Positron Emission Tomography

CERN Accelerator School

Small Accelerators

Zeegse, the Netherlands

A.M.J. Paans

Nuclear Medicine & Molecular Imaging

UMC Groningen

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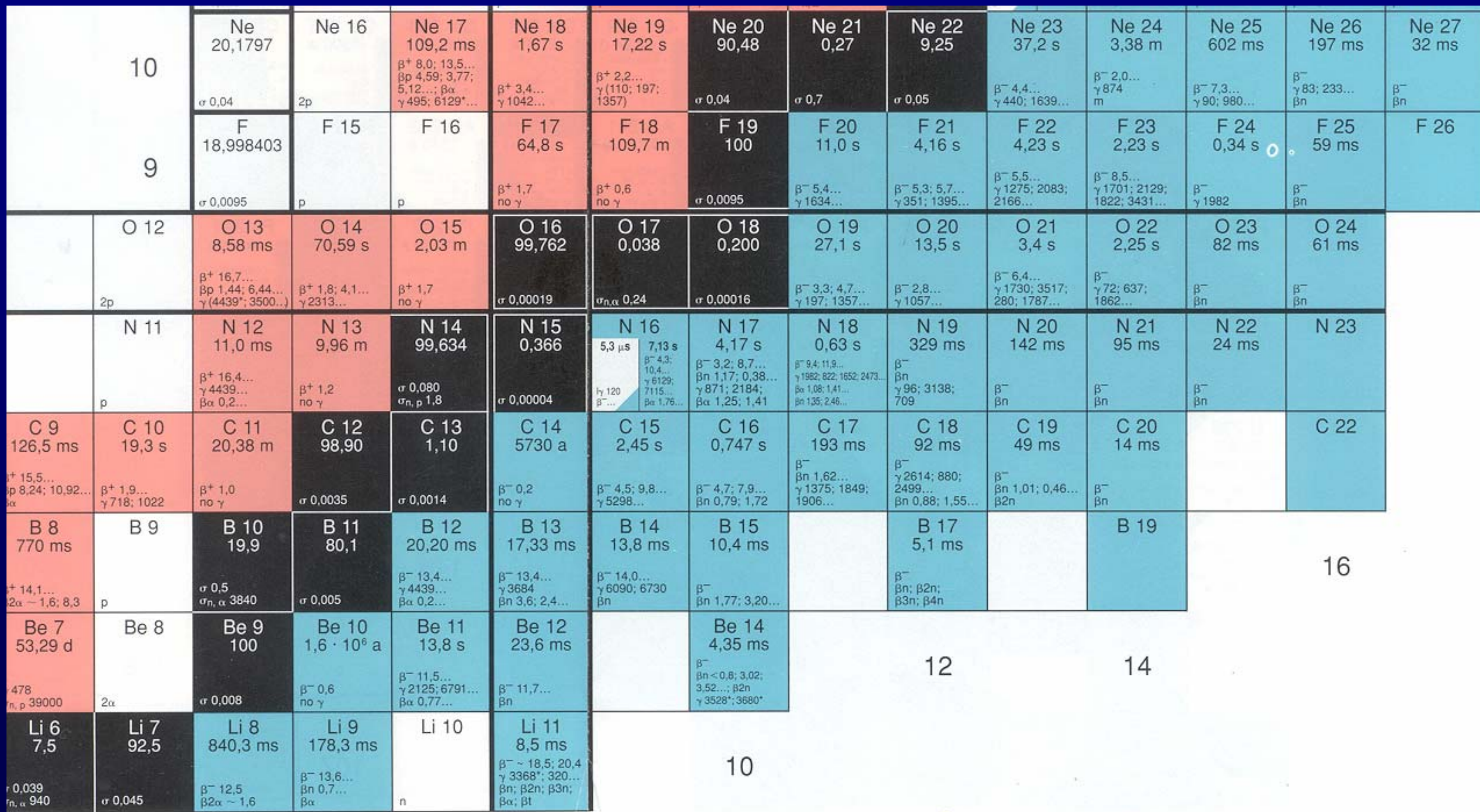
Elements of Life	PET-nuclide
Hydrogen	^{18}F (110 min)
Carbon	^{11}C (20 min)
Nitrogen	^{13}N (10 min)
Oxygen	^{15}O (2 min)


10
9
16
12
14
10
Ne 20,1797
Ne 16
Ne 17 109,2 ms
Ne 18 1,67 s
Ne 19 17,22 s
Ne 20 90,48
Ne 21 0,27
Ne 22 9,25
Ne 23 37,2 s
Ne 24 3,38 m
Ne 25 602 ms
Ne 26 197 ms
Ne 27 32 ms
F 18,998403
F 15
F 16
F 17 64,8 s
F 18 109,7 m
F 19 100
F 20 11,0 s
F 21 4,16 s
F 22 4,23 s
F 23 2,23 s
F 24 0,34 s
F 25 59 ms
F 26
O 12
O 13 8,58 ms
O 14 70,59 s
O 15 2,03 m
O 16 99,762
O 17 0,038
O 18 0,200
O 19 27,1 s
O 20 13,5 s
O 21 3,4 s
O 22 2,25 s
O 23 82 ms
O 24 61 ms
N 11
N 12 11,0 ms
N 13 9,96 m
N 14 99,634
N 15 0,366
N 16 5,3 µs 7,13 s
N 17 4,17 s
N 18 0,63 s
N 19 329 ms
N 20 142 ms
N 21 95 ms
N 22 24 ms
N 23
C 9 126,5 ms
C 10 19,3 s
C 11 20,38 m
C 12 98,90
C 13 1,10
C 14 5730 a
C 15 2,45 s
C 16 0,747 s
C 17 193 ms
C 18 92 ms
C 19 49 ms
C 20 14 ms
C 22
B 8 770 ms
B 9
B 10 19,9
B 11 80,1
B 12 20,20 ms
B 13 17,33 ms
B 14 13,8 ms
B 15 10,4 ms
B 17 5,1 ms
B 19
Be 7 53,29 d
Be 8
Be 9 100
Be 10 1,6 · 10⁶ a
Be 11 13,8 s
Be 12 23,6 ms
Be 14 4,35 ms
Li 6 7,5
Li 7 92,5
Li 8 840,3 ms
Li 9 178,3 ms
Li 10
Li 11 8,5 ms

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PET: A multidisciplinary approach

Cyclotron	radionuclides, simple form
Chemistry	on-line/off-line synthesis
	labeled compound
	purification
Pharmacy	pharmaceutical quality, QC
Medicine	PET-scan
	evaluation, compartment model

A joint effort/multidisciplinary approach

- Chemistry
- Medicine
- Pharmacy
- Physics

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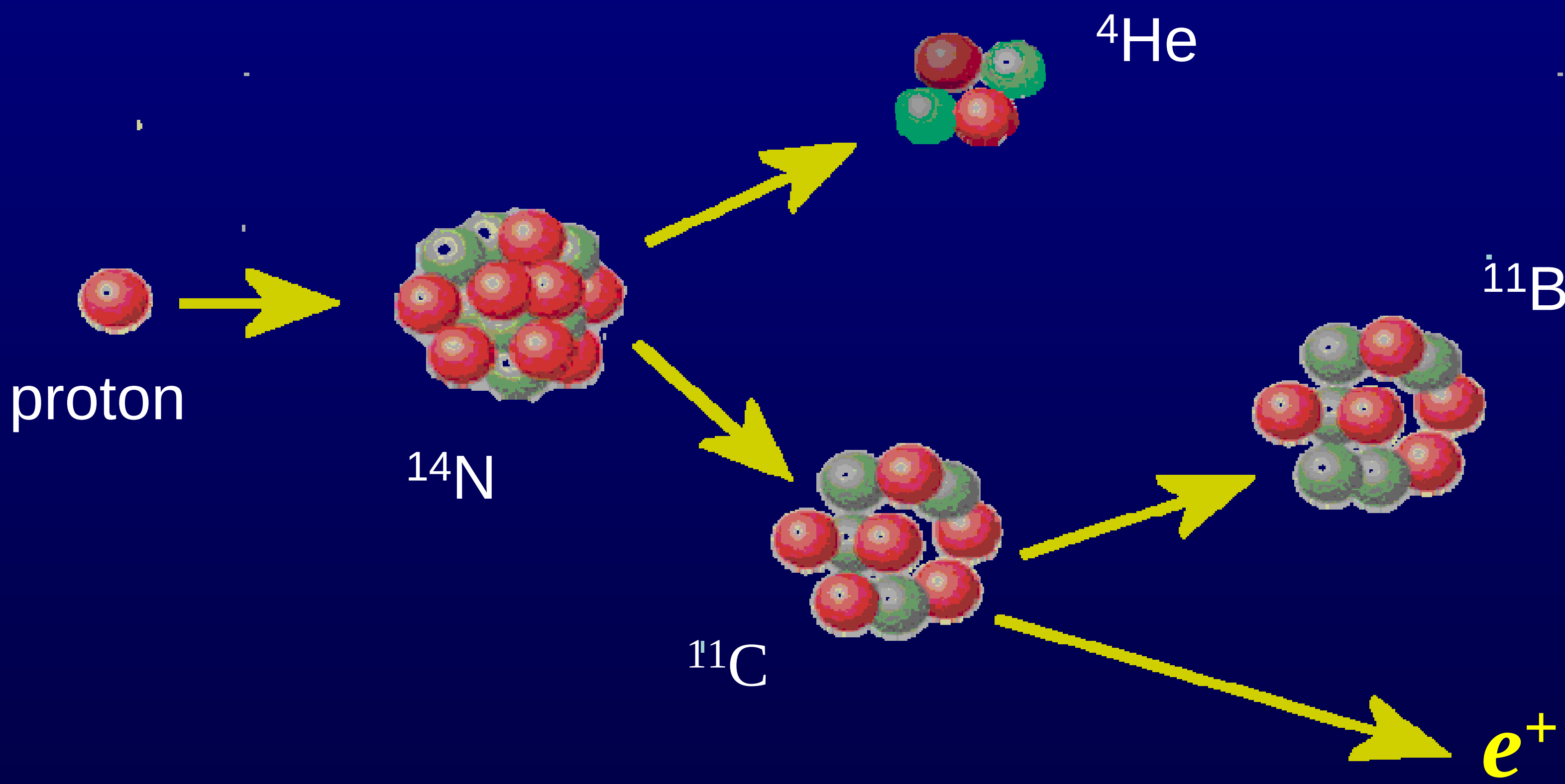
Nuclear Reaction	Q-value	Target	Product
$^{18}O(p,n)^{18}F$	- 2.4 MeV	$H_2{}^{18}O$	$^{18}F^-$
		$^{18}O_2$ $(+F_2)$	$^{18}F_2$
$^{20}Ne(d,\alpha)^{18}F$	+ 2.8 MeV	Ne $(+F_2)$	$^{18}F_2$
$^{14}N(p,\alpha)^{11}C$	- 2.9 MeV	N_2 $(+O_2)$	$^{11}CO_2$
$^{16}O(p,\alpha)^{13}N$	-5.2 MeV	H_2O	$^{13}NO_3$, $^{13}NO_2$
		+ EtOH	$^{13}NH_3$
$^{14}N(d,n)^{15}O$	+ 5.1 MeV	N_2 $(+O_2)$	$^{15}O_2$
$^{15}N(p,n)^{15}O$	- 3.5 MeV	$^{15}N_2$ $(+O_2)$	$^{15}O_2$

Positron Emitters:
Production and decay



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Specific activity   Theoretical: A (Bq) = $N_0 . \lambda$

^{11}C	9.2×10^{9} Ci/mol	=	340 TBq/µmol
^{13}N	1.9×10^{10} Ci/mol	=	700 TBq/µmol
^{15}O	9.2×10^{10} Ci/mol	=	3400 TPBq/µmol
^{18}F	1.7×10^{9} Ci/mol	=	63 TBq/µmol

For comparison

^{14}C	6.2×10^{1} Ci/mol	=	2.3 MBq/mmol

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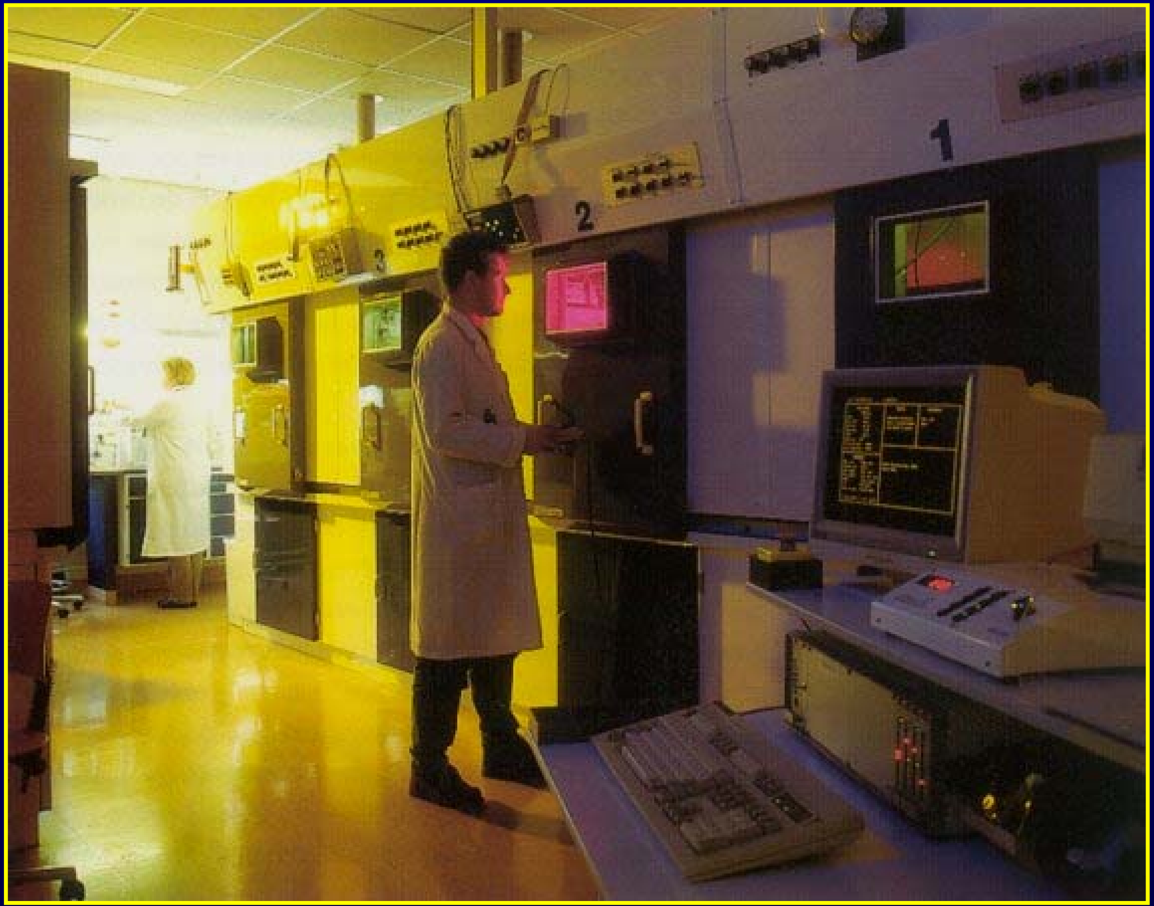
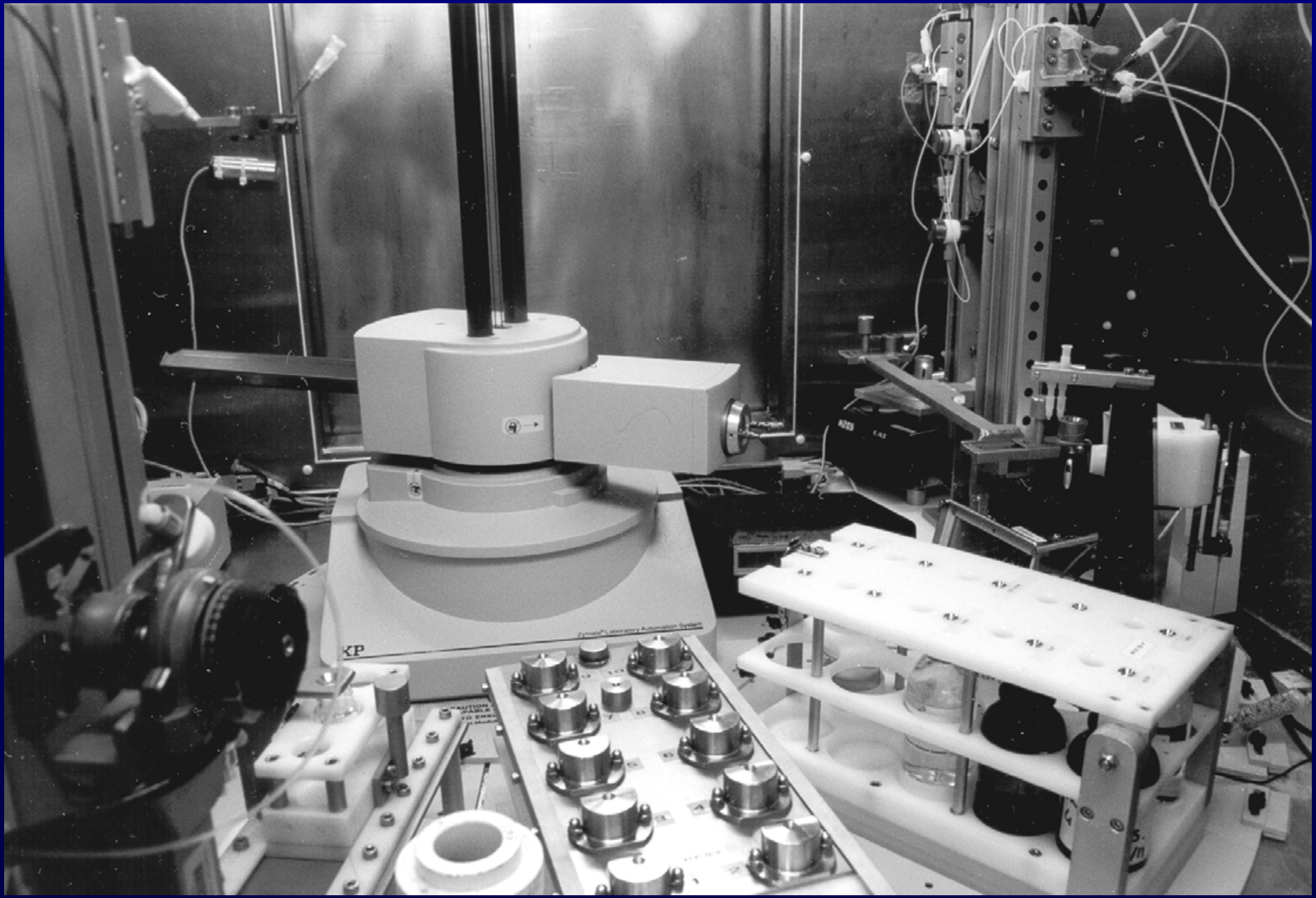
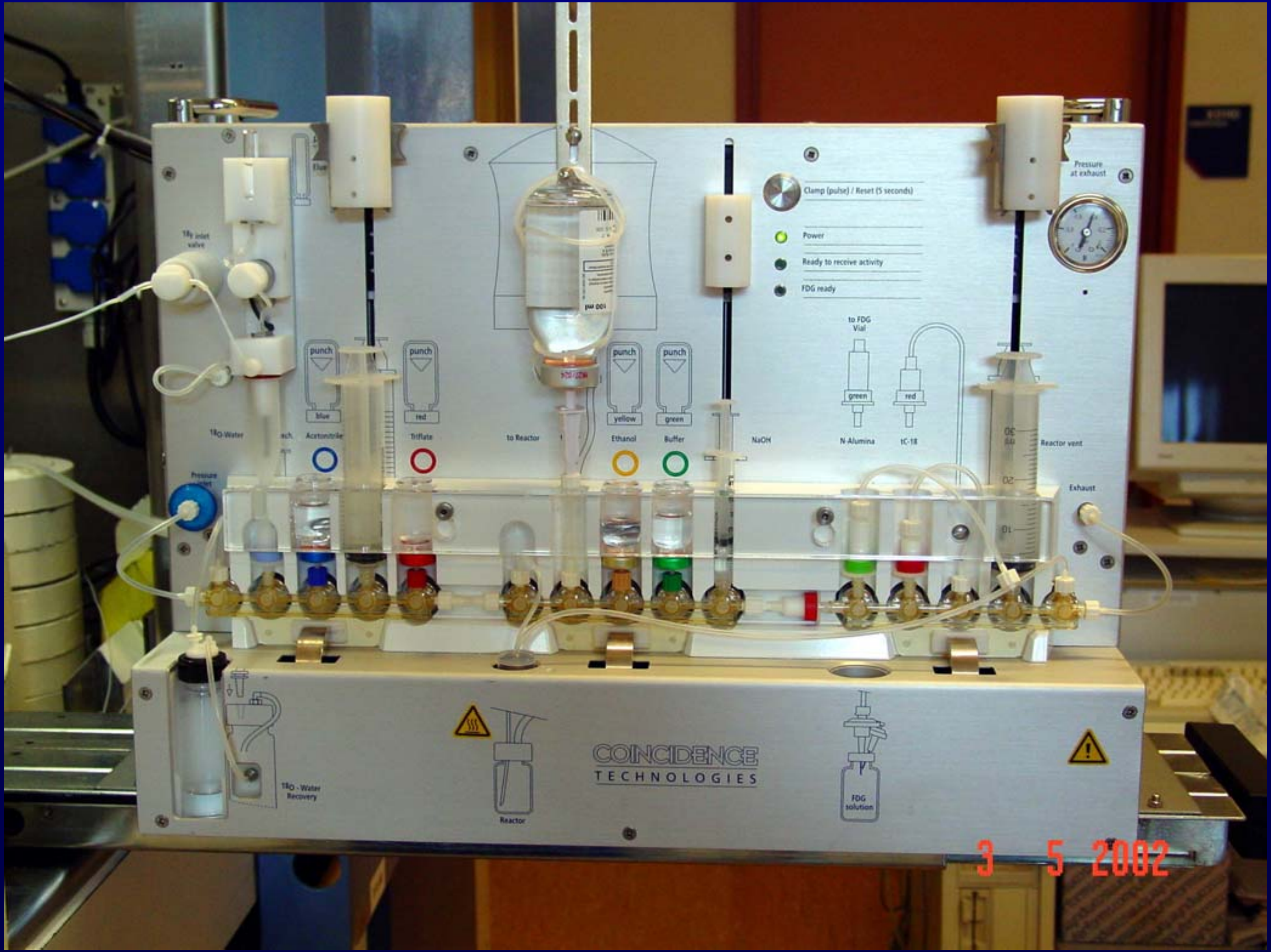
“Hot cells” in the radiochemistry lab



