PCSV Plate-forme de Calcul pour les Sciences du Vivant
Computing Platform for Life Sciences

Monte Carlo image reconstruction for medical applications

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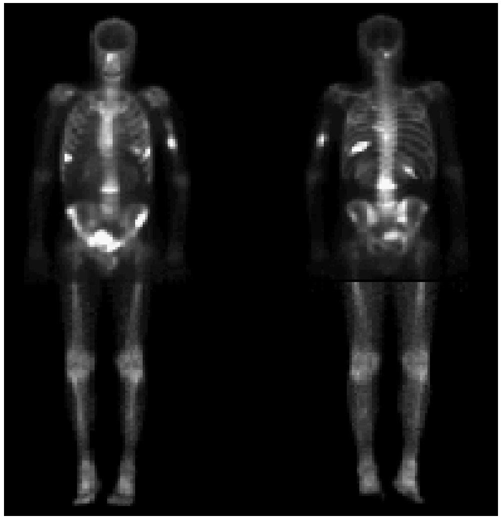
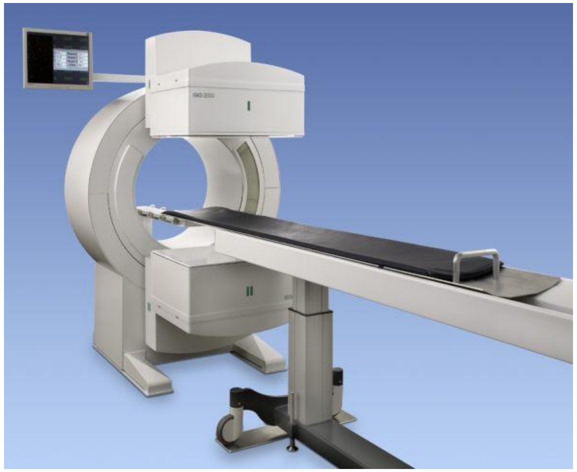
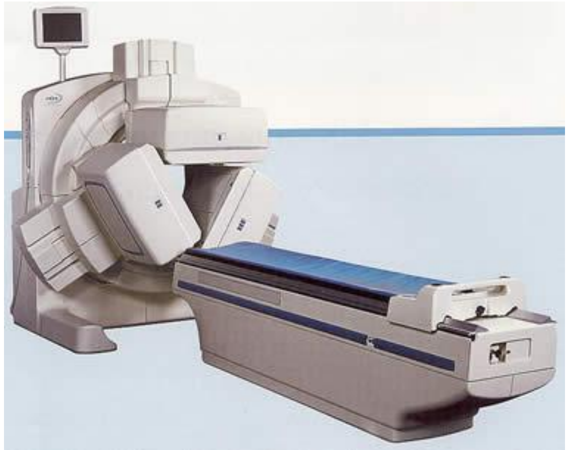
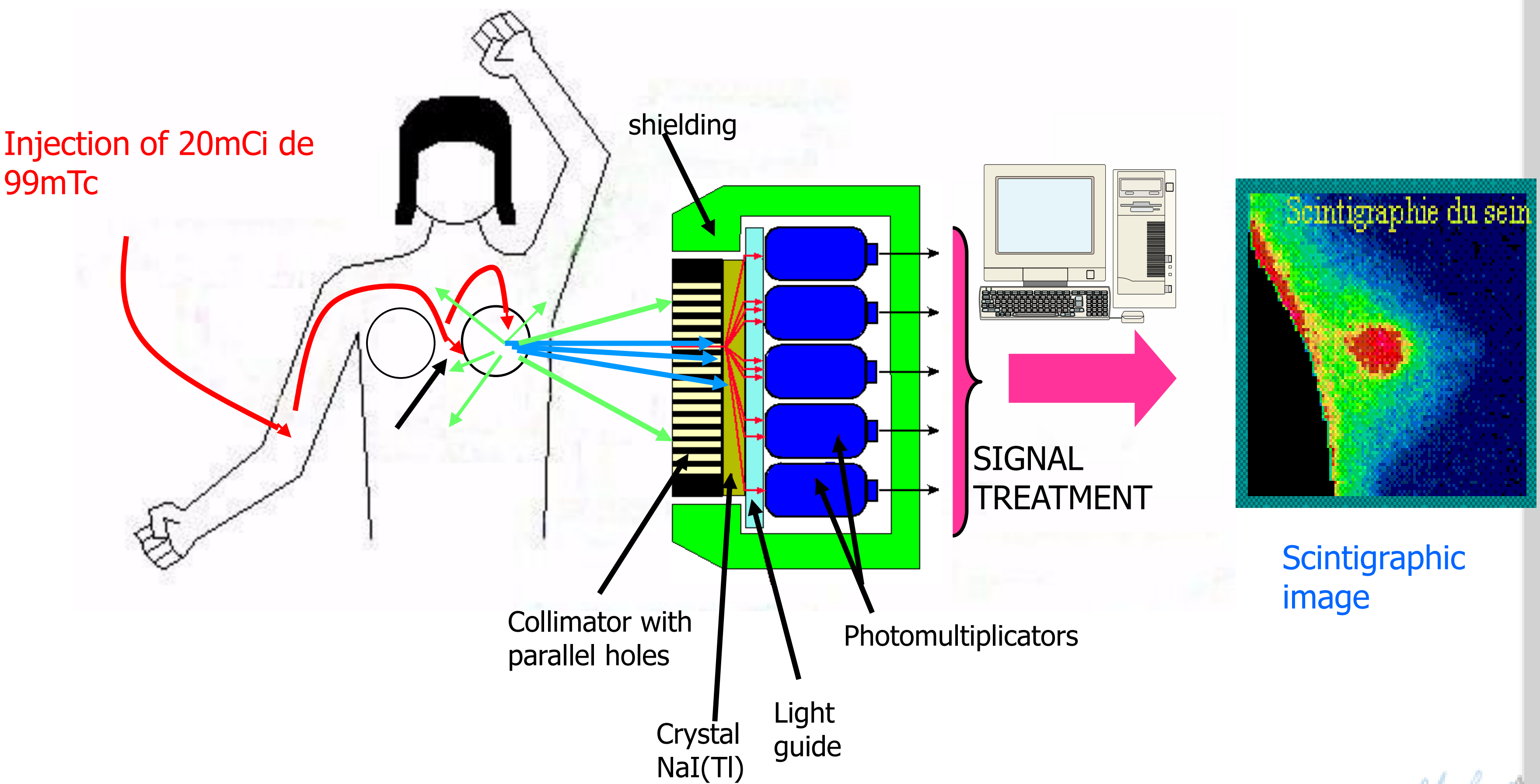
SPECT imaging



