IMAGERIE MEDICALE

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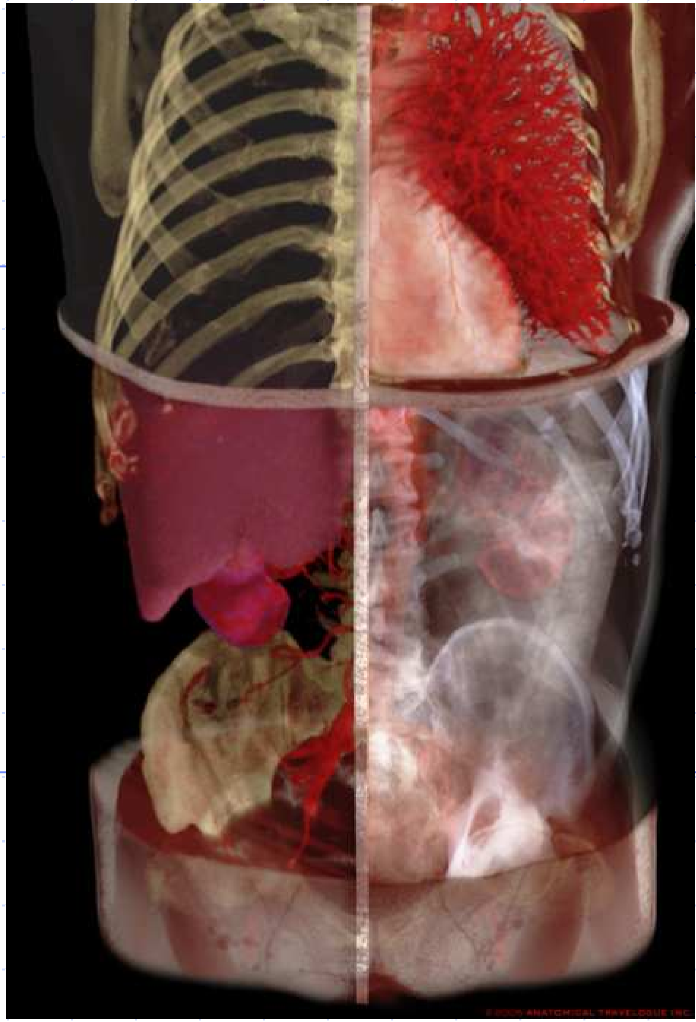
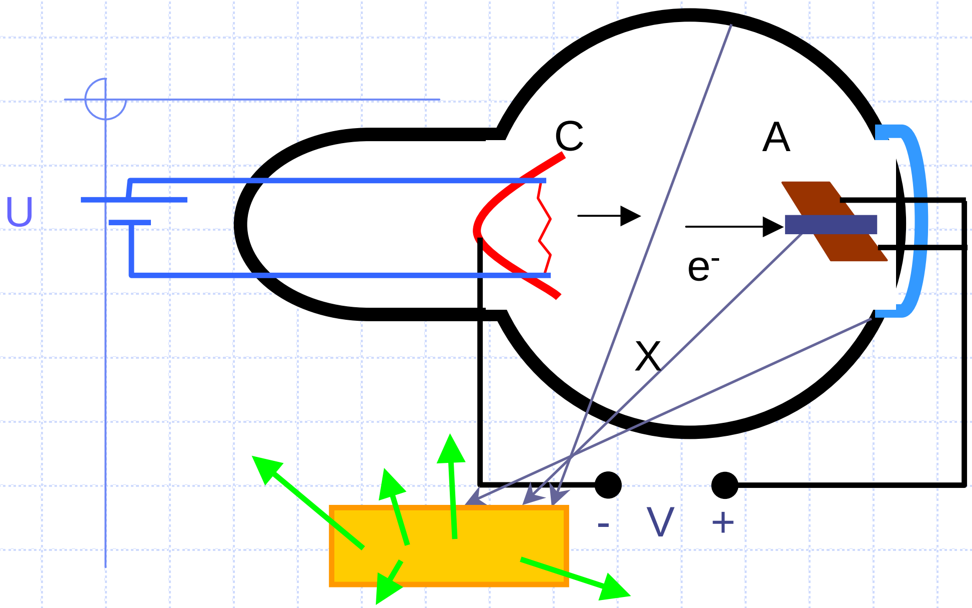
Plan général

- Les modalités de l'imagerie médicale
- Reconstruction tomographique 2D et 3D
- Traitement et analyse multimodal
- Visualisation volumique

Les modalités d'imagerie

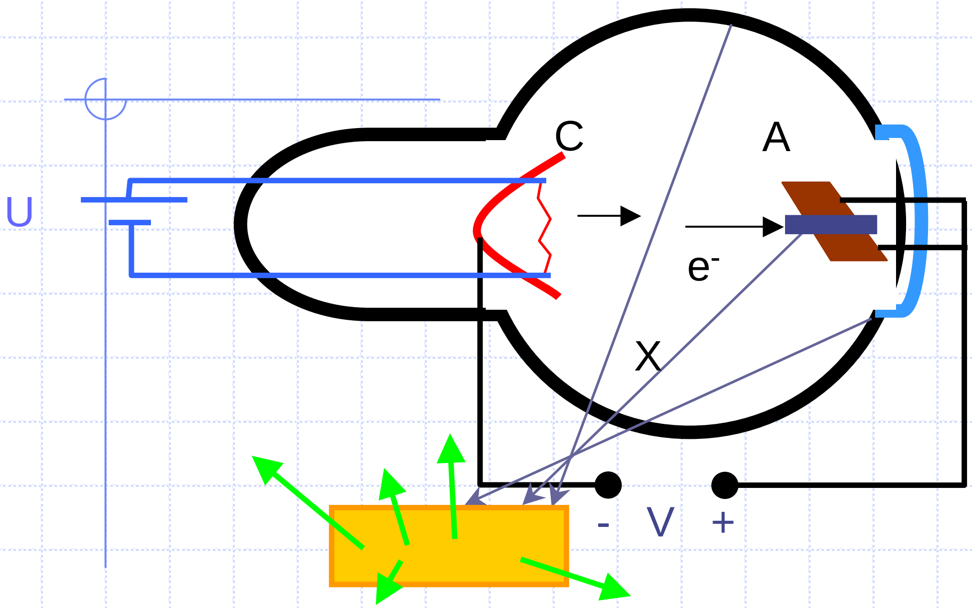


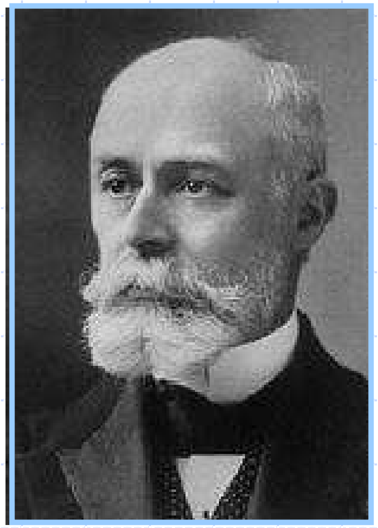
Rayons X, rayons γ ...



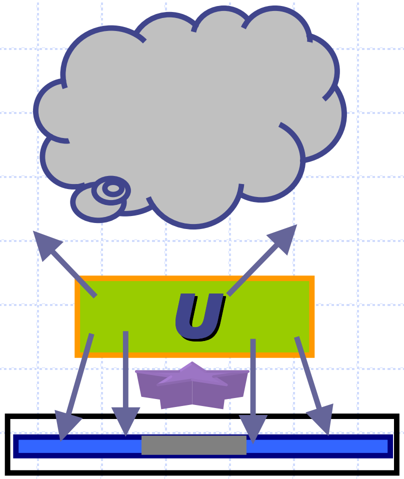
Röntgen 1895

Rayons X, rayons γ …



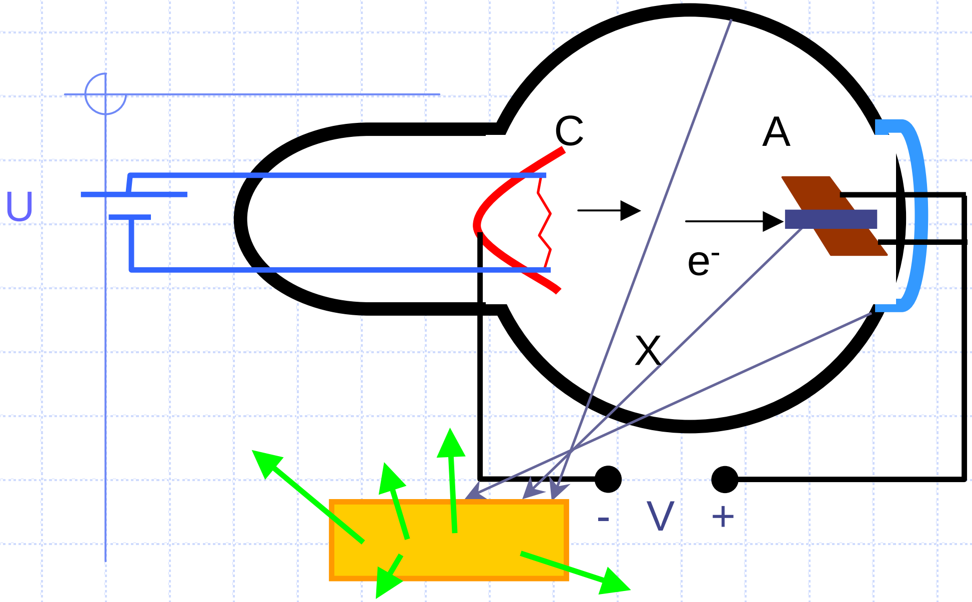


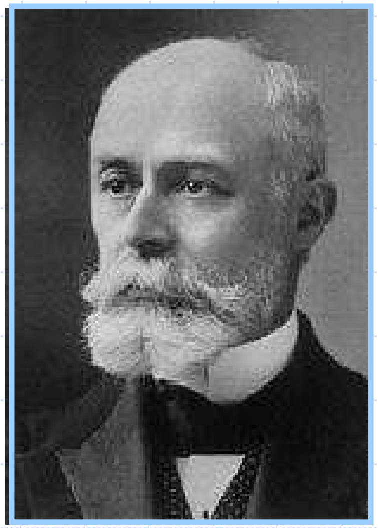
Becquerel 1896



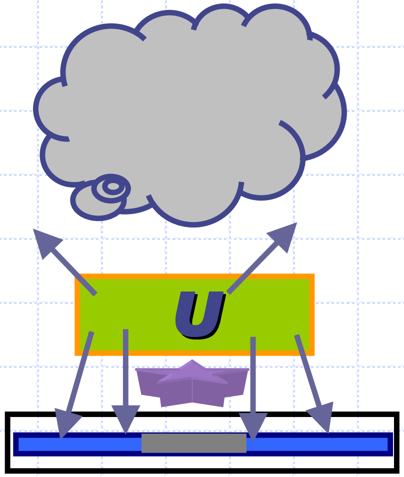
Röntgen 1895

Rayons X, rayons γ ...

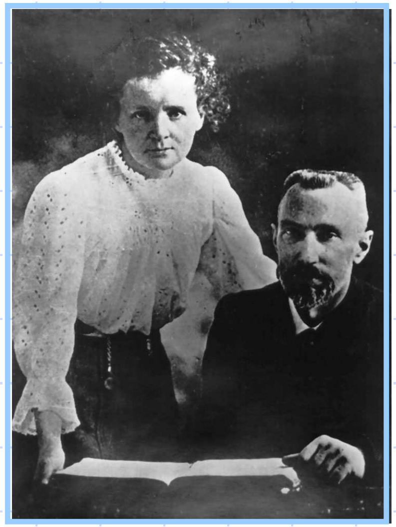




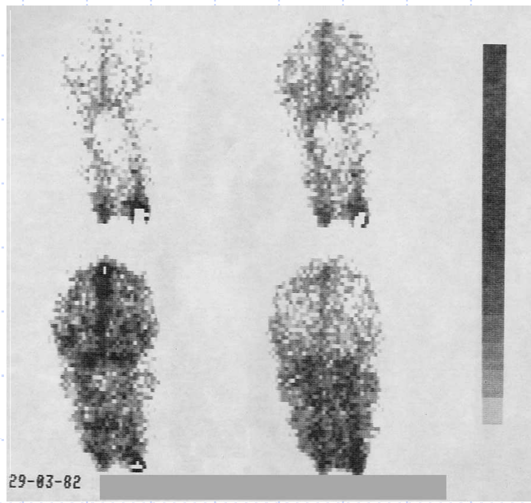
Becquerel 1896



Röntgen 1895



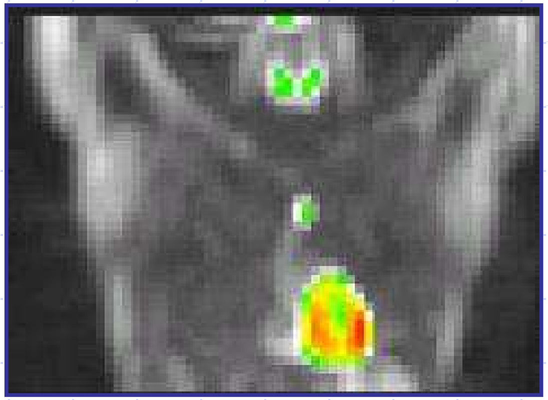
Curie 1934



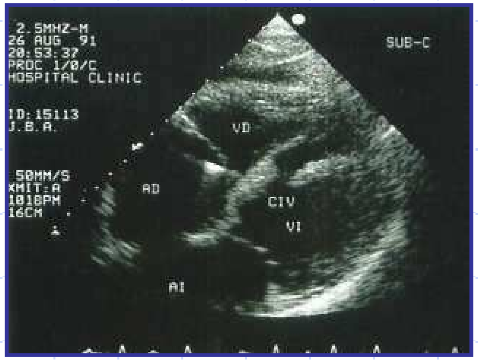
Modalites d'imagerie

- Imagerie de transmission
  - Radiologie X

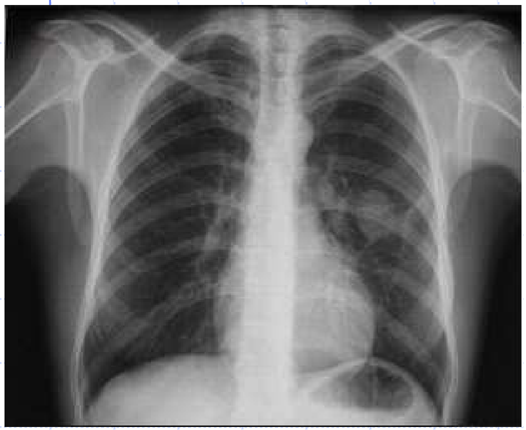
- Imagerie d'émission
  - Scintigraphie γ
  - TEP
  - IRM

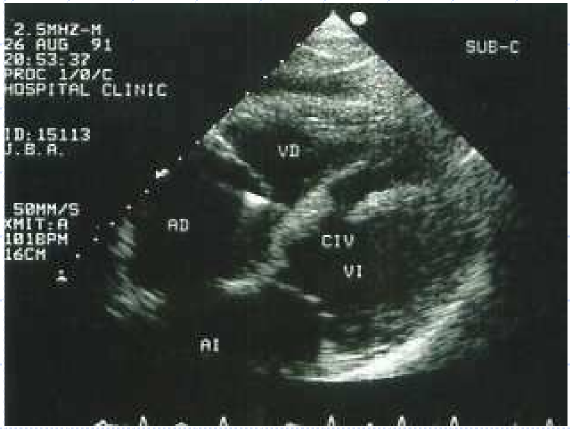


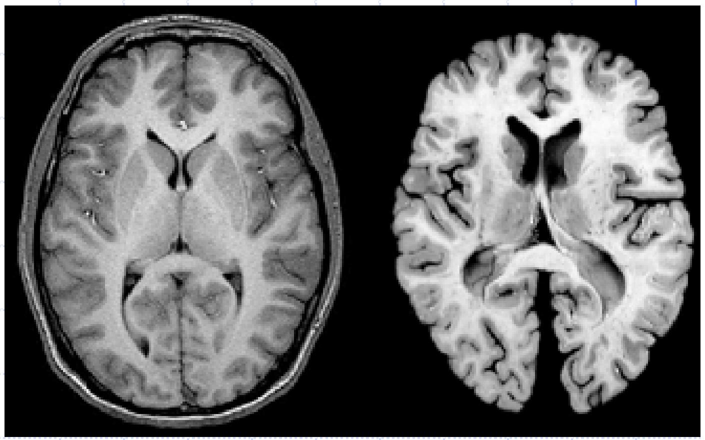
- Imagerie de réflexion
  - Echographie



Imagerie anatomique







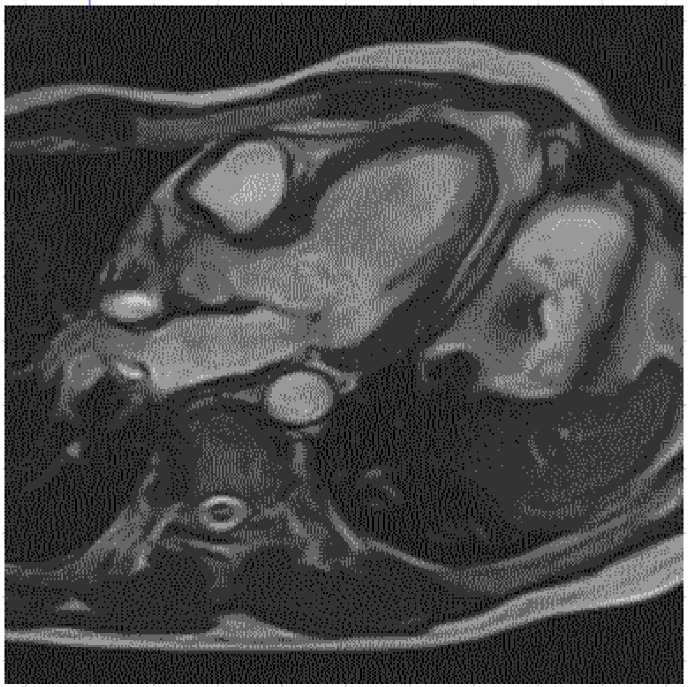
Radiographie

Echographie

IRM

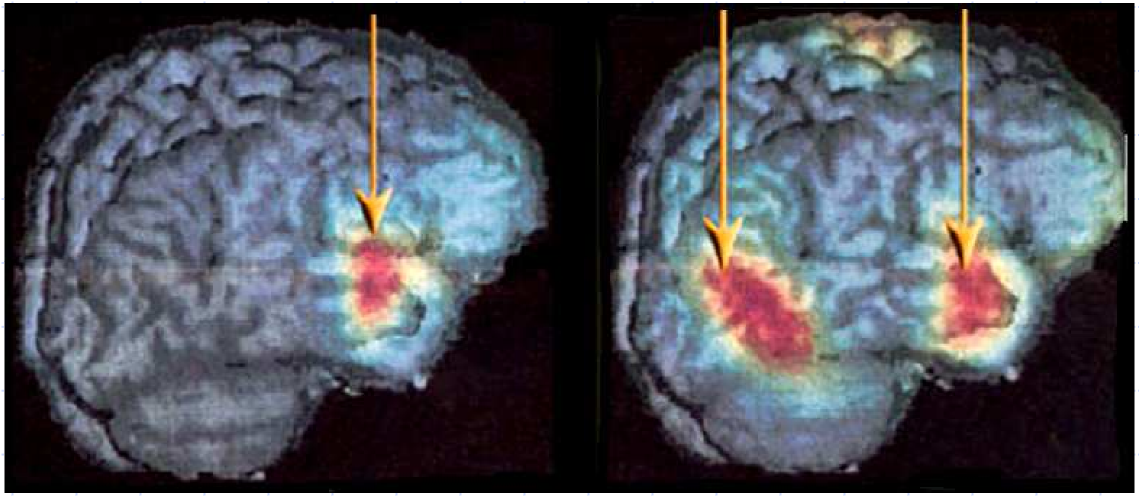
Post mortem

Imagerie fonctionnelle



Cortex auditif

Cortex visuel



Sujet normal

Aveugle de naissance

Kujala et al., 2000

Imagerie métabolique moléculaire

VECTEUR

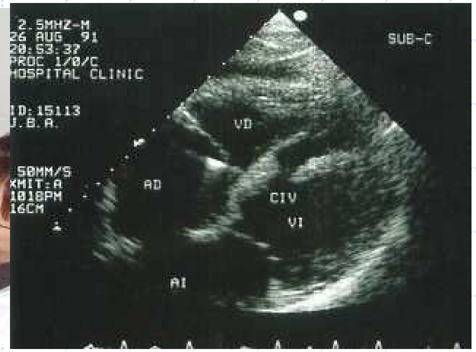
MARQUEUR

```
     O        O
     ||       ||
HO-P-CH2-P-OH
     |        |
     O       O
       \    /
   HO-Tc-OH
       /    \
     O      O
     |        |
HO-P-CH2-P-OH
     ||       ||
     O       O
```