Radiochemistry with robotics



FDG-module ready for synthesis



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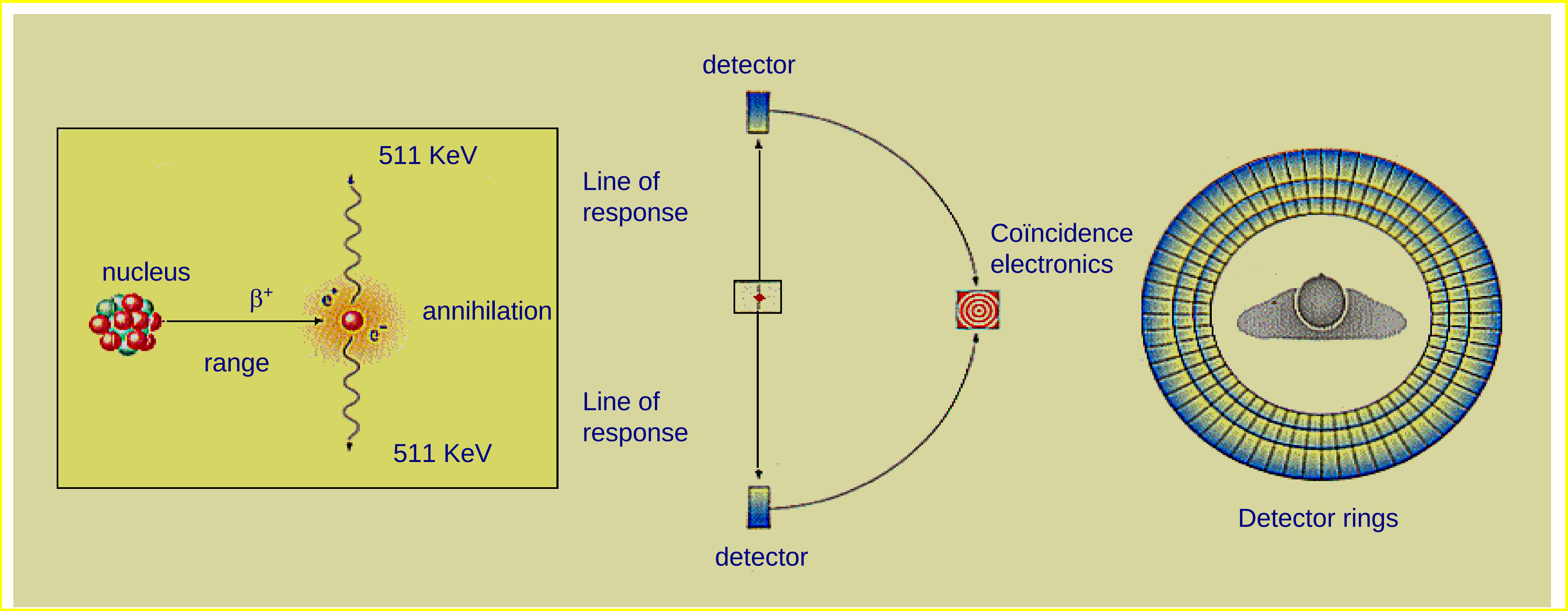
Annihilation & coincidence detection



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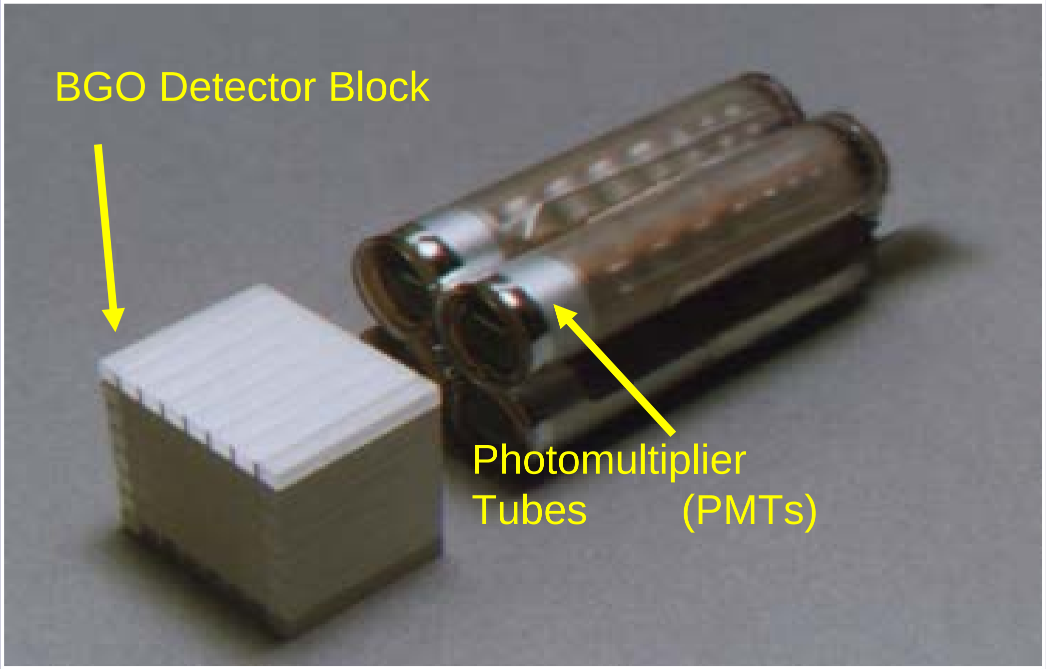
Detector materials	NaI	BGO	GSO	LSO
Density (g/cc)	3.67	7.13	6.7	7.4
Eff Atomnumber	51	75	59	66
Hygroscopic	yes	no	no	no
Decay time (ns)	230	300	56/600	40
Rel light yield	100%	15%	25%	75%
Energy resolution	7.8%	10.1%	9.5%	10.%

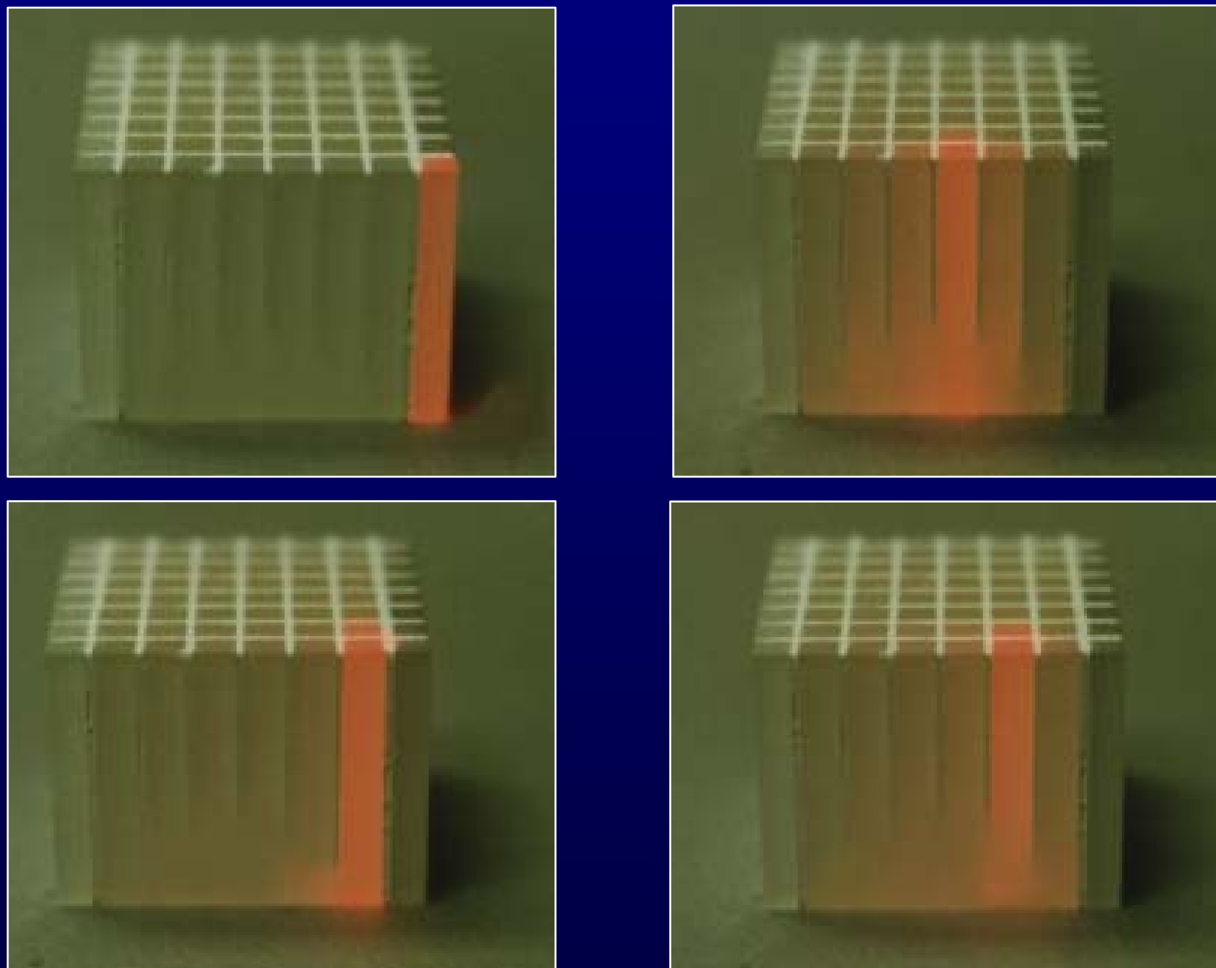


8 x 8 matrix of BGO crystals per detector

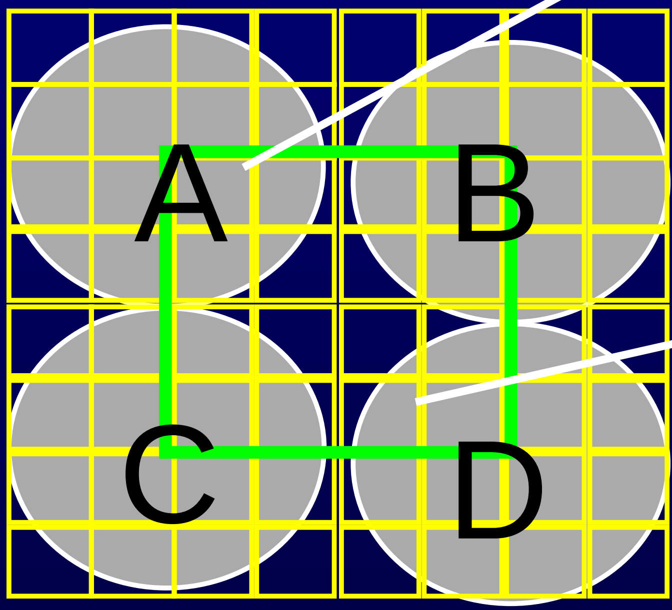
64 BGO crystal elements per detector

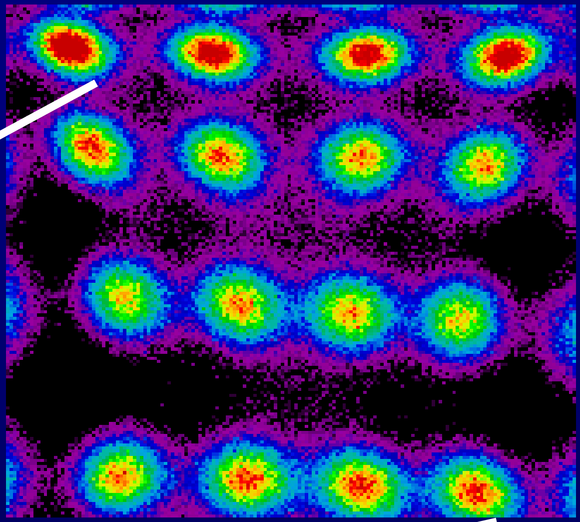
4 photomultiplier tubes per detector

Patented light guides channel the scintillation light . . .



. . . producing a unique combination of signals in the four photomultiplier tubes (PMTs).





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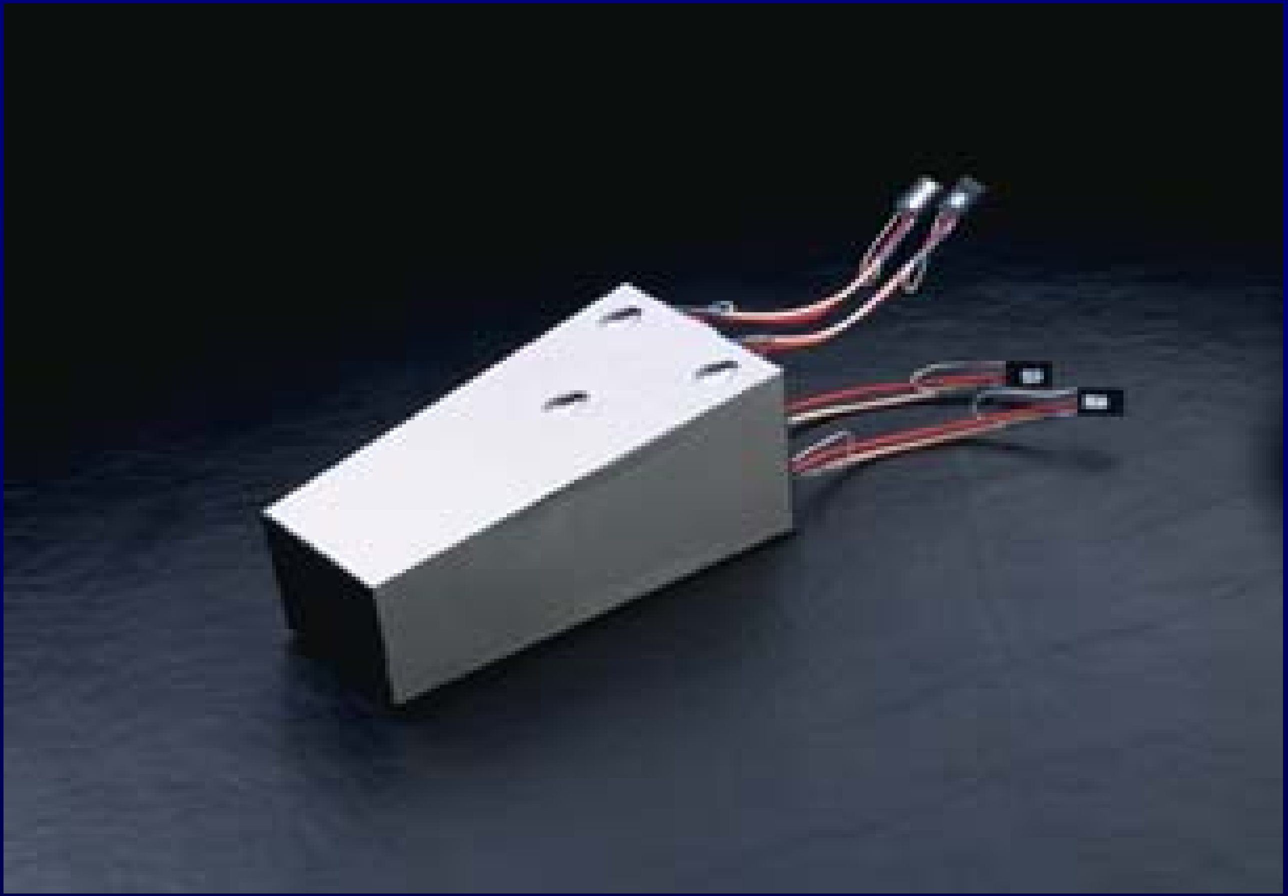

