" [Sphere: x=-14   y=1.2 r=0.6] CTMAT(1.05)                       REL     }
{ "C12" [Sphere: x=-11.6 y=1.2 r=0.6] CTMAT(1.05)                       REL     }
{ "C13" [Sphere: x= -9.2 y=1.2 r=0.6] CTMAT(1.05)                       REL     }
{ "C14" [Sphere: x=- 6.8 y=1.2 r=0.6] CTMAT(1.05)                       REL     }
{ "C15" [Sphere: x=- 4.4 y=1.2 r=0.6] CTMAT(1.05)                       REL     }

{ "C21" [Sphere: x=-14 y=-0.6 r=0.5] CTMAT(1.05)                        REL     }
{ "C22" [Sphere: x=-12 y=-0.6 r=0.5] CTMAT(1.05)                        REL     }
{ "C23" [Sphere: x=-10 y=-0.6 r=0.5] CTMAT(1.05)                        REL     }
{ "C24" [Sphere: x=-8  y=-0.6 r=0.5] CTMAT(1.05)                        REL     }
{ "C25" [Sphere: x=-6  y=-0.6 r=0.5] CTMAT(1.05)                        REL     }
```

Outline

- What we can learn from the medical imaging community
- Simulation methods and tools

A very simple simulation

Monoenergetic x-rays

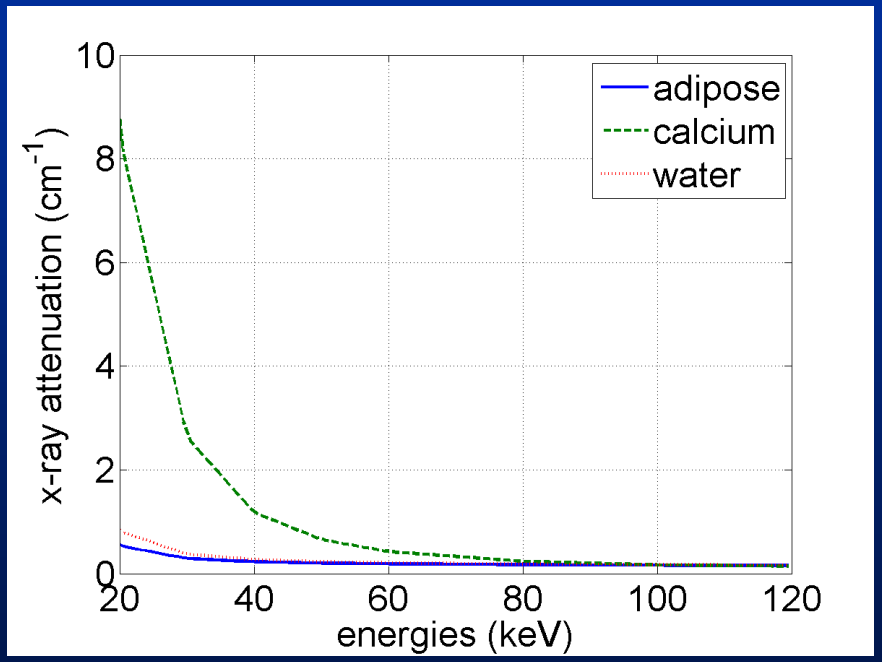


$$N = N_0 e^{-(\mu_1 x_1 + \mu_2 x_2)}$$

Polychromaticity

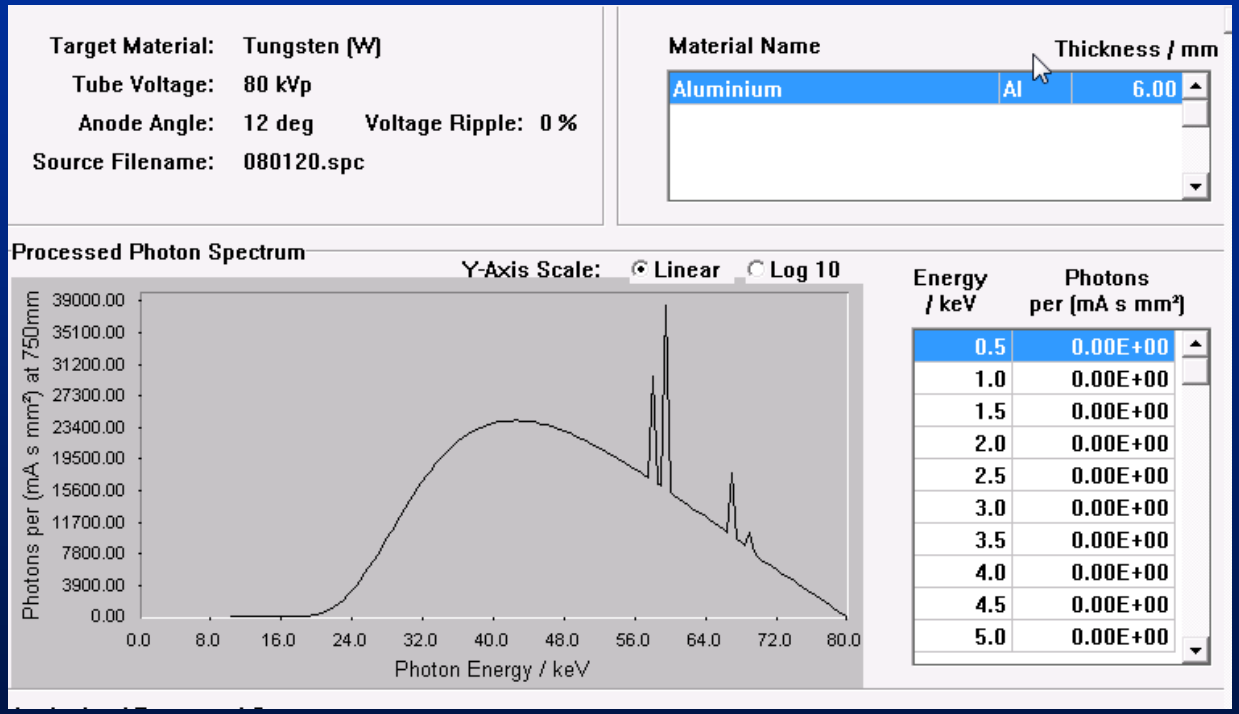
In practice, No and m are energy dependent:

NIST XCOM database provides m values for elemental and compound materials



http://www.nist.gov/pml/data/xcom/index.cfm

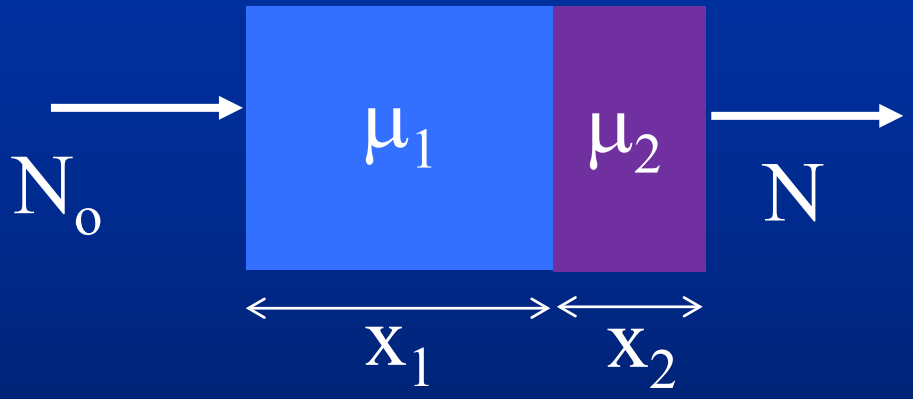
Polychromaticity



IPEM Report 78 Software estimates spectrum

http://www.ipem.ac.uk/

Polychromaticity

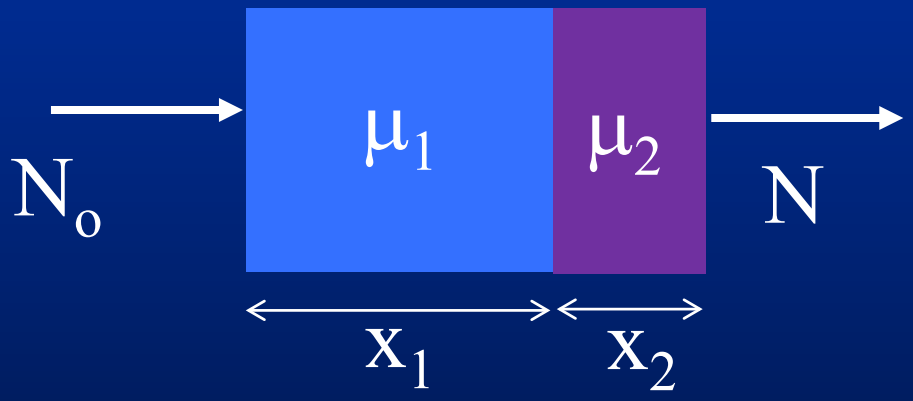