TRACEUR RADIOACTIF

Les techniques radiologiques

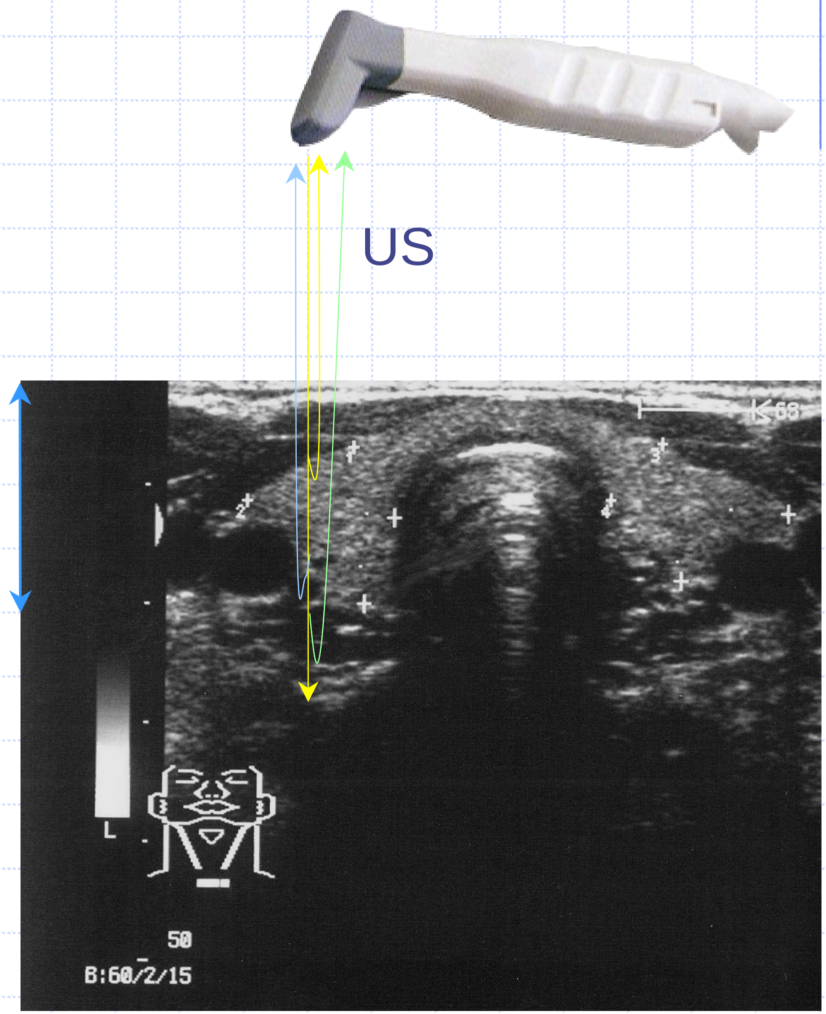
- Echographie



- IRM

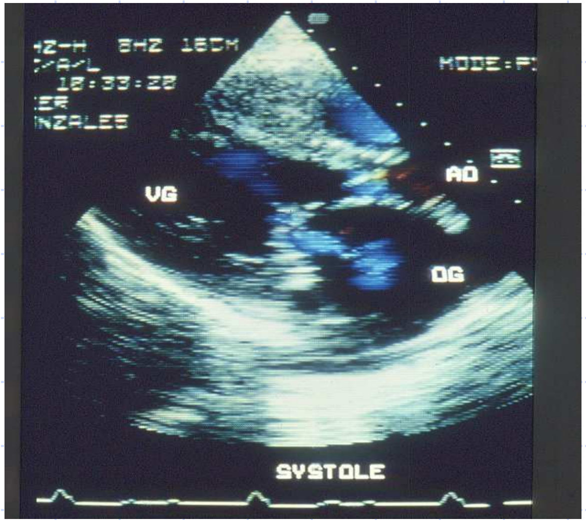
- Radiographie

Echographie

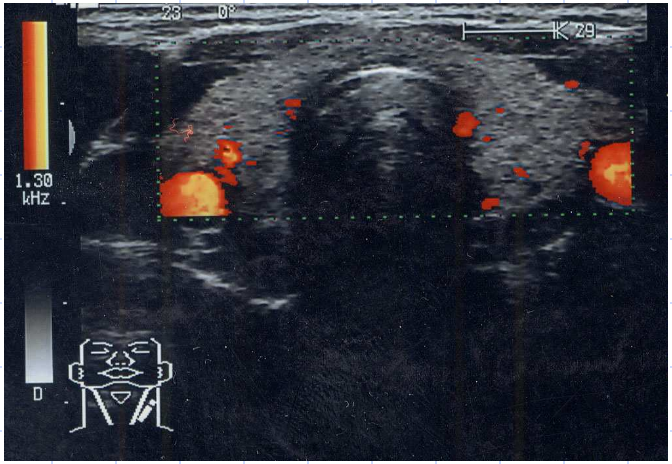


$$Z = \rho \, c$$

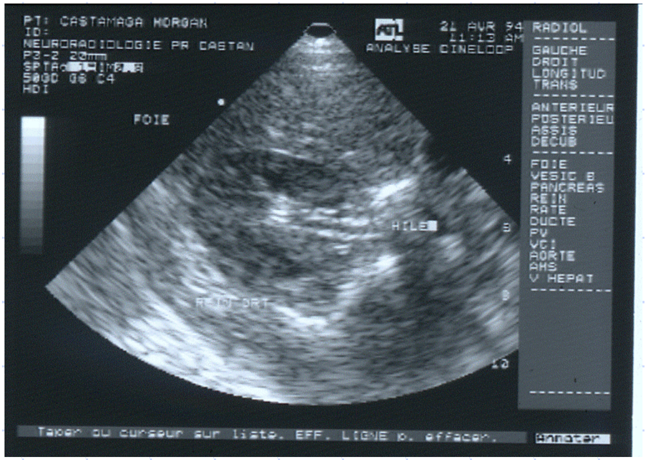
Echographie : applications



Cœur



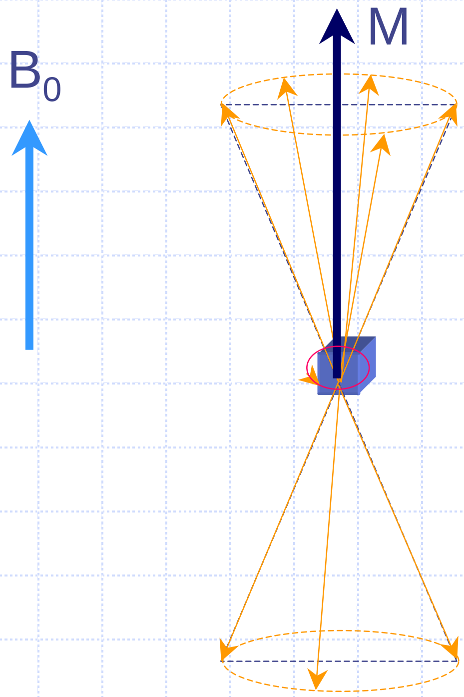
Thyroïde

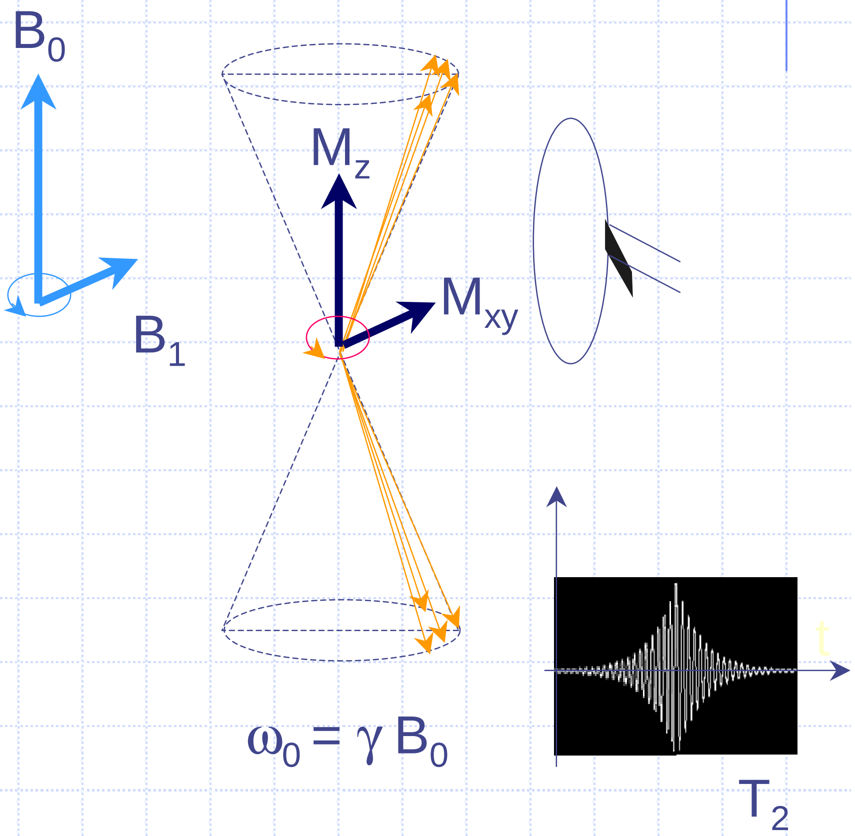


Rein

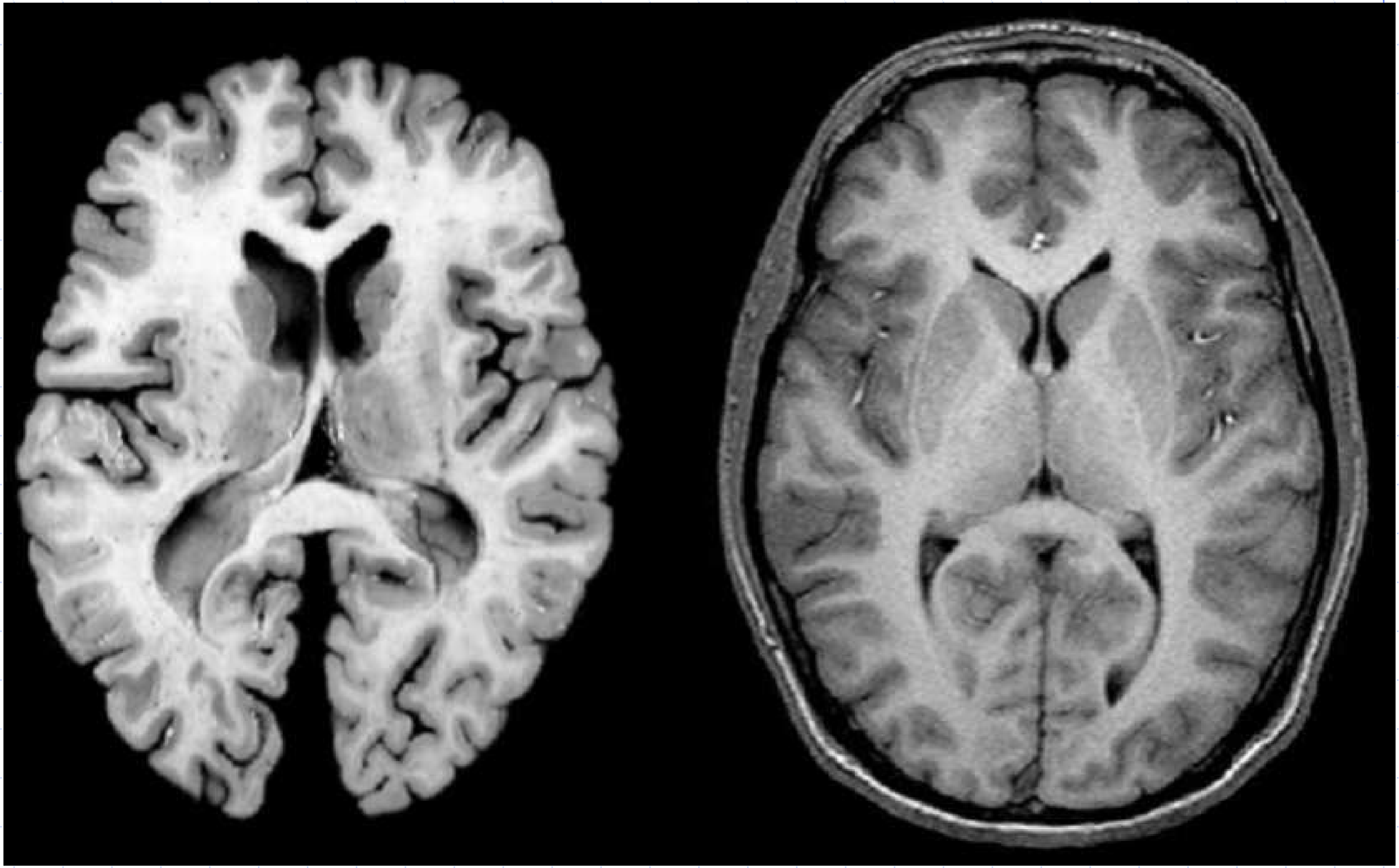
Foetus

Imagerie par résonance magnétique nucléaire

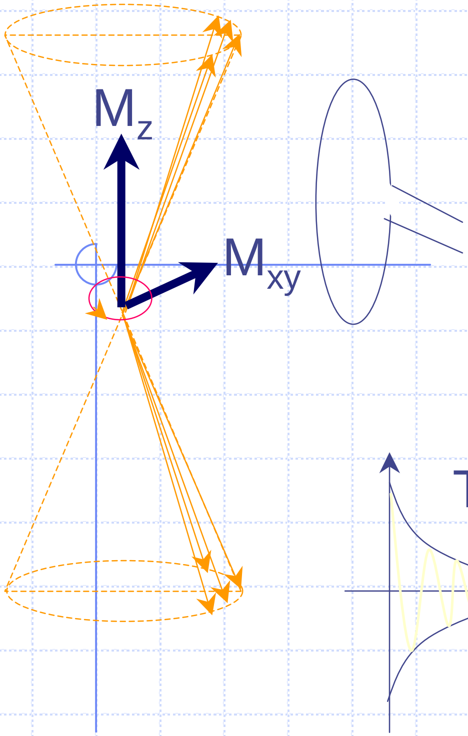


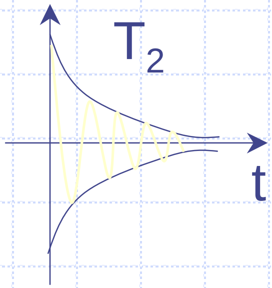


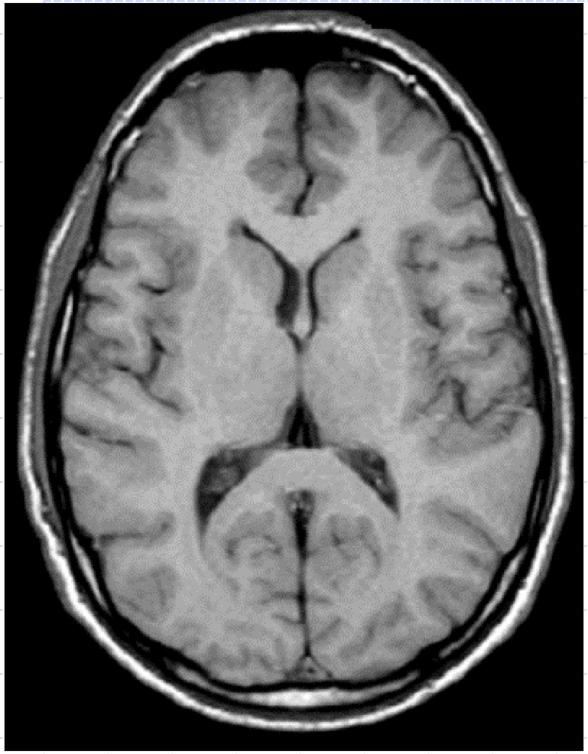
1946 : Bloch & Purcell
1970 : Damadian
1973 : Lanterbur & Mansfield



post mortem in vivo

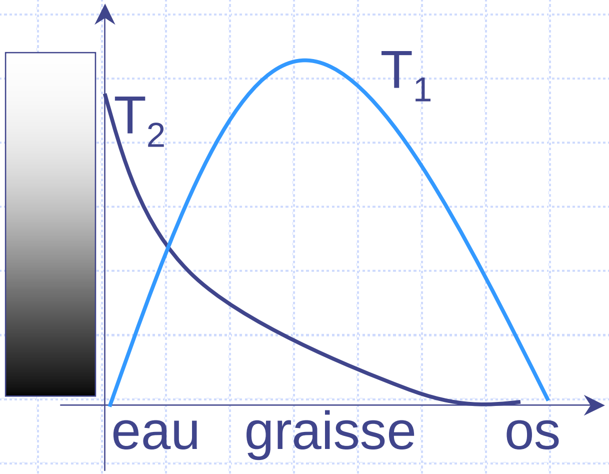




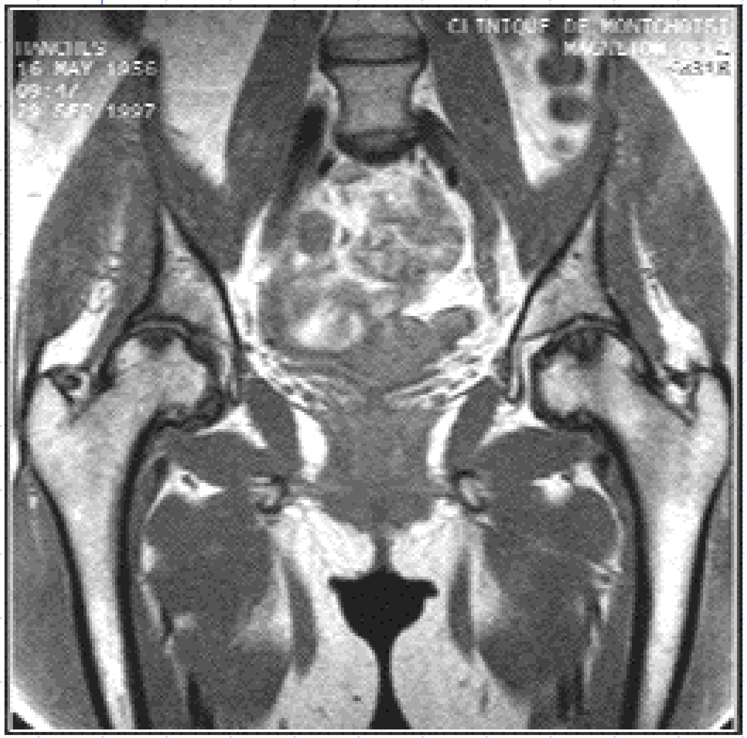


T1

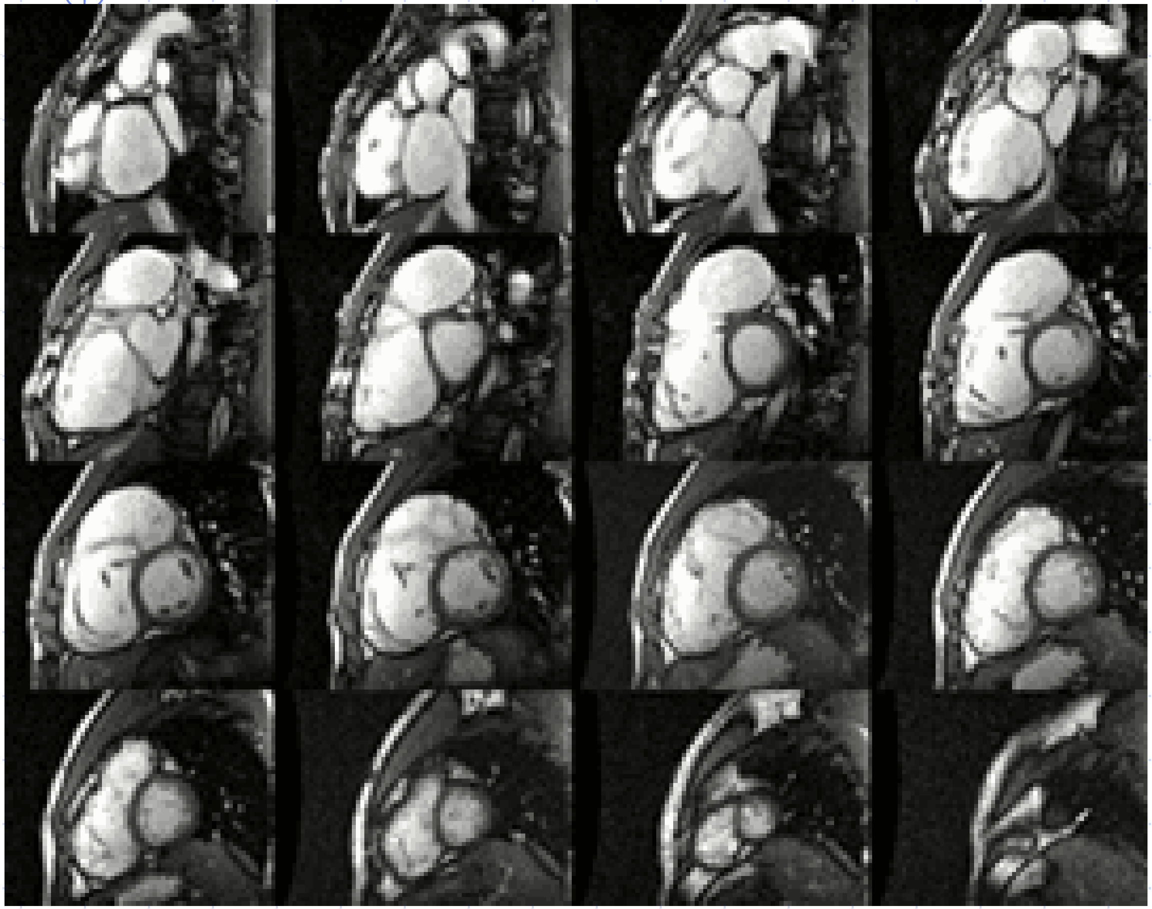
T2

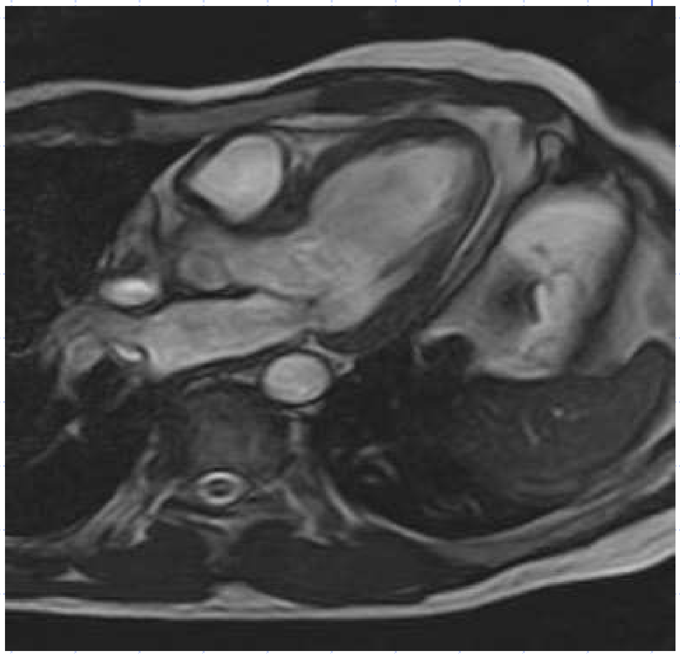


Imagerie par résonance magnétique nucléaire



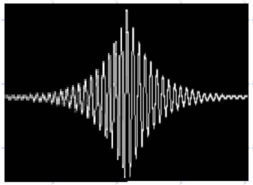
Imagerie par résonance magnétique nucléaire

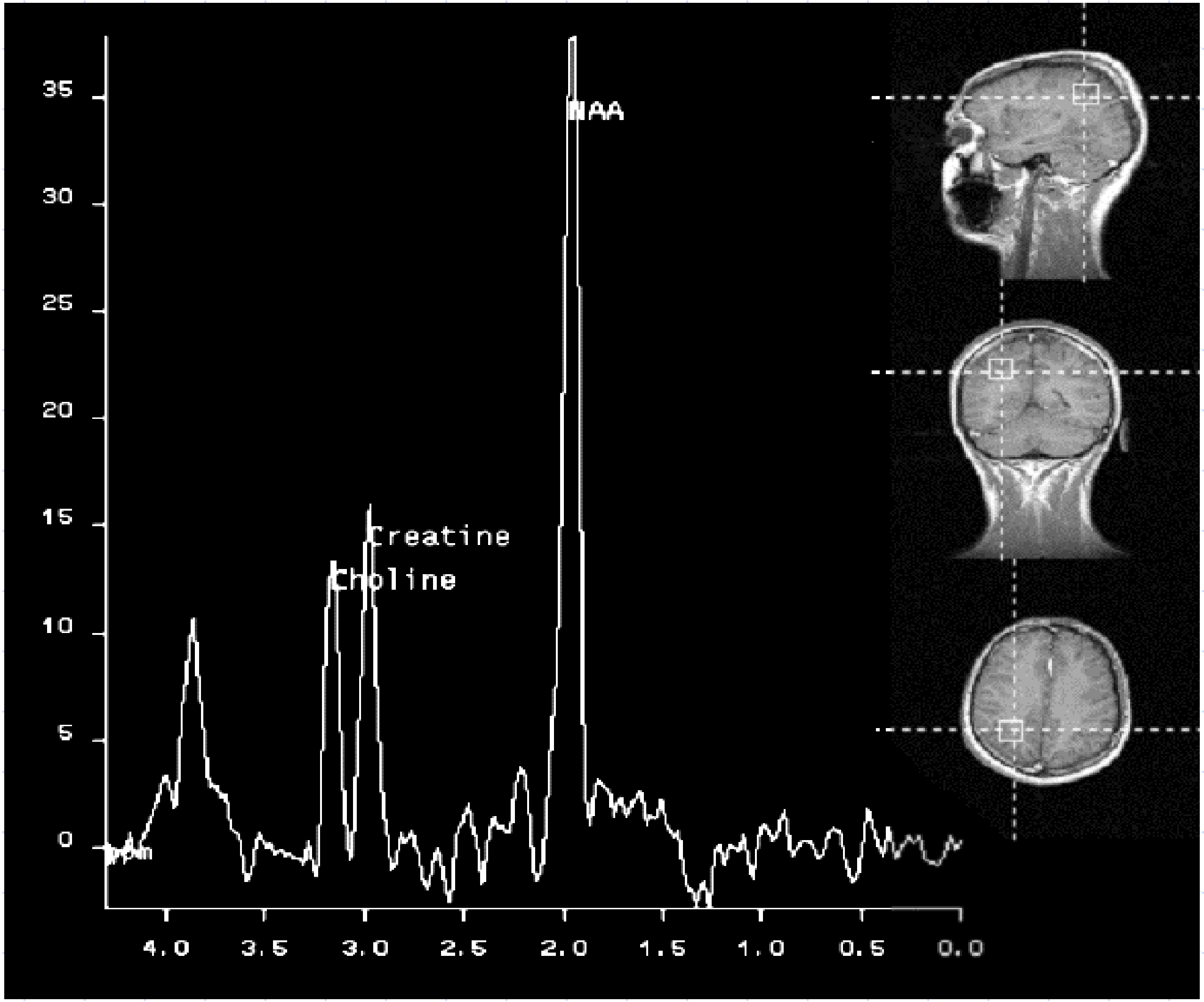




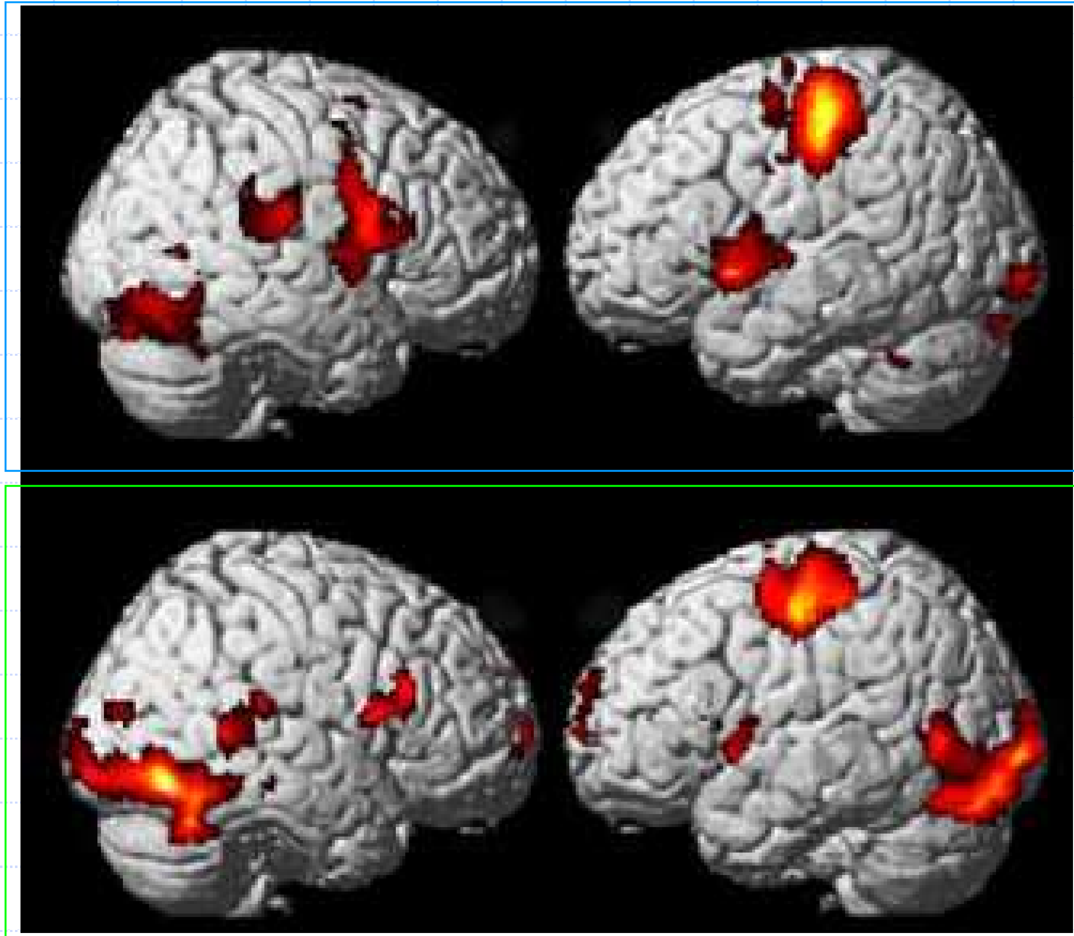
Spectrométrie RMN

Spectre du ^1H





IRM FONCTIONNELLE



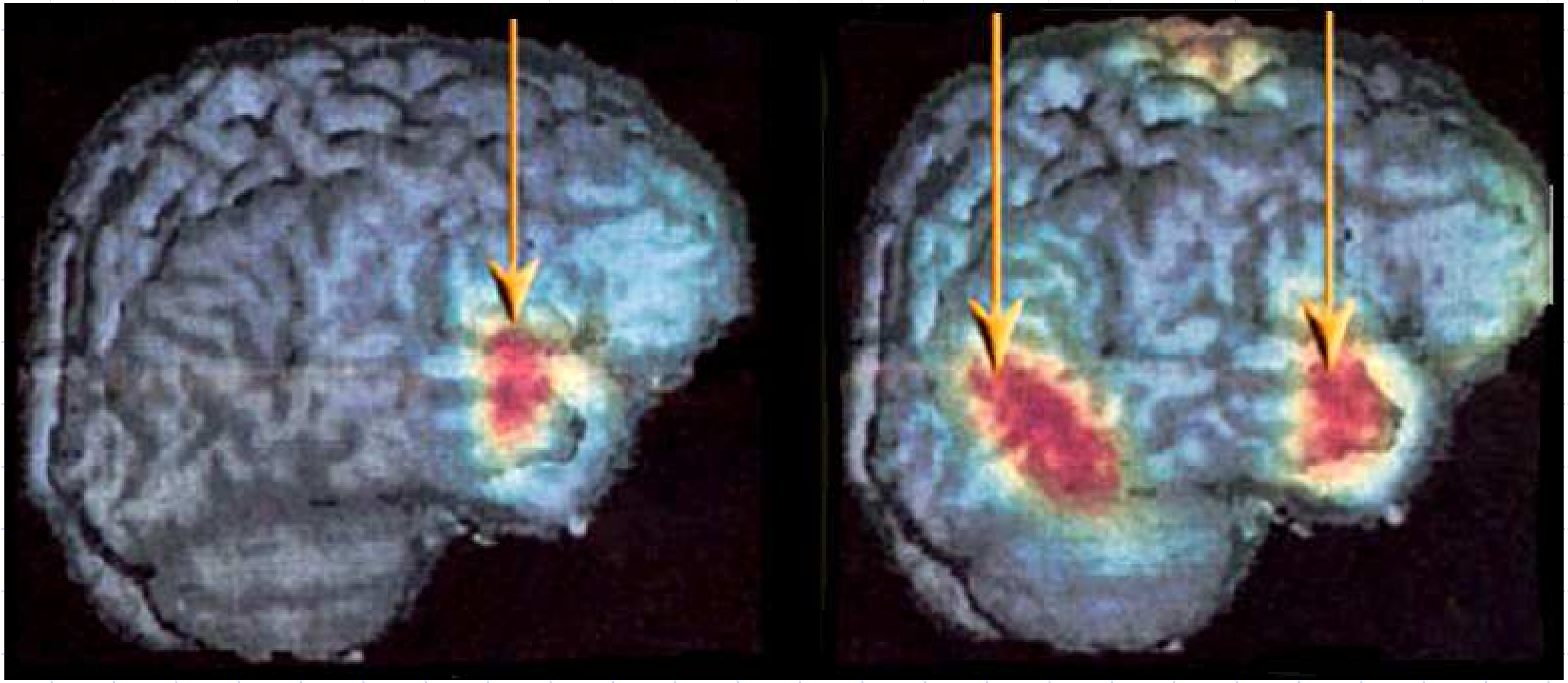
Exécution
de
mouvements de
la main droite