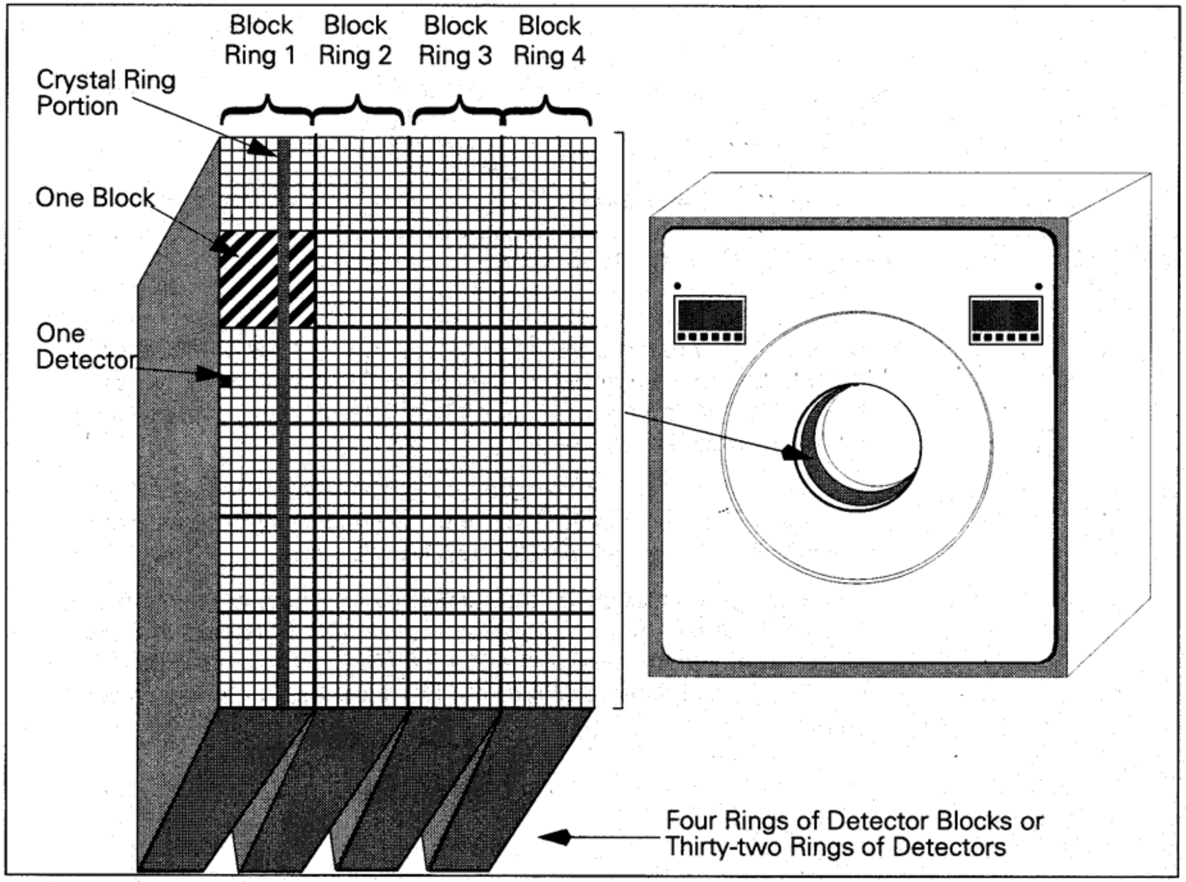

Figure A-1. Blocks and Detectors in an ECAT EXACT HR⁺ Scanner.

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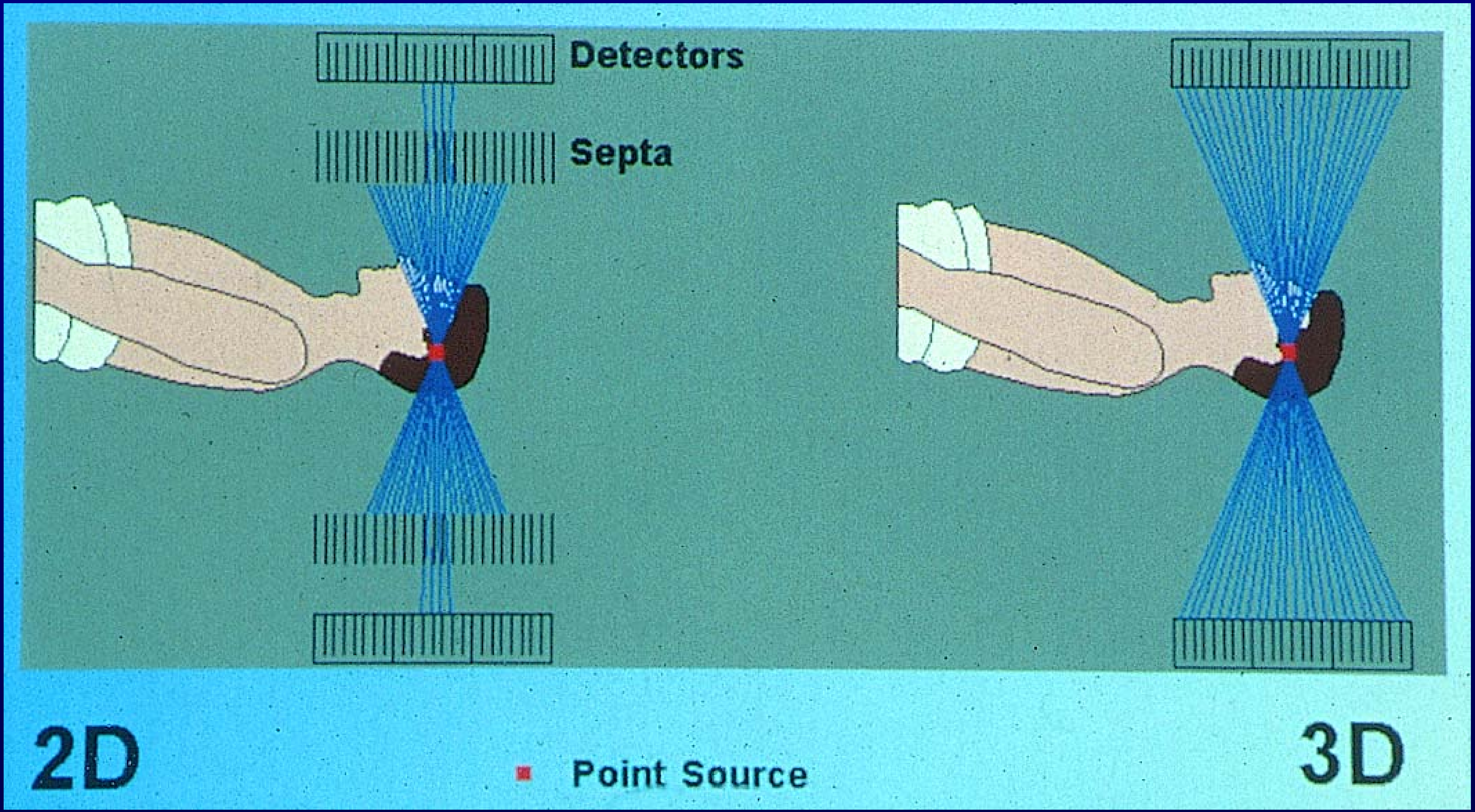
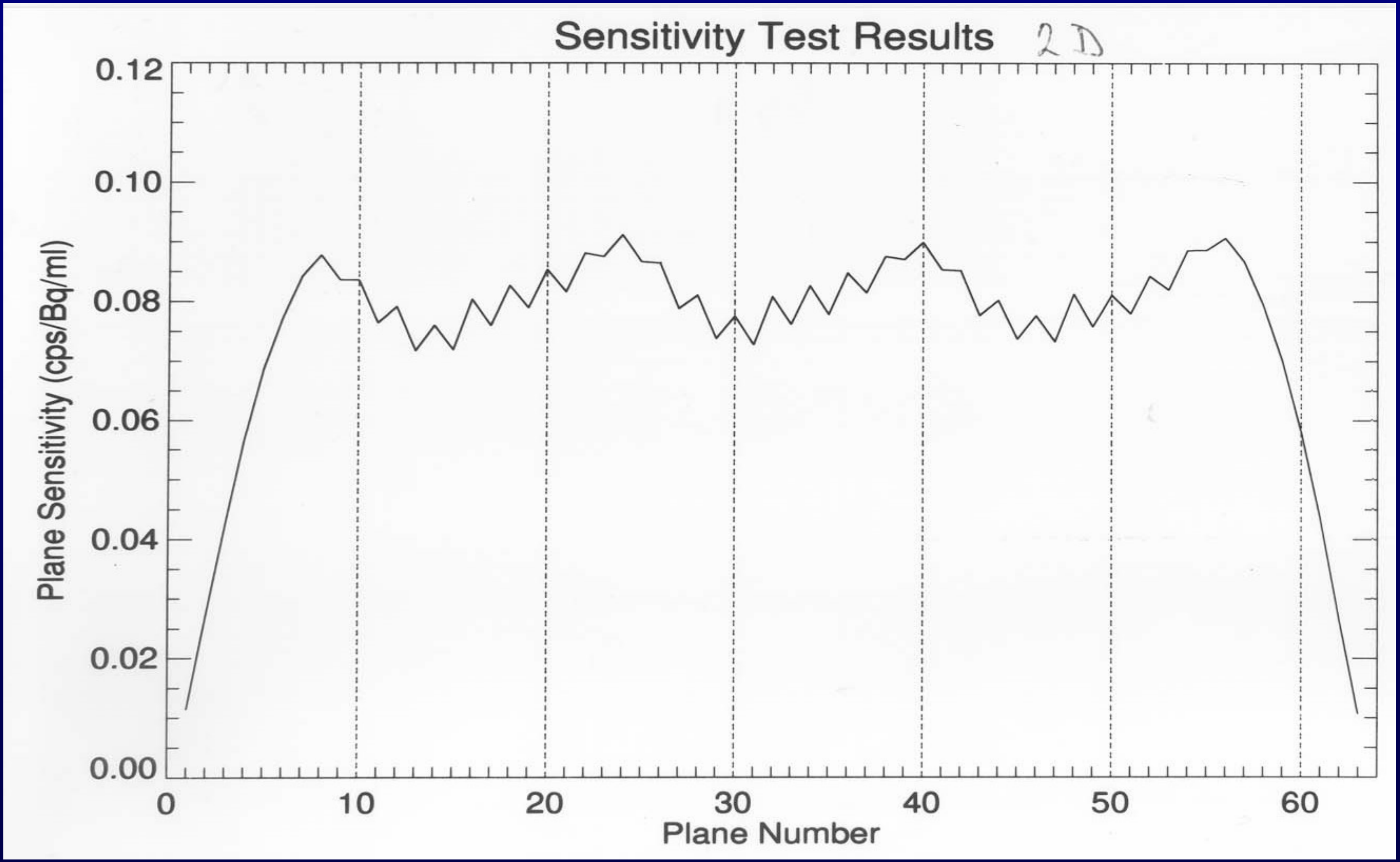
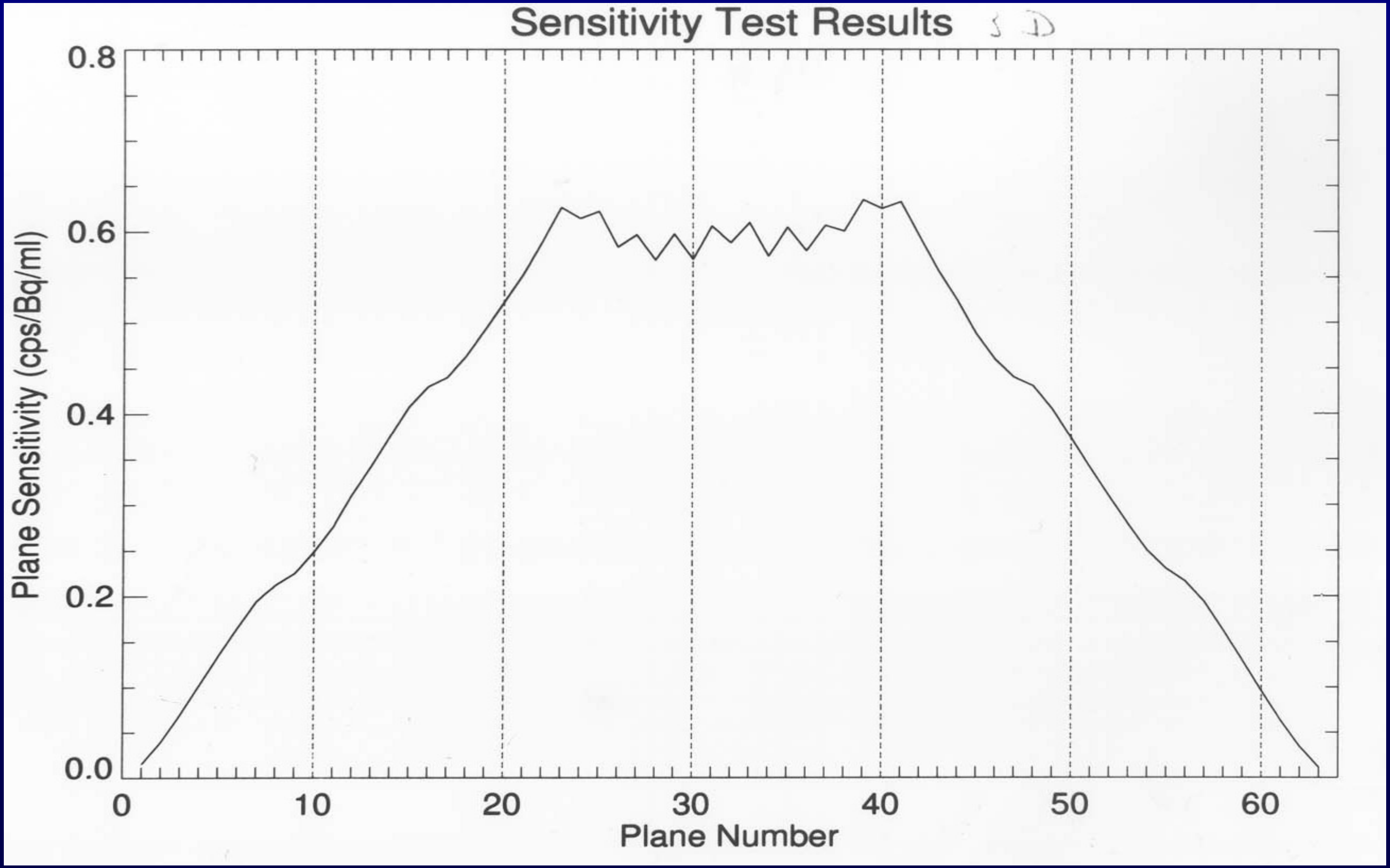


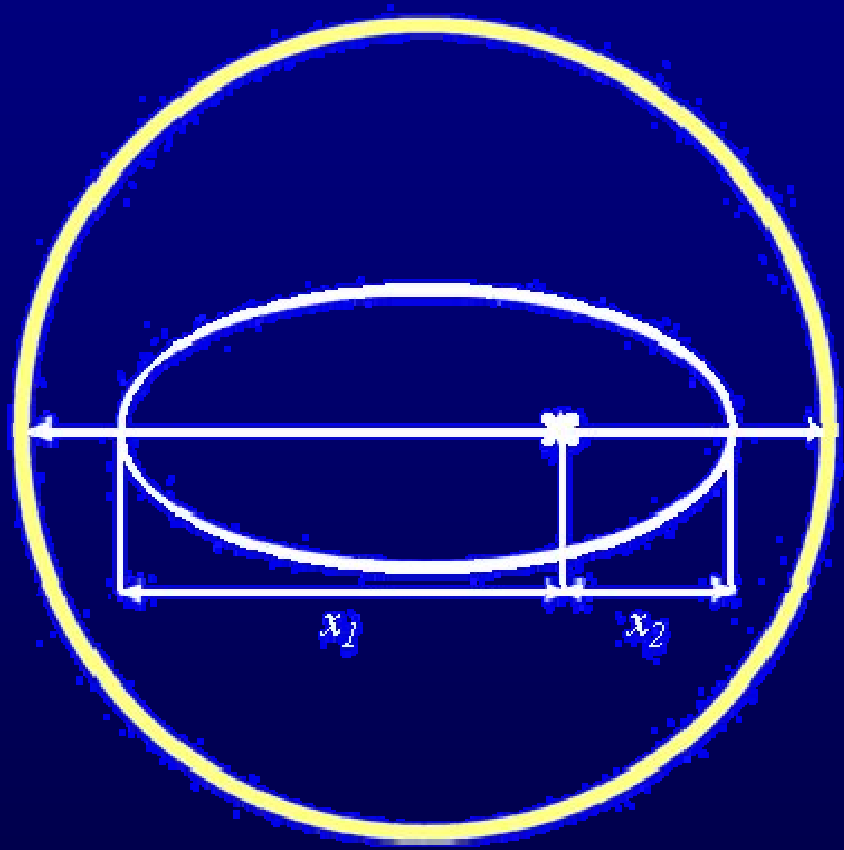


Sensitivity Test Results
2D
Plane Sensitivity (cps/Bq/ml)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
10
20
30
40
50
60
Plane Number



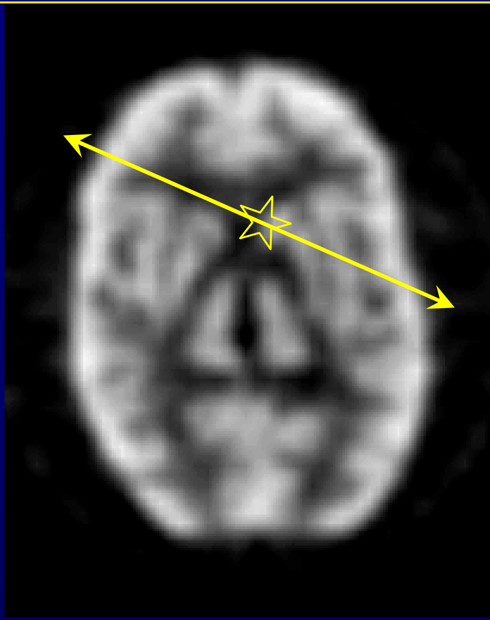
Sensitivity Test Results
Plane Sensitivity (cps/Bq/ml)
0.0
0.2
0.4
0.6
0.8
0
10
20
30
40
50
60
Plane Number