$$N = N_0 e^{-(\mu_1 x_1 + \mu_2 x_2)}$$

$$N = \int N_o(E) e^{-(\mu_1(E) x_1 + \mu_2(E) x_2)} dE$$

Adding Noise

CT noise is primarily dominated by Poisson photon-counting noise



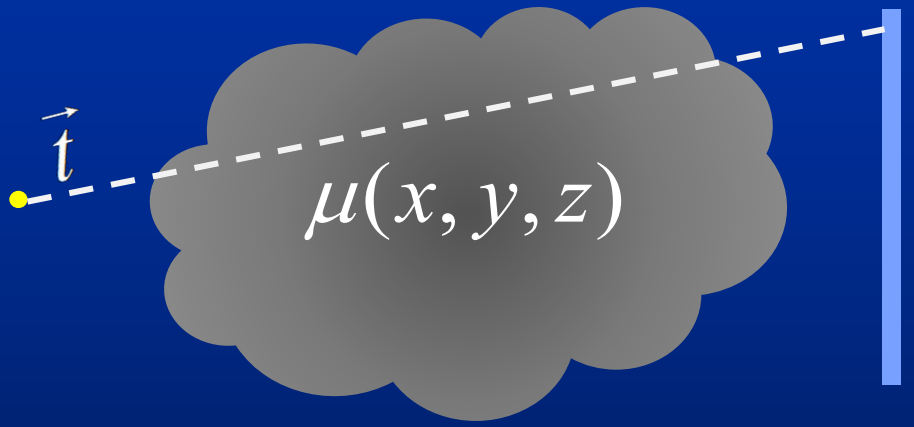
$$\bar{N} = \int N_o(E) e^{-(\mu_1(E)x_1 + \mu_2(E)x_2)} dE$$

Simulated value drawn from Poisson distribution with mean $\bar{N}$

Other Nonideal Effects

- Source aperture
- Detector aperture
- Detector crosstalk
- Afterglow
- HVPS drifts
- Geometric errors
- Electronic noise
- Sampling during rotation

More realistic, complex objects



$$\bar{N} = \int N_o(E) e^{\left(-\int \mu(x,y,z)\, d\vec{t}\right)} dE$$

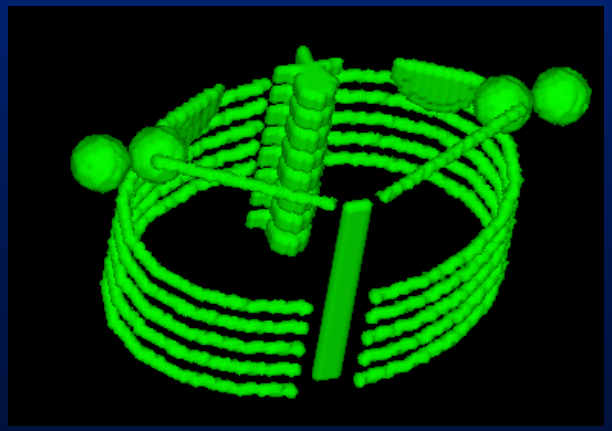
How to calculate line integrals through μ(x,y,z)?