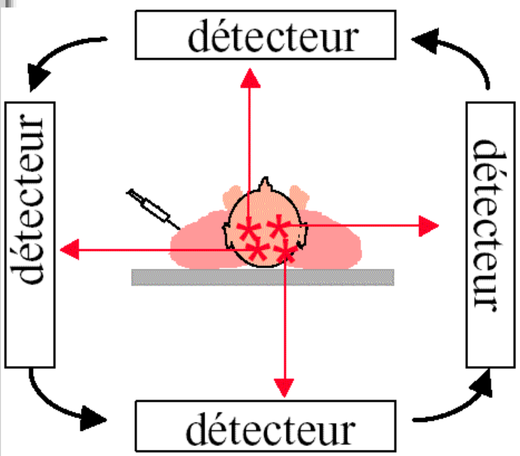


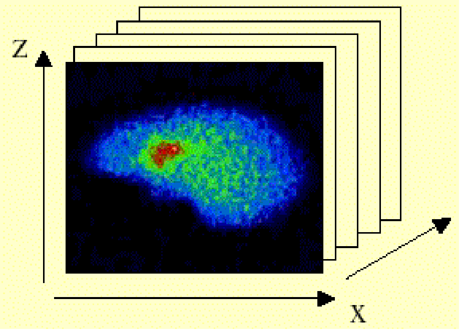


SPECT: methodology



Tomographic reconstruction: principle

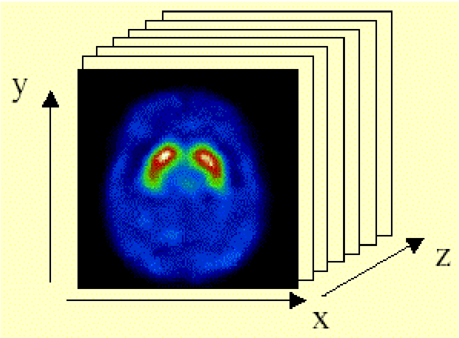




Set of 2D measured projections p

$$p(u,\theta) = \int_{-\infty}^{+\infty} f(x,y)\,dv$$

Tomographic reconstruction



Set of projections for $\theta = [0,\pi]$ = Radon transform of f(x,y)

$$R[f(x,y)] = \int_0^{\pi} p(u,\theta)\,d\theta$$

Problematic: inverse the Radon transform, i.e. estimate f(x,y) from p(u,θ)