Attenuation correction



Attenuation correction in PET

- In coincidence detected 511 keV photons
- Attenuation is function of the effective length on the LOR
- Simple measurement with external source



$$Atn = Atn_1 * Atn_2 = e^{-\int_{x1}^{a} \mu(s)ds} * e^{-\int_{a}^{x2} \mu(s)ds} = e^{-\int_{x1}^{x2} \mu(s)ds}$$

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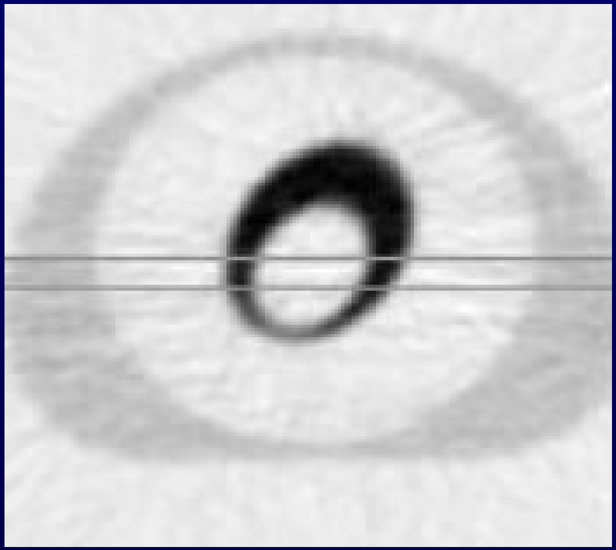
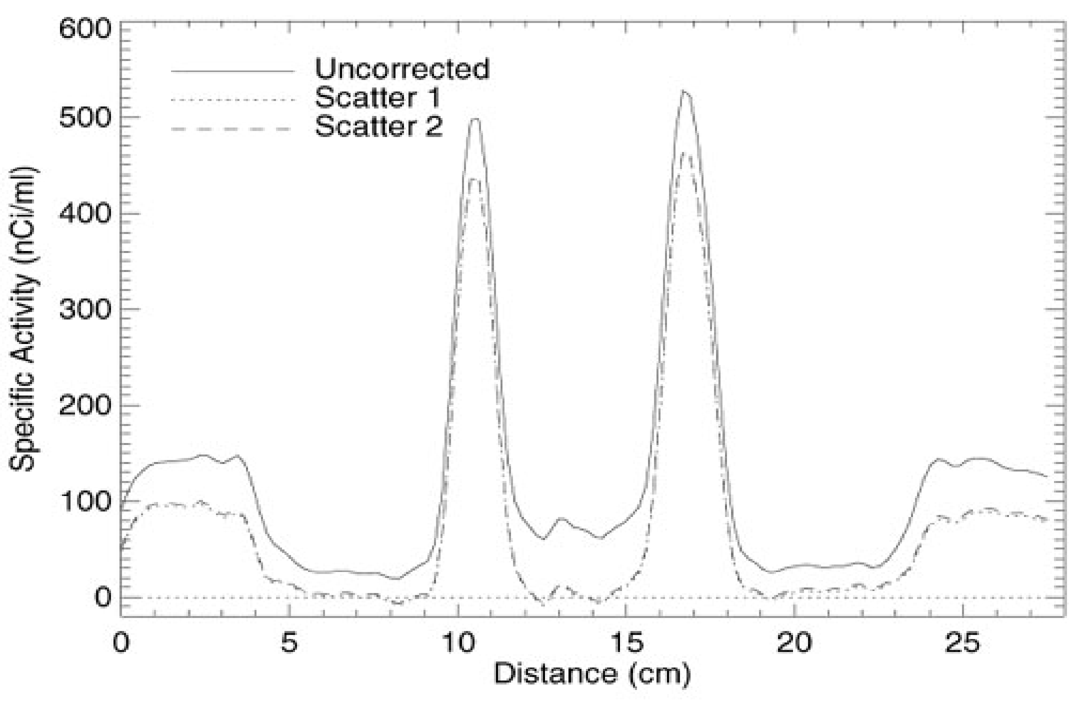
3D Scatter Correction

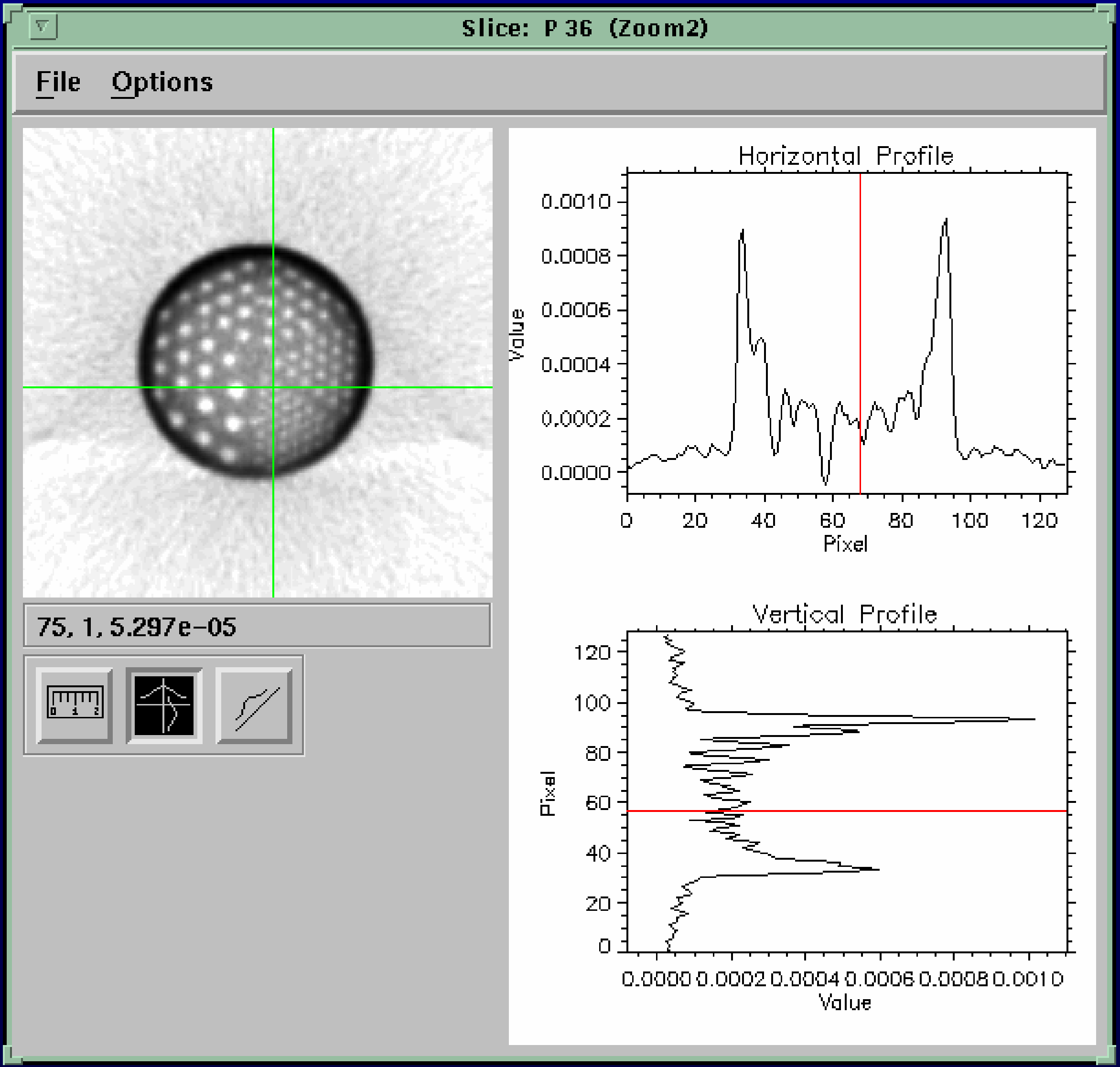
- Scatter correction based on scatter model
- Combined emission & transmission scans





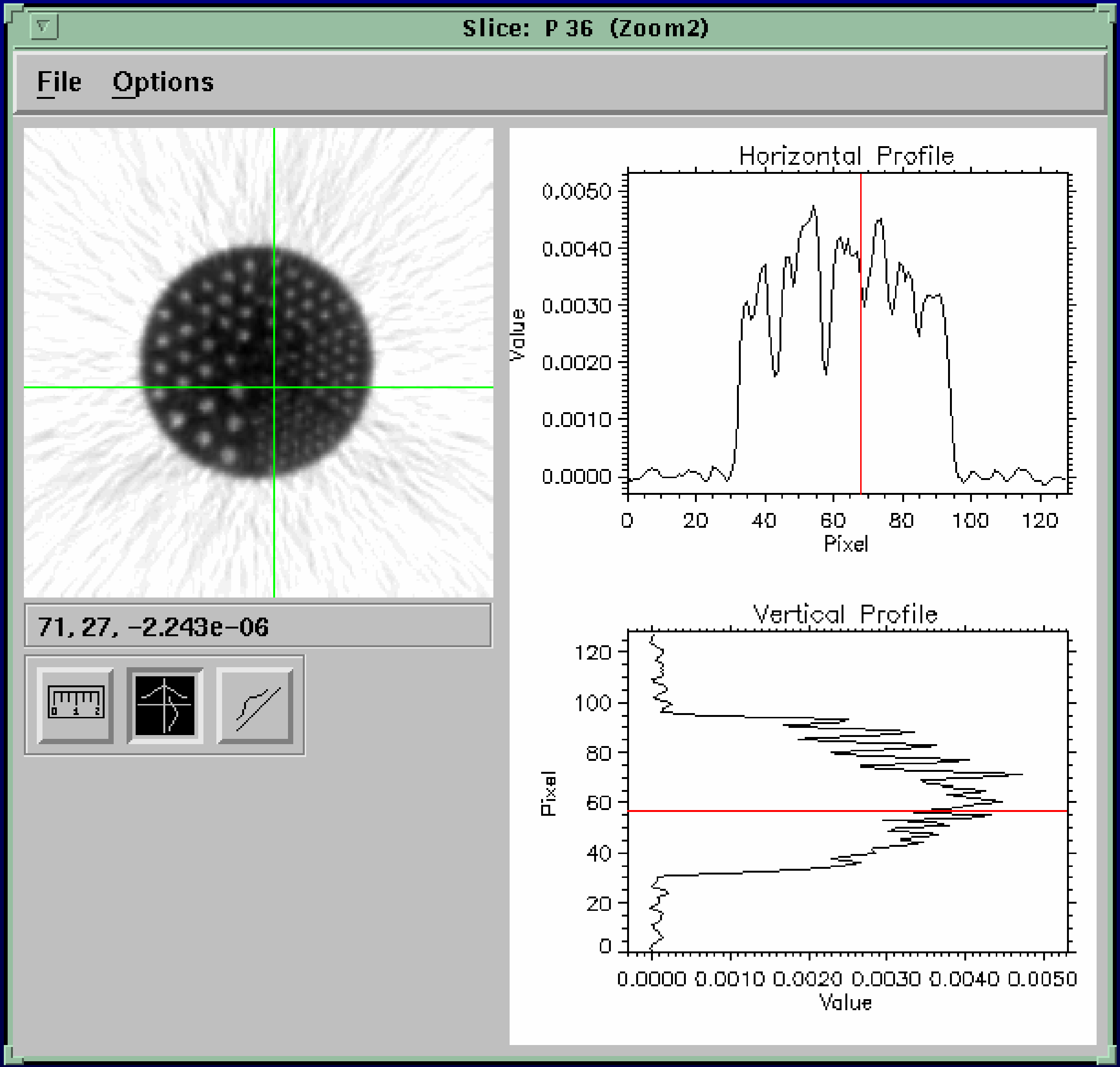
Jaszczak phantom

NO corrections



Jaszczak phantom

attenuation corrected



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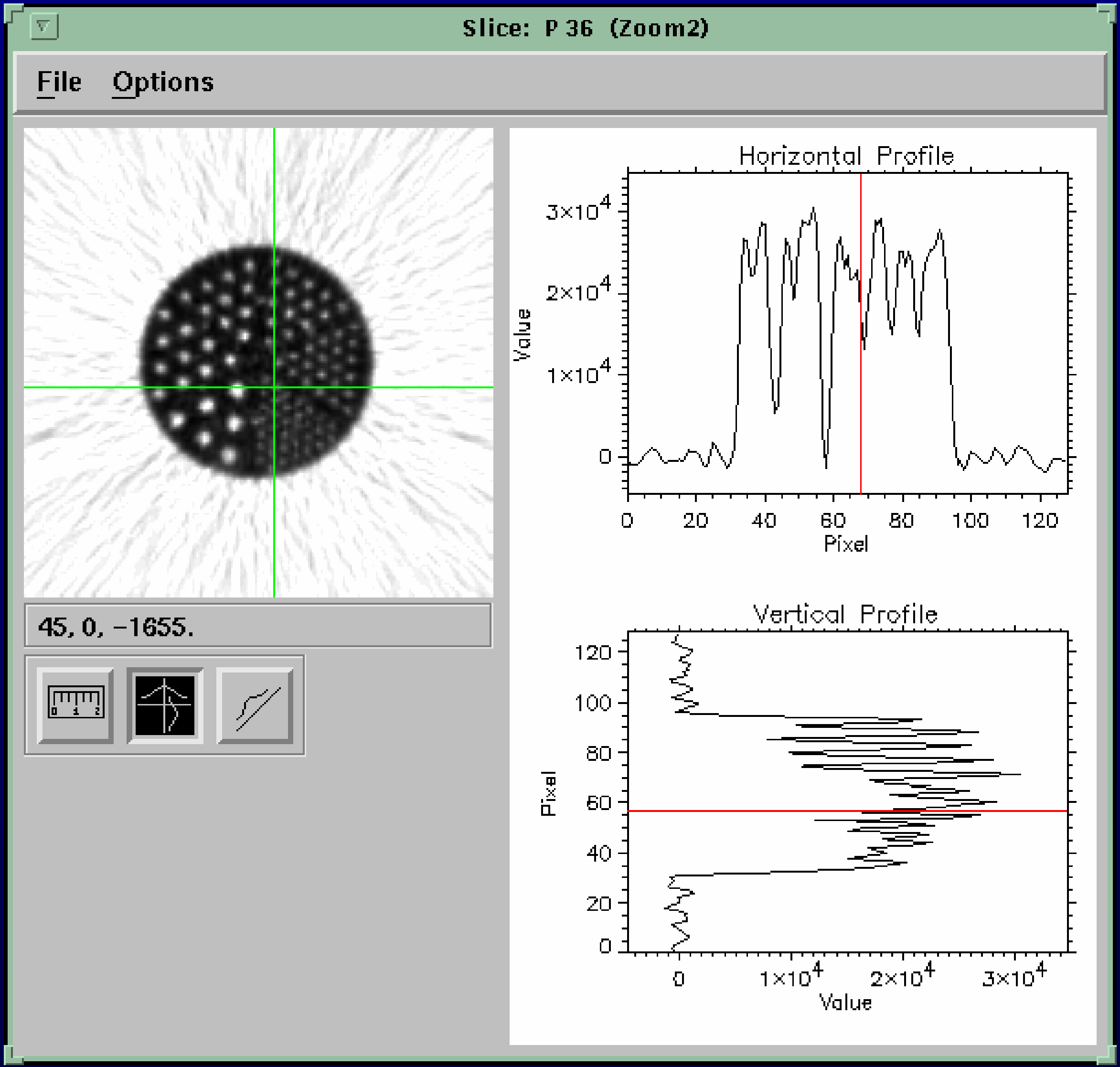
Jaszczak phantom

attenuation & scatter corrected



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Data reconstruction

Data is generated by measuring according projection lines, line integrals

Basic reconstruction is Filtered Back Projection (FBP) according to mathematics described by Radon (1917)

Maximum Likelyhood Expectation Maximization (ML-EM) is a iterative method that maximizes the probability of the reconstructed image for a given set of measured projection data.

Data reconstruction

In PET ML-EM is successful because of Poisson statistics

Problem of iterative methods: NO objective stopping criterium and procedure will easy generate artefacts

Advantage: If stopped at the correct moment, a superior image quality with less noise

Disadvantage: the correct stopping criterium is not a general rule but has to be established per procedure

Data reconstruction

- FBP or ML-EM
- Attenuation correction
- Scatter correction

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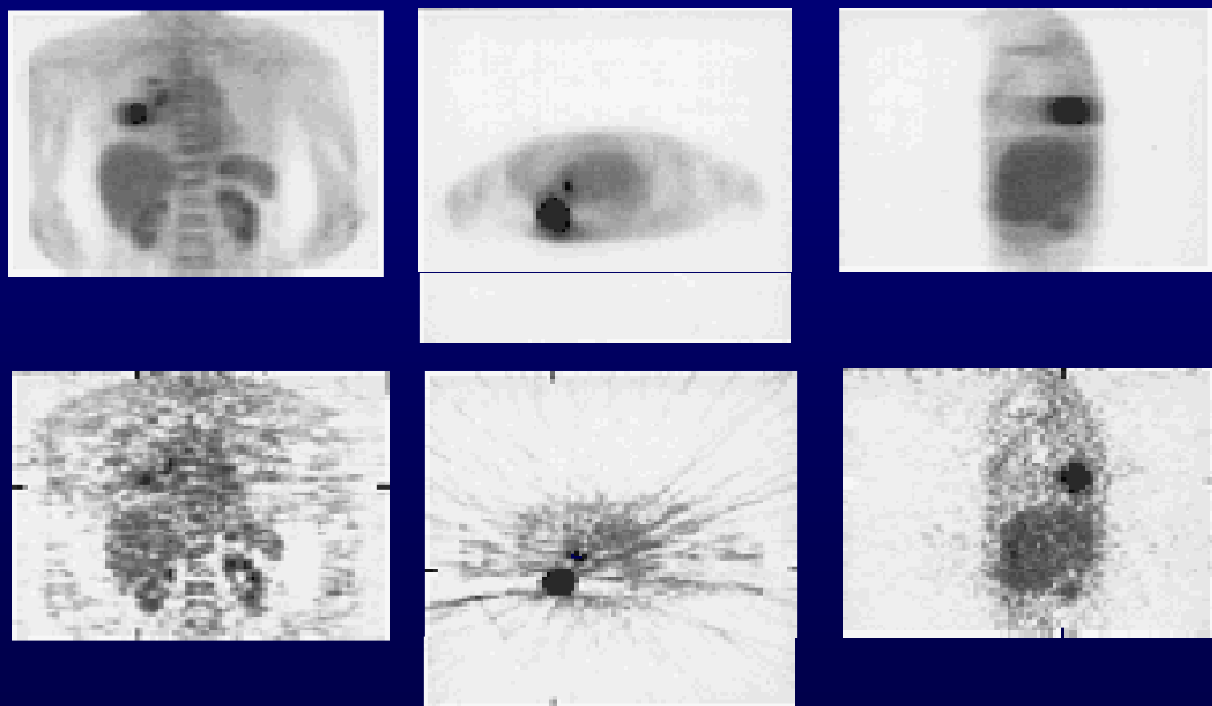
Reconstruction Techniques