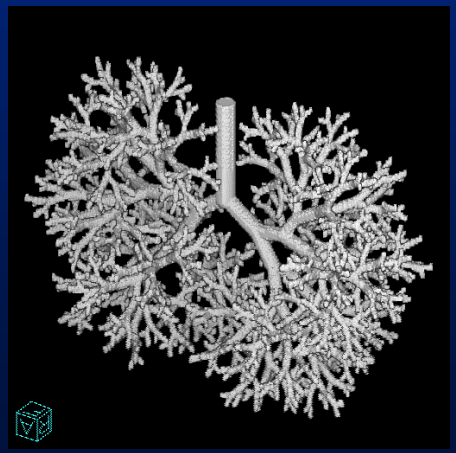
Ray Tracing Methods

- Analytical calculation of line integrals
- Voxelized forward projection
- Monte Carlo methods
  - scatter

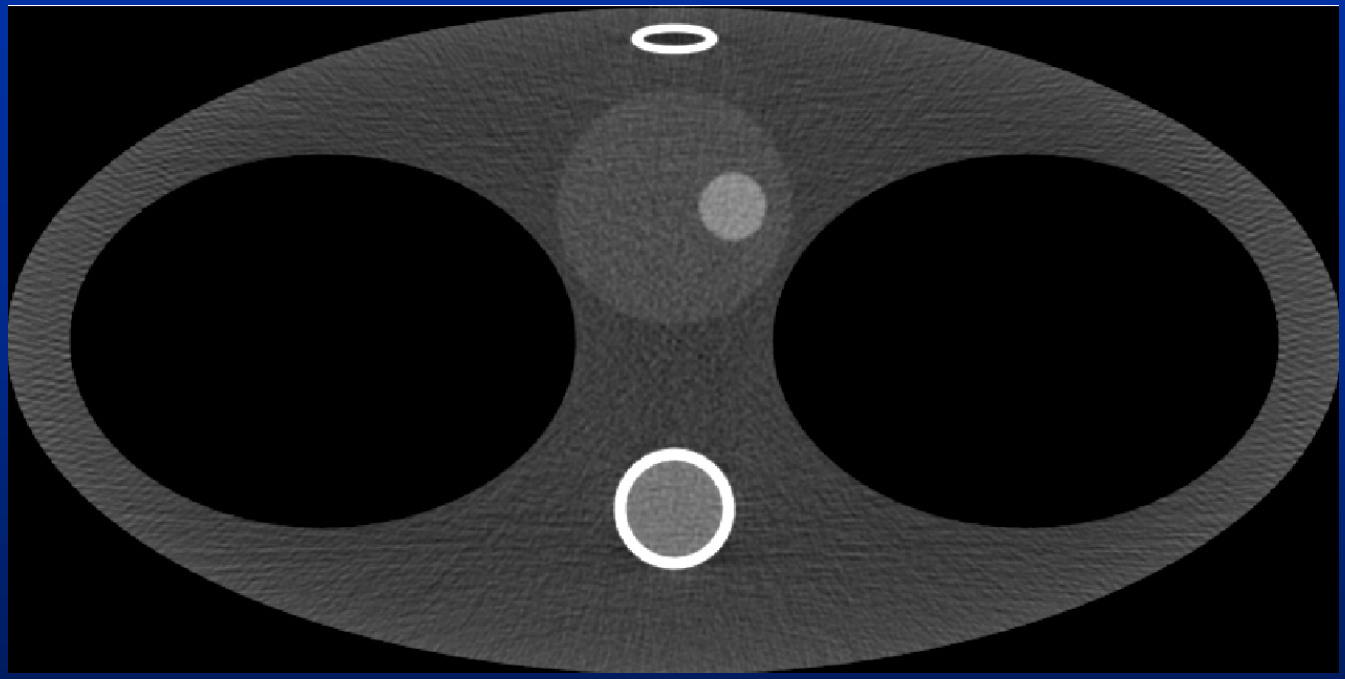
Analytical Ray Tracing

- Analytical expressions for the intersection of a line and 3D objects
  -spheres, ellipses, cylinders, boxes, cones...