Observation
de ces
mouvements

M. Burgmer et al., neuroImage 2005

IRM FONCTIONNELLE

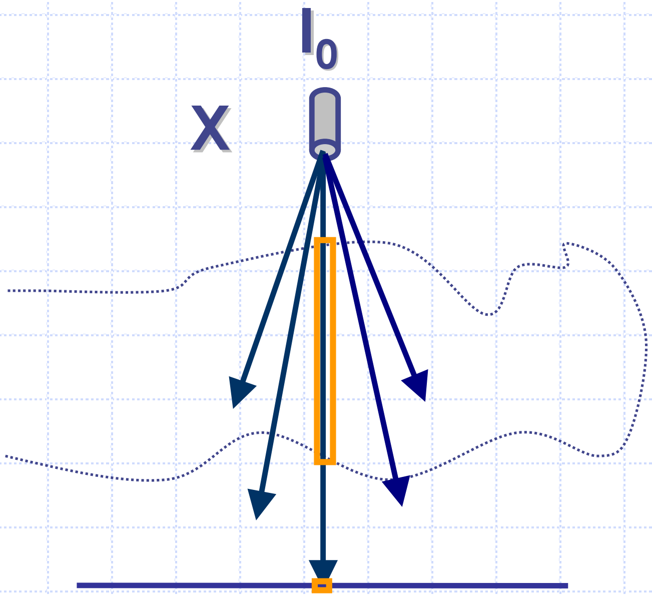
Cortex auditif Cortex visuel

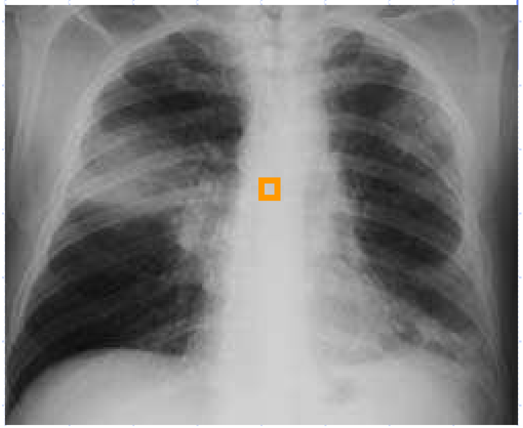


Sujet contrôle Aveugle de naissance

Kujala et al., 2000

Radiographie



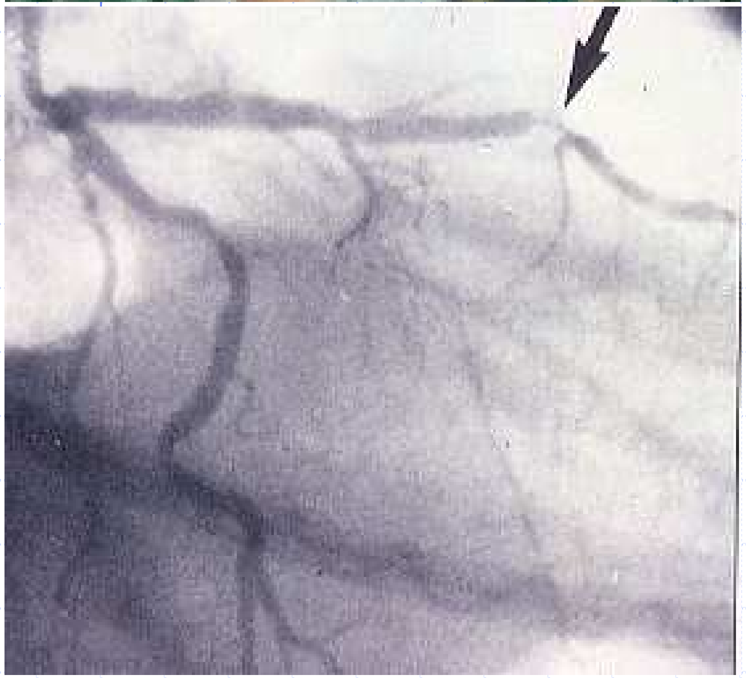


$$I = I_0\, e^{-\sum \mu_i x_i}$$

$$\mu_{PE} = -\frac{\frac{dI}{I}}{dx} \approx k\, \frac{Z^3}{E^3}\rho$$

$$x_i = x \Rightarrow p = -\frac{1}{x}\ln\left(\frac{I}{I_0}\right) = \sum \mu_i$$

Radiographie



Médecine nucléaire: principes

VECTEUR

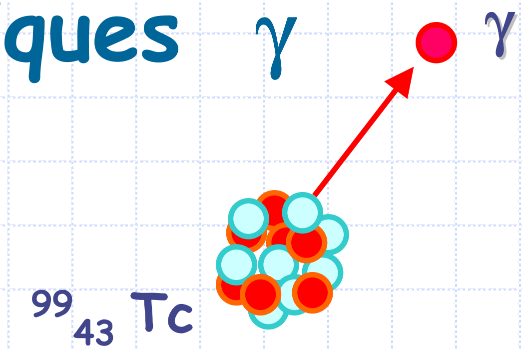
MARQUEUR

```
     O          O
     ||         ||
HO-P-CH2-P-OH
      |          |
      O        O
        \     /
     HO-Tc-OH
        /     \
       O     O
       |       |
HO-P-CH2-P-OH
       ||       ||
       O       O
```

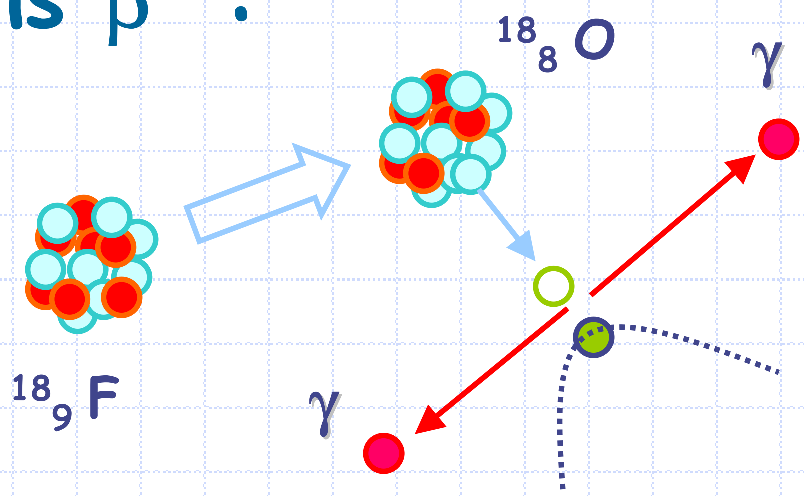
TRACEUR RADIOACTIF

Médecine nucléaire: marqueurs

- **Emetteurs de photons uniques** γ
  - Tc, (Xe, Kr, Ga, Tl, In ...)



- **Emetteurs de positons** β^+ **:**
  - F, (C, N, O,...)



Fabrication des isotopes

Séparation des produits de fission : ^{99}Tc, ^{131}I, ^{133}Xe

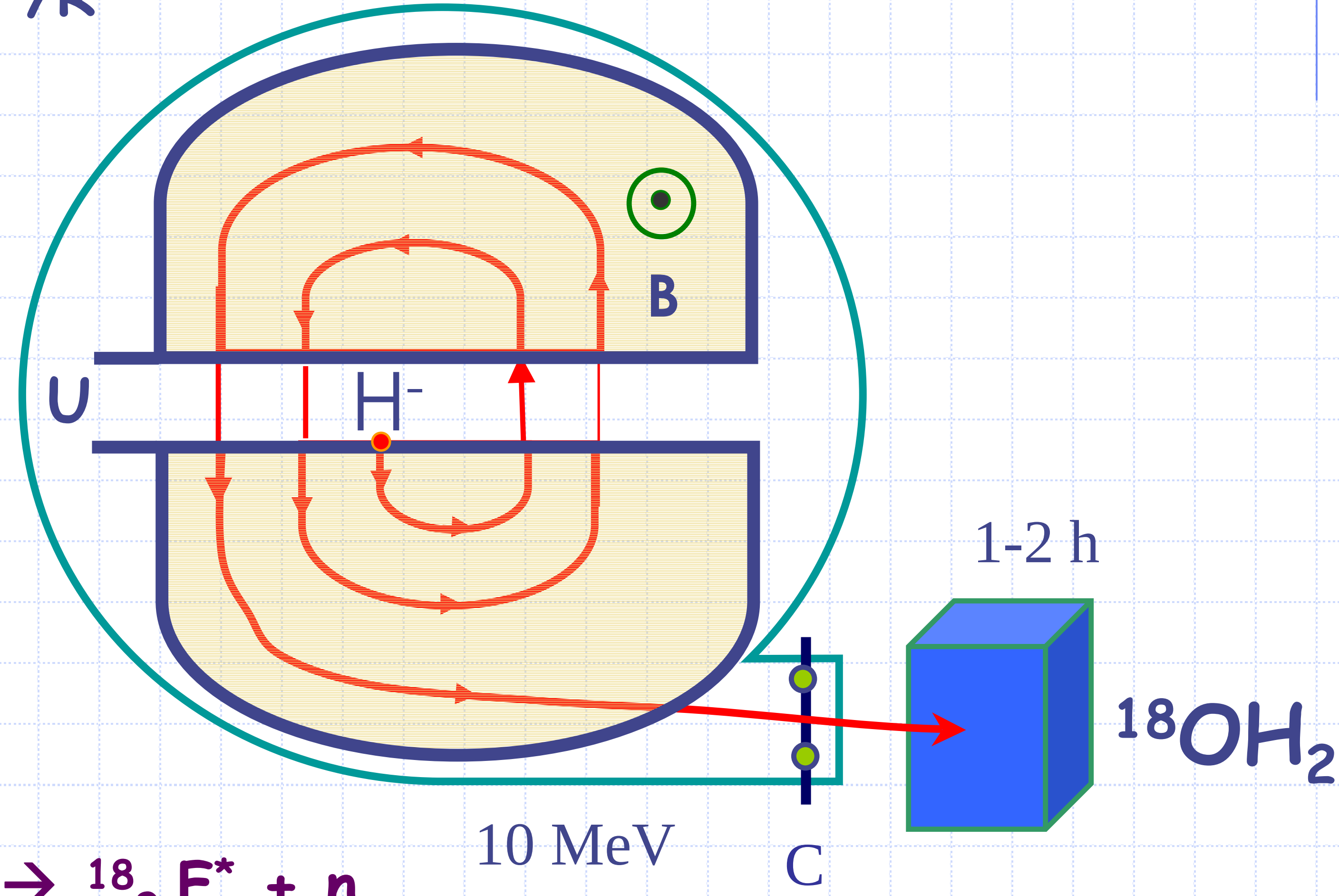
$^{235}_{92}U + n_{th} \rightarrow {}^{99}_{40}Zr \rightarrow {}^{99}_{41}Nb \rightarrow {}^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc$

Bombardement particulaire : ^{18}F, ^{201}Tl, ^{123}I, ^{111}In, ^{67}Ga

CYCLOTRON : Exemple du $^{18}_{9}F$

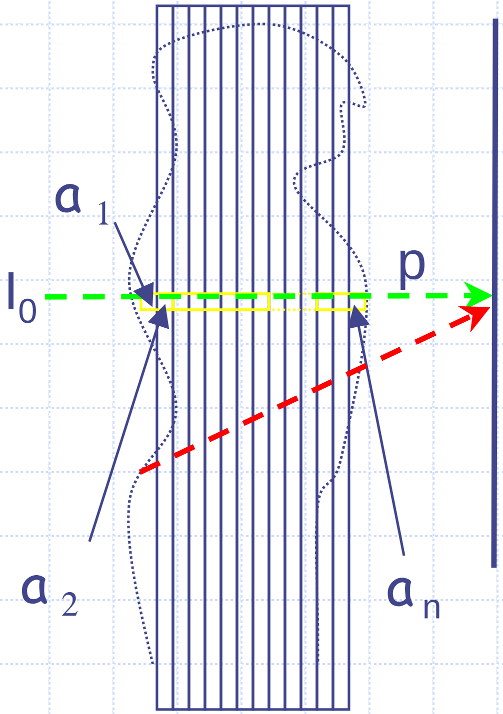
Le cyclotron (E Lawrence 1930)

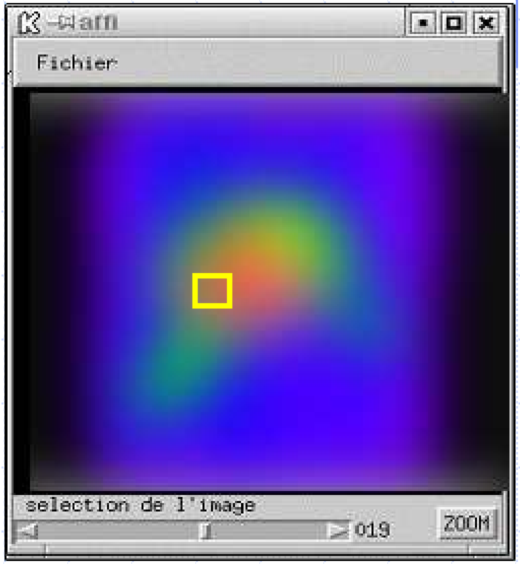
$evB = mv^2/R$

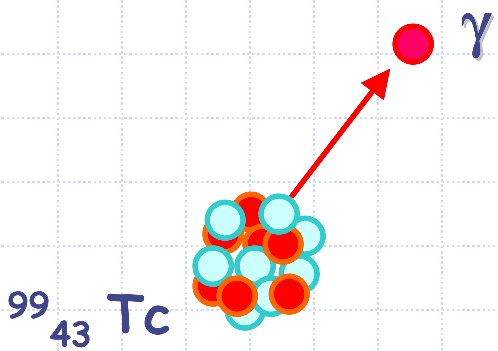


$^{18}_{8}O + p \rightarrow ^{18}_{9}F^* + n$

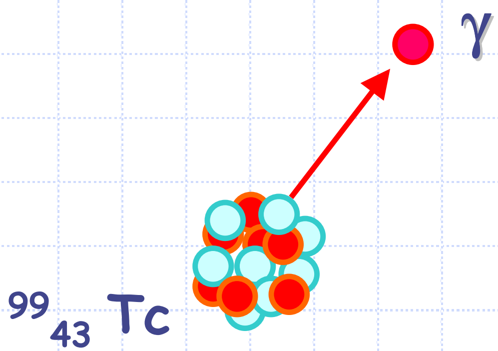
Scintigraphie d'émission mono- photonique γ