Iterative vs Filtered Back Projection (FBP)



Iterative reconstruction

FBP

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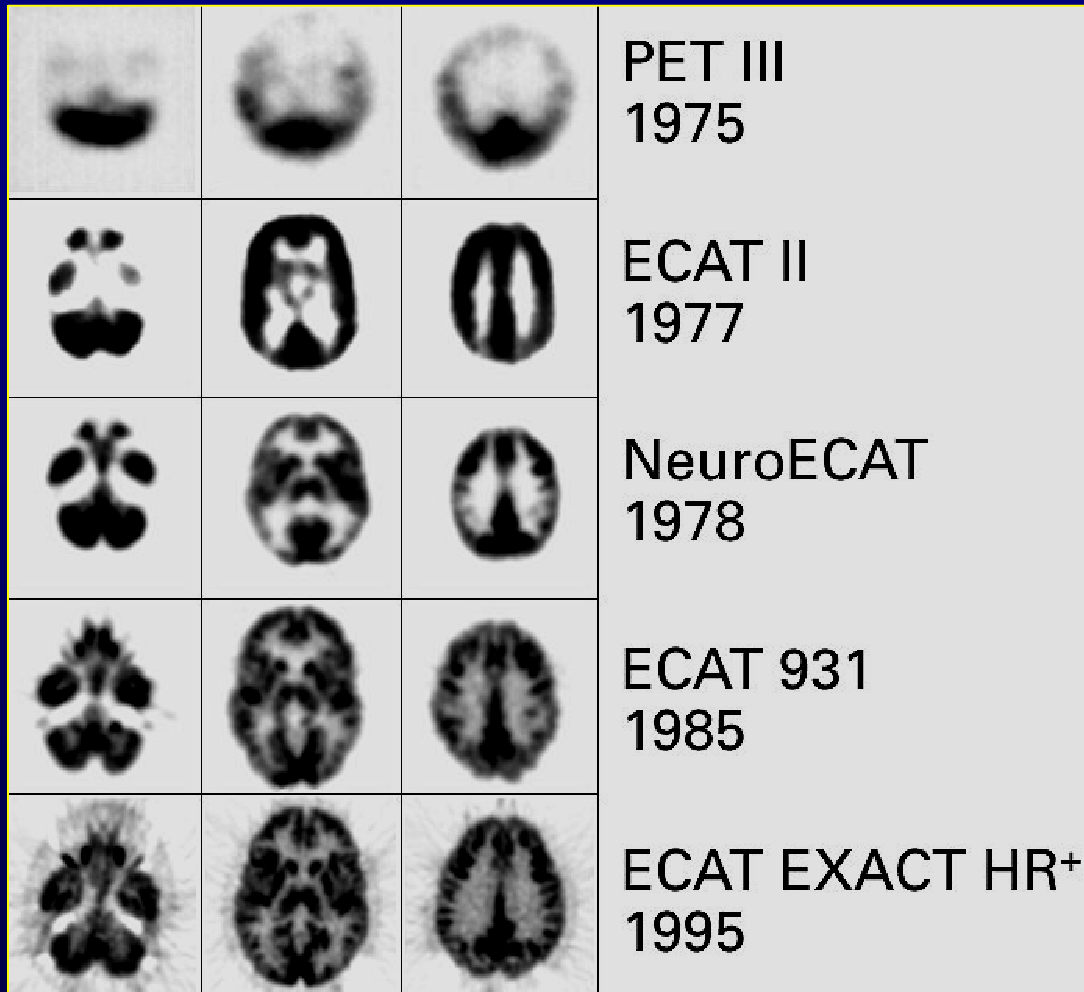
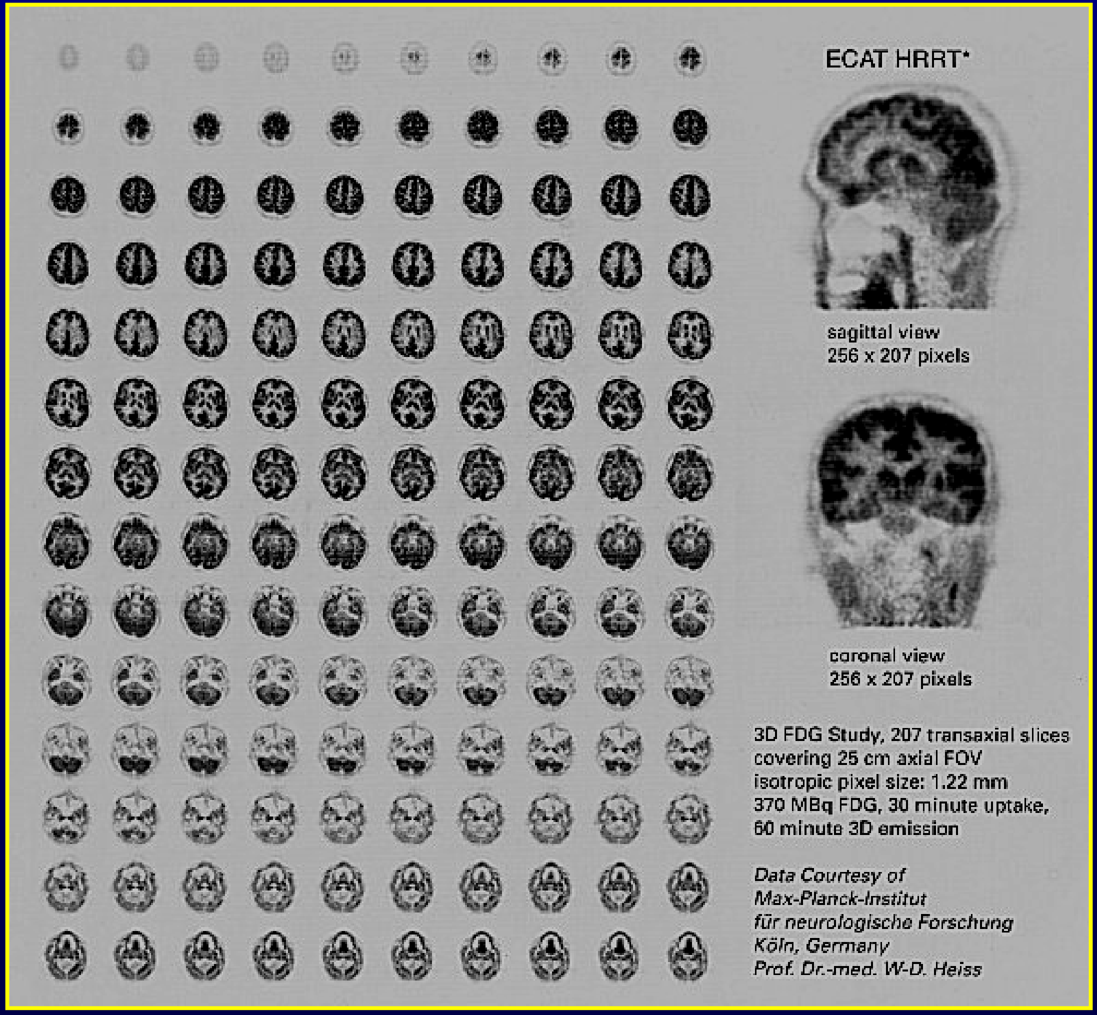
Resolution evolution in time



ECAT HRRT at MPI Cologne



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Positron energies and ranges

Nuclide	$E_{\beta max}$ (MeV)	Range (mm)	$E_{\beta mean}$ (MeV)	Range (mm)
^{11}C	0.961	3.9	0.38	1.1
^{13}N	1.190	5.1	0.48	1.5
^{15}O	1.723	8.0	0.69	2.5
^{18}F	0.635	2.3	0.25	0.6
^{52}Fe	0.804	3.1	0.32	0.9
^{68}Ga	1.899	8.9	0.76	2.9
^{75}Br	1.740	8.1	0.70	2.6
^{82}Rb	3.350	17.	1.34	5.9

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Fundamental Limitations in Spatial Resolution

- Range of the positrons

  The mean range varies from 0.6 mm (^{18}F),

  1.1 mm (^{11}C), 1.5 mm (^{13}N) to 2.5 mm (^{15}O)

  or 5.9 mm (^{82}Rb)

-Non-zero momentum at moment of annihilation

  Finite angular width of 0.5^{o} FWHM about the

  mean angle of 180^{o}

Time Of Flight (TOF) measurement

Detectors A and B at distance 2d, source at distance x from center

PA - PB = (d+x) - (d-x) → dt = 2x/c

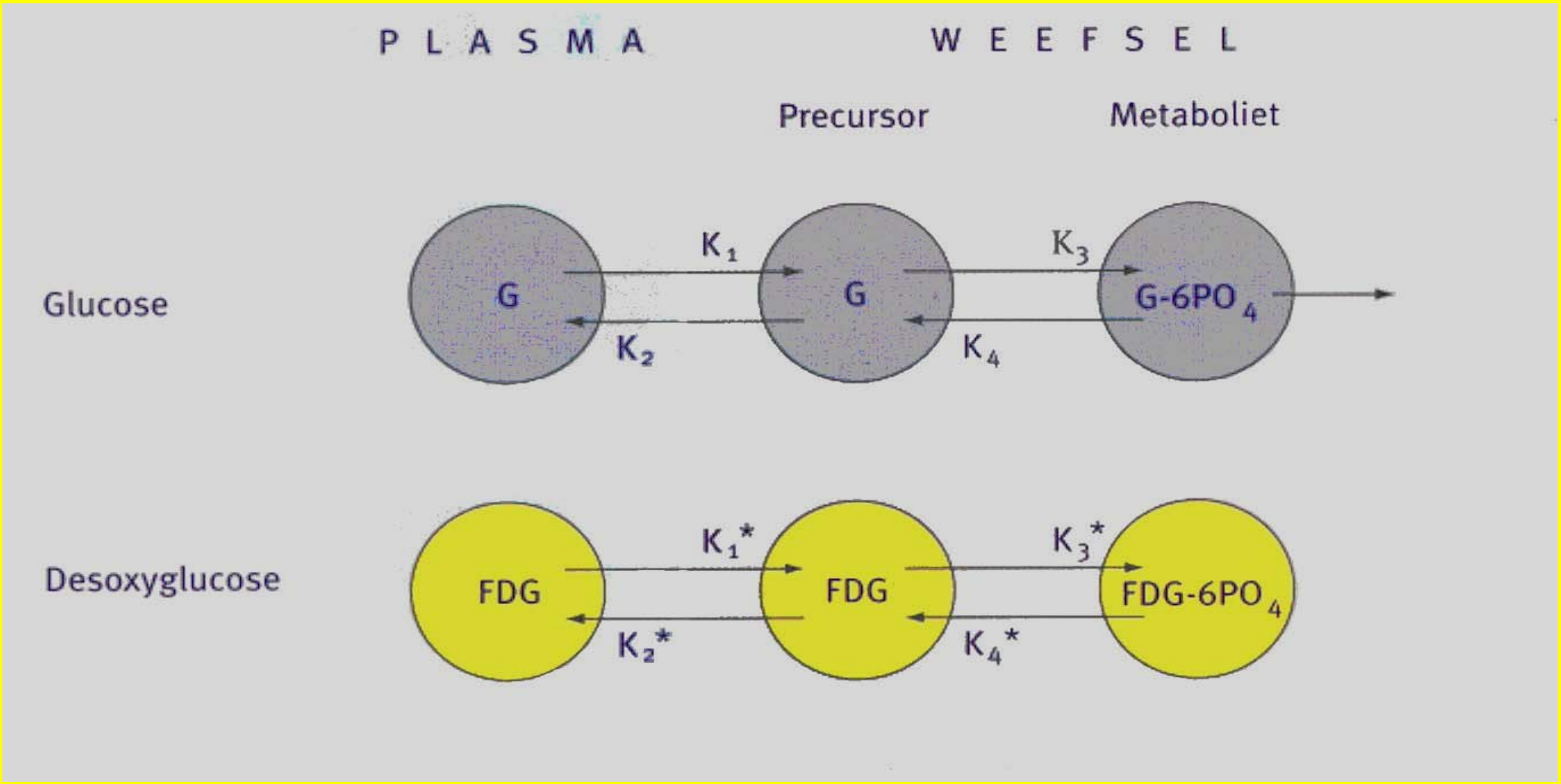
With x = 1 mm → dt = 3.3 ps

Detectors that fast and sensitive to 511 keV do not exist

Brain research

- Blood flow	$H_2{}^{15}O$, $C^{15}O_2$ } oxygen extraction
- Blood volume	^{11}CO, $C^{15}O$
- Glucose metabolism	^{18}FDG
- Tumor metabolism	^{18}FDG, ^{11}C-amino acids
- Receptor density	^{11}C-raclopride, ^{18}F-DOPA, ^{18}FESP
- Stimulus research	$H_2{}^{15}O$, ^{18}FDG

Pathophysiology: FDG-model



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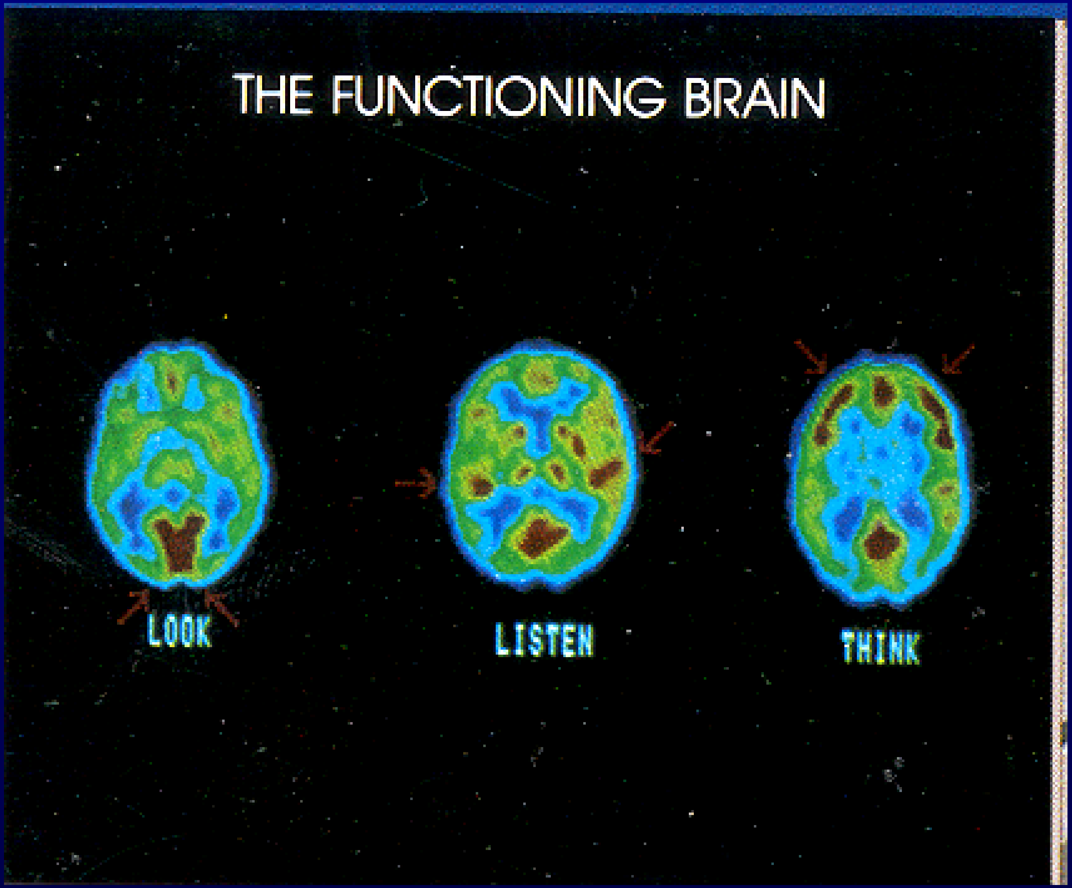

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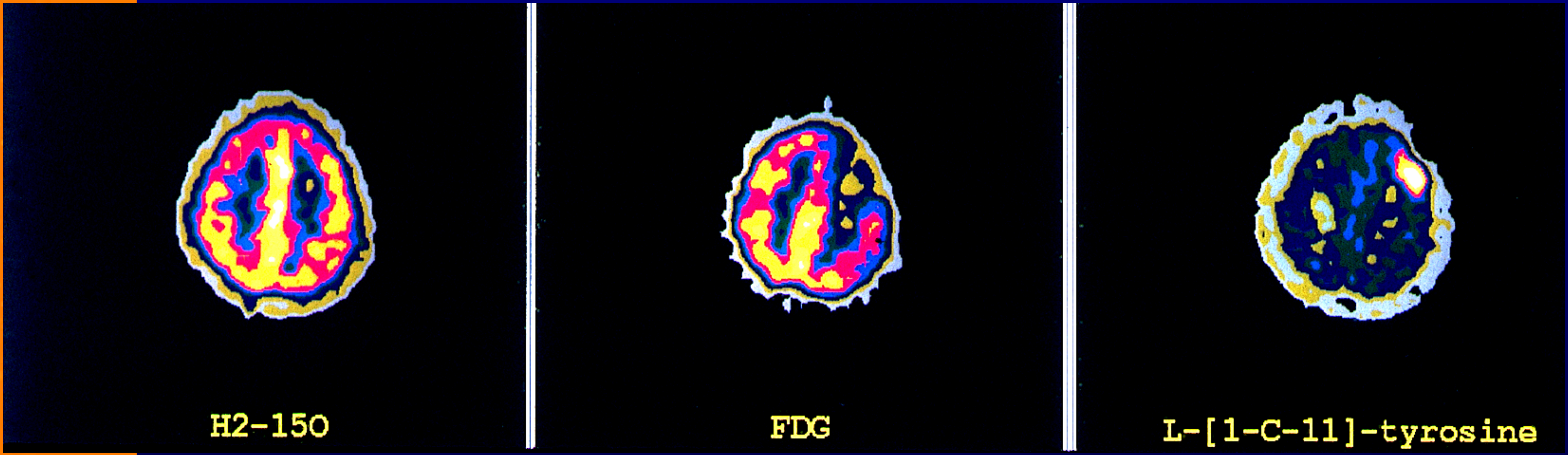

