BioMaps
LABORATOIRE D'IMAGERIE BIOMÉDICALE

UNIVERSITÉ PARIS SUD | FACULTÉ DE MÉDECINE
université PARIS-SACLAY

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Inserm

GATE activities @ BioMaps – Orsay

New labs in the Service Hopitalier Frédéric Joliot (SHFJ)
Multimodality Medical Imaging Labs (Nuclear ; MRI & US modalities) for oncology, neurology and pharmacology applications

Outline

A Cerenkov detector for Arterial Input Function estimation in the context of molecular PET imaging

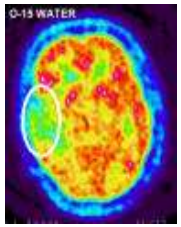
- Metabolic modelling in PET
- Compartment models
- Arterial Input Function : AIF
- Idea of a Cerenkov detector
- Simulation studies
- Perspectives on this project

Metabolic modeling in PET

From de PET image quantification in bq/cc

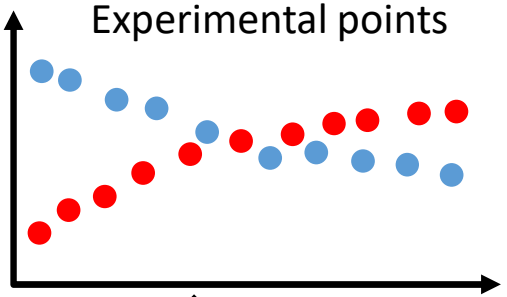
To the physiological parameters
Ex : CMRglu *(µmol.ml^{-1}min^{-1})*