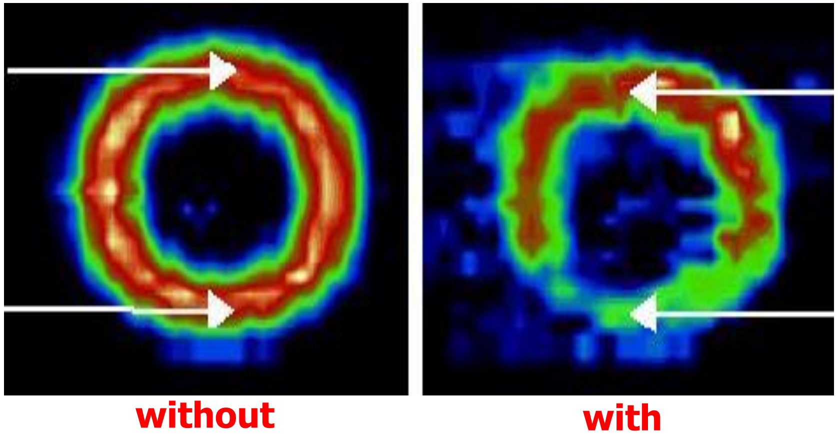
Physical factors affecting the quantification in imaging

- **Quantification:**
  - **Absolute:** measure the concentration of the radiopharmaceutic or a tumor volume
  - **Relative**: ratio of concentrations between healthy and tumoral tissue

- **Main barriers for the quantification:**
  - **Physical:**
    - ✓ attenuation
    - ✓ Compton scattering
  - **Limits of the detection**
    - ✓ Spatial resolution of the camera

Attenuation (SPECT imaging)

^{99m}Tc cardiac SPECT



- Attenuation of photons in patient

  ⇒ loss of a large number of photons and decreased signal-to-noise

- **Possible corrections**
  - **Before the tomographic reconstruction**
    1. Transmission tomography (external source) to deduce the attenuation map (correction coefficients)
    2. Multiply the projections acquired by correction coefficients
  - **After the tomographic reconstruction**

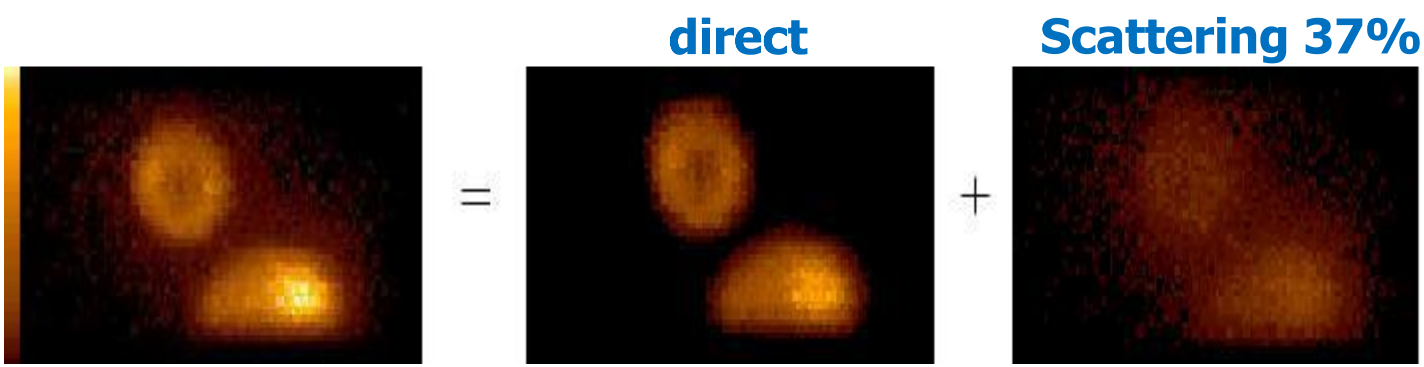
    Multiply the reconstructed images by correction coefficients (Chang method)
  - **During the tomographic reconstruction**

    We model the attenuation process during the reconstruction

Scattering (SPECT imaging)

- Compton scattering process in the patient, in the collimator, in the crystal (20 to 50%)

  ⇒ Misplaced photons having lost their energy, causing blur in the images, a decrease of contrast and quantitative bias



- Strategies for correction
  - **Substract scattered photons (Loss of sensitivity and increasing of noise)**
  - **Repositionning misplaced photons (modeling of scattered photons in the projector using analytic or Monte Carlo)**
  - **More than 30 methods**

Algorithms

- 2 approaches to reconstruct images:

1. Analytic reconstruction: continuous expression of the reconstruction problem

   ➡ **Analytic inversion of the Radon transform**

   Most common method: Filtered BackProjection (FBP)

2. Iterative reconstruction: discrete expression of the reconstruction problem

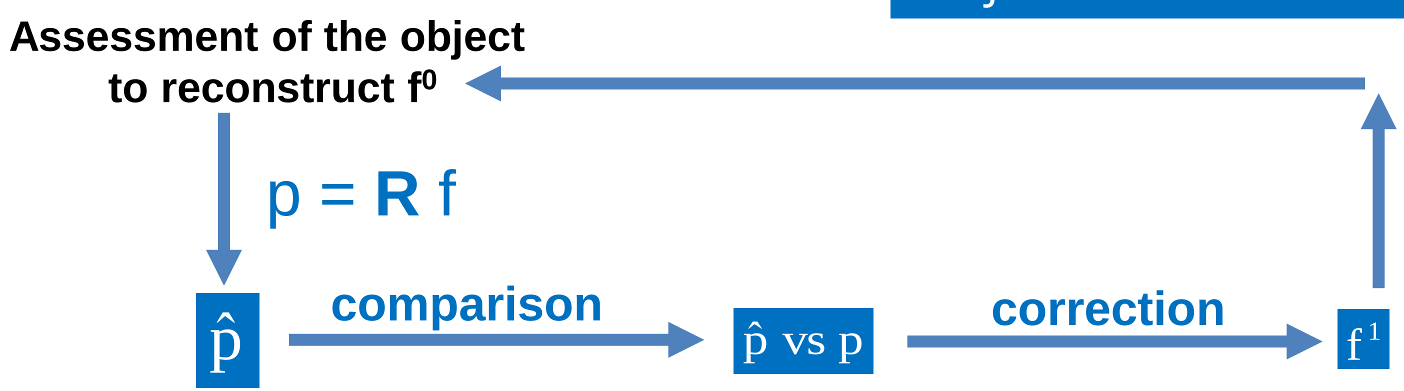
   - Maximum Likelihood Expectation Maximization (MLEM),
   - Ordered Subset Expectation Maximization (OSEM),
   - SIRT, ART, …

Iterative reconstruction method

- **Discrete expression of the problem for tomographic reconstruction usi a matrix**
- **Iterative inversion of this great system of equations**

$$\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} = \begin{bmatrix} r_{11} & & & r_{14} \\ & & & \\ & & & \\ r_{41} & & & r_{44} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix}$$

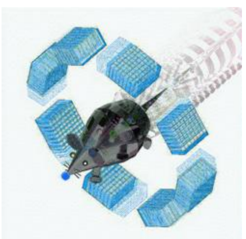
Acquired Projections | Operator | Object to reconstruct



- **Algorithms: MLEM, OSEM…**

Interest of using MC simulation for image reconstruction

❑ 3D approach



GATE

Modeling the projector in 3D

R

- **attenuation**
- **Compton scattering**
- **Spatial resolution of the system**