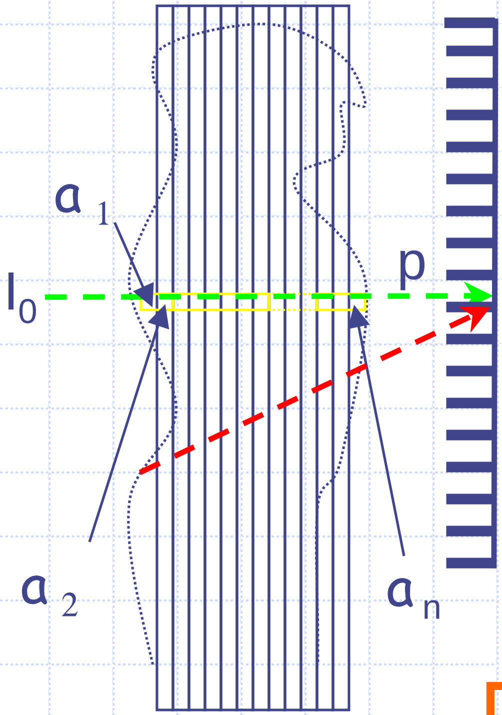


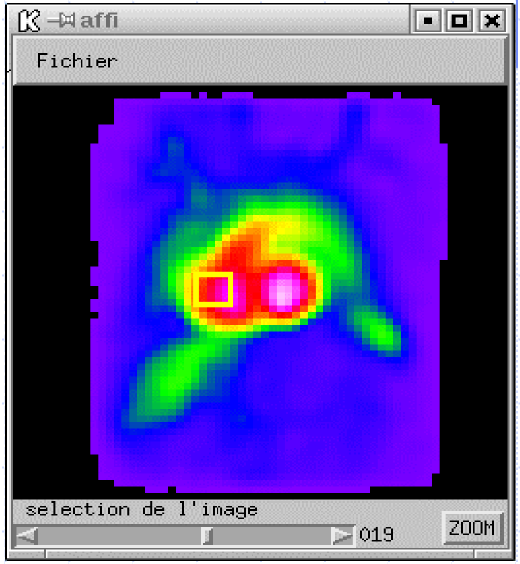




Scintigraphie d'émission mono- photonique γ

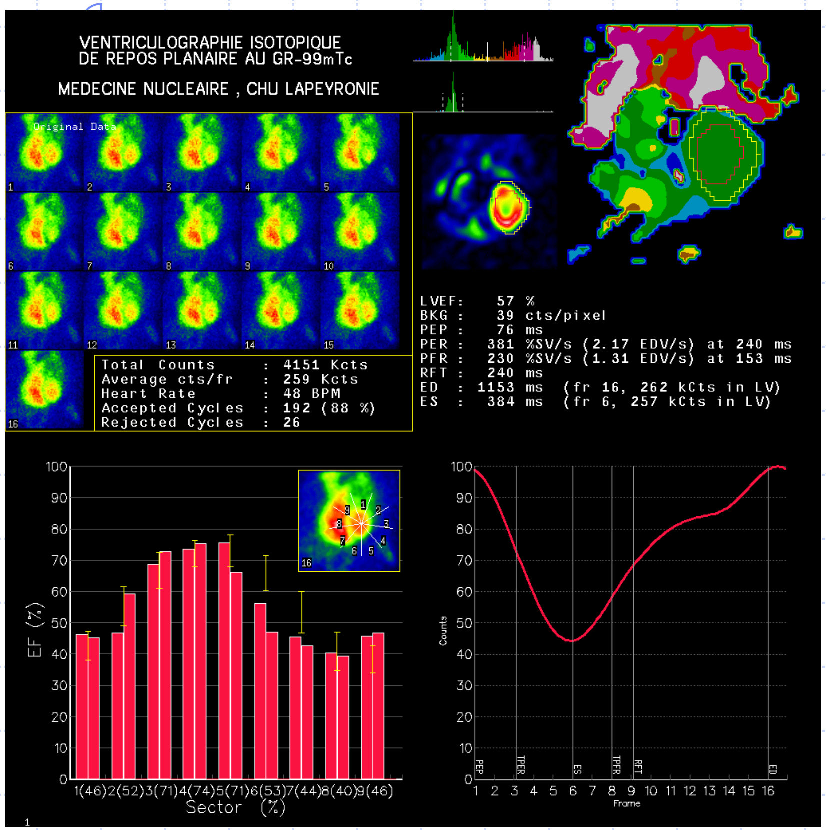






$$p = a_1 + a_2 + \ldots + a_n$$

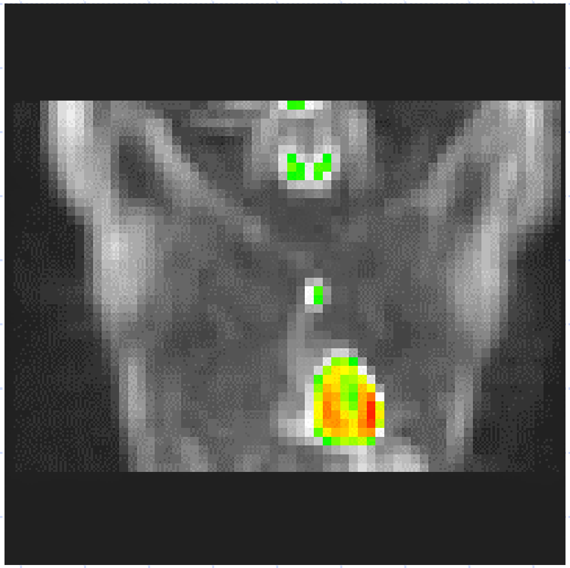
Exemples de scintigraphies γ



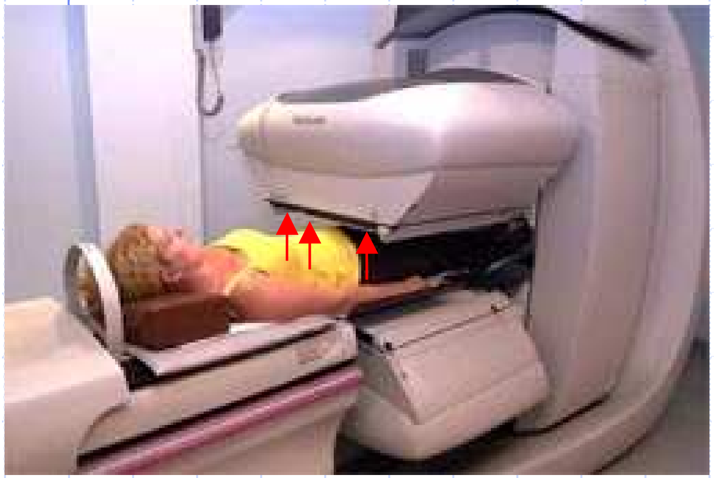
Hématies-Tc

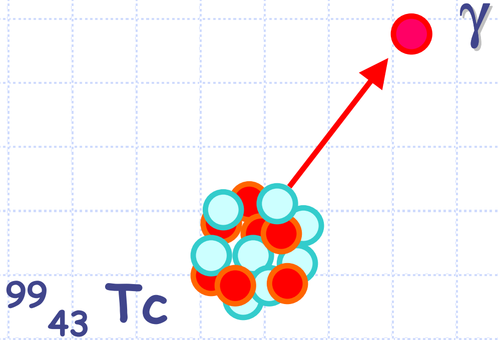
Diphosphonate-Tc

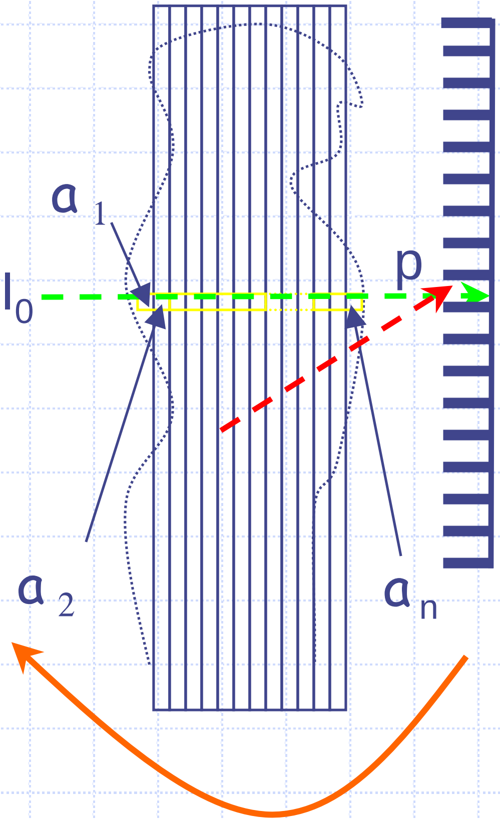
MIBI-Tc



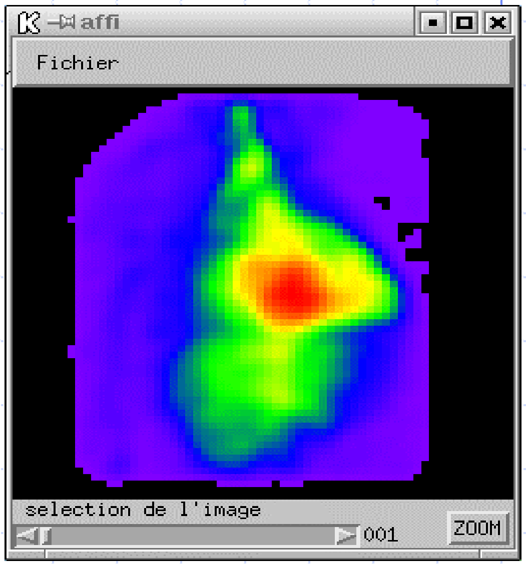
Tomo-scintigraphie par EMP γ

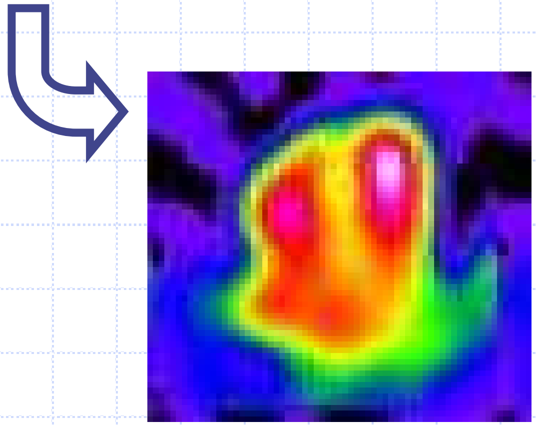




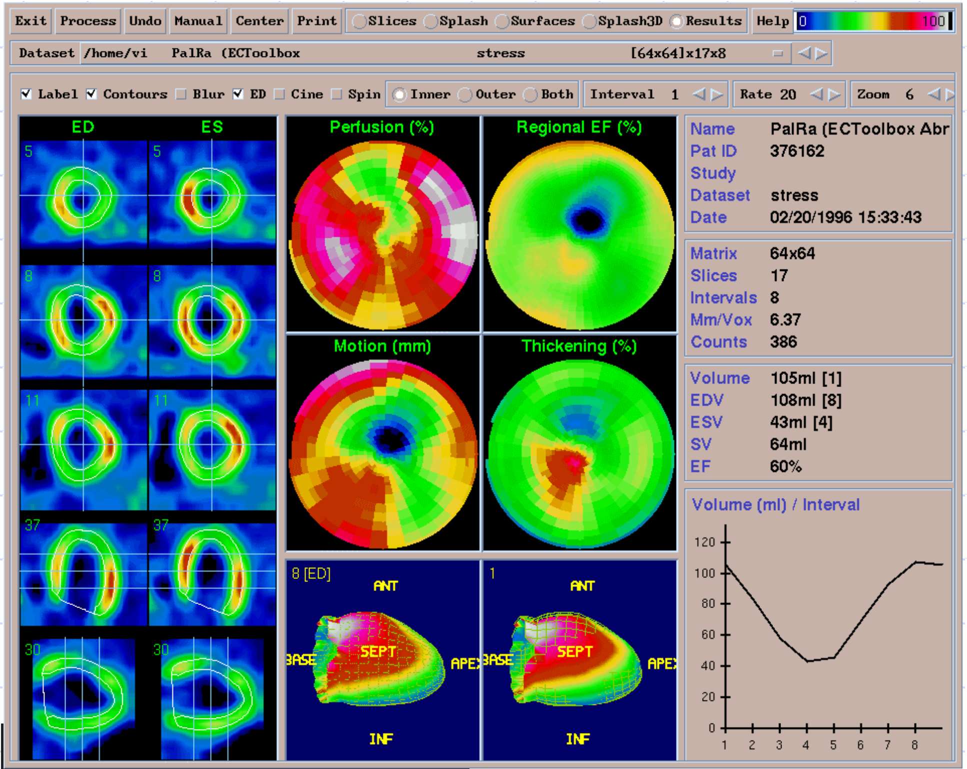


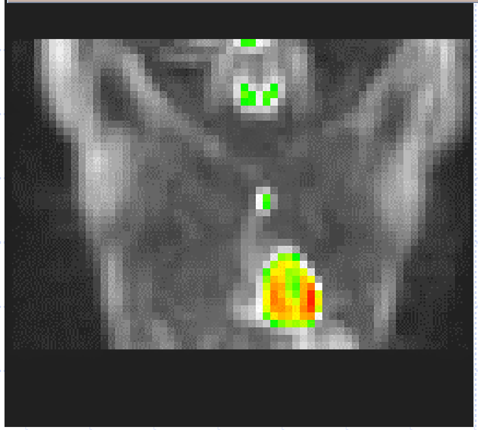
$$p^j = \sum R_i^j a_i$$



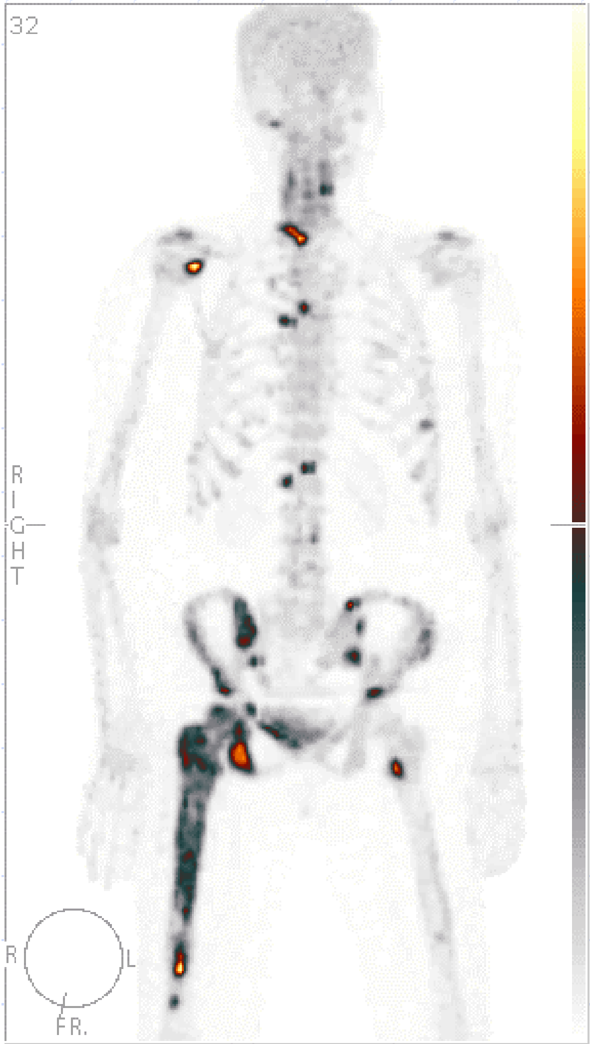


Exemples de scintigraphies γ



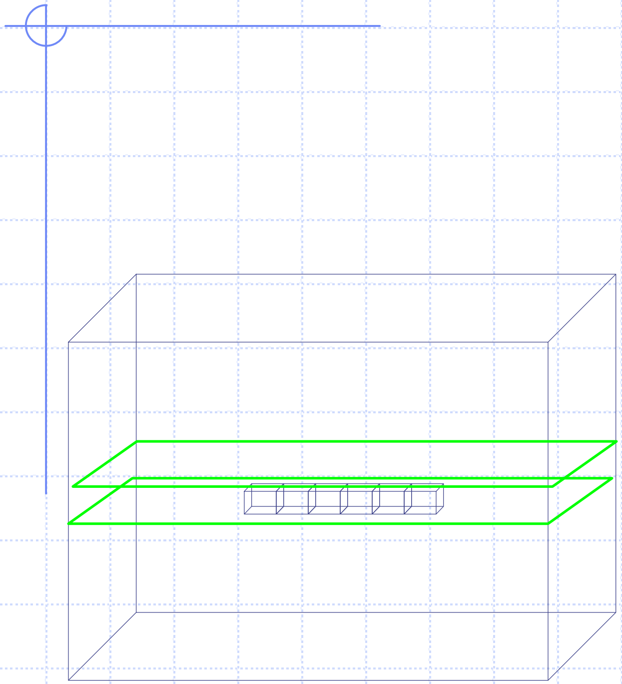


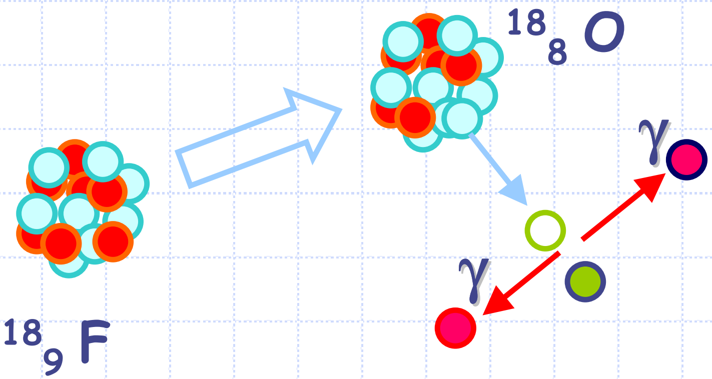
Cations lipophiles-Tc

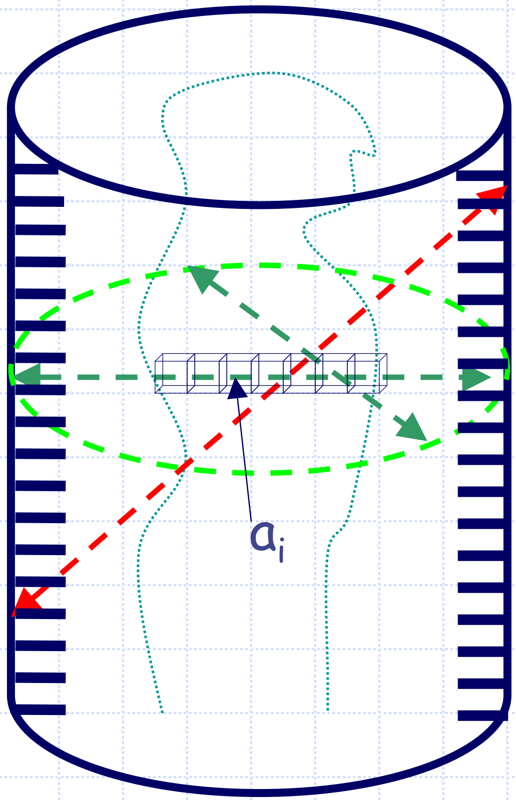


Diphosphonate-Tc

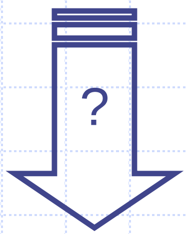
Tomographie en coïncidence 2D

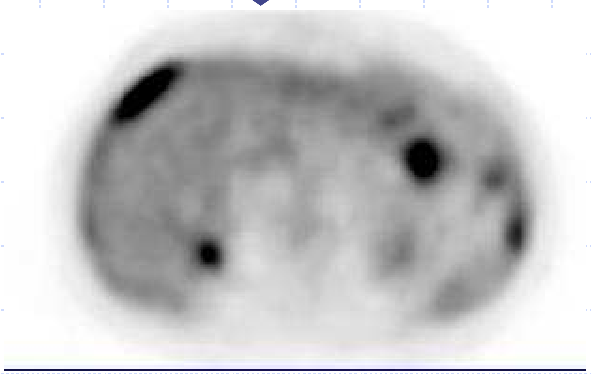




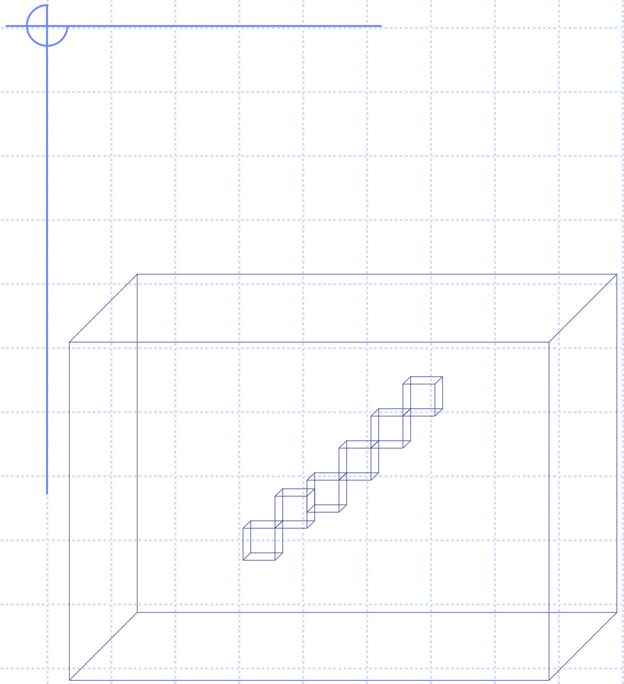


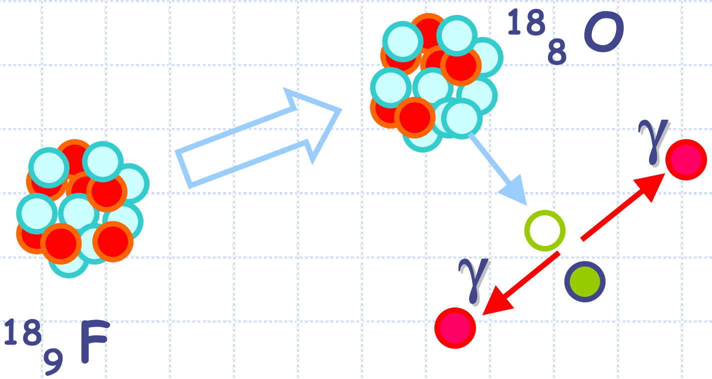
$$p = \sum R_i a_i$$

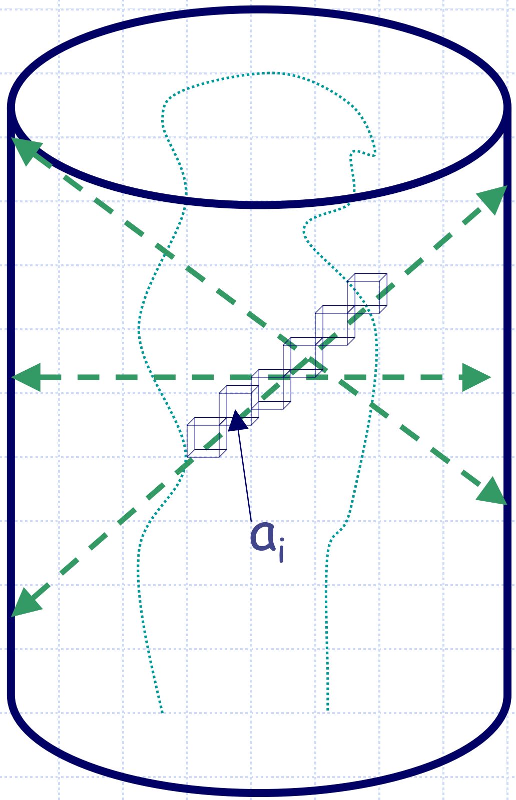




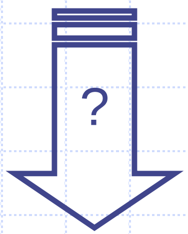
Tomographie en coïncidence 3D

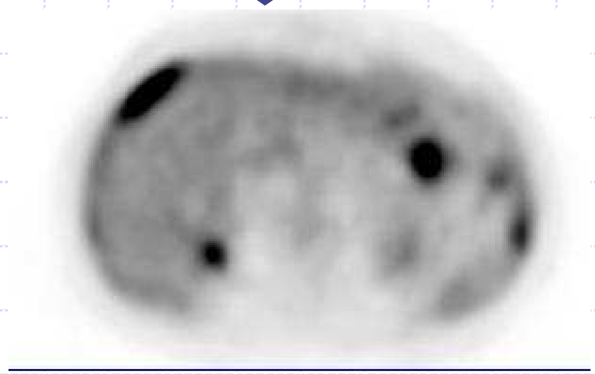






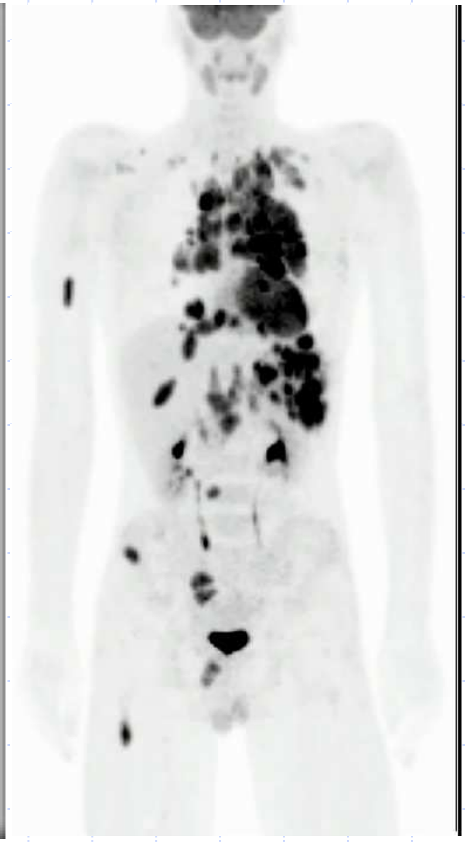
$$p = \sum R_i a_i$$



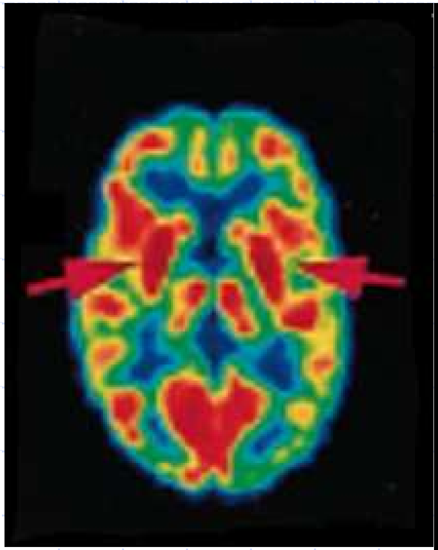


Exemples de TEP

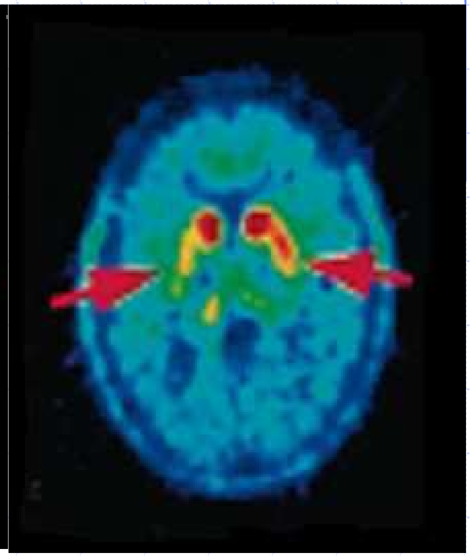
^{18}F Na



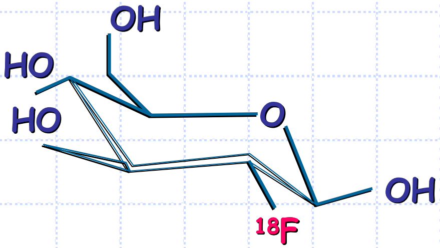
^{18}F DG



Métabolisme
^{18}F DG



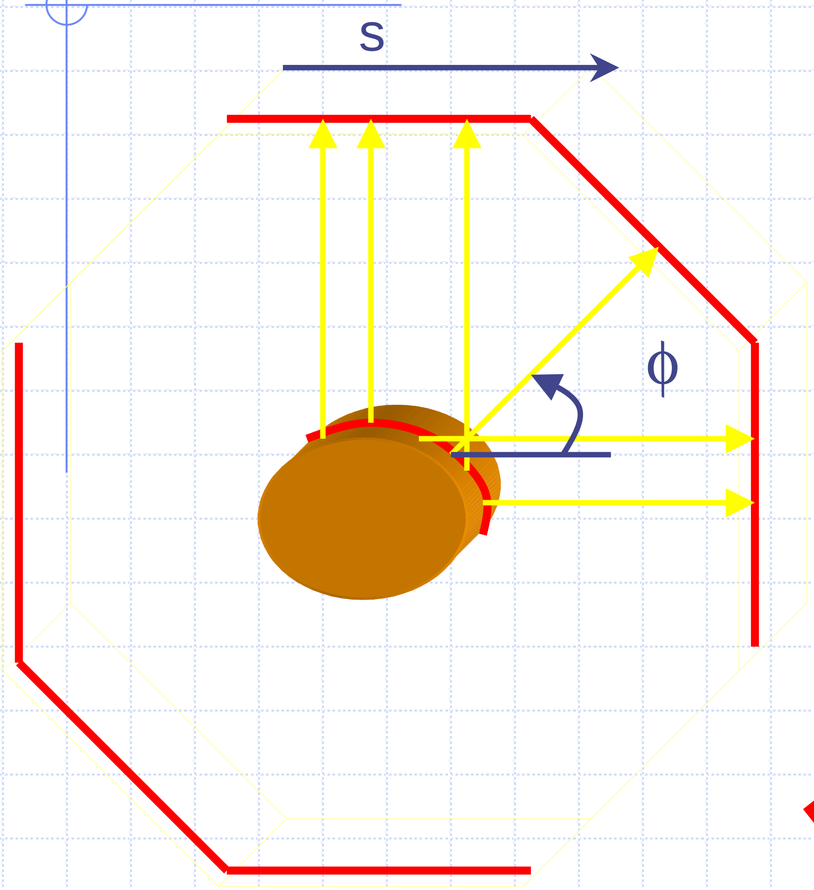
^{18}F DOPA, voie
Pré-synaptique

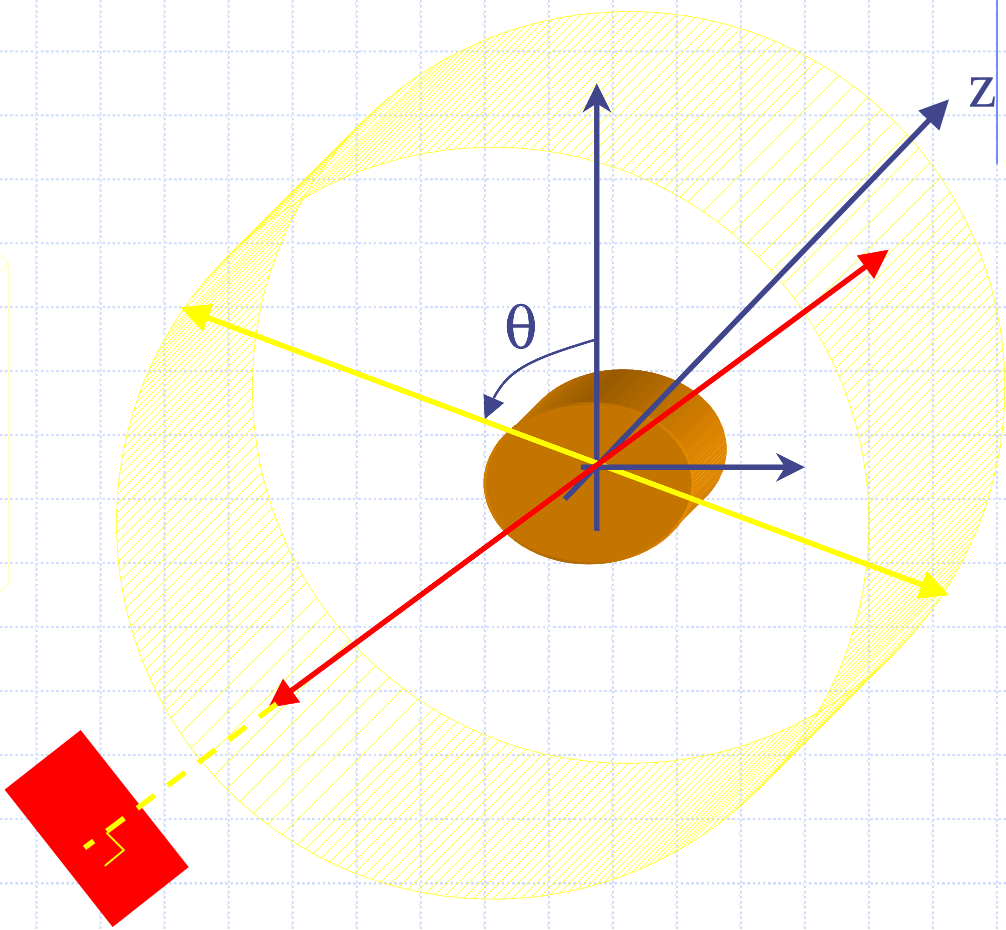


Perte
fonction
DaT
Putamen D

Reconstruction tomographique

Tomographie 2D et 3D



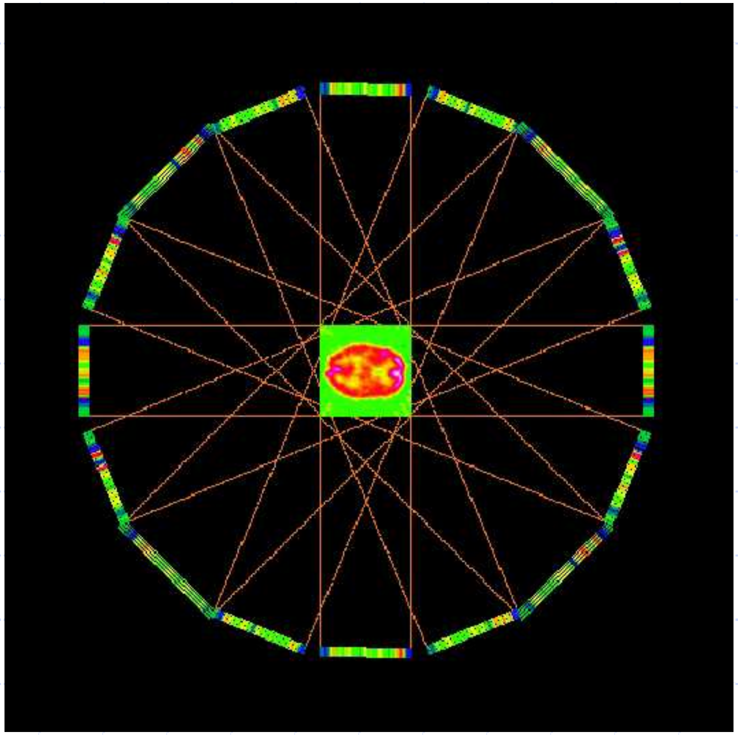


$p(s,\phi)$: lignes

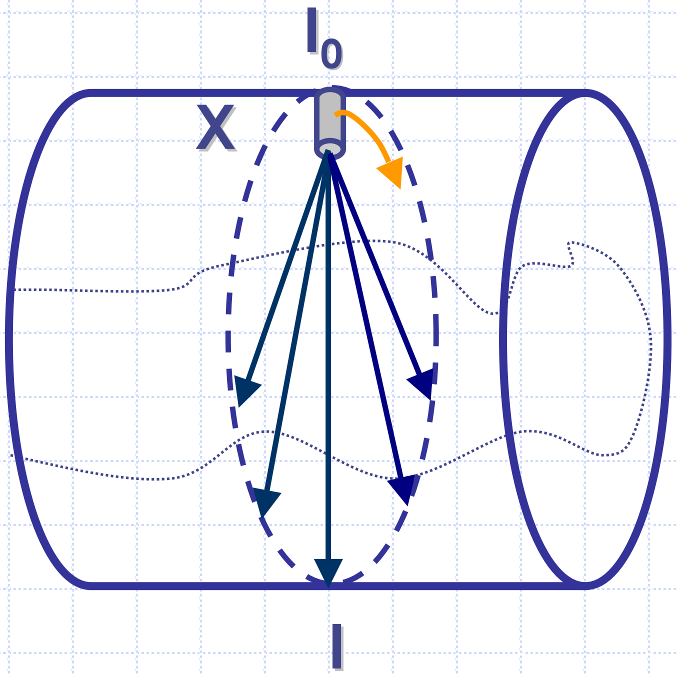
$p(s,\phi,z,\theta)$: plans

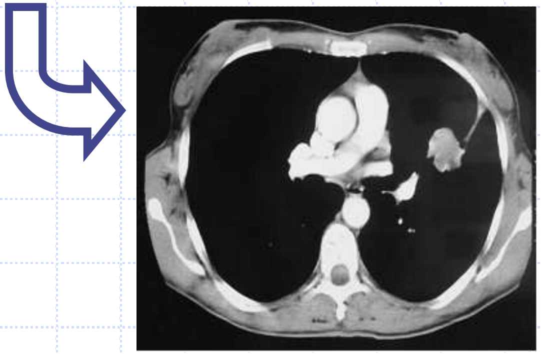
Tomographique 2D

- Modélisations analytique et algébrique
- Théorème de Radon
- Rétroprojection filtrée
- Algorithmes itératifs
- Régularisation



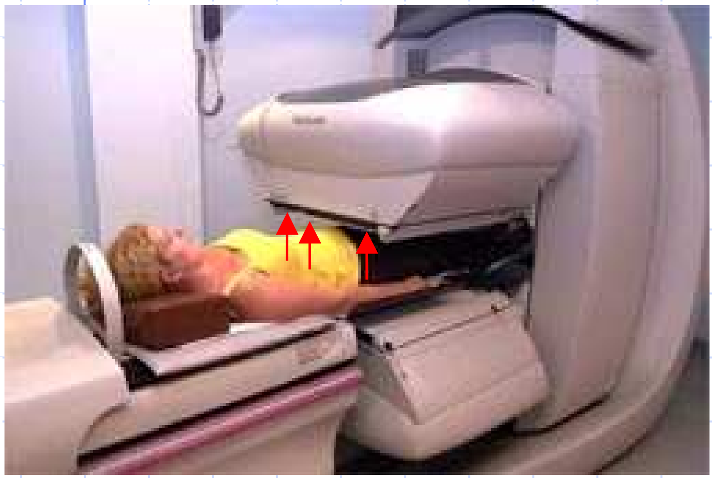
Tomodensitométrie (scanner X)

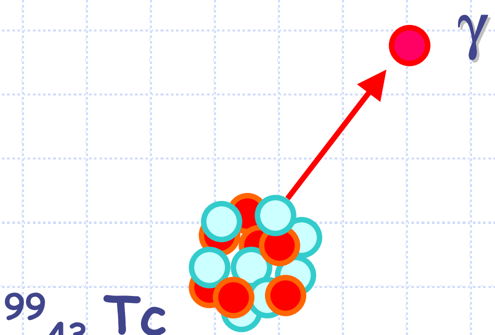


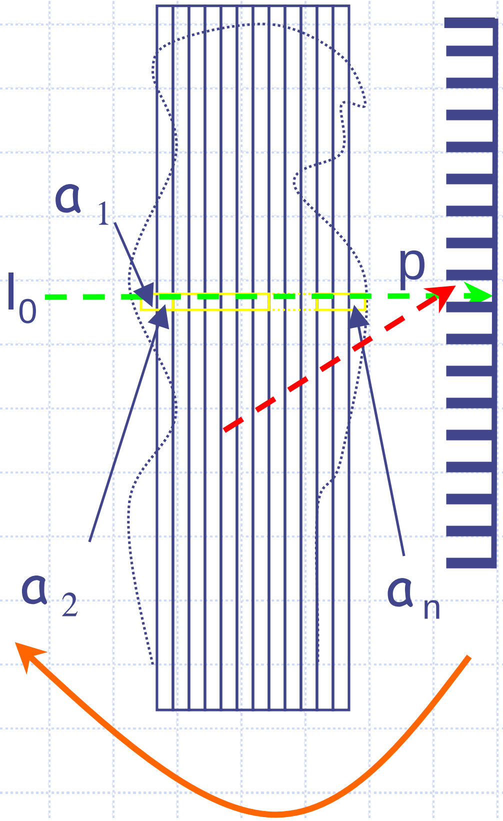


$$p = \mu_1 + \mu_2 + \ldots + \mu_n$$

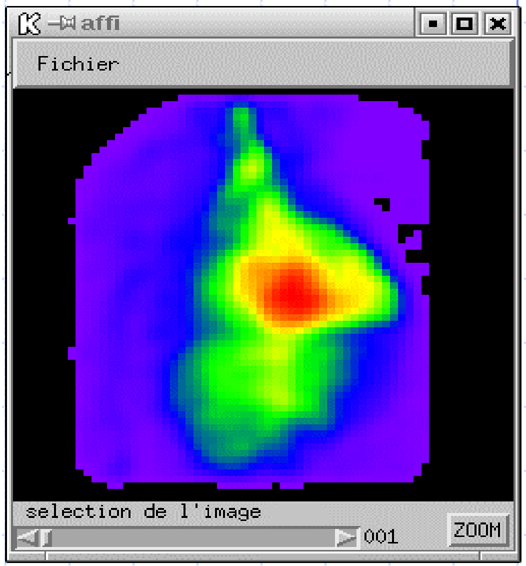
Scintigraphie d'émission mono- photonique γ