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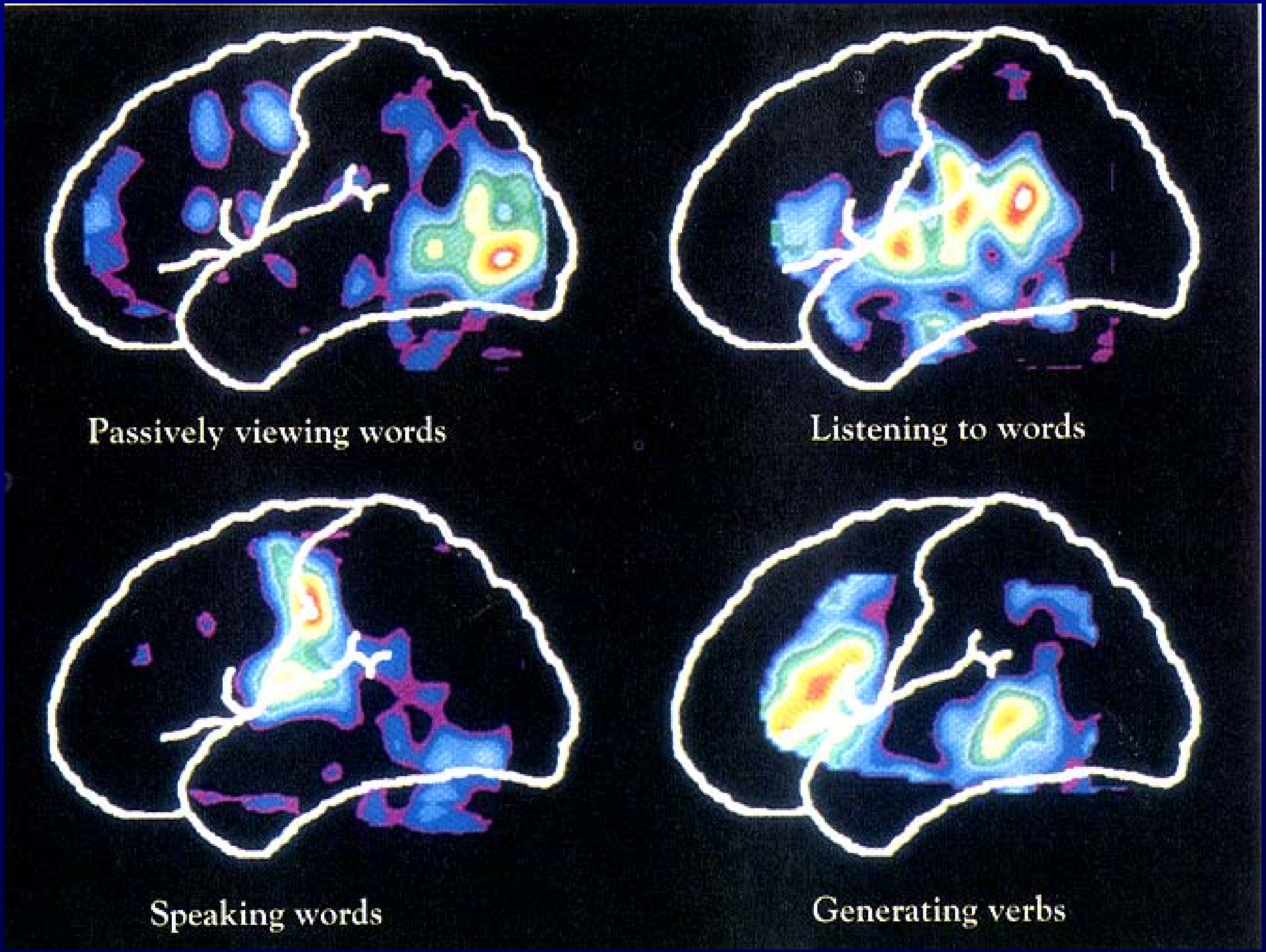
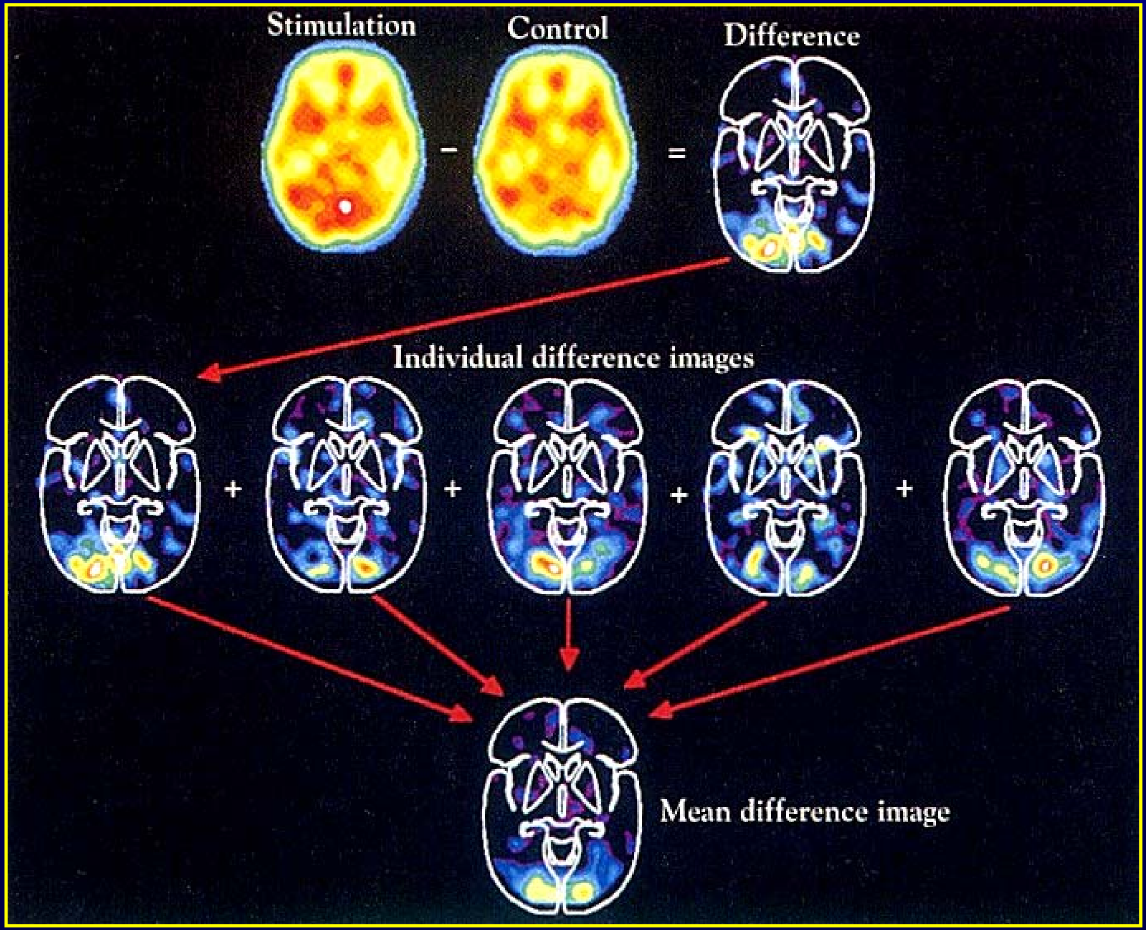
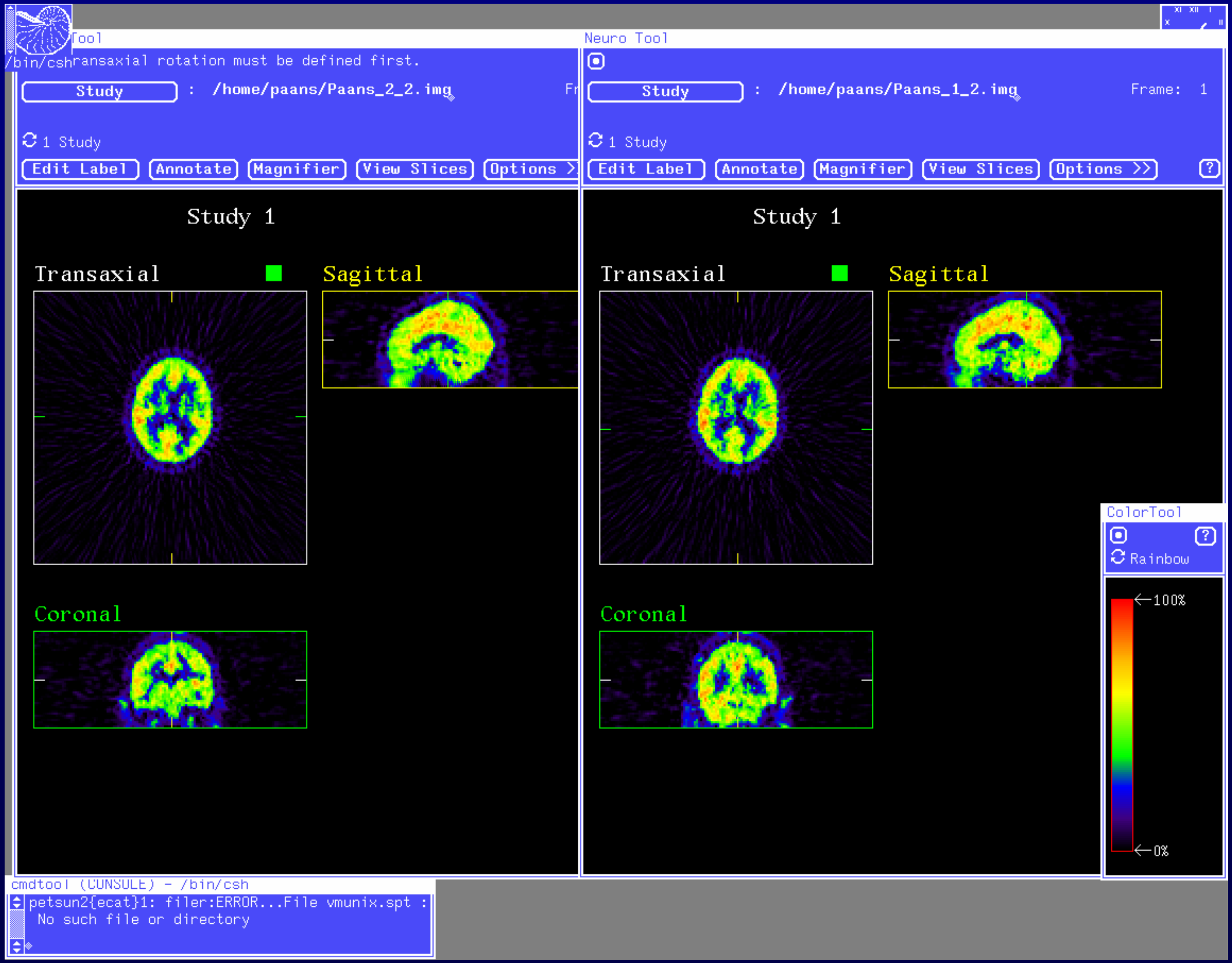

Passively viewing words
Listening to words
Speaking words
Generating verbs

datum

Functional Neuro-anatomy: The Concept



Visual stimulation vs rest



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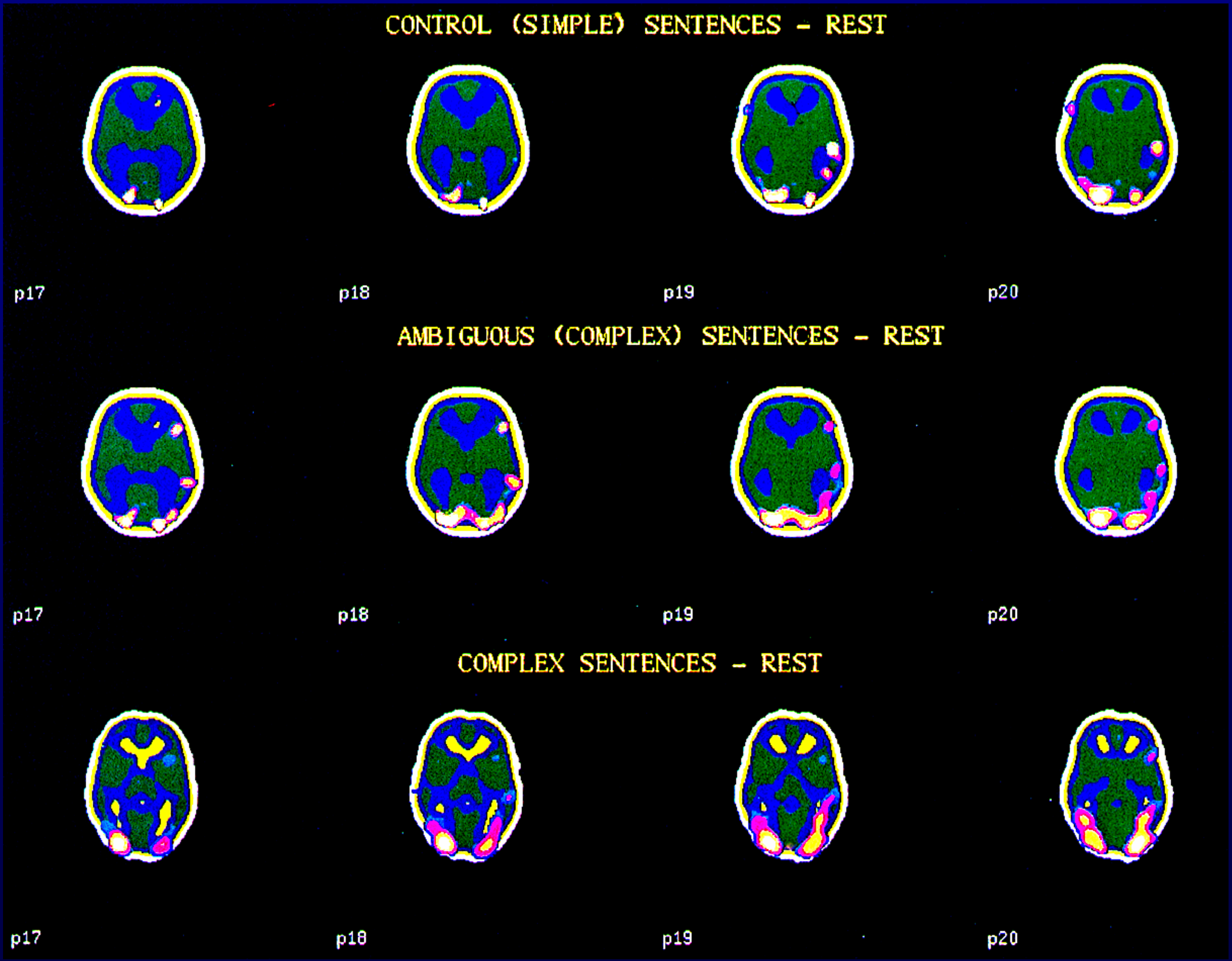
Language Study: Functional Brain Imaging

Complex Dutch Sentense

Of hogere straffen waartegen rechters protesteren dergelijke ongevallen voorkomen kan betwijfeld worden.

Ambiguous Dutch Sentense

Zij kunnen bakken met zulk deeg niet verplaatsen.



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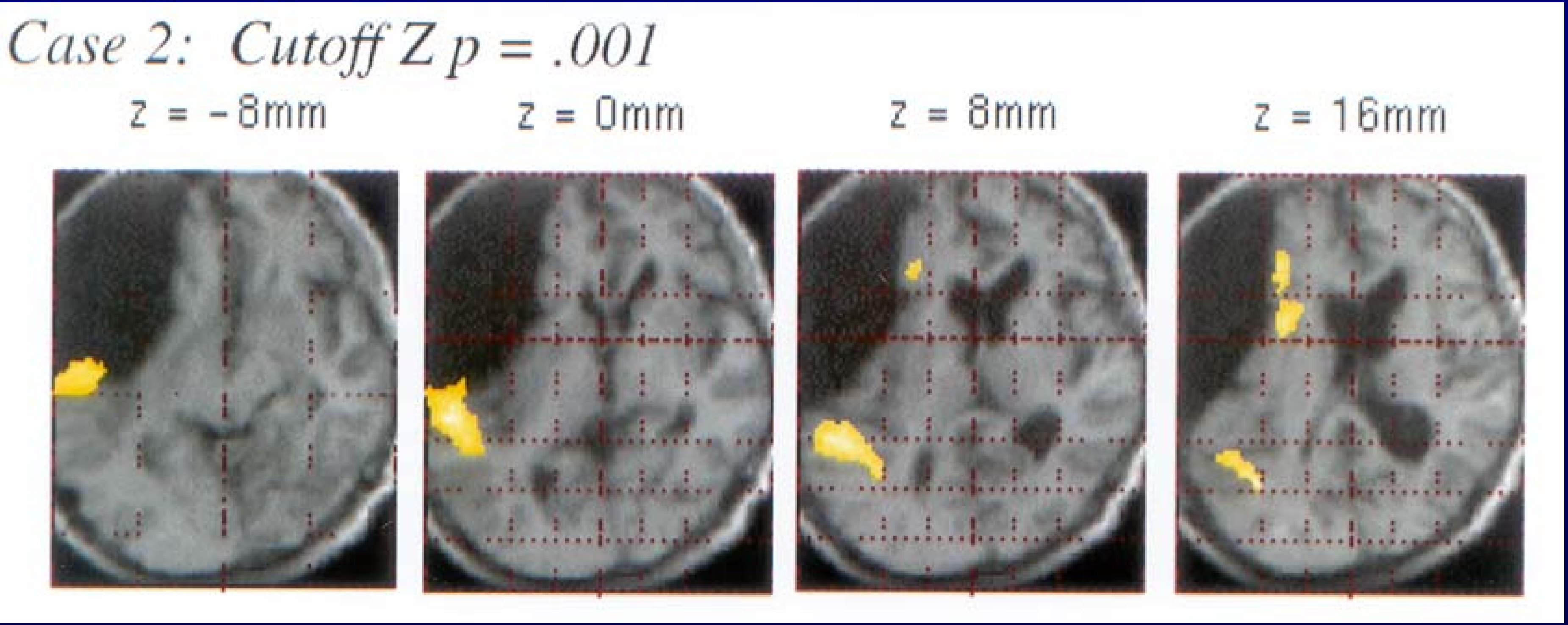
Language localization in case of LTL arachnoid cyst