Estimate the object to to reconstruct f^0

$p = R\, f$

$\hat{p}$

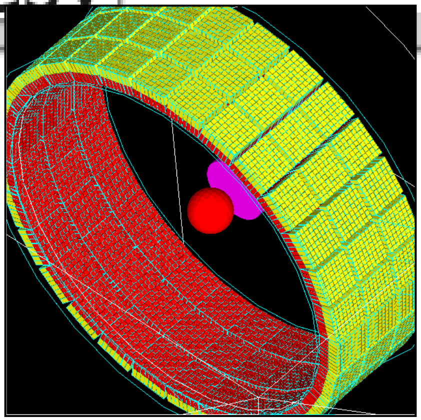
comparison

$\hat{p}$ vs p

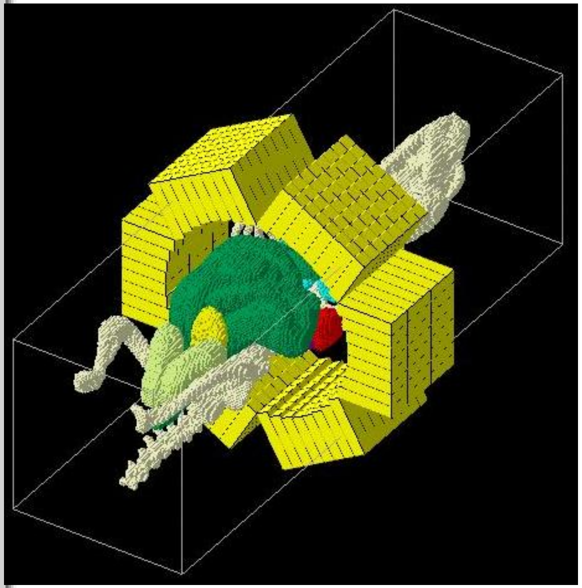
MLEM correction

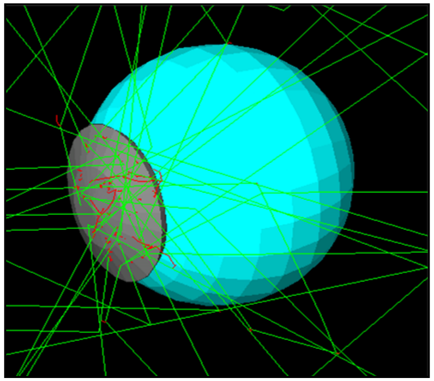
f^1

GATE for medical physics simulations

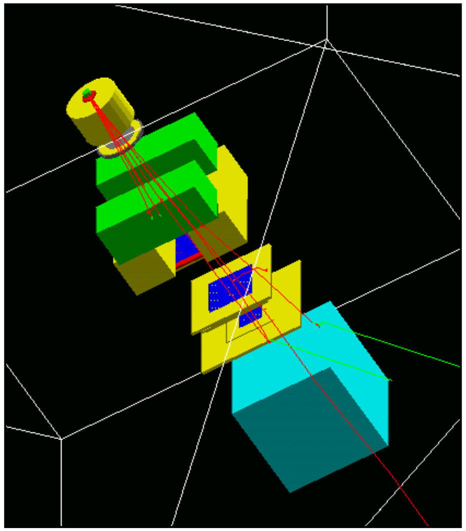


PET camera

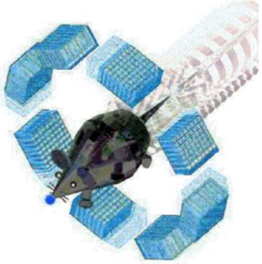




Ocular brachytherapy treatment



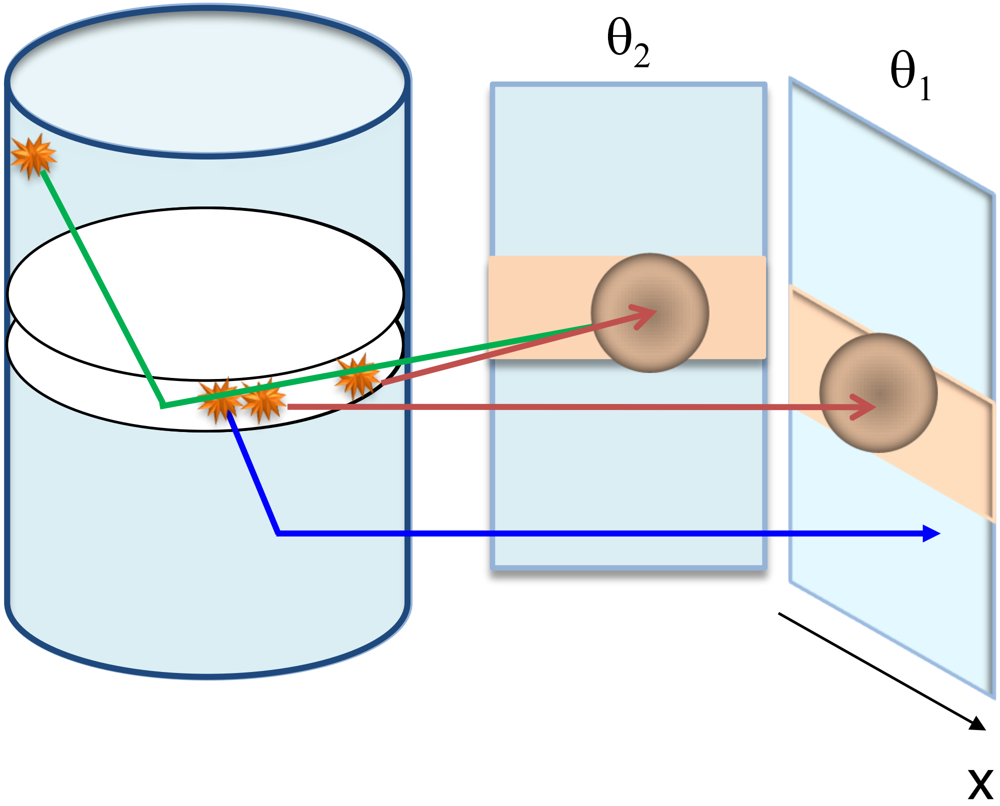
Radiotherapy



OpenGATE collaboration

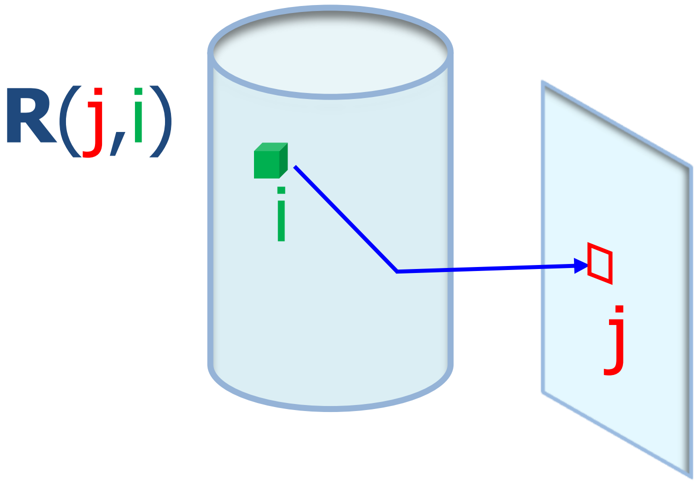
http://www.opengatecollaboration.org

Context: limits of 2D image reconstruction in SPECT



the **whole image** (and not only a row) contains events coming from activity in the slice of interest

Theory: mathematical formulation of the problem