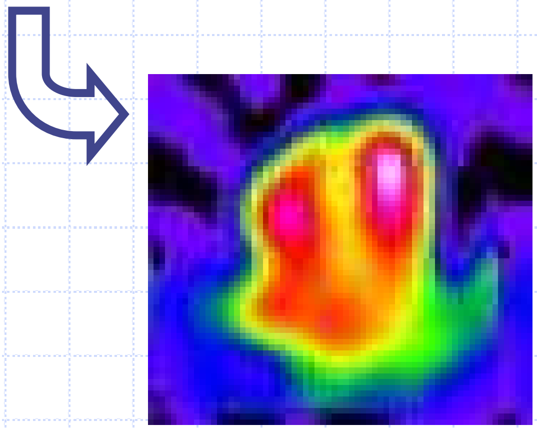




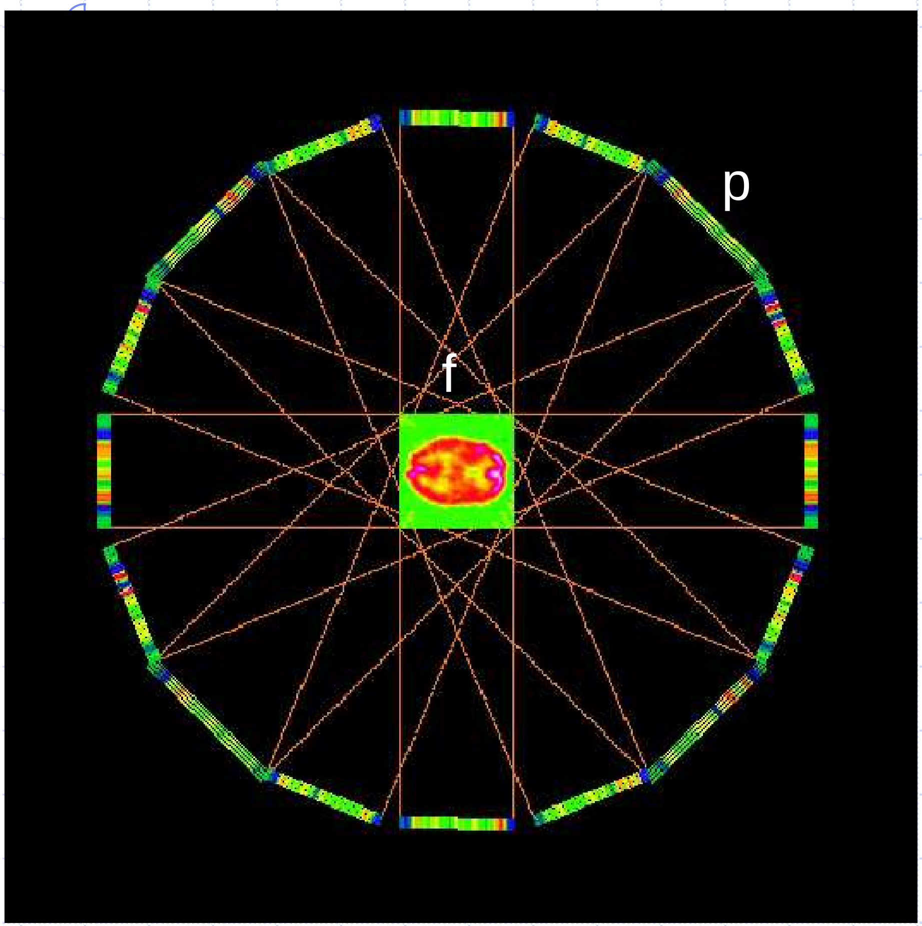


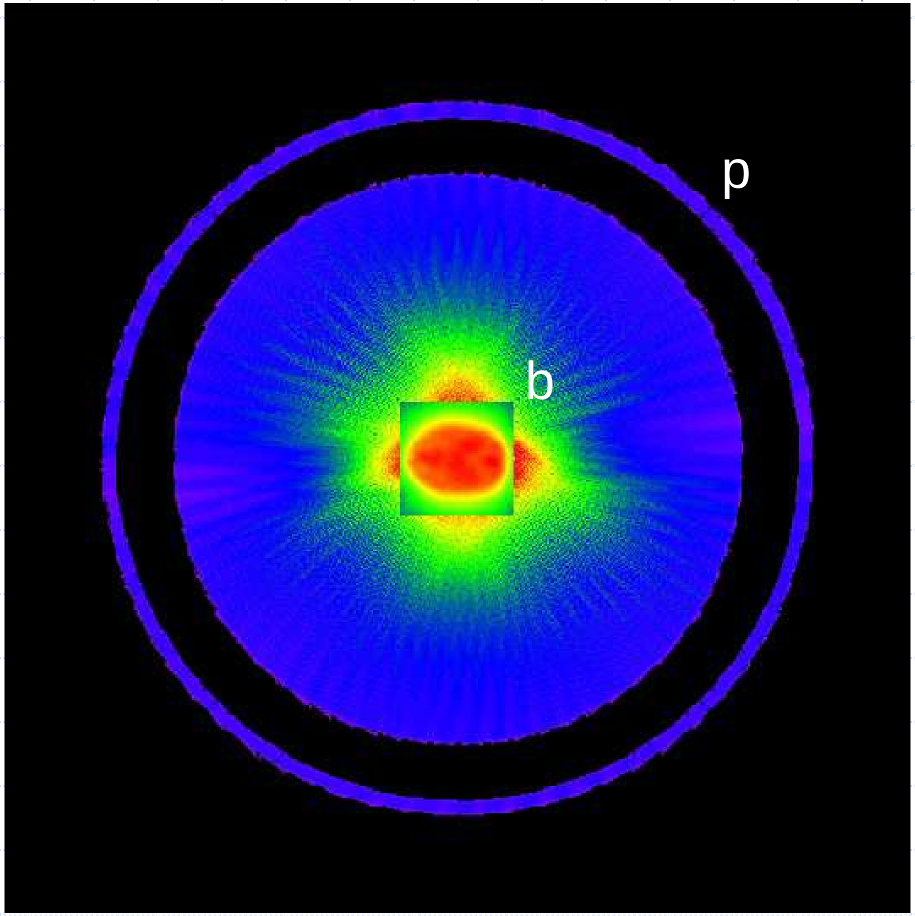
$$p = a_1 + a_2 + \ldots + a_n$$





Projection / Rétroprojection

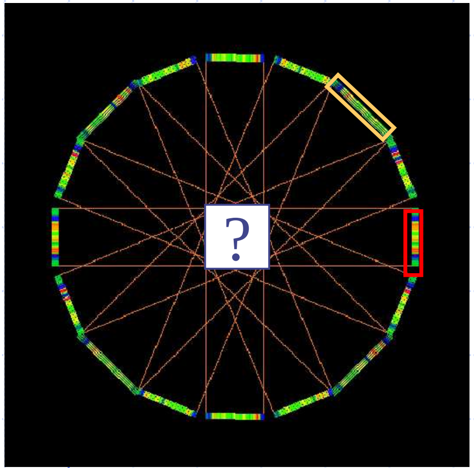




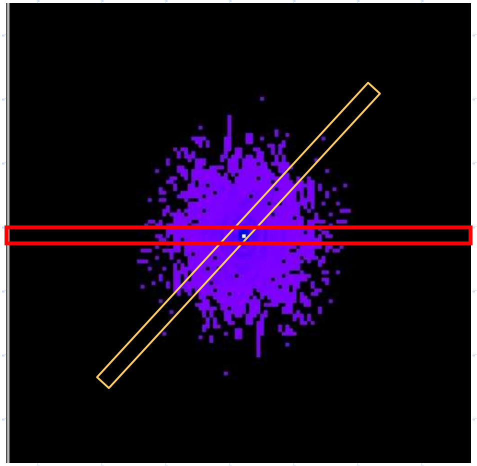
$$R.\vec{f} = \vec{p}$$

$$^{t}R.\vec{p} = \vec{b}$$

Interprétation (I)



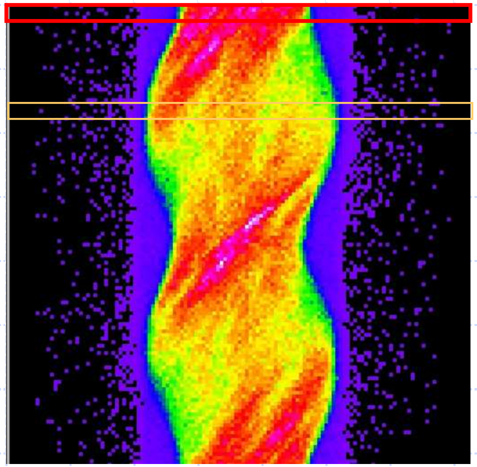
$$\hat{p}_{\vec{\theta}}(\sigma) = \hat{f}\left(\sigma.\vec{\theta}\right)$$

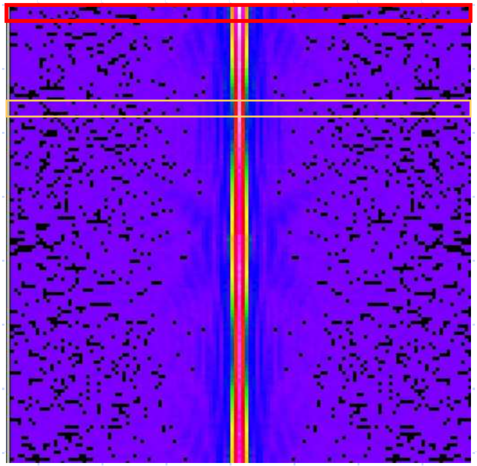


f ⟺ TF ⟺ $\hat{f}$

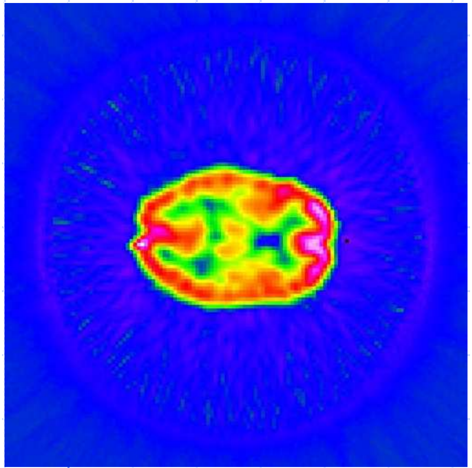
R ⇕ ‖ ⇕

$p_{\vec{\theta}}(s)$ ⟺ TF ⟺ $\hat{p}_{\vec{\theta}}(\sigma)$

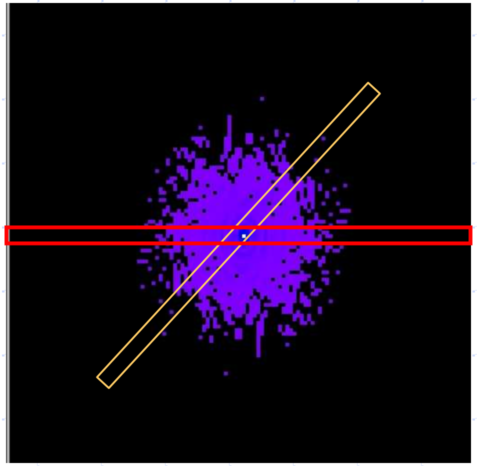




Interprétation (I)



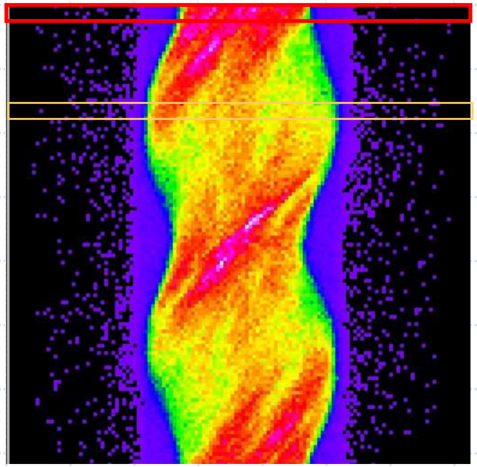
$$\hat{p}_{\vec{\theta}}(\sigma) = \hat{f}\left(\sigma.\vec{\theta}\right)$$

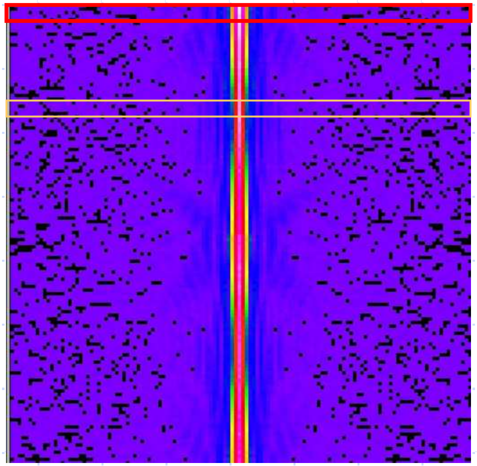


f ⟺ TF ⟺ $\hat{f}$

⇕ R ⇕ ||

$p_{\vec{\theta}}(s)$ ⟺ TF ⟺ $\hat{p}_{\vec{\theta}}(\sigma)$

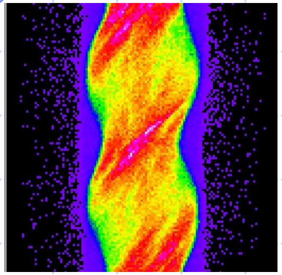




Rétroprojection filtrée (III)

$$f(i,j) = (R^* p')(i,j)$$

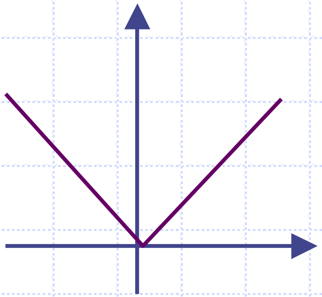
Projections sur 180°



$p_{\vec{\theta}}$

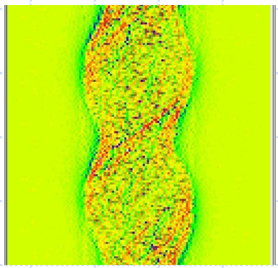
↓

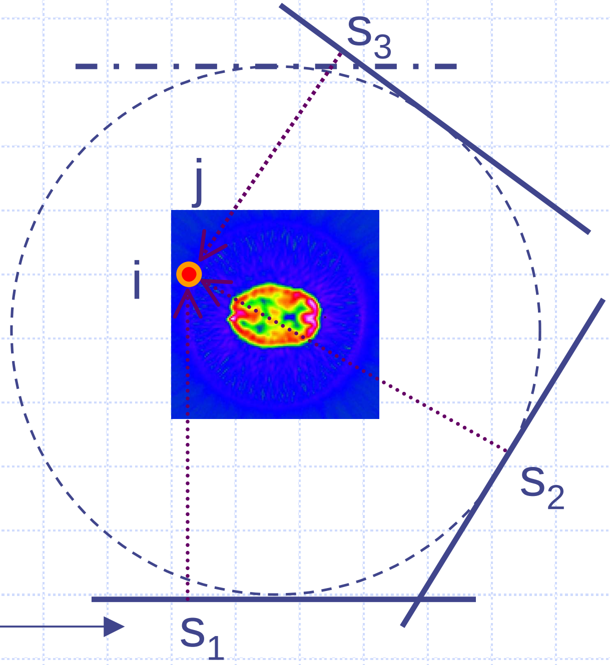
$\hat{p}_{\vec{\theta}}$ abs



x

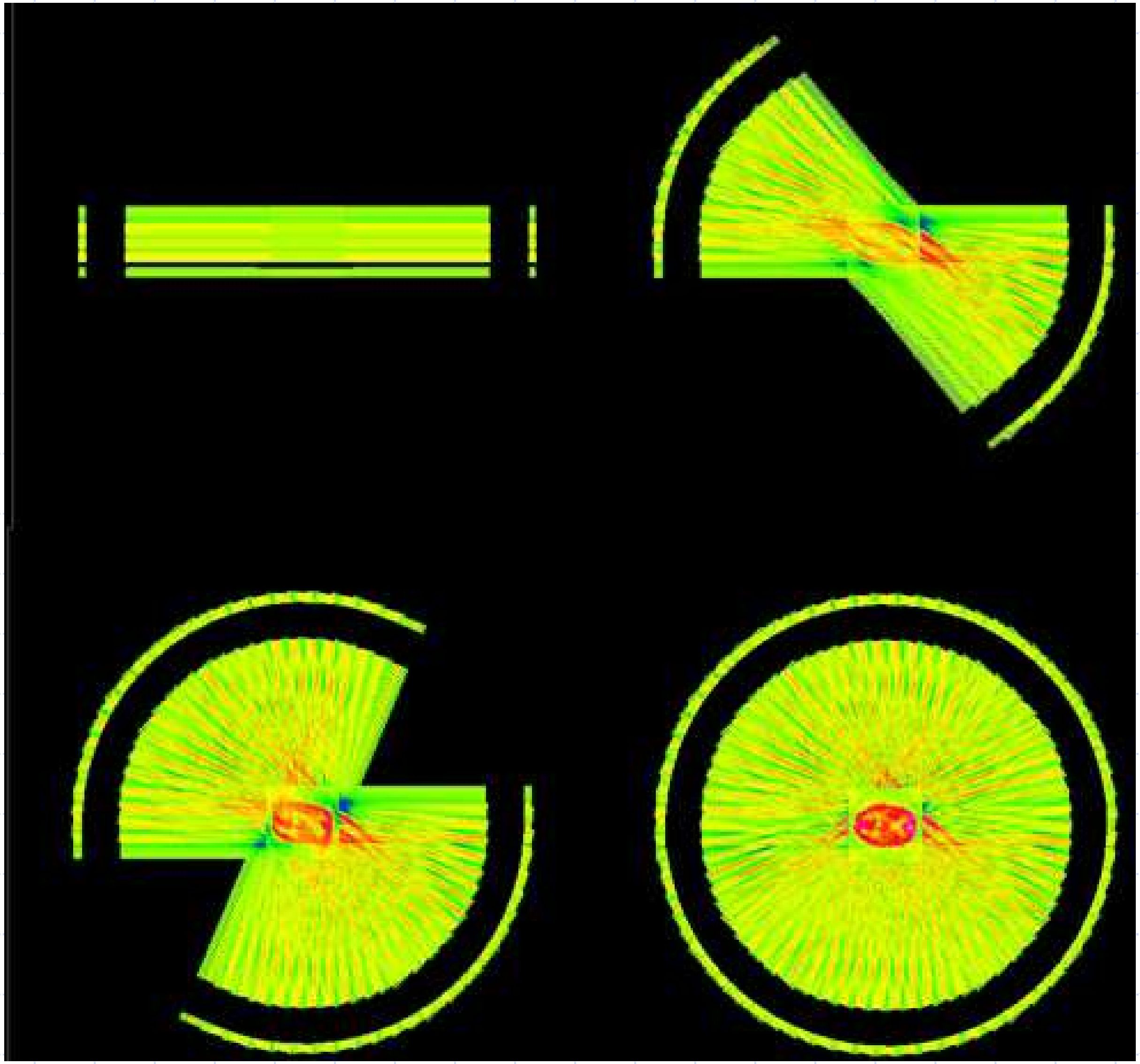
$$TF_s^{-1}\left[\hat{p}_{\vec{\theta}} \,.\, abs\right] = p'_{\vec{\theta}}$$



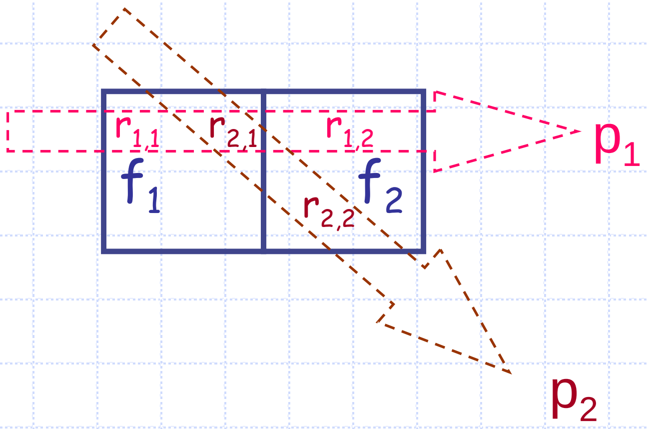


s = i.cosθ + j.sinθ

Rétro-Projection Filtrée

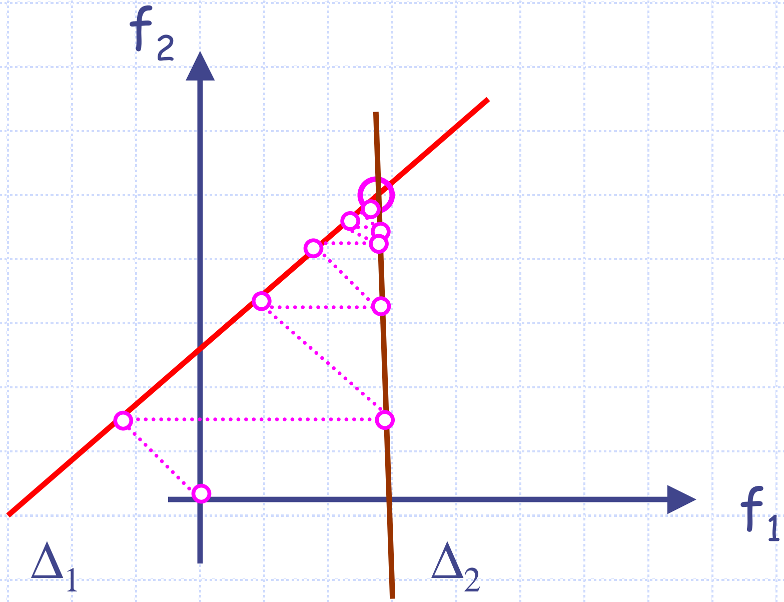


Algorithmes itératifs (ART)



$$\begin{cases} \Delta_1 & p_1 = r_{1,1} f_1 + r_{1,2} f_2 \\ \Delta_2 & p_2 = r_{2,1} f_1 + r_{2,2} f_2 \end{cases}$$

Kaczmarz



Algorithmes itératifs (ART)

$$\begin{cases} \vec{f}^{\,n+1} = \vec{f}^{\,n} + d \dfrac{\vec{\omega}_1}{\|\vec{\omega}_1\|} \\ d = \dfrac{p_1 - \langle \vec{f}^{\,n}, \vec{\omega}_1 \rangle}{\|\vec{\omega}_1\|} \end{cases}$$

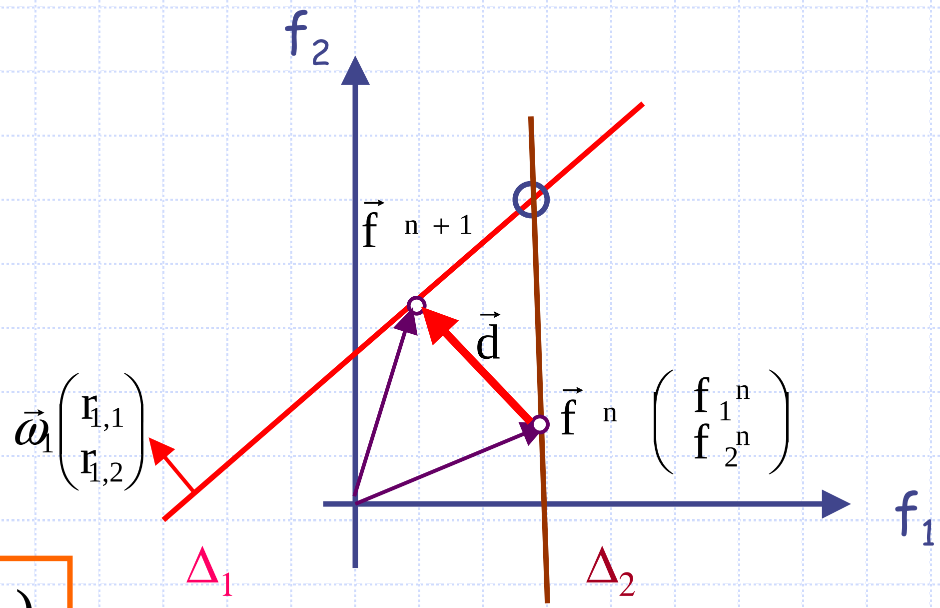
Δ_1 $p_1 = r_{1,1} f_1 + r_{1,2} f_2$

Δ_2 $p_2 = r_{2,1} f_1 + r_{2,2} f_2$

$$p_1^n = r_{1,1} f_1^n + r_{1,2} f_2^n$$

$$\vec{f}^{\,n+1} = \vec{f}^{\,n} + \frac{p_1 - p_1^n}{\|\vec{\omega}_1\|^2} \vec{\omega}_1$$

$$\vec{f}^{\,n+1} = \vec{f}^{\,n} + R * (p_1 - p_1^n)$$



ART

$$\vec{f}^{\,n+1} = \vec{f}^{\,n} + R * (p_1 - p_1^{n})$$

0	0	0	← 45 - 0 = 15 + 15 + 15
0	0	0	← 90 - 0 = 30 + 30 + 30
0	0	0	← 45 - 0
45	90	45	

15	15	15
30	30	30
15	15	15

	45	90	45
-	60	60	60
	-15	30	-15

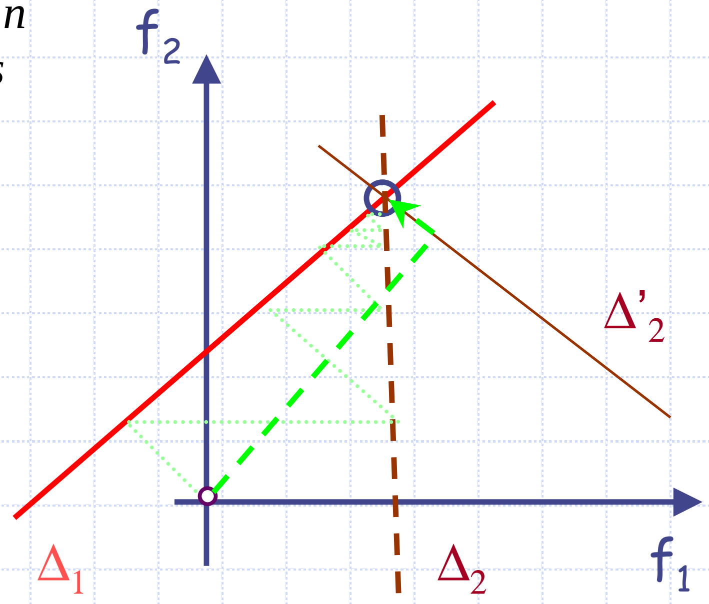
10	25	10
25	40	25
10	25	10

Méthodes Algébriques EM (I)

- Maximiser -log[Proba(p/f)]
- Bruit de Poisson sur p

$$f_i^{n+1} = f_i^n \cdot \frac{1}{\sum_{l'=1}^{P} r_{l',i}} \sum_{l=1}^{P} r_{l,i} \frac{p_l}{\sum_{s=1}^{N} r_{l,s} f_s^n}$$

$$\vec{f}^{\,n+1} = \vec{f}^{\,n} \cdot \frac{1}{\sum_{l'} r_{l',i}} R^* \left[\frac{p_l}{p_l^n} \right]$$



Méthodes Algébriques (II)

- Gradient conjugué :

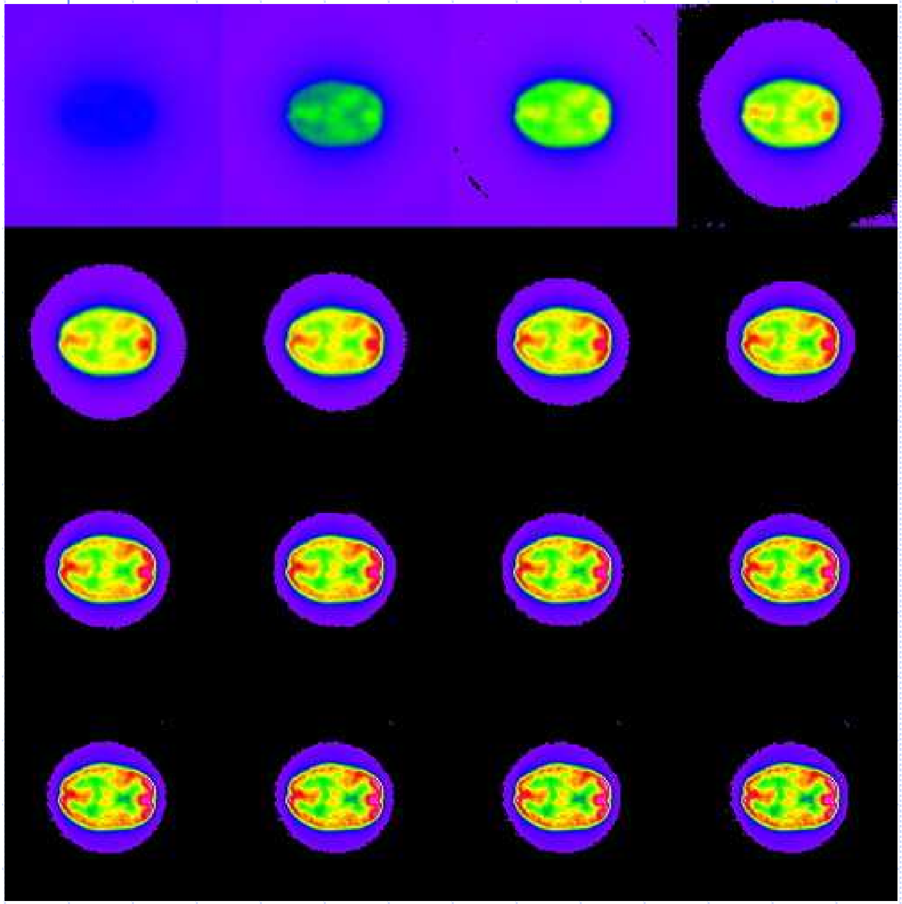
Minimiser $\chi^2(\vec{f}^{\,n}) = \left\| R\,\vec{f}^{\,n} - \vec{p} \right\|^2$

$$\vec{f}^{\,n+1} = \vec{f}^{\,n} + a_n \,.\, R^* (\vec{p} - R\,\vec{f}^{\,n})$$

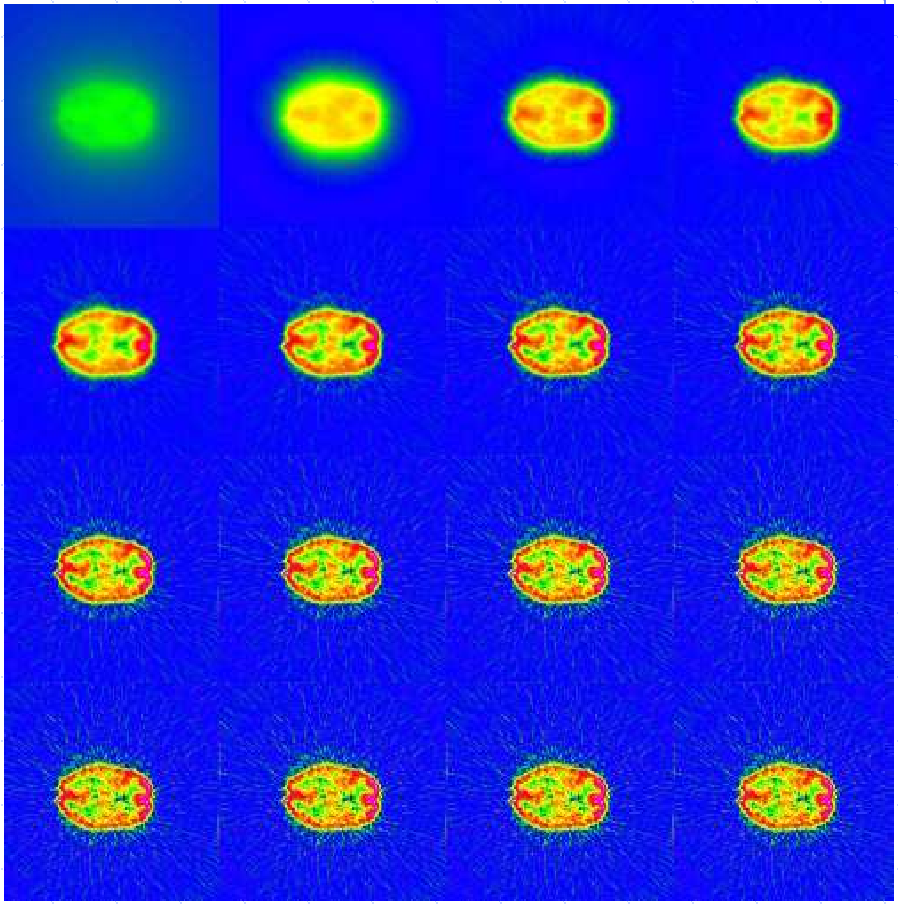
$$\vec{\nabla}\chi^2(\vec{f}^{\,n}) = R^*(\vec{p} - R\,\vec{f}^{\,n})$$

$$a_n = \frac{\left\| \vec{\nabla}\chi^2(\vec{f}^{\,n}) \right\|^2}{\left\langle \vec{\nabla}\chi^2(\vec{f}^{\,n}) \,,\, R.R^* (\vec{\nabla}\chi^2(\vec{f}^{\,n})) \right\rangle}$$