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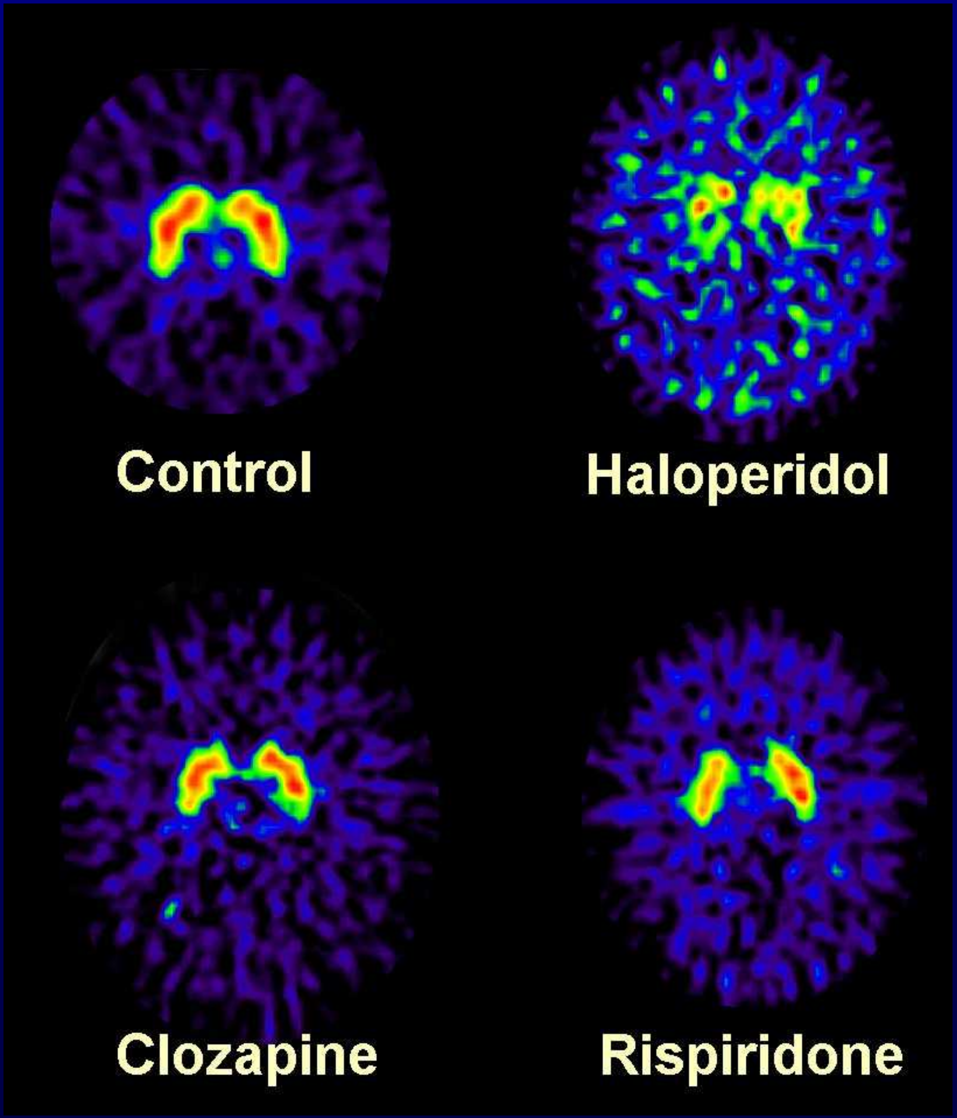
FESP and medication



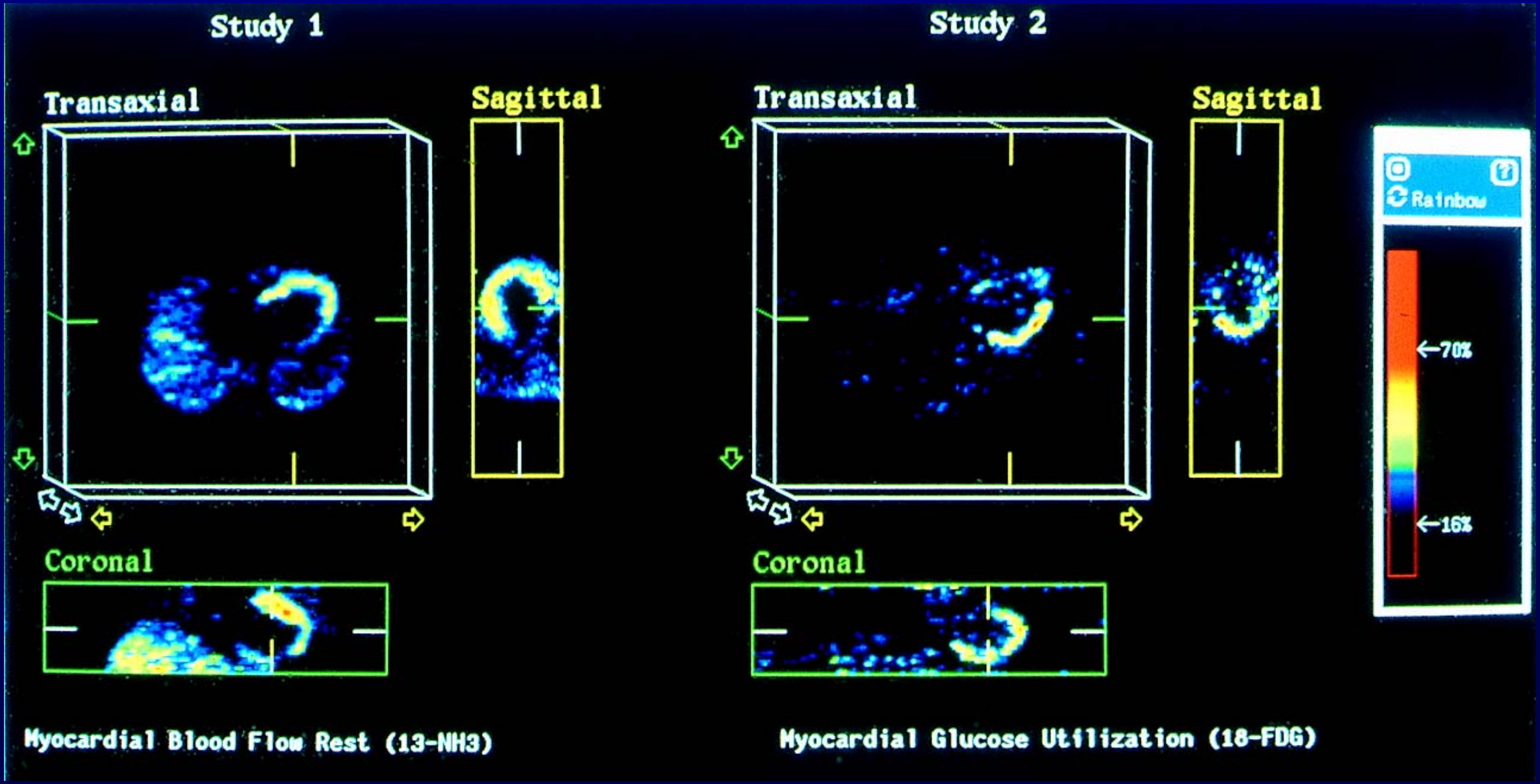
Cardiac research

- Flow $^{13}NH_3$, $H_2{}^{15}O$, ^{82}Rb

- Metabolism ^{18}FDG, ^{11}C-fatty acids, ^{11}C-acetate

- Hypoxia ^{18}F-fluoromisonidazole

- Receptors ^{11}C-CGP-12177



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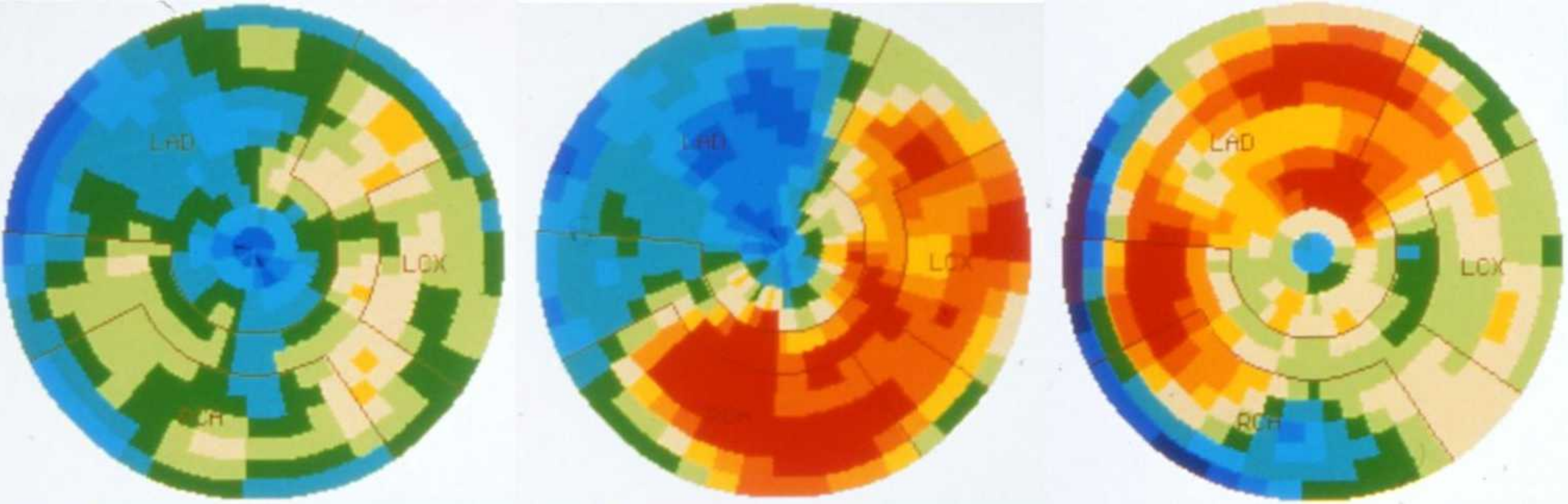
Bypass surgery: yes or no?

Flow at rest **Flow at stress** **Glucoseconsumption**



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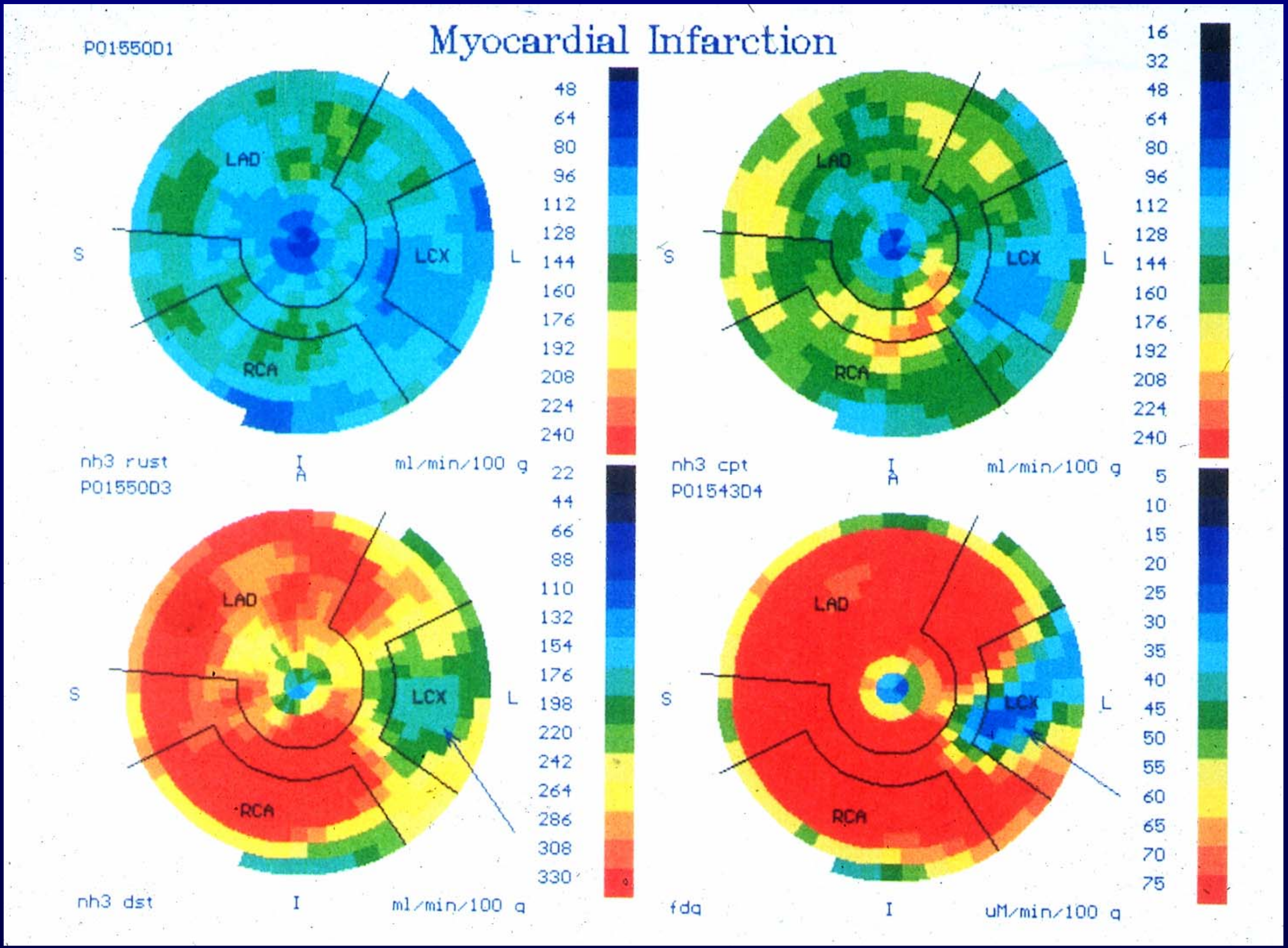
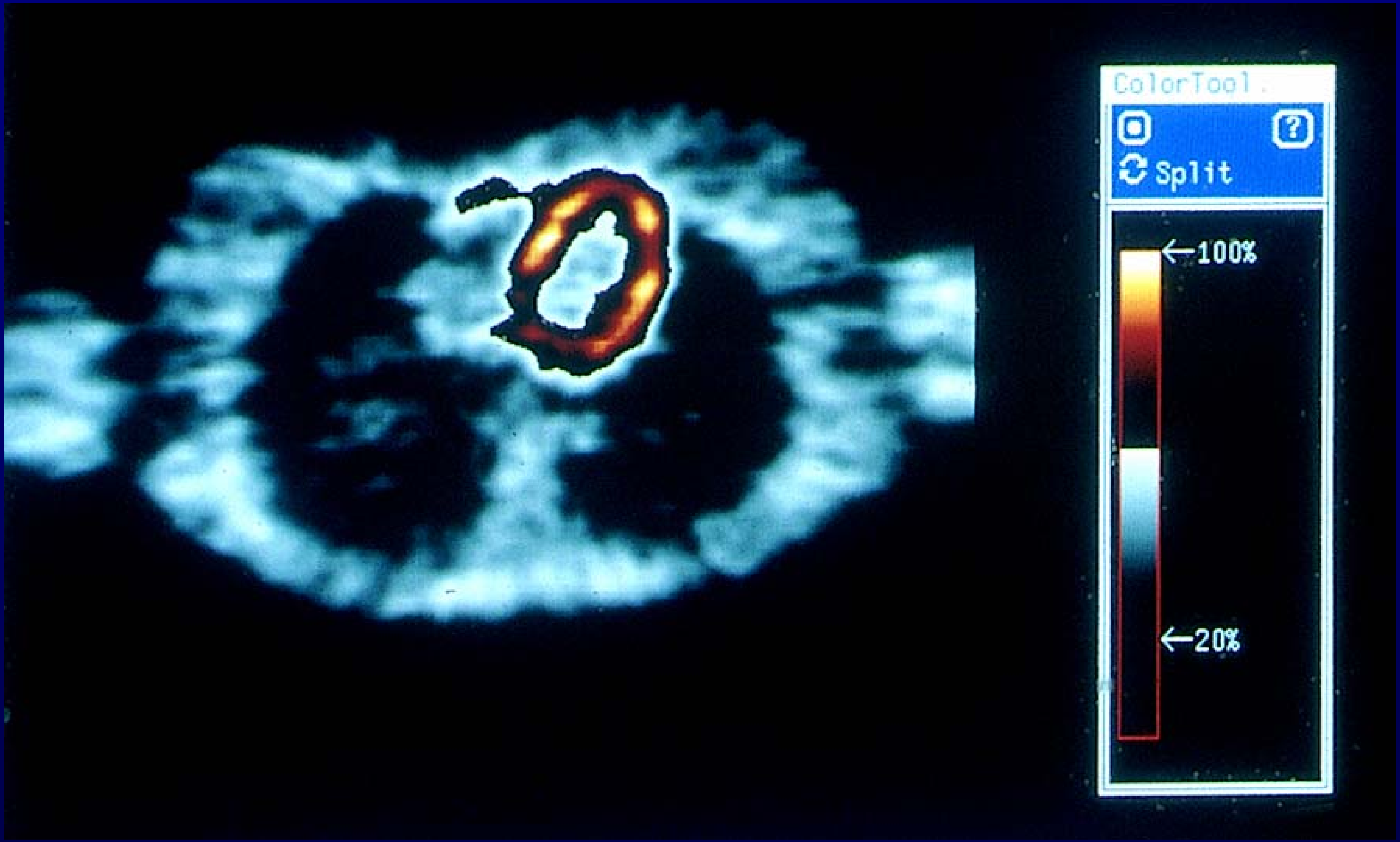


Myocardial Infarction
P0155OD1
LAD
S
LCX
L
RCA
nh3 rust
I
A
ml/min/100 g
48
64
80
96
112
128
144
160
176
192
208
224
240
nh3 cpt
ml/min/100 g
16
32
48
64
80
96
112
128
144
160
176
192
208
224
240
P0155OD3
22
44
66
88
110
132
154
176
198
220
242
264
286
308
330
nh3 dst
ml/min/100 g
P0154304
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
fdg
uM/min/100 g

datum



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Oncological research

- Tumor flow	$^{13}NH_3$, $H_2{}^{15}O$
- Tumor metabolism	^{18}FDG, ^{11}C-tyrosine, ^{11}C-methionine, ^{11}C-thymidine, ^{18}FLT
- Cytotostatic kinetics	^{11}C-cytostatics
- Therapy monitoring	Change in metabolism

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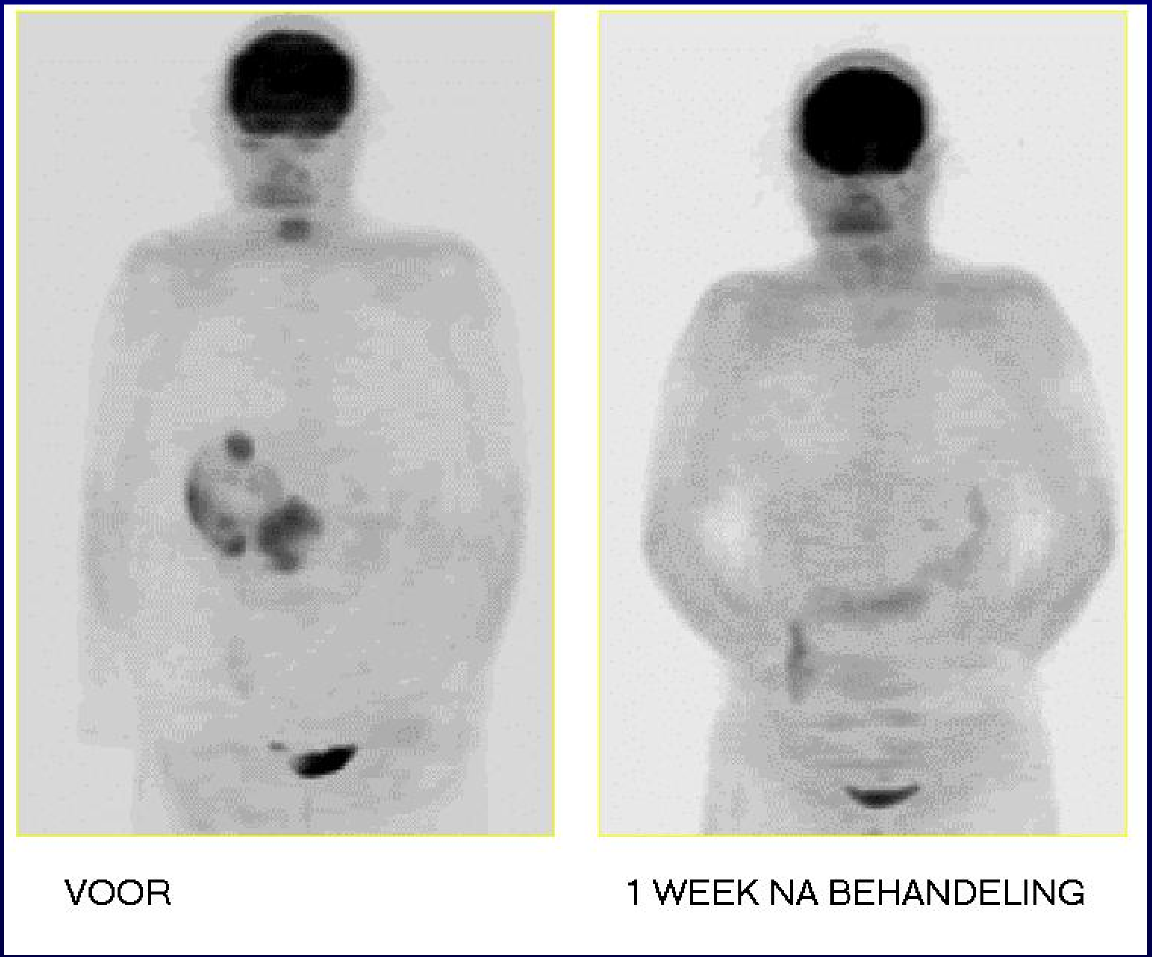
Therapy evaluation