$$p = \mathbf{R} f$$

i : number of voxels to be reconstructed

(Or number of voxels belonging to the attenuating medium)

j : number of pixels in the projections

$$\begin{pmatrix} \\ \\ \mathbf{R}(j,i) \\ \\ \\ \end{pmatrix}$$

for 60 projections 128 x 128

$p = P \times N^2$ (P=Number of projections, NxN number of pixels)

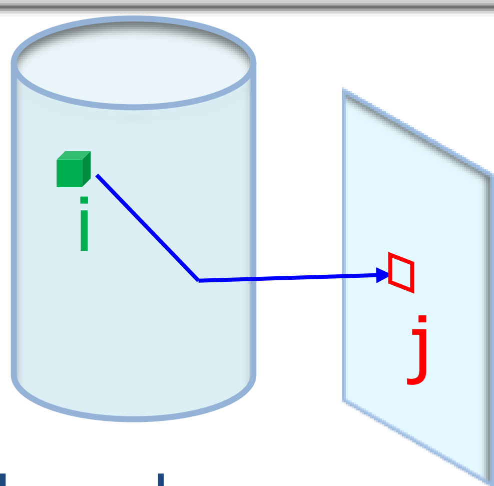
$f = N^3$ (N transaxial slices of NxN pixels)

$R = (60 \times 128^2, 128^3)$

Size = 2Tb *(but most of the voxels are with value = 0)*

Theory: modeling the projector R

R(j,i)



N photons emitted from voxel i

$$\mathbf{R}(j,i) = \frac{\text{number of photons detected in } j}{N}$$

Monte Carlo simulation

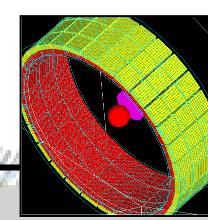
R(i,j) depends on:

- the geometry and attenuating properties of the object

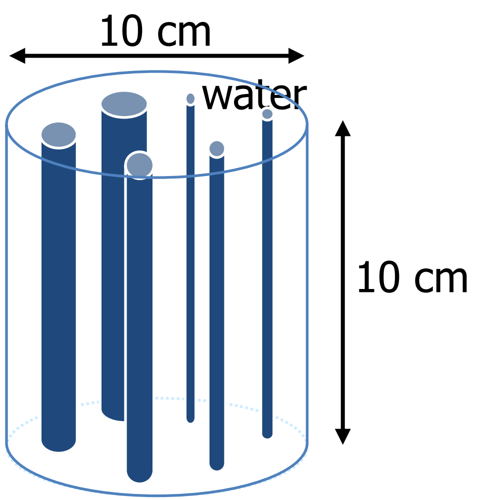
CT scan of the object

- the characteristics of the detection system

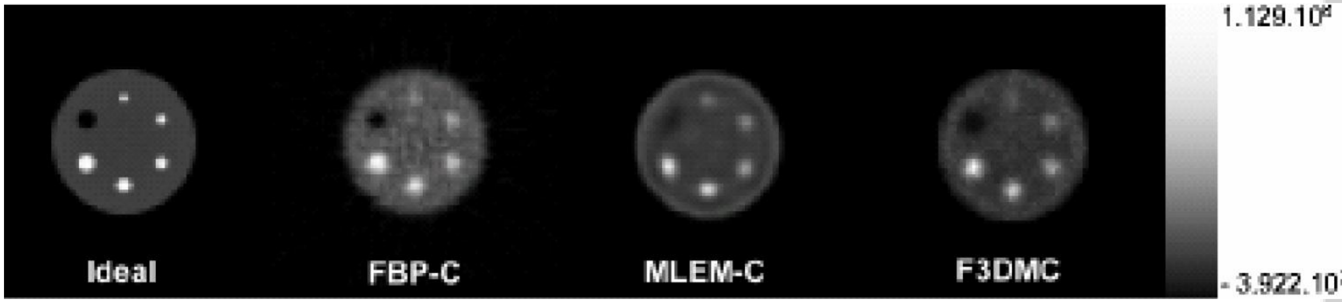
technical data and experiments



Results



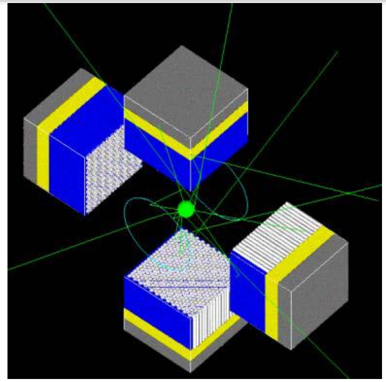
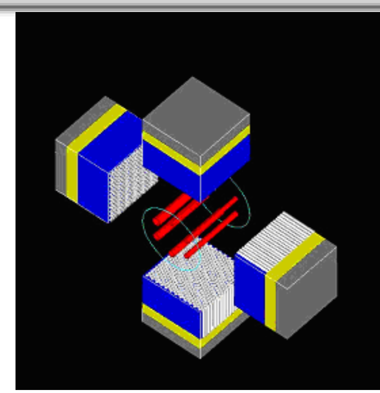
Tc^{99m} (38.2 kBq/mL)

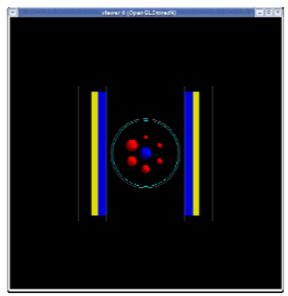
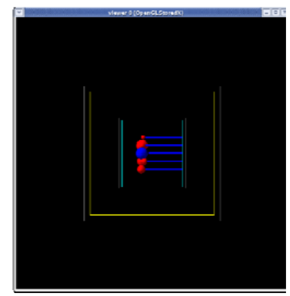


Méthode de reconstruction	Rapports d'activité Cyl1	Cyl2	Cyl3	Cyl4	Cyl5	Cyl6	% AR	RSB
Idéale	4,00	4,00	4,00	4,00	4,00	0,00		-
Après échantillonnage	1,92	2,23	2,46	2,54	2,73	0,41	100	-
FBP-C	1,55 ± 0,05	1,81 ± 0,05	1,98±0,06	2,27 ± 0,07	2,44 ± 0,07	0,49 ± 0,02	90,0	39
	(-19, 3 %)	(-18, 8 %)	(-19, 5 %)	(-10, 6 %)	(-10, 6%)	(19, 5 %)		
MLEM-C	1,61 ± 0,03	1,80 ± 0,04	1,93 ± 0,04	2,47 ± 0,07	2,46 ± 0,05	0,71 ± 0,02	84,2	44
	((-16,2%)	(-19, 3 %)	(-21, 5 %)	(-2, 8 %)	(-9, 9 %)	(73, 2 %)		
F3DMC + ACP	1,68 ± 0,06	2,04 ± 0,07	2,33 ± 0,07	2,82 ± 0,07	3,01 ± 0,07	0,45 ± 0,02	98,6	43
	(-12, 5 %)	(-8, 5 %)	(-5, 3 %)	(11, 0 %)	(10, 3 %)	(8, 9 %)		