Les itérations

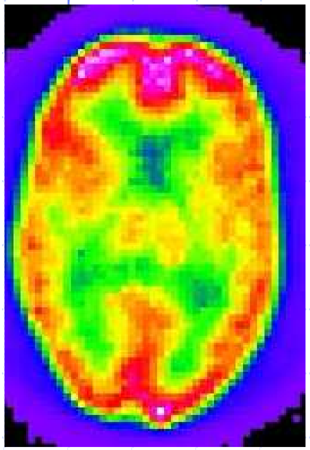


MLEM

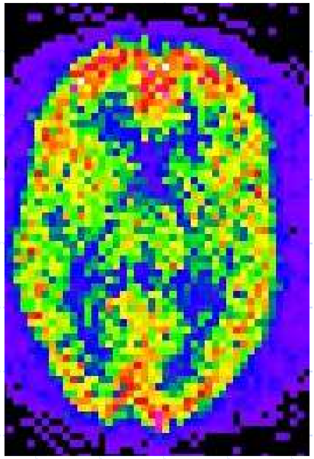


Gradient Conjugué

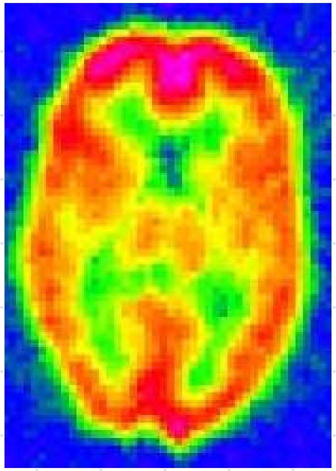
Comparaison des résultats



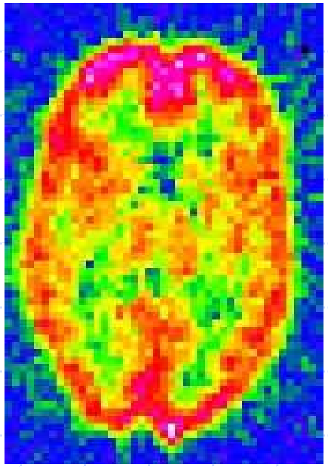
MLEM 6



MLEM 200

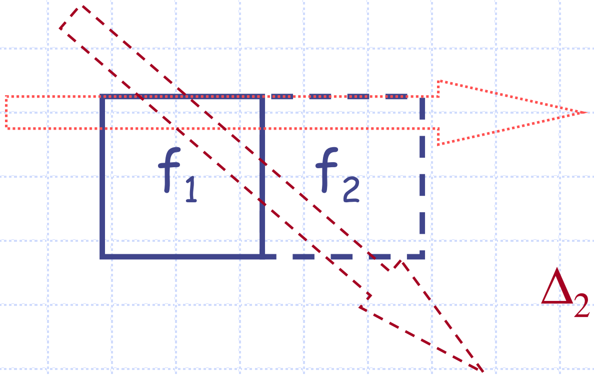


GC 6



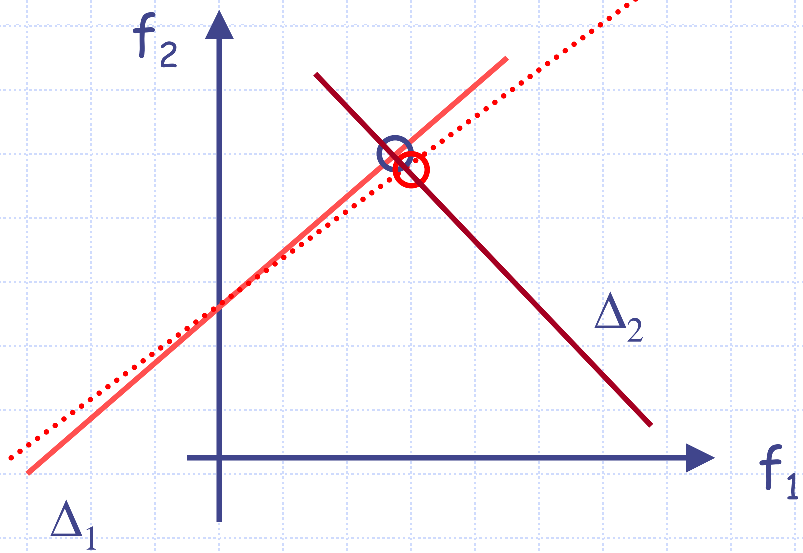
GC 16

Approche intuitive (I)

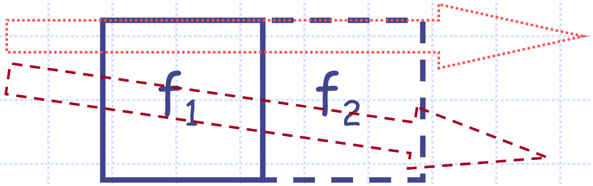


$\Delta_1 : p_1 = r_{1,1}\ f_1 + r_{1,2}\ f_2$

$\Delta_2 : p_2 = r_{2,1}\ f_1 + r_{2,2}\ f_2$

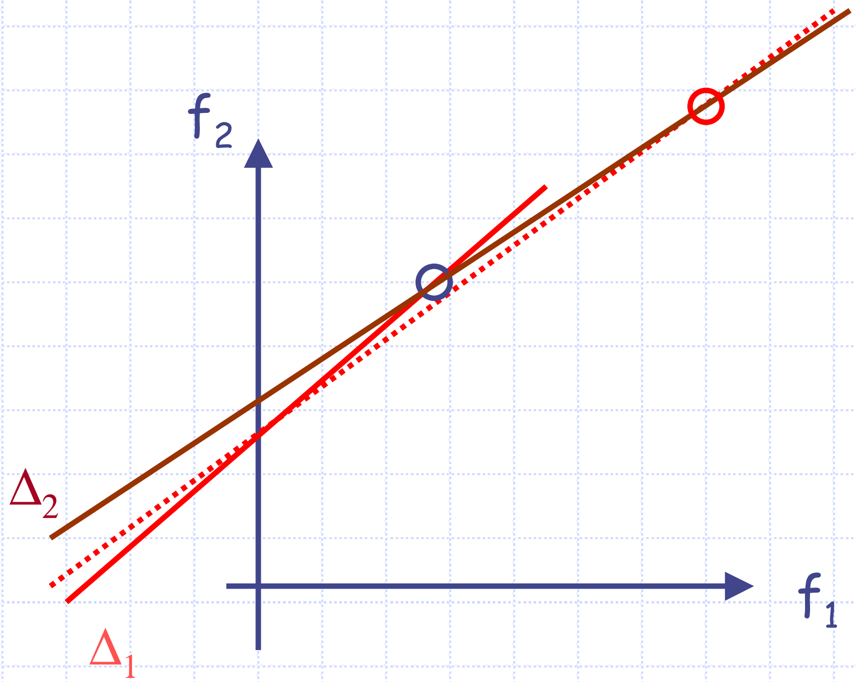


Approche intuitive (II)



$\Delta_1 : p_1 = r_{1,1}\, f_1 + r_{1,2}\, f_2$

$\Delta_2 : p_2 = r_{2,1}\, f_1 + r_{2,2}\, f_2$



$64^2 = 4\ 096$

$128^2 = 16\ 384$

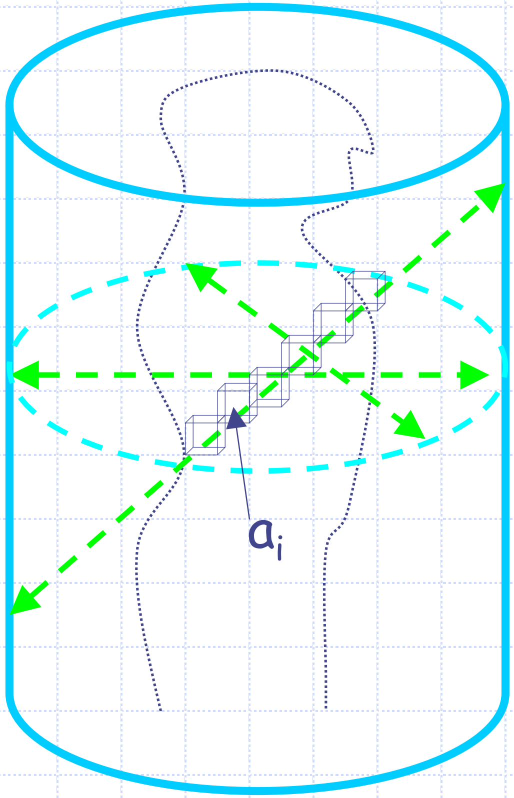
$256^2 = 65\ 536$

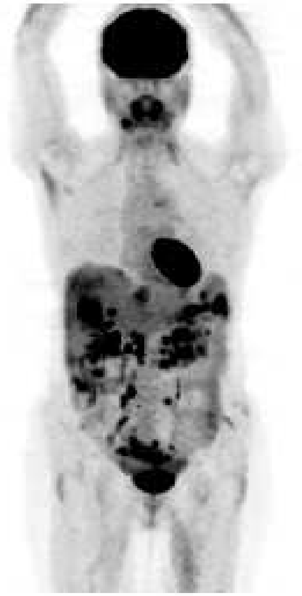
$512^2 = 262\ 144$

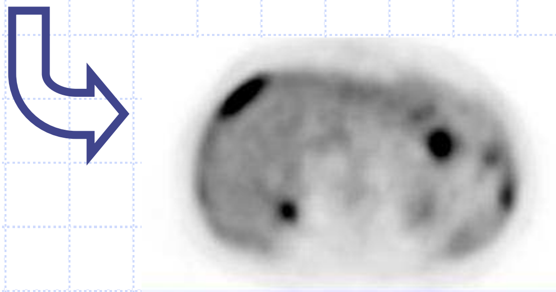
Reconstruction tomographique 3D

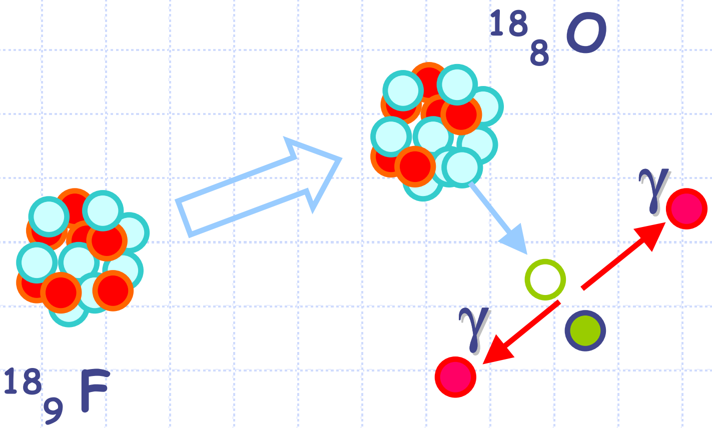
- Condition d’Orlov et projections tronquées
- Théorème de Radon 3D et RPF 3D
- Algorithmes de ré-arrangement

Tomographie en coïncidence 3D









$$p = a_1 + a_2 + \ldots + a_n$$

Tomographie 3D

- Emission radioactive : aléatoire
- Loi binomiale → Loi de poisson
- Rapport signal sur bruit :

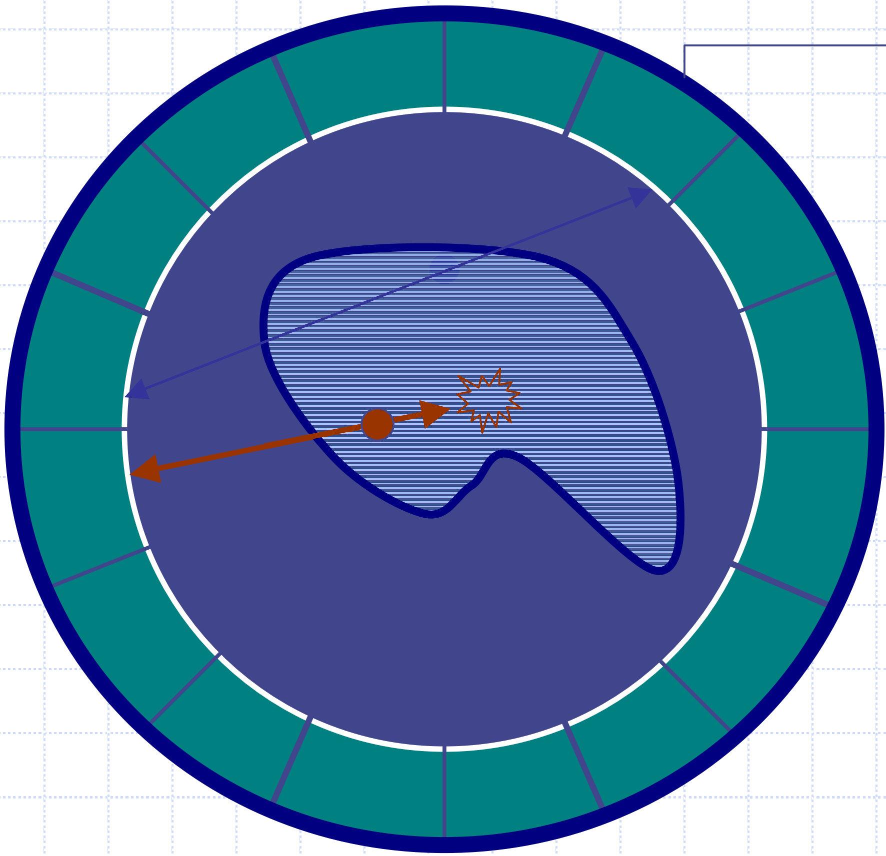
↳ Exploiter les projections obliques (redondantes)

Reconstruction en TEP

- **Reconstruction 2D de données 2D (septa)**
  - Faible statistique de comptage
- **Réarrangement 2D de données 3D**
  - Algorithmes de «rebinning » (single, multi, FORE)
  - S/B ↗ mais approximation
- **Reconstruction 3D de données 3D**
  - S/B ↗ mais temps de calcul ↗↗
  - Techniques analytiques ou algébriques

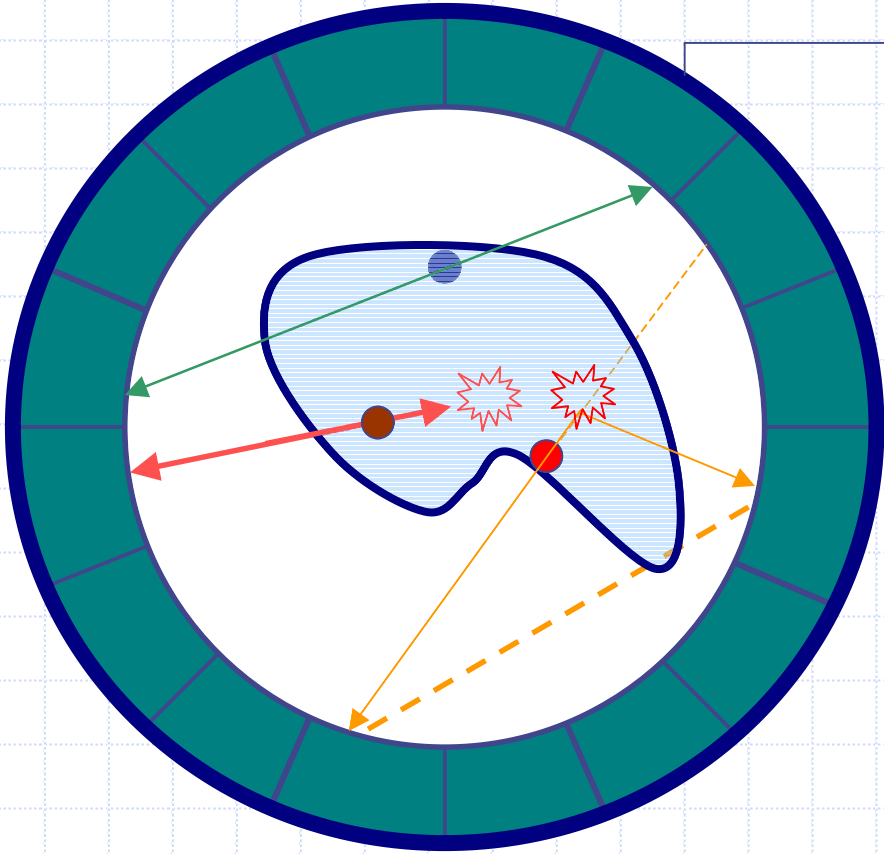
Traitement
et analyse multimodal

Interactions Photons-Matière en TEP



Fenêtre de détection des coïncidences

Interactions Photons-Matière en TEP



Fenêtre de détection des coïncidences

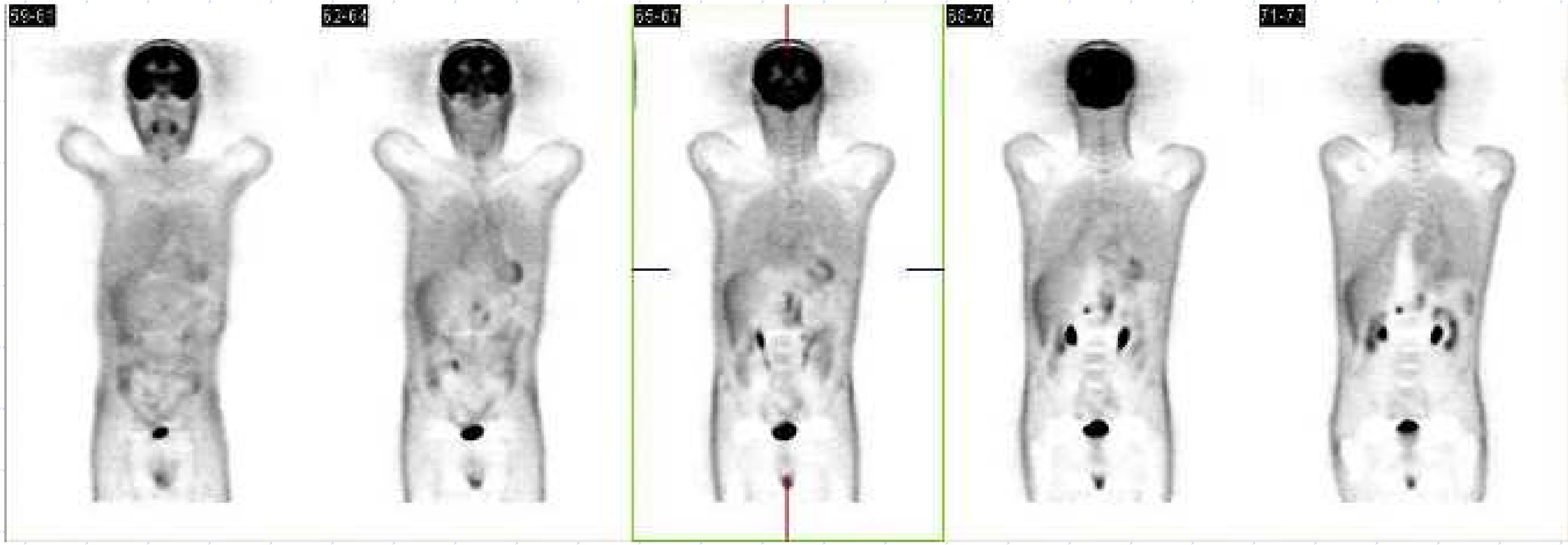
Atténuations

- **Photo-électrique**
  - **Sous-estimation des activités «profondes»**

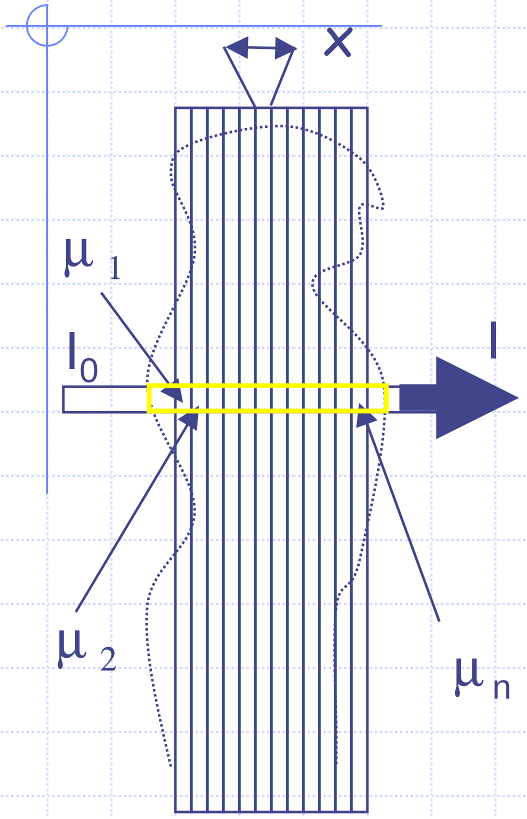
$$\mu_{PE} \approx k \; \frac{Z^3}{E^3} \, \rho$$

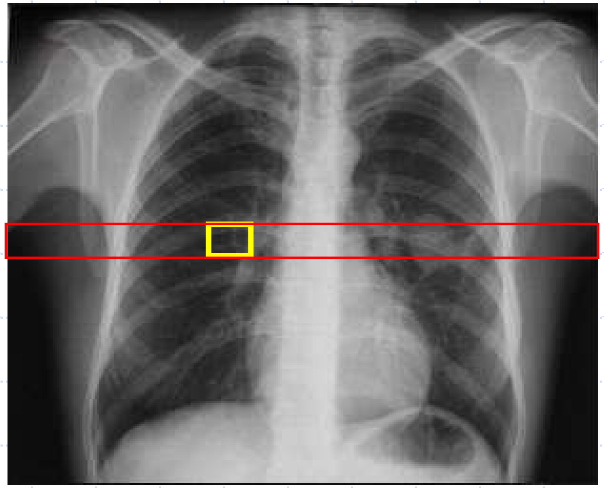
- **Compton**
  - **20% (2D) à 50% (3D) des détections**
  - **Médiocre résolution en énergie (15-20%)**
  - **Activité du cerveau et de la vessie**

$$\mu_C \approx k' \; \rho$$



Tomographie de transmission



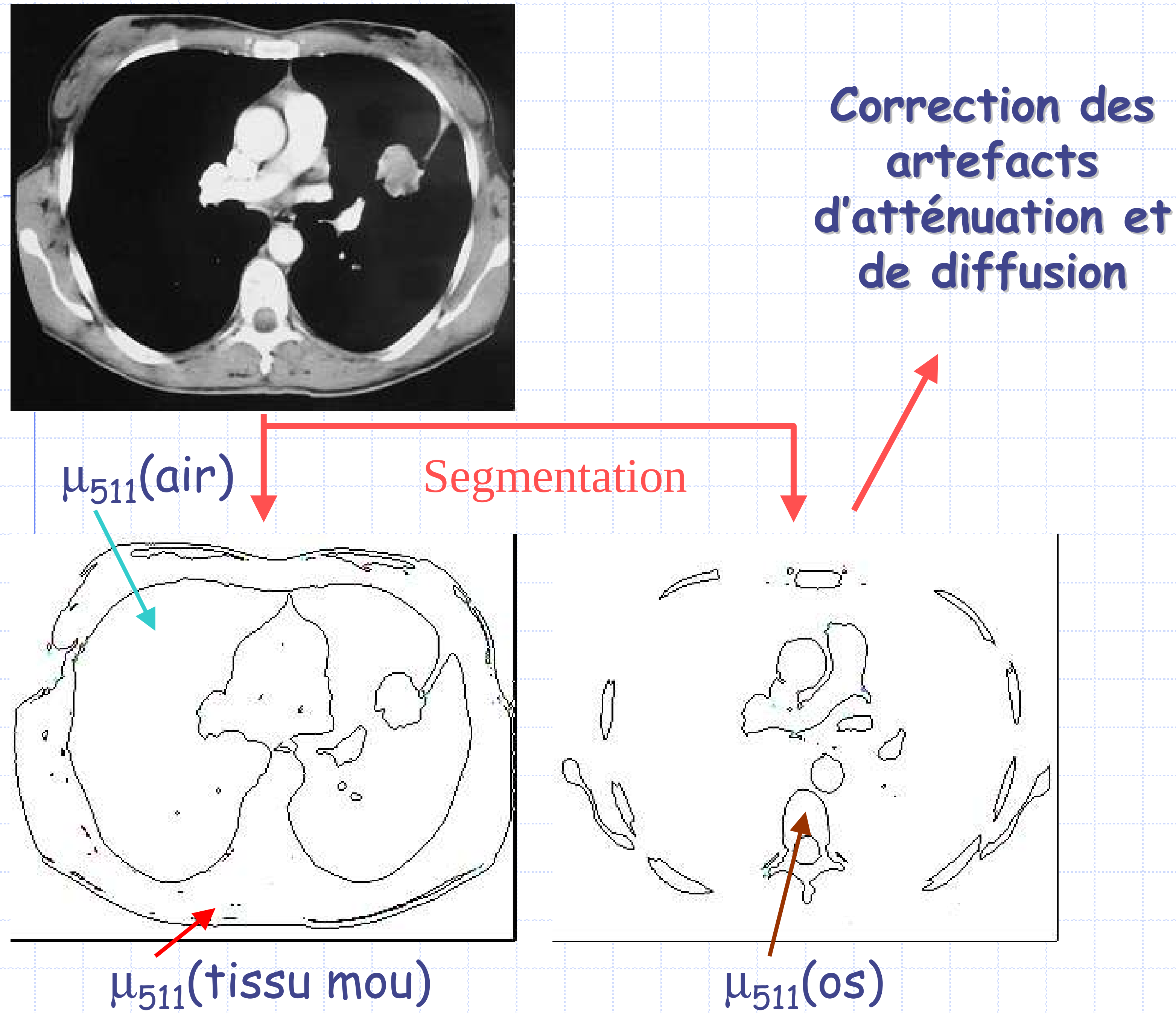


$$I = I_0\, e^{-x \sum_i \mu_i}$$

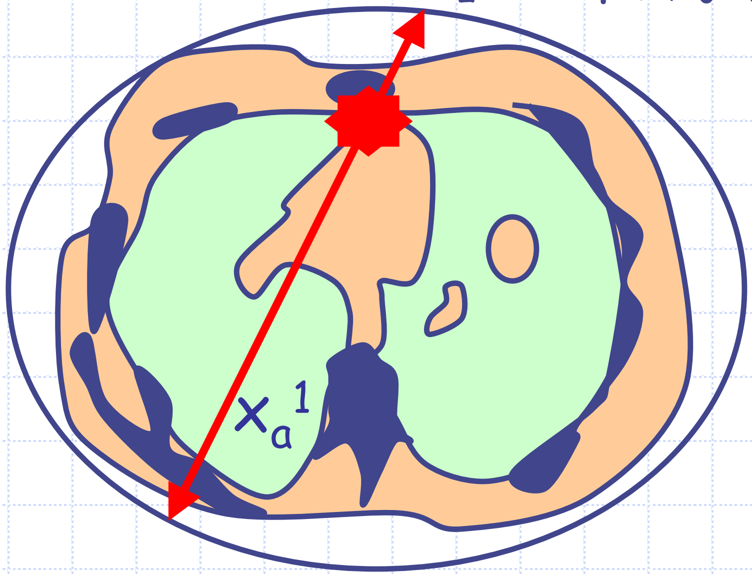
$$p = -\frac{1}{x} \ln\left(\frac{I}{I_0}\right) = \sum_i \mu_i$$

$$\mu_{PE} \approx k\, \frac{Z^3}{E^3}\, \rho$$

$$\mu_C \approx k'\, \rho$$


Correction des artefacts d'atténuation et de diffusion
μ_{511}(air)
Segmentation
μ_{511}(tissu mou)
μ_{511}(os)

Corrections de l'atténuation P.E.