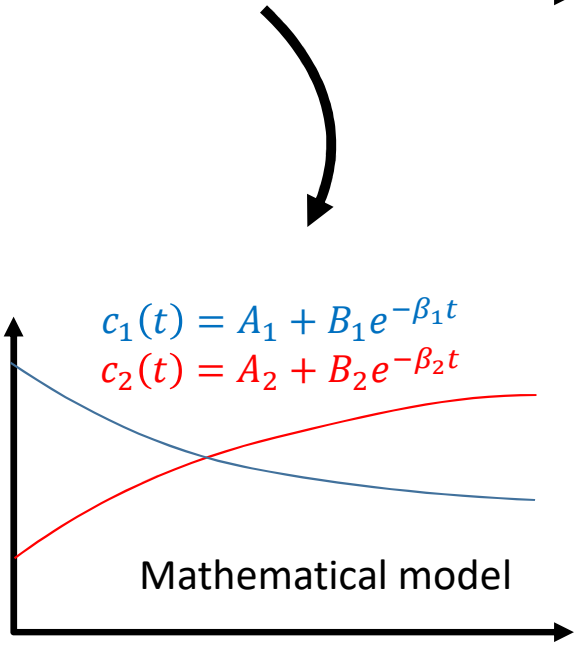
Image



Functional dynamic acquisition

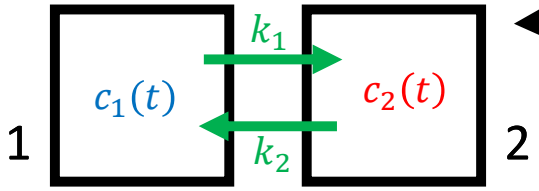
Experimental points





Metabolic modeling

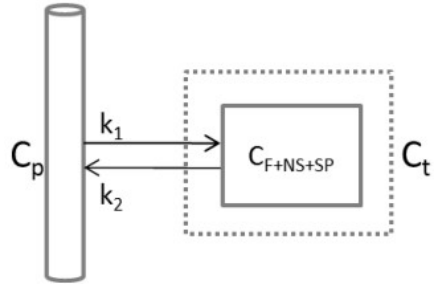
Biological parameter



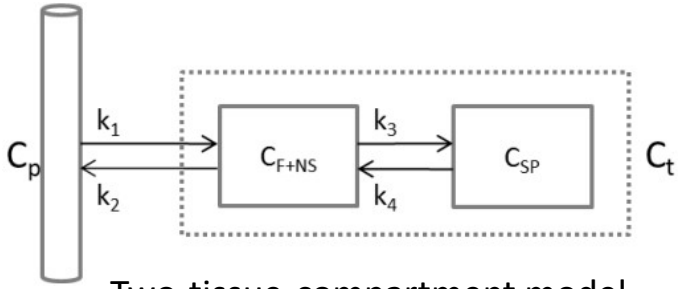
Main compartment models

To model the tracer biodistribution

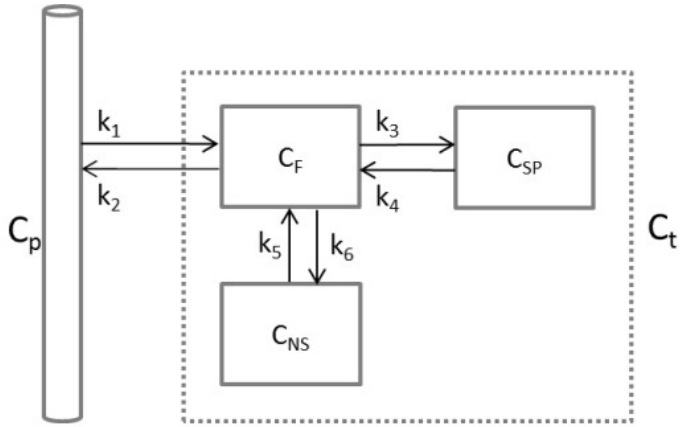
- Compartment models
- Blood compartment
- Tissue compartments
- Tracer can have several components in the tissue *(free, non-specific, specific…)*
- The model define a differential equations system to compute the rate parameters *(k_i)*



One-tissue-compartment model
(=two-compartment model)

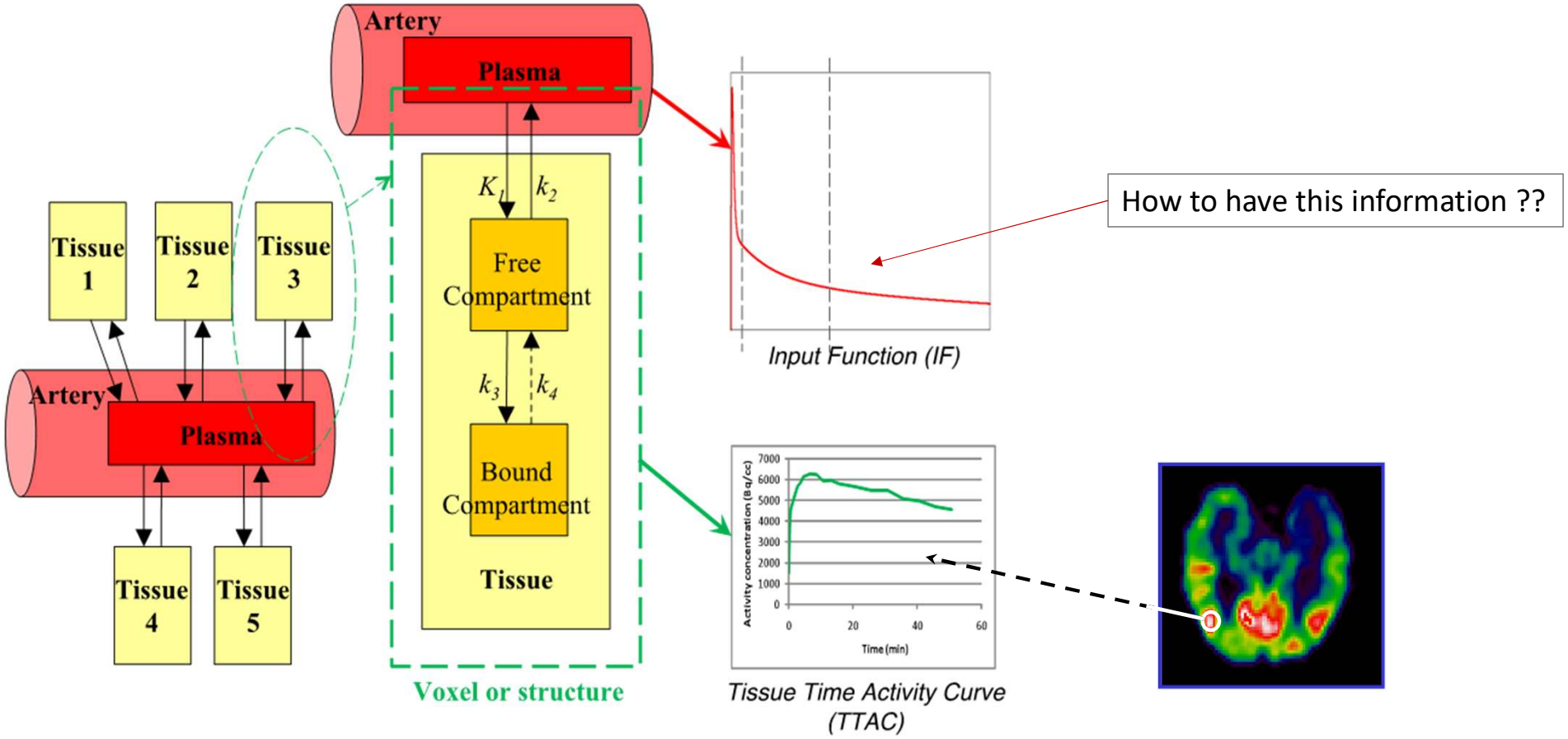


Two-tissue-compartment model
(=three-compartment model)



Three-tissue-compartment model
(=four-compartment model)