Contrast improved using F3DMC

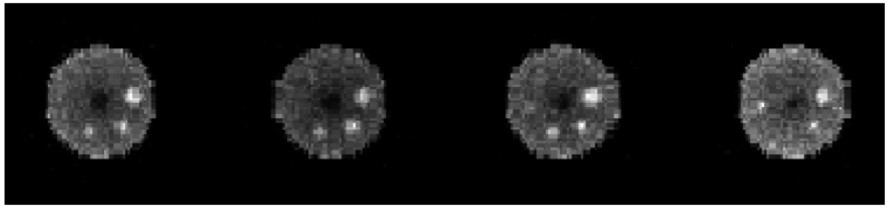
Results

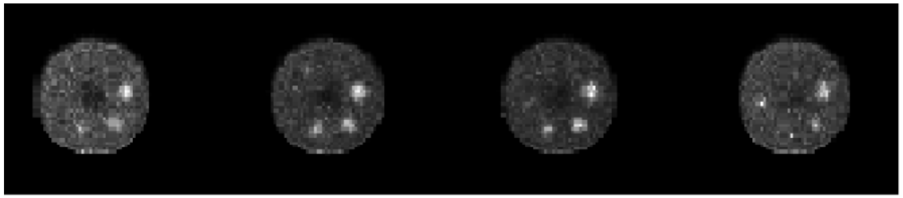



- AXIS (Philips) gamma camera (LEHR collimator)
- 60 projections over 60 angles each 6°
- 126-154 keV and 92-125 keV energy windows
- Projections=64x64 pixels, pixel size=3.138x3.138 mm
- 240 billion of generated photons
- 24 million of detected photons

Results



(a)



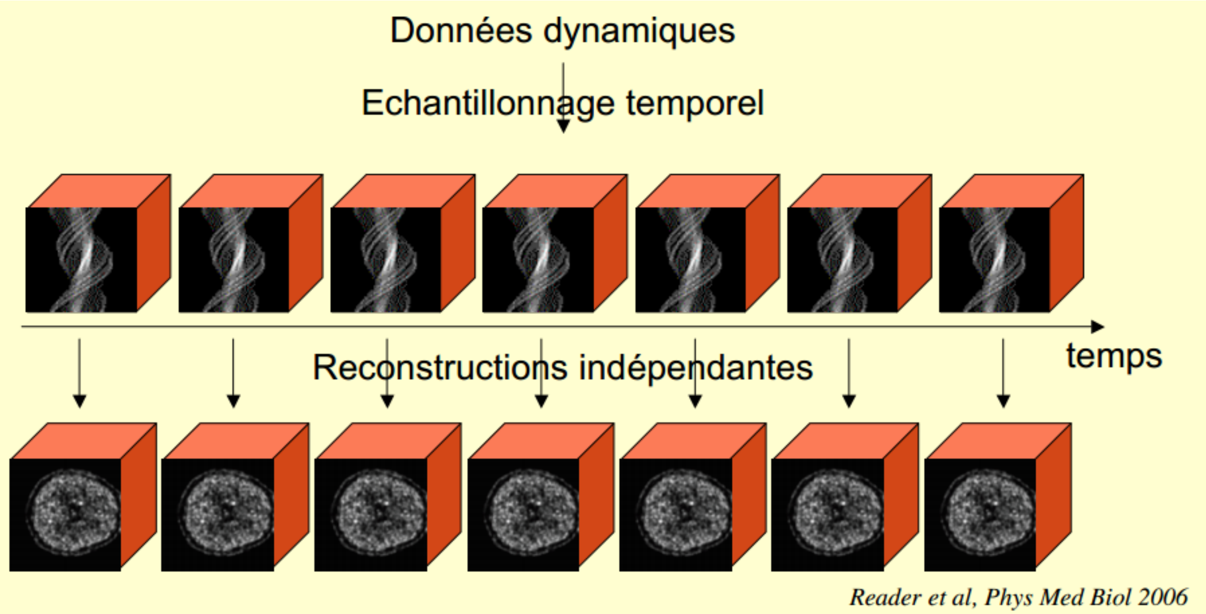
(b)

Coupes reconstruites avec les méthodes: a) OSEM-C. b) F3DMC.

Méthode de reconstruction	Rapports d'activité Ø=1,85 cm	Ø=2,2 cm	Ø=2,7 cm	Ø=3,3 cm	Ø=3,8 cm	RSB
Idéale	4,00	4,00	4,00	4,00	0,00	-
Après échantillonnage	1,93	2,11	2,31	2,39	0,46	-
OSEM-C	1,70 (-12 %)	1,69 (-20 %)	1,90 (-18 %)	2,07 (-13 %)	0,70 (+52 %)	7,18
F3DMC	2,05 (+6 %)	2,09 (+1 %)	2,21 (-4 %)	2,40 (+1 %)	0,69 (+51 %)	12,08

New challenges

- 4D tomographic reconstruction
  - 3D + time
  - Pharmacokinetics studies



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