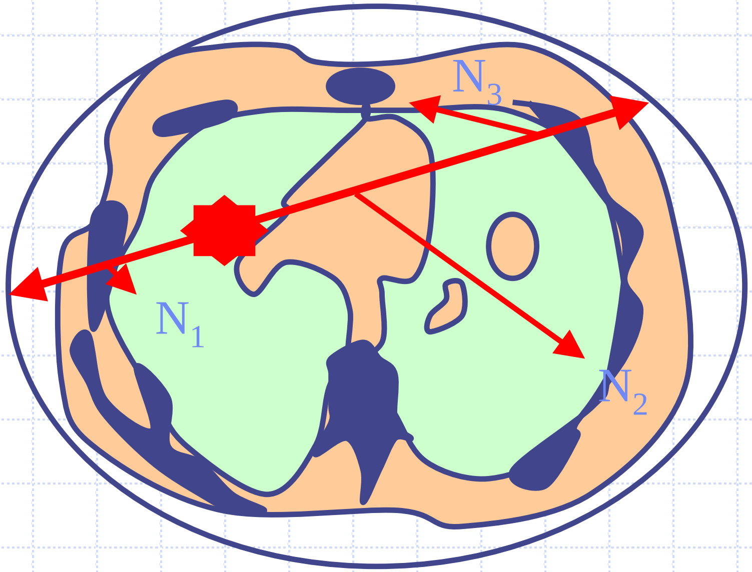
$f_1 = exp(-\mu_o x_o^1 - \mu_{tm} x_{tm}^1 - \mu_a x_a^1) = I_1/Io$

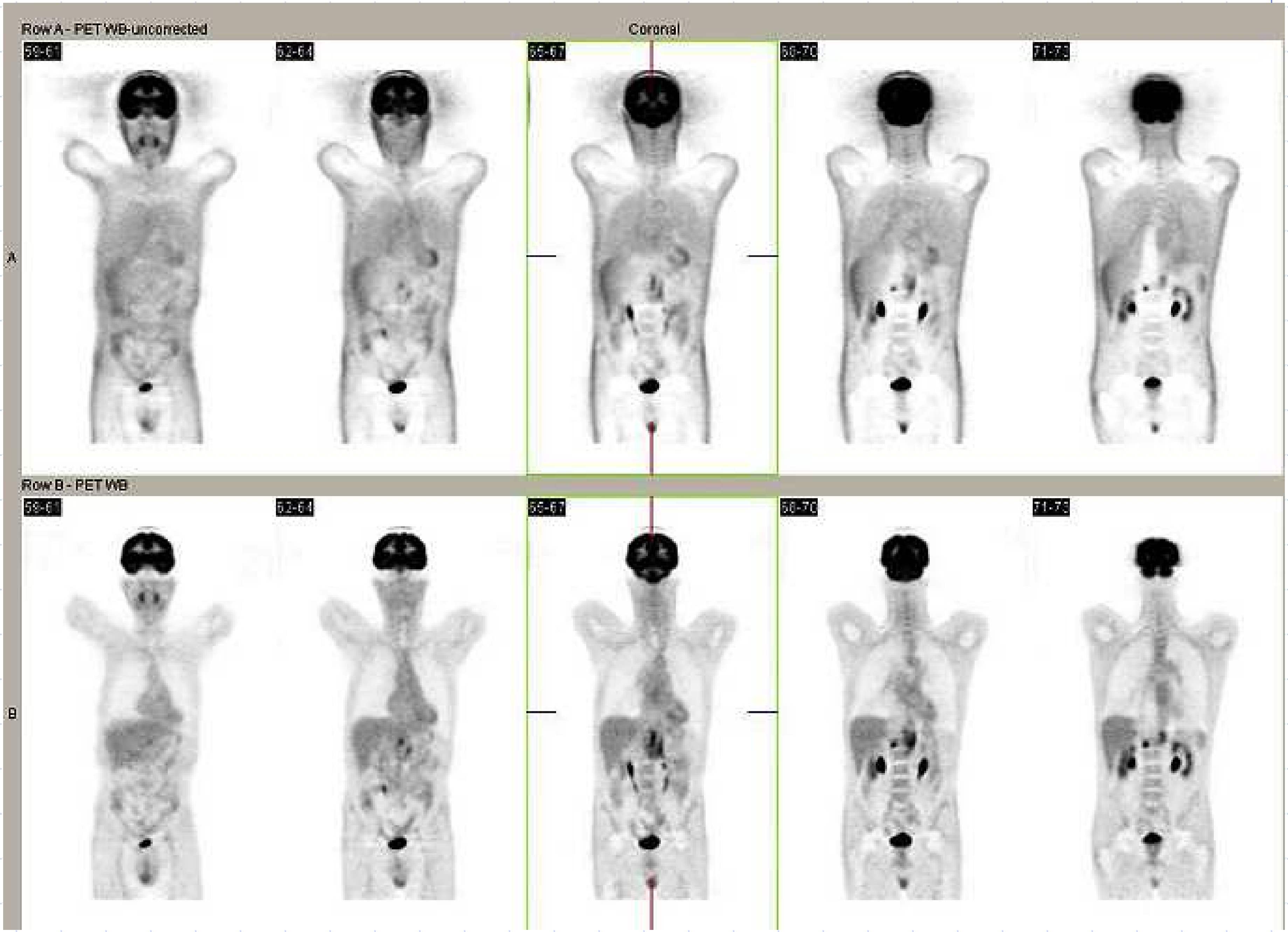
- Simple division par une constante f sur chaque projection

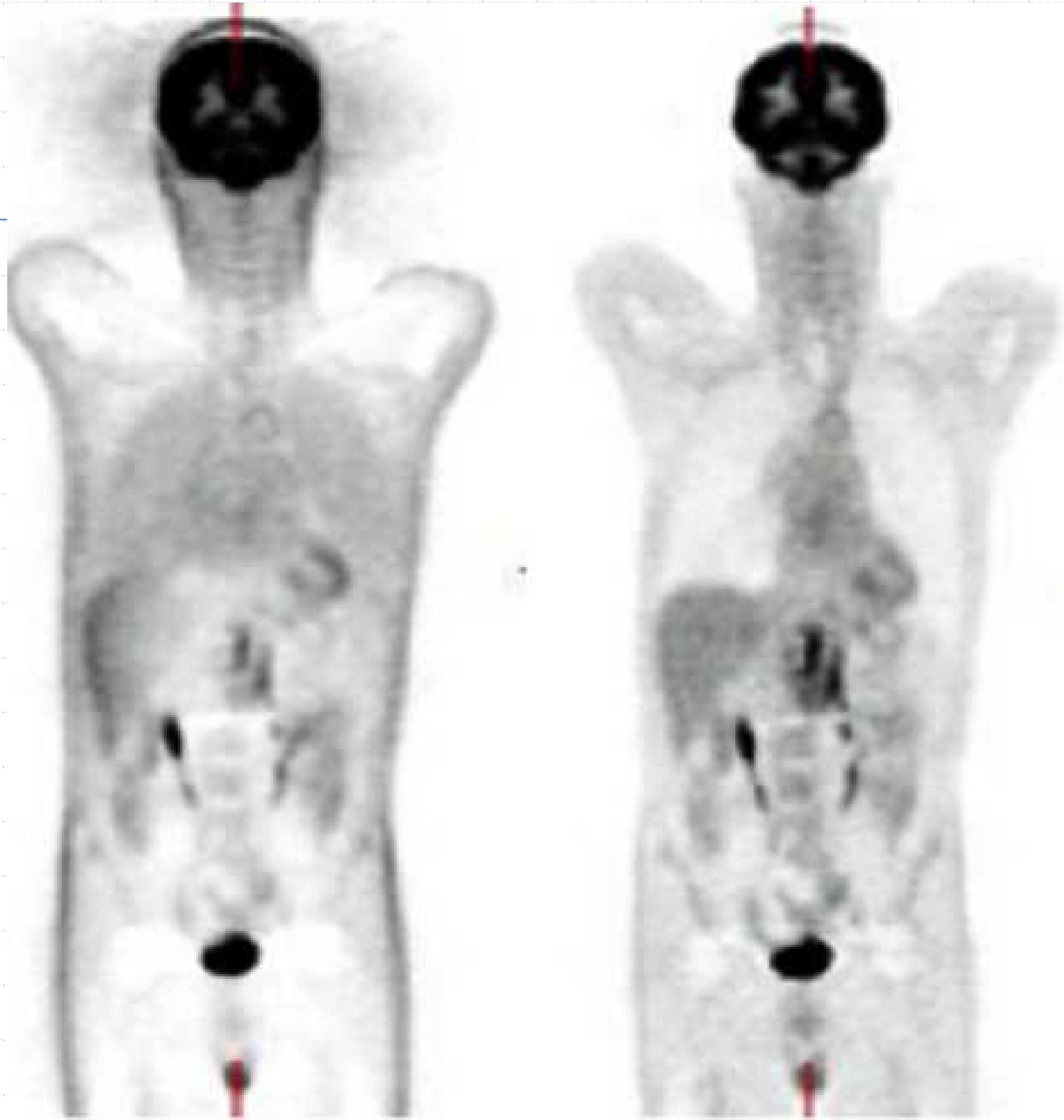
$$\mathbf{f = f_1 \times f_2 = exp(-\mu_o x_o - \mu_{tm} x_{tm} - \mu_a x_a)}$$

Correction du diffusé Compton

Simulation (Monte-Carlo) à partir des μ_C à 511 keV



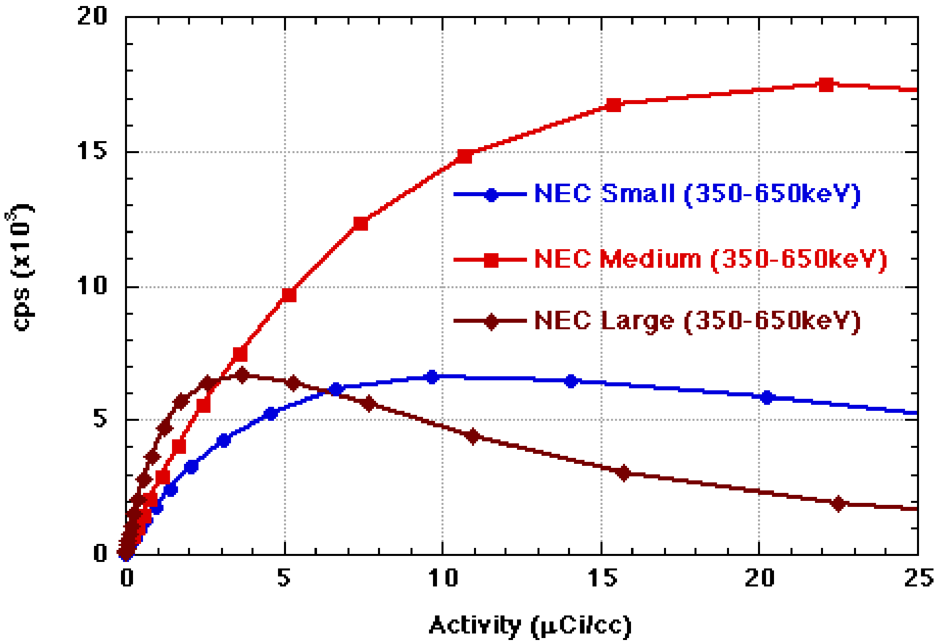

Row A - PET WB-uncorrected
Coronal
59-61
62-64
65-67
68-70
71-73
A
Row B - PET WB
59-61
62-64
65-67
68-70
71-73
B



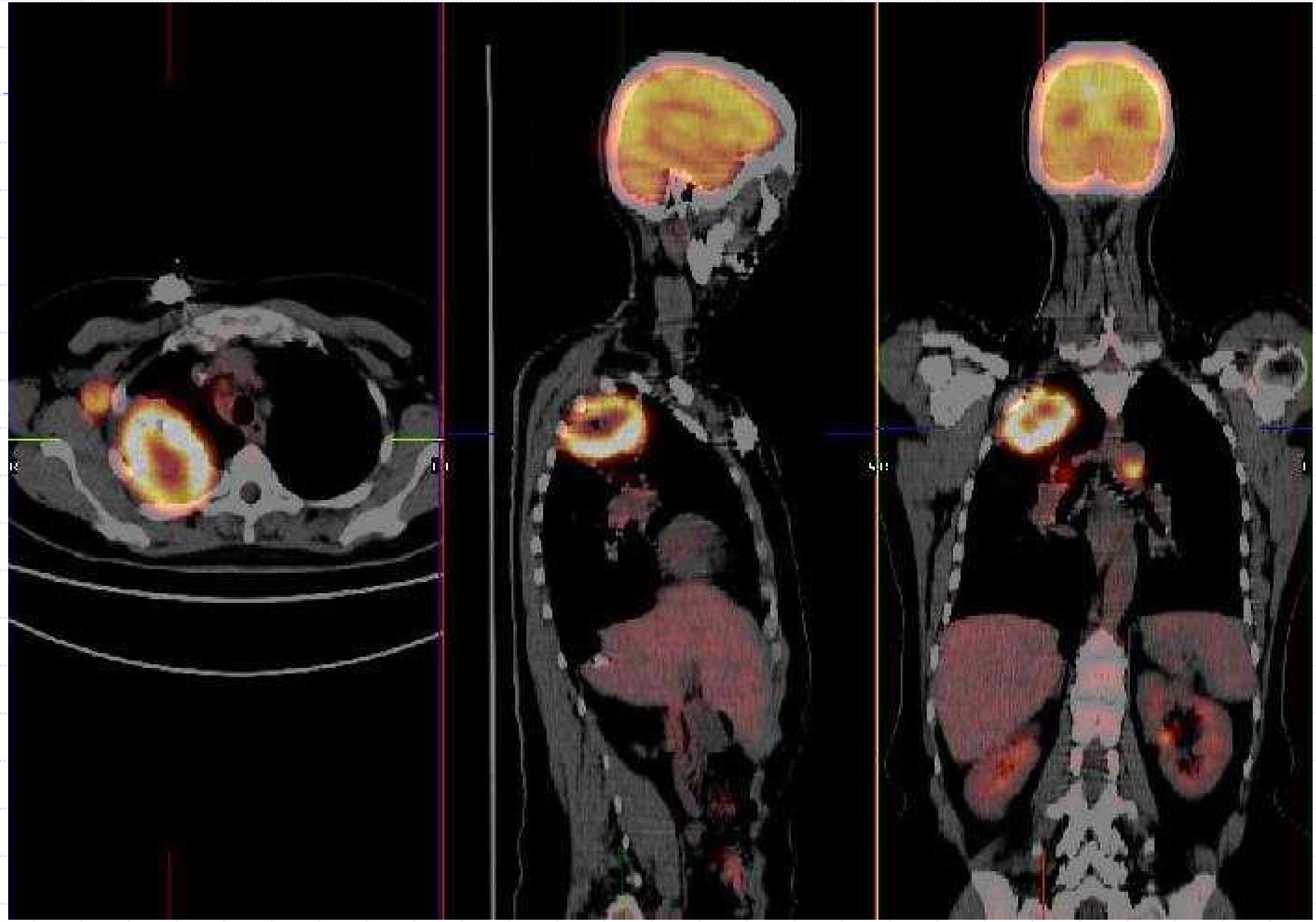
Qualité globale d'un TEP

$$NECR = \left(\frac{S}{B}\right)^2 = \frac{V^2}{V+D+k.F} = f\left(\frac{\mu Ci}{mL}\right)$$

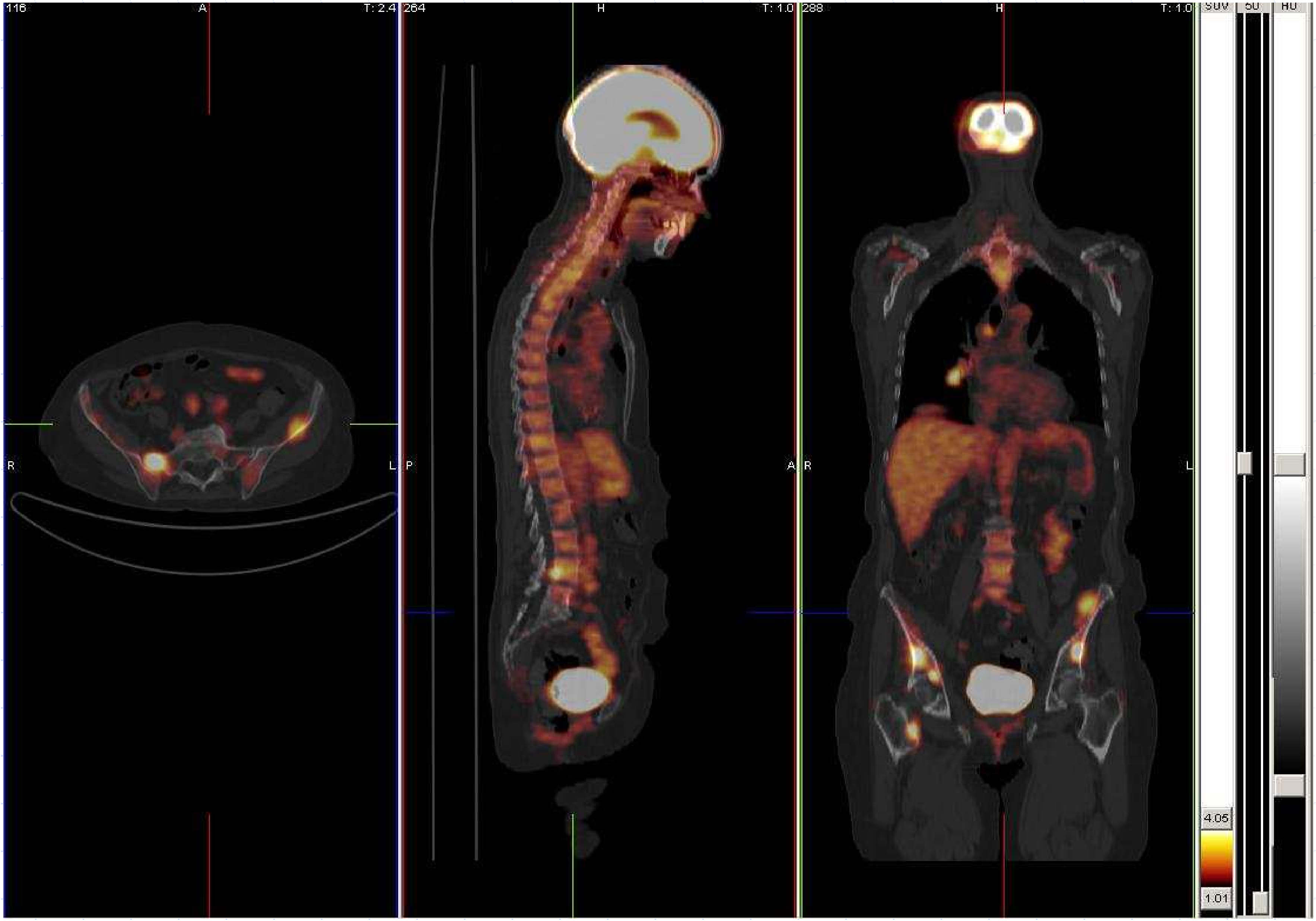
k=1 sauf si F sont mesurés (k=2)



Fusion TEP-CT

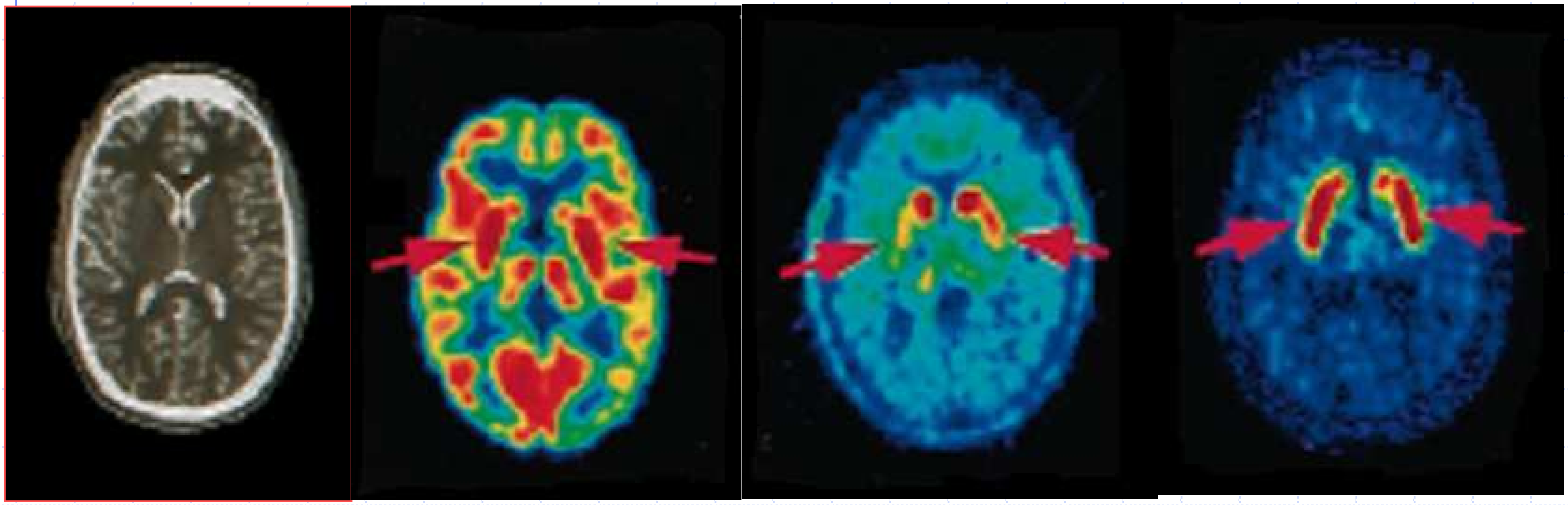


Fusion TEP-CT



« L'imagerie moléculaire »

Hémi Parkinson cliniquement gauche



IRM ^{1}H

Métabolisme ^{18}FDG

^{18}F-DOPA, voie Pré-synaptique

Perte fonction DaT Putamen D

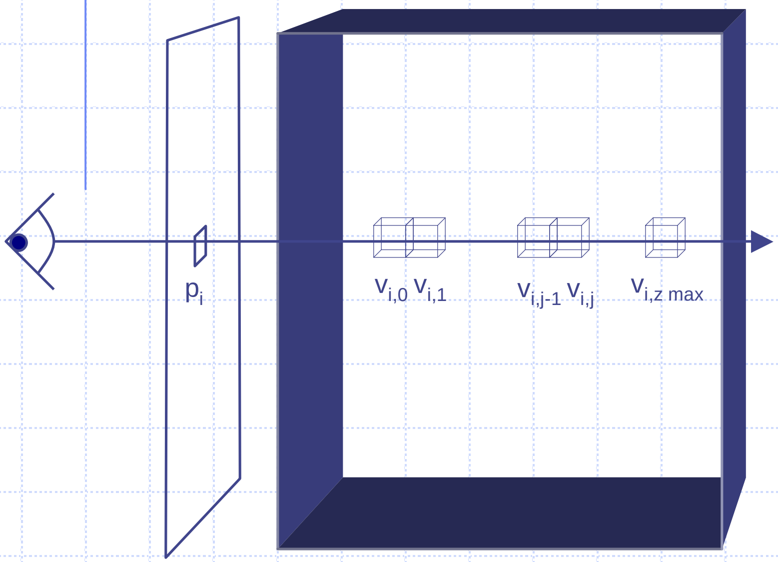
^{18}F-Ethyl Spipérone, voie Post-synaptique

Pas d'atteinte RD2

VISUALISATION VOLUMIQUE

Rendu volumique

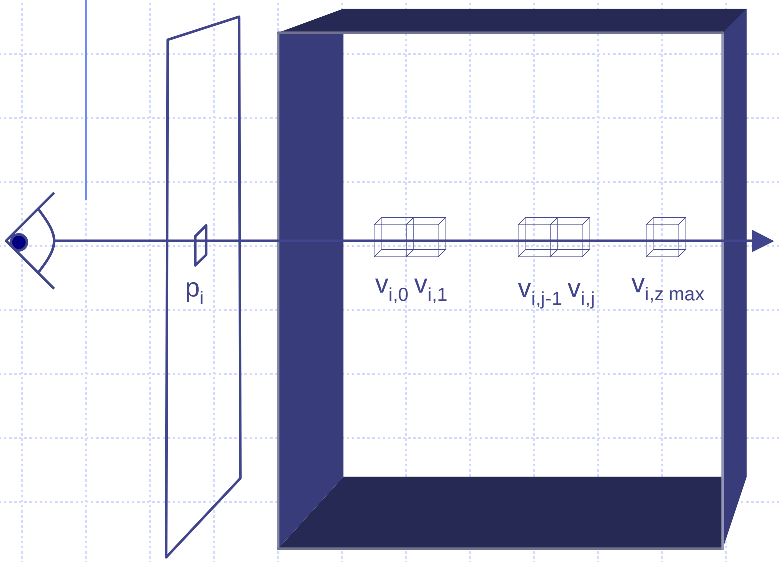
$$C_\lambda(p_i) = \sum_{j=1}^{z_{max}} c_\lambda(v_{i,j})\,\mathrm{Contrib}(v_{i,j})$$



$$\mathrm{Contrib}(vi,j) = \alpha(vi,j)\,P(ka,\ kd\ ;\ vi,j)\prod_{k=0}^{j-1}(1-\alpha(vi,k))$$