To summarise for PET imaging



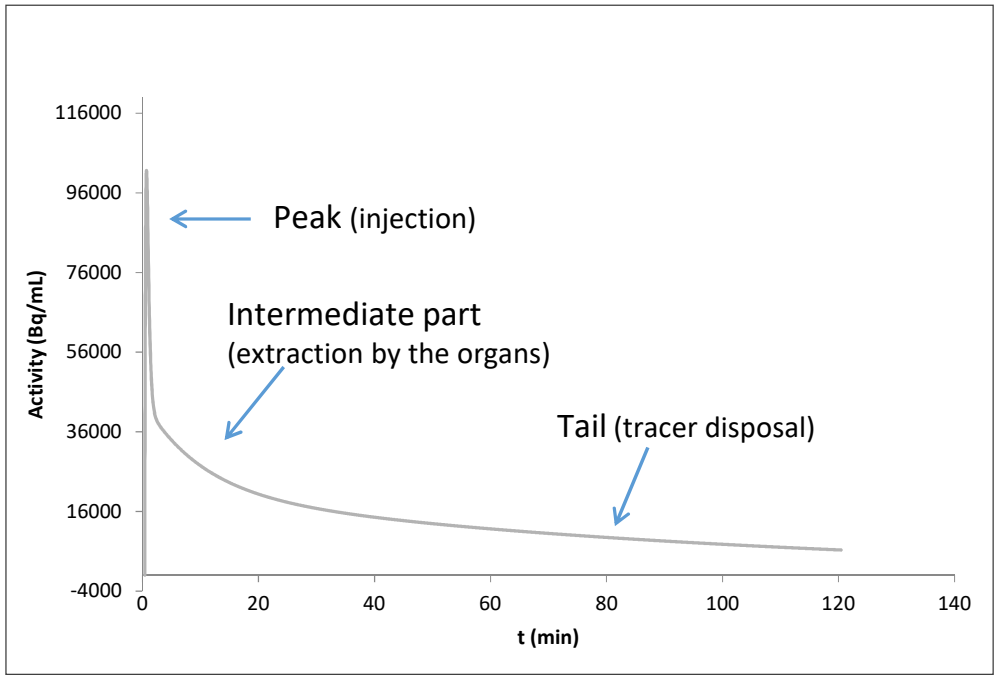
The arterial input function - AIF

Definition: Concentration

- In the arterial plasma
- of the free

(non linked to plasma proteins)

-non–metabolized tracer



Reference estimation method:

Arterial blood sampling (very invasive)

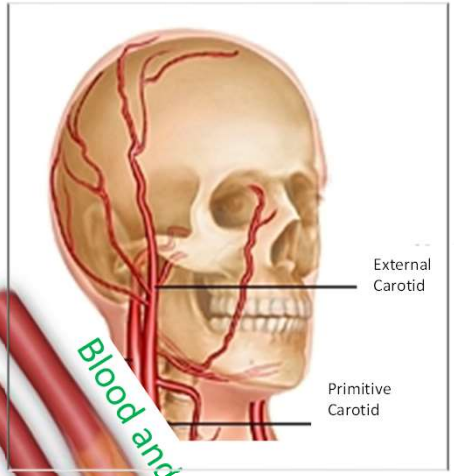
⇒ Alternative methods :

⇒ Image-derived input function *(image processing with an arterial ROI in the image FOV)*

⇒ Dedicated devices….

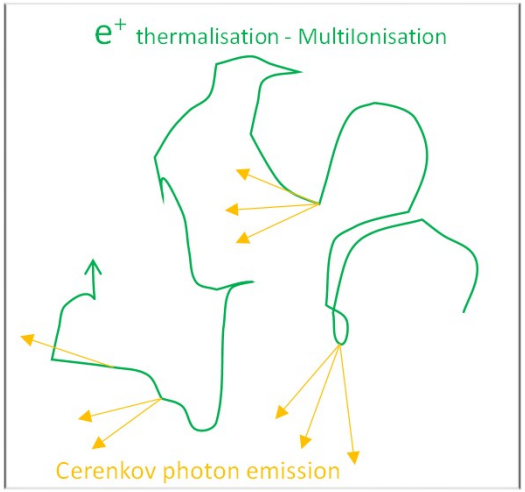
A dedicated device for PET imaging

Use the Cerenkov effect for AIF estimation



Carotid in the neck

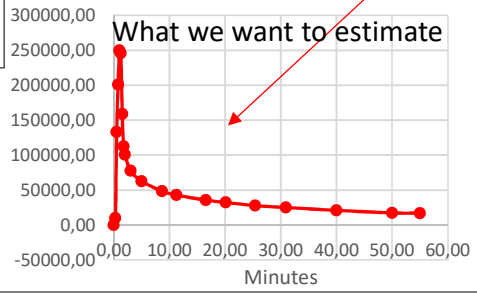
Physical processes