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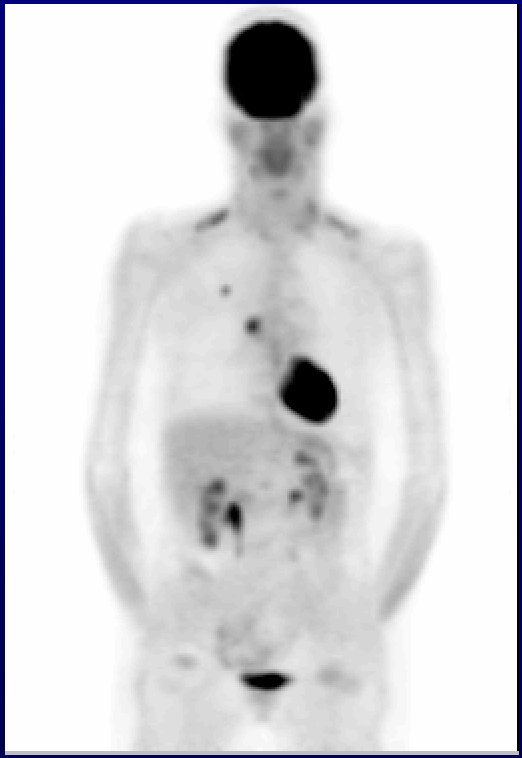
Data Analysis of PET Data

- **Visual analysis**
- **Normalised uptake (SUV)**
- **Pharmacokinetic modelling**



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PET/CT

the Siemens solution

SIEMENS 4

NM

Biograph: The imager for life

- ECAT EXACT HR+: High performance PET scanner
- ECAT Accel: High throughput PET scanner
- Siemens Somatom Emotion: High performance, spiral CT
- 70 cm patient port
- Optimized bed design
- Siemens syngo-based computer system

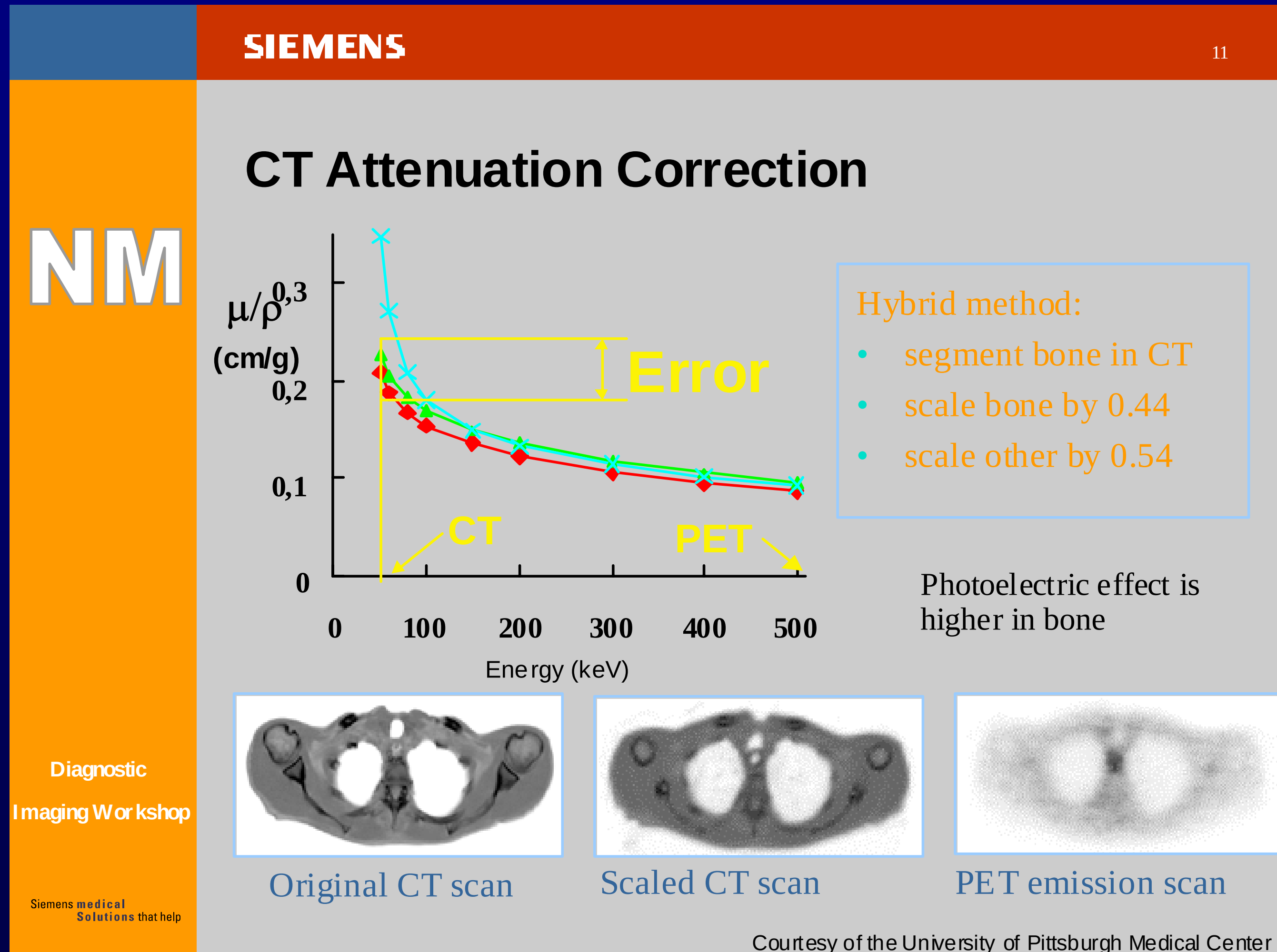
Diagnostic Imaging Workshop

Siemens medical Solutions that help

Attenuation correction

at CT energy (~ 70 keV)

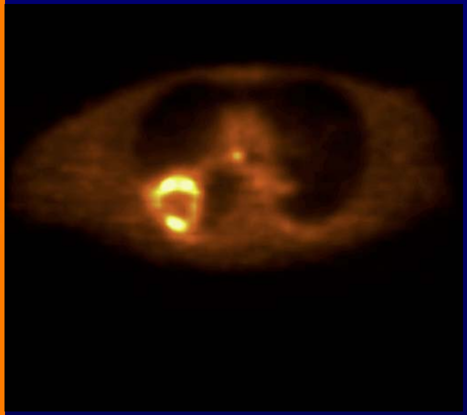
at PET energy (511 keV)



datum

Camera development: PET/CT

- **Hardware fusion**



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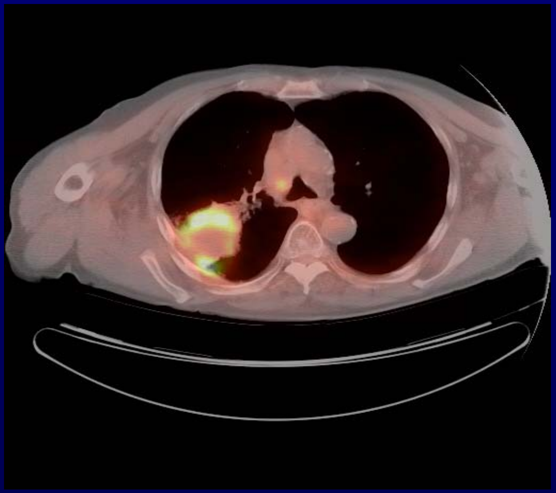
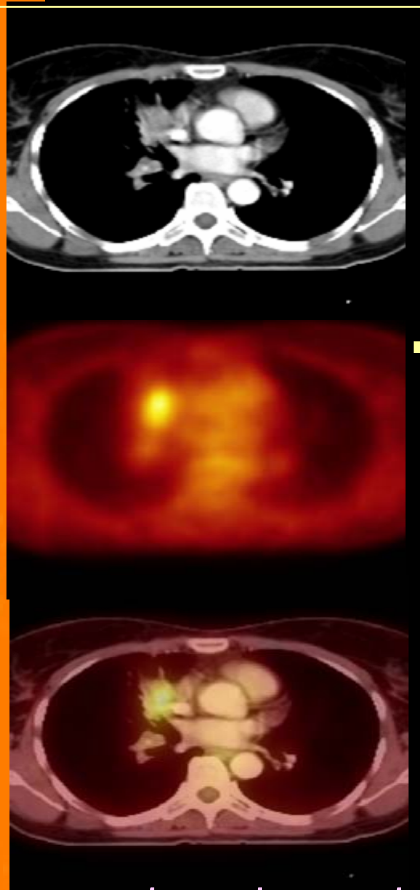
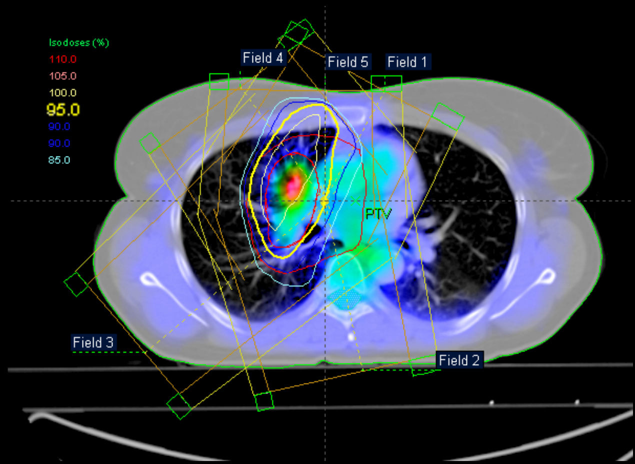


PET **CT** **PET/CT**

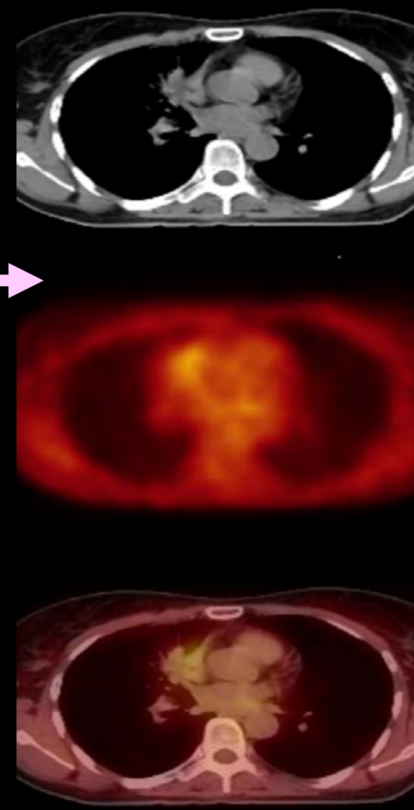
datum



pre-treatment



Treatment plan



post-treatment

RT planning and response

Case: Female with bronchial CA for RTP.

Scan protocol:
Standard whole-body PET/CT scan pre- and post-therapy. Pre- and post-therapy PET/CT can be registered using manual syngo-fusion tool.

Findings:
Evaluate extent of disease prior to RT. RT planning based CT or PET/CT. Evaluate RT response.

Data Courtesy of University Essen (Dr s S Marnitz and S Mueller)

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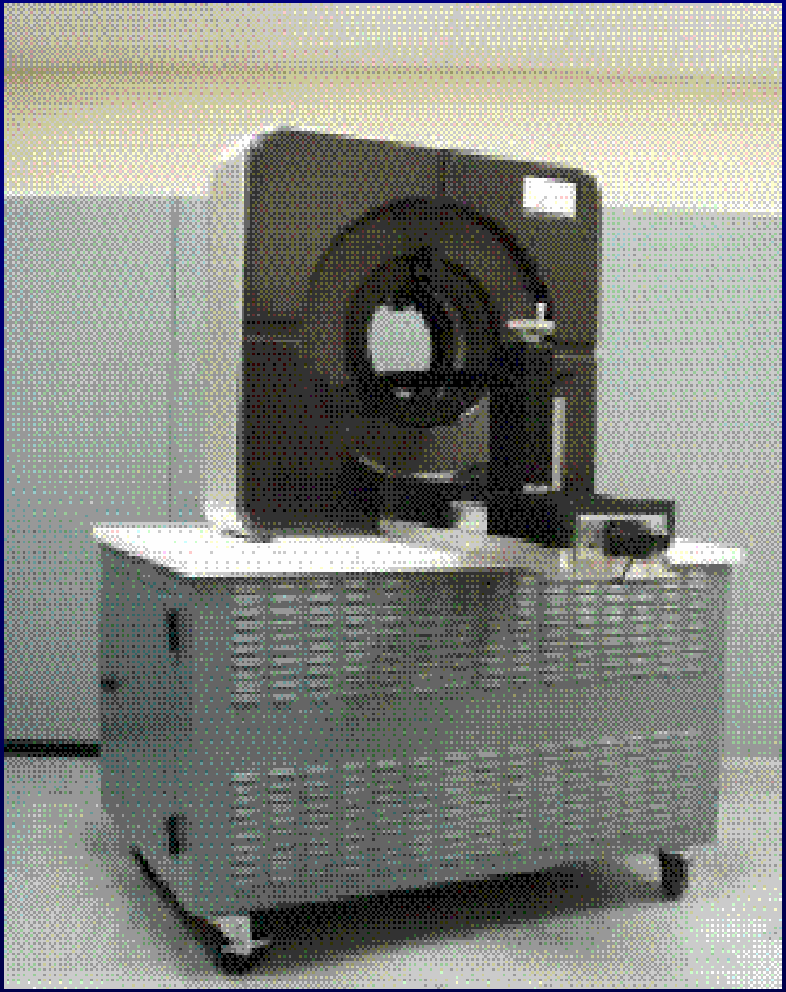
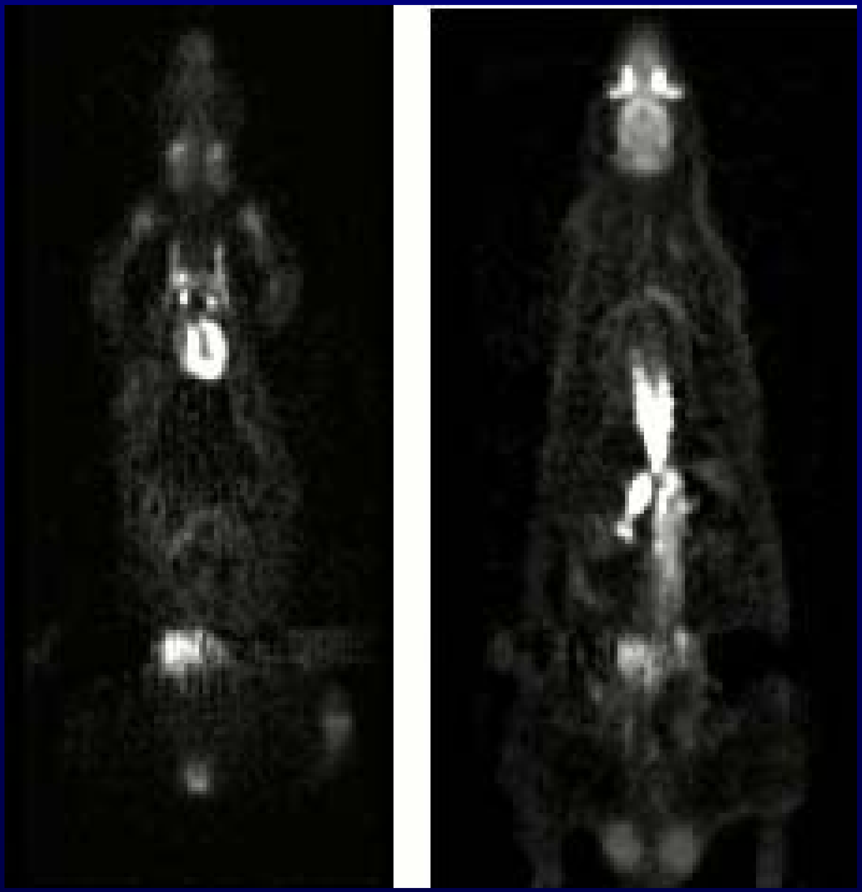
MicroPET-P4



^{18}FDG-Whole body rat images with MicroPET



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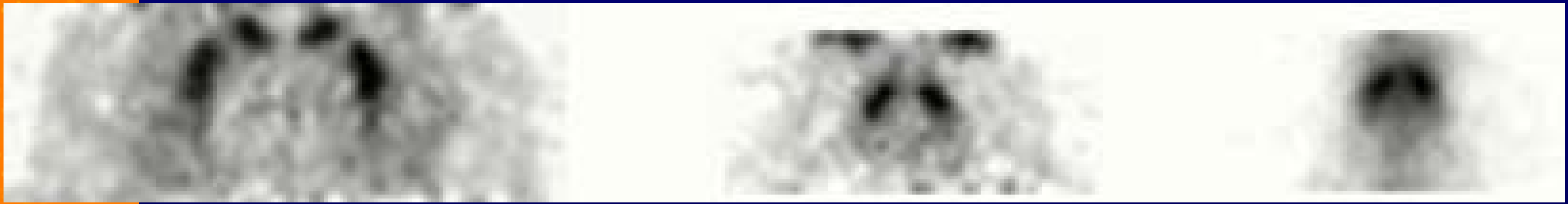
^{11}C-WIN 35,428 for Pre-synaptic DA-transport imaging

Monkey Rat Mouse



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