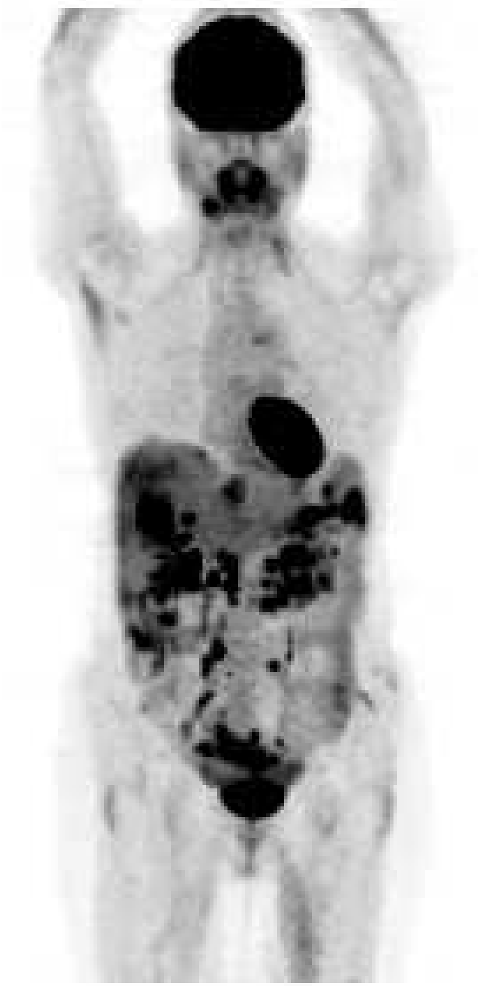
$$\begin{cases} \alpha(Vi,j) = s\,[\,\|\vec{\nabla} f(vi,j)\|\,].\,k.\ a[f(vi,j)] \\ P(ka,\ kd\ ;\ vi,j) = ka + kd\,\|\vec{\nabla}_n f(vi,j).\vec{L}\| \end{cases}$$

Rendu volumique

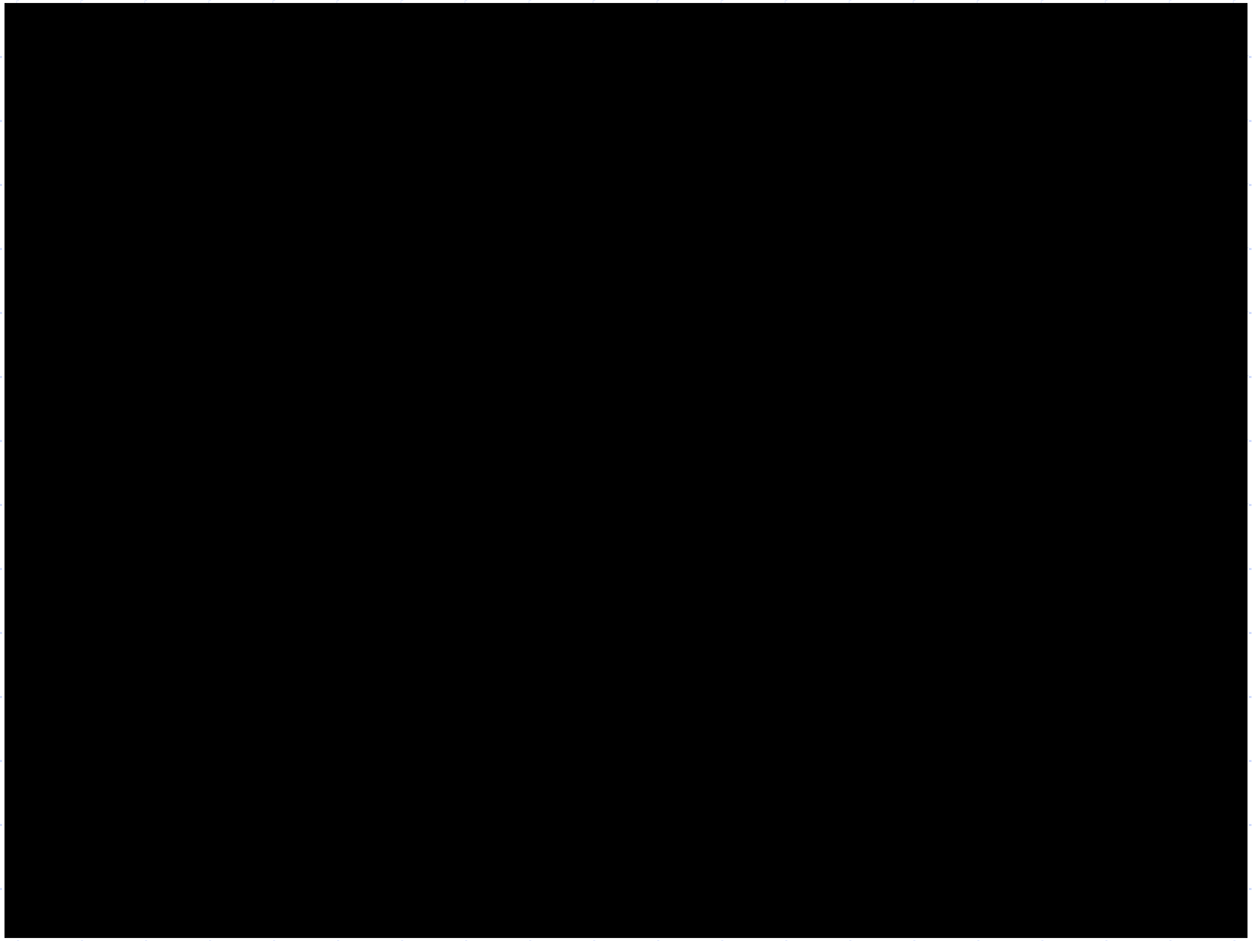


$$C_\lambda(p_i) = \sum_{j=1}^{z_{max}} c_\lambda(v_{i,j})\,\mathrm{Contrib}(v_{i,j})$$

MLEM puis MIP

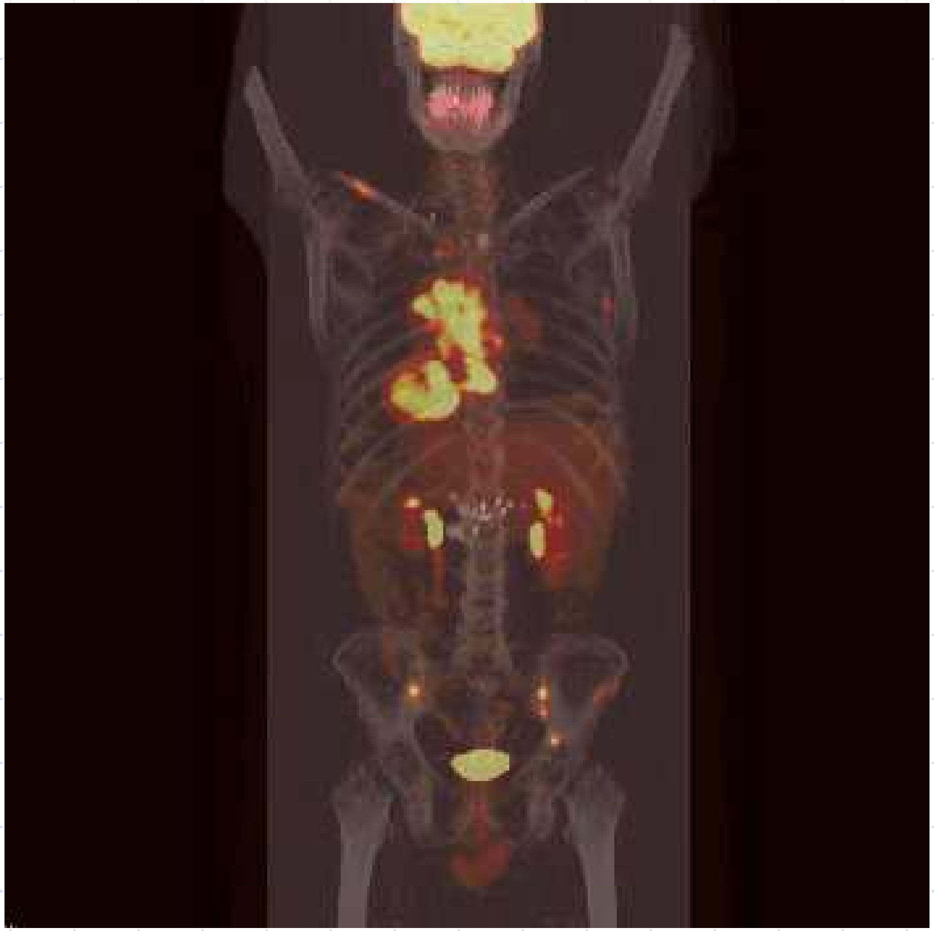


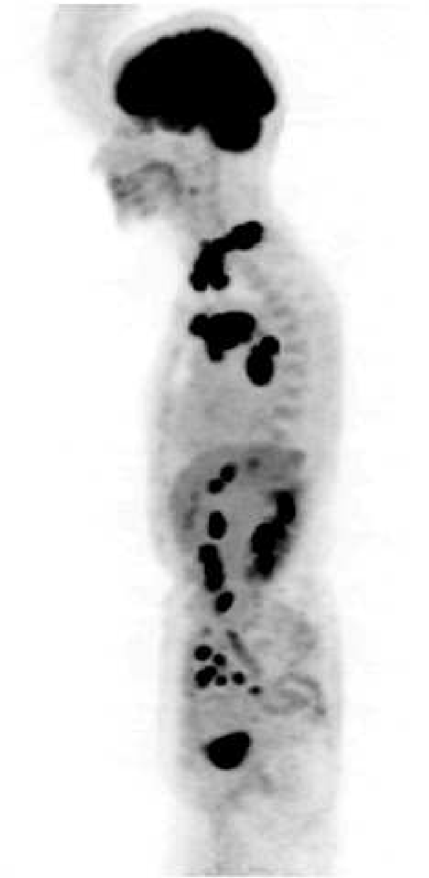
TEP (FORE)

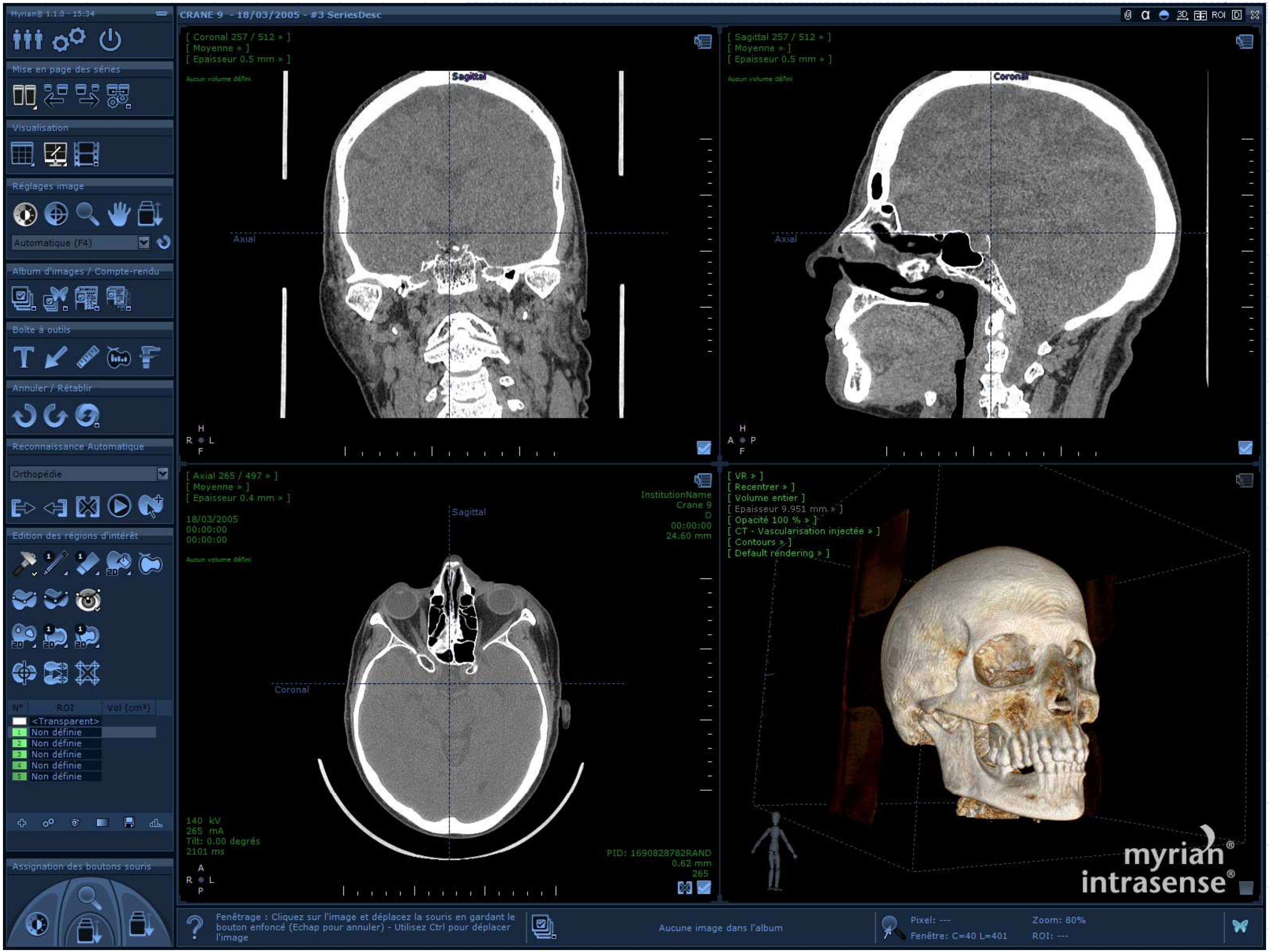


TDM

Lymphome et Hodgkin






CRANE 9 - 18/03/2005 - #3 SeriesDesc
Mise en page des séries
Visualisation
Réglages image
Automatique (F4)
Album d'images / Compte-rendu
Boîte à outils
Annuler / Rétablir
Reconnaissance Automatique
Orthopédie
Edition des régions d'intérêt
N° ROI Vol (cm³)
<Transparent>
Non définie
Assignation des boutons souris
[Coronal 257 / 512 »]
[Moyenne »]
[Epaisseur 0.5 mm »]
Sagittal
Axial
[Sagittal 257 / 512 »]
Coronal
[Axial 265 / 497 »]
[Epaisseur 0.4 mm »]
18/03/2005
InstitutionName
Crane 9
140 kV
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Tilt: 0.00 degrés
2101 ms
PID: 1690828782RAND
0.62 mm
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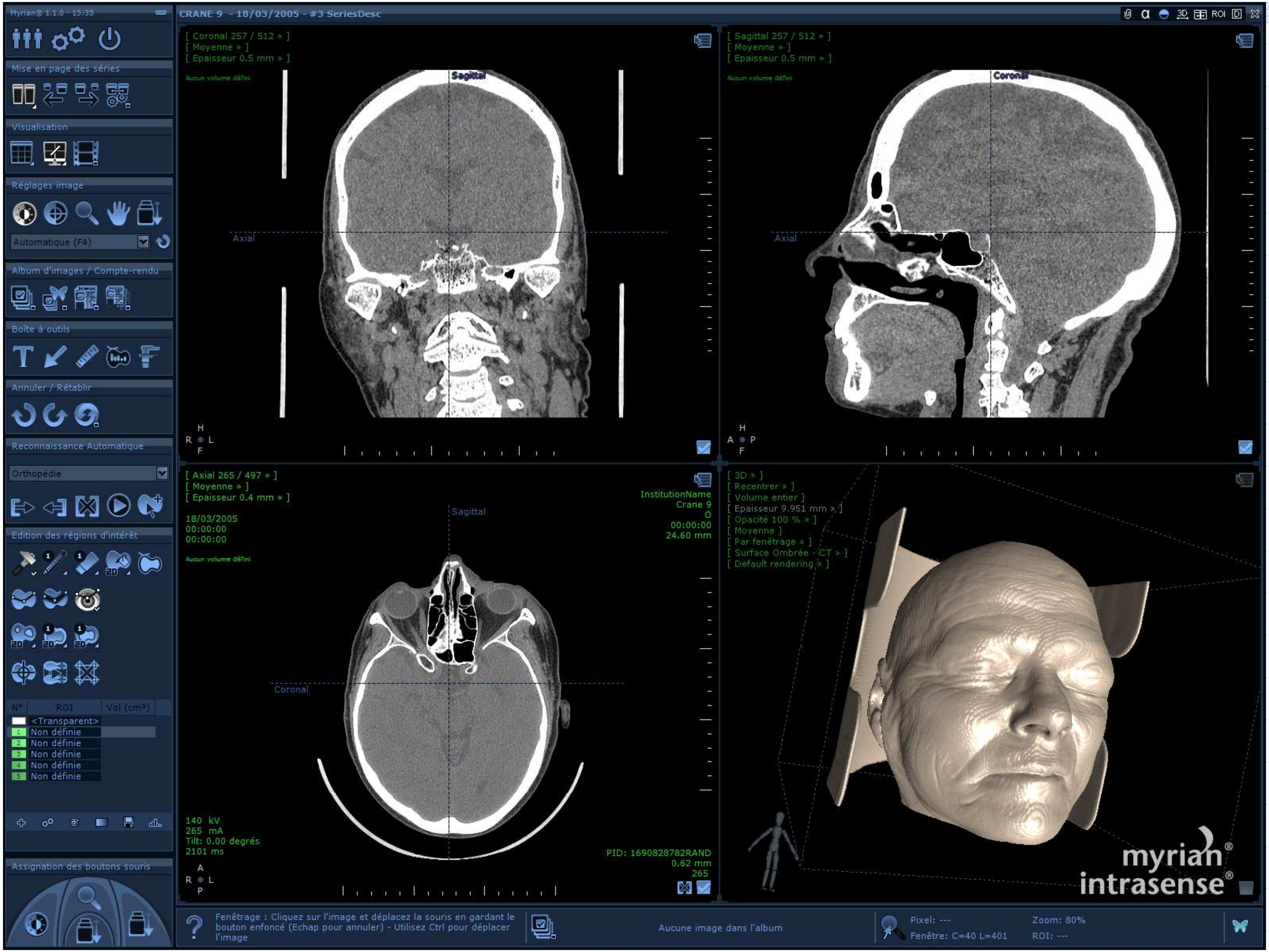
[Recentrer »]
[Volume entier]
[Epaisseur 9.951 mm »]
[Opacité 100 % »]
[CT - Vascularisation injectée »]
[Contours »]
[Default rendering »]
myrian
intrasense
Fenêtrage : Cliquez sur l'image et déplacez la souris en gardant le bouton enfoncé (Echap pour annuler) - Utilisez Ctrl pour déplacer l'image
Aucune image dans l'album
Pixel: ---
Fenêtre: C=40 L=401
Zoom: 80%
ROI: ---



Myrian® 1.1.0 - 15:35
CRANE 9 - 18/03/2005 - #3 SeriesDesc
Mise en page des séries
Visualisation
Réglages image
Automatique (F4)
Album d'images / Compte-rendu
Boîte à outils
Annuler / Rétablir
Reconnaissance Automatique
Orthopédie
Edition des régions d'intérêt
N° ROI Vol (cm³)
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Non définie
Non définie
Non définie
Non définie
Non définie
Assignation des boutons souris
[Coronal 257 / 512 »]
[Moyenne »]
[Epaisseur 0.5 mm »]
Sagittal
Axial
[Sagittal 257 / 512 »]
[Moyenne »]
[Epaisseur 0.5 mm »]
Coronal
Axial
[Axial 265 / 497 »]
[Moyenne »]
[Epaisseur 0.4 mm »]
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[Surface Ombrée - CT »]
[Default rendering »]
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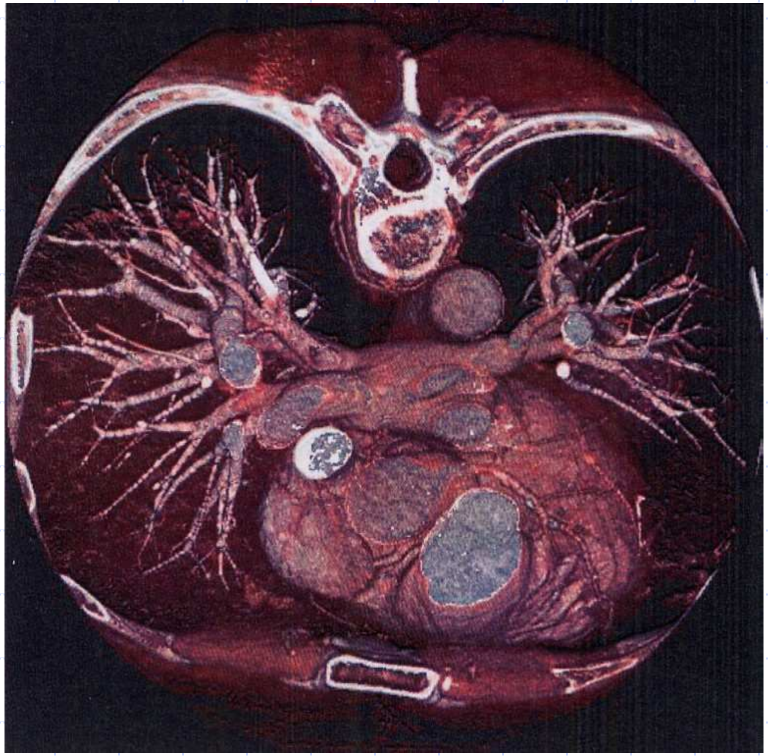
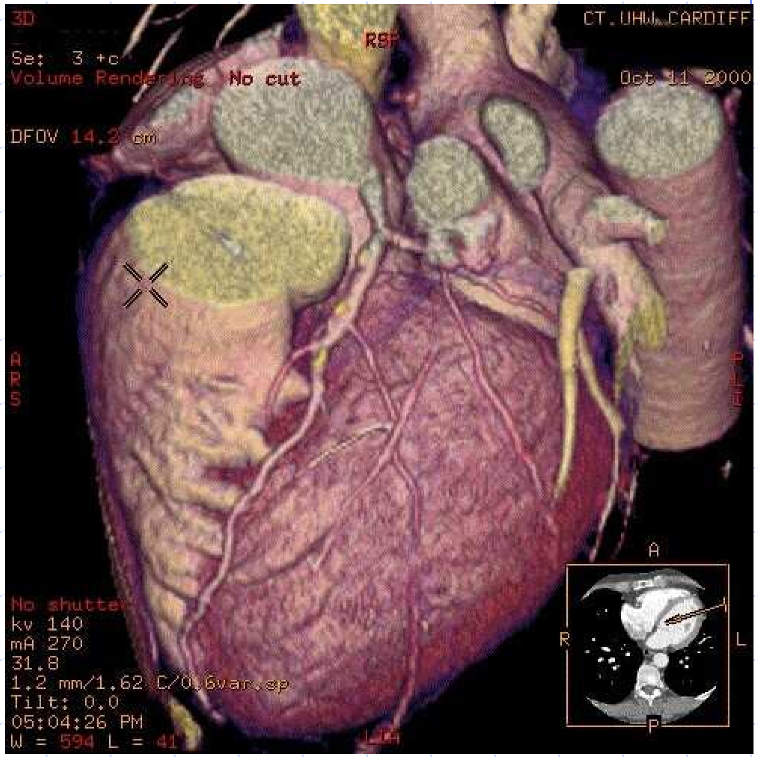
Fenêtrage : Cliquez sur l'image et déplacez la souris en gardant le bouton enfoncé (Echap pour annuler) - Utilisez Ctrl pour déplacer l'image
Aucune image dans l'album
Pixel: ---
Fenêtre: C=40 L=401
Zoom: 80%
ROI: ---





3D
CT.UHW.CARDIFF
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L
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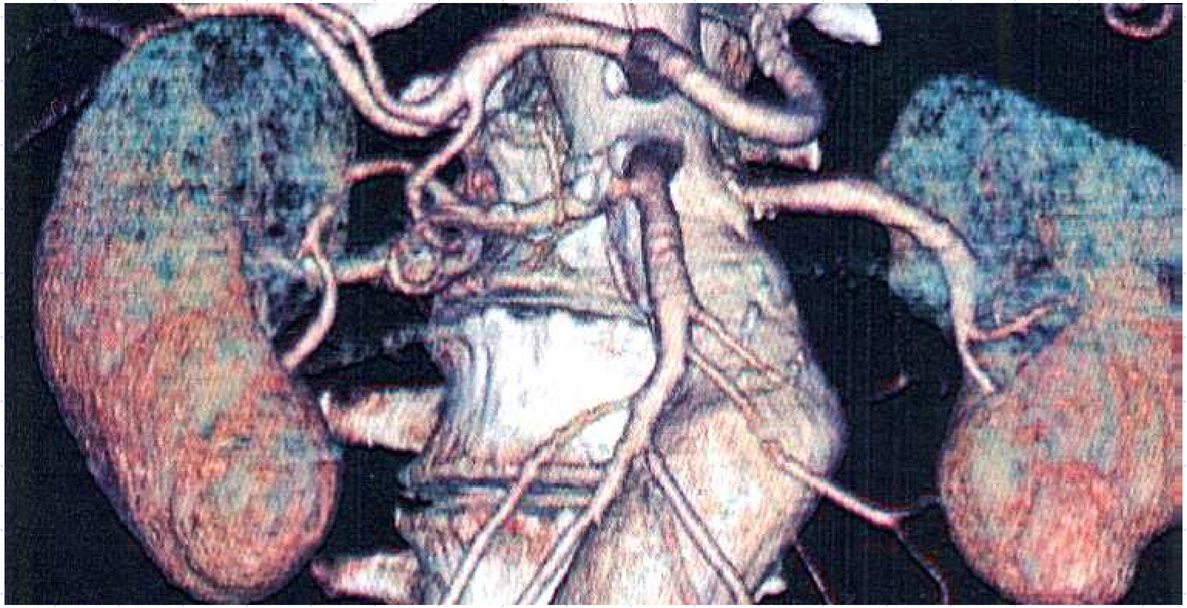
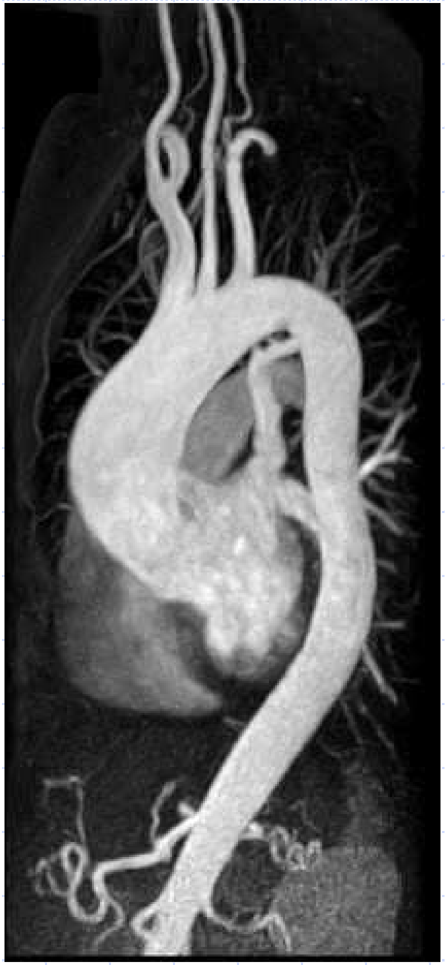
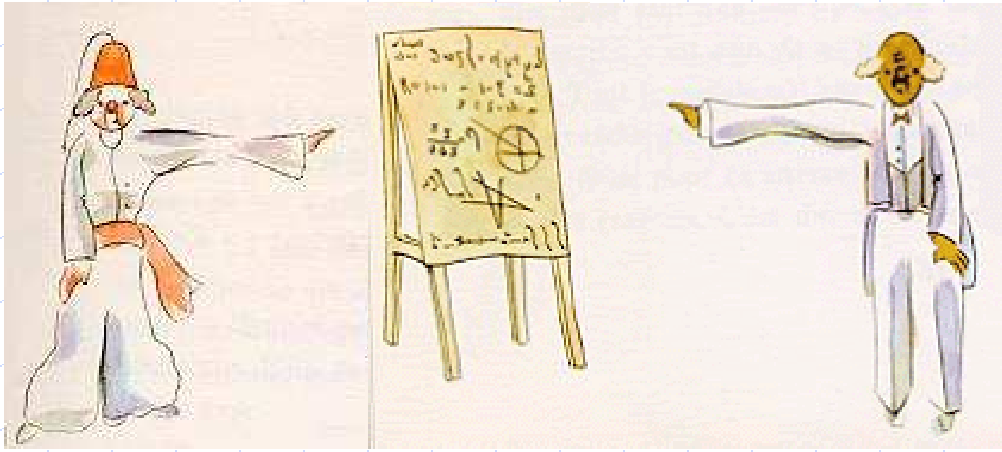


MIP EN IRM





The Mathematics of
Computerized Tomography.
F. Natterer. 2001. SIAM.

Positron Emission Tomography.
Basic Sciences and Clinical Practice.
PE Valk, DL Bailey,
DW Towsend, MN Maisey.
2003. Springer.

Merci de votre attention…