- g3d software (Carl Crawford) performs these calculations



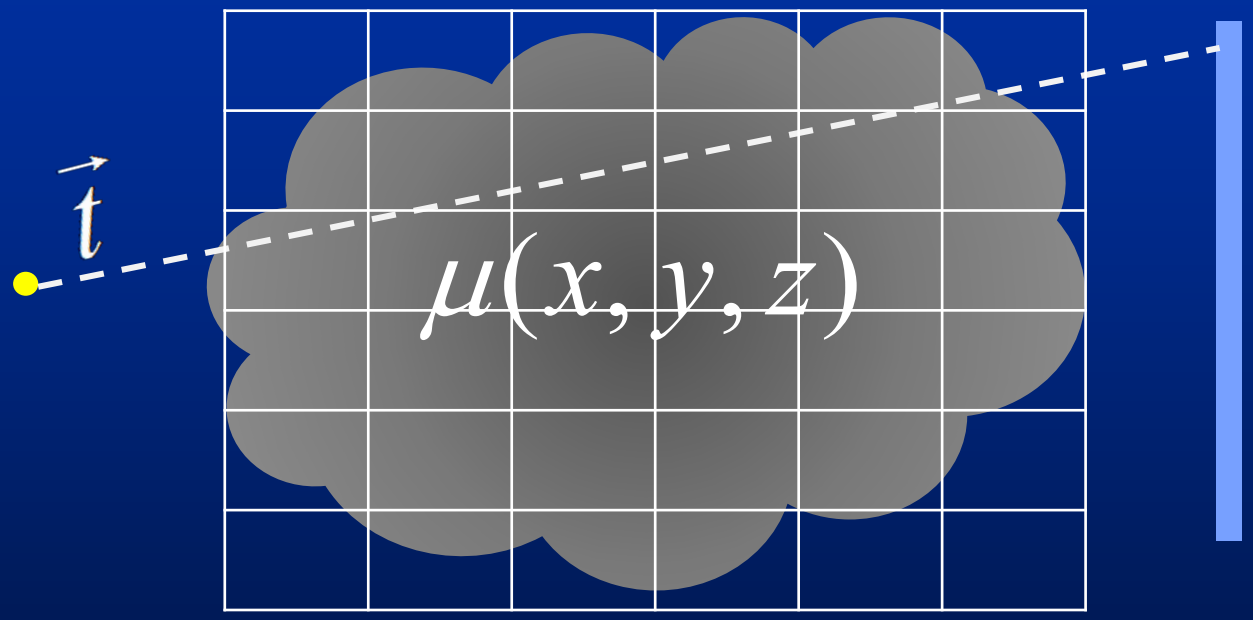


Analytic Ray Tracing Result



- CT image reconstructed from simulated data
- Simulations included polychromaticity, noise, finite focal spot, detector aperture

Voxelized Ray Tracing



source

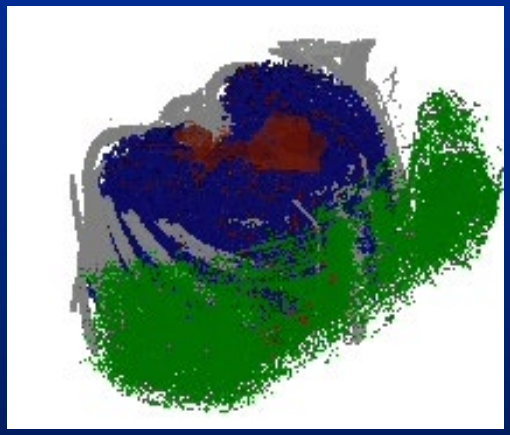
detector

Next Steps

- Identify and define test objects→task based
- Develop packing algorithm
- Integrate and modify g3d software for security applications
- Validate by simulating and experimentally scanning similar bags
- Disseminate to security community

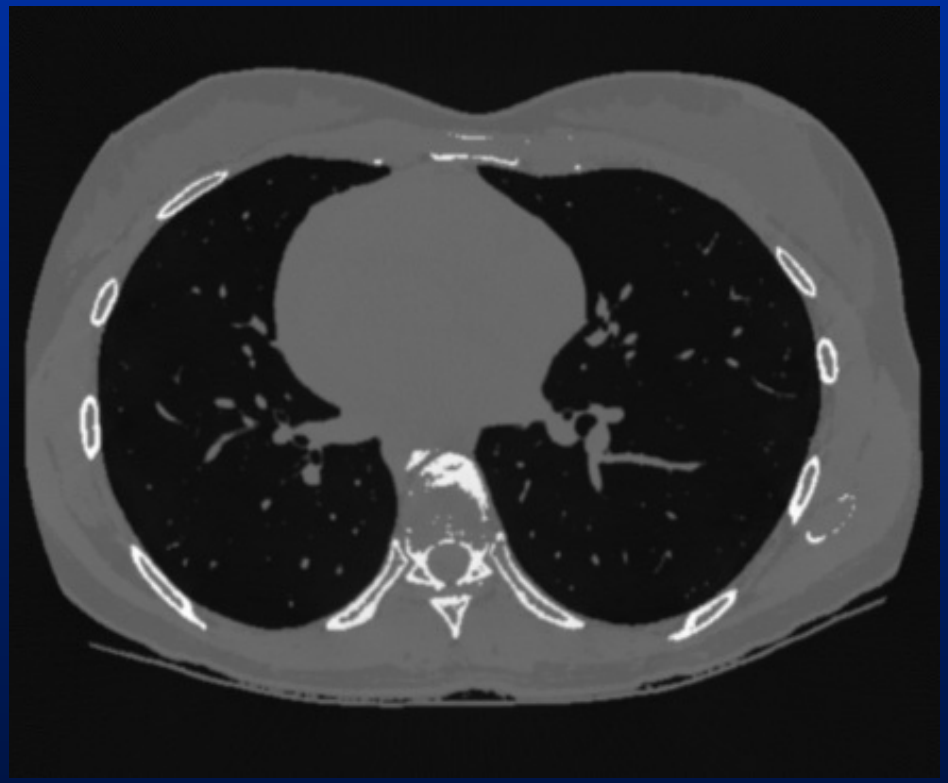
Voxelized Ray Tracing

- Represent complex objects by cartesian grid of voxels. Each voxel has one μ value
- Ray tracing algorithms (Siddon, Med Phys, 1985)
- Can convert an experimental image set into a software phantom



Voxelized Ray Tracing

- CT image converted to voxelized phantom
- Image reconstructed from simulated data
- Simulations included polychromaticity, noise, finite focal spot, detector aperture



Scatter Effects

- Generally requires Monte Carlo simulations
- - GEANT4, PENELOPE, etc.
- Analytical or voxelized models
- Computationally expensive
- Typically a combination of deterministic ray tracing and Monte Carlo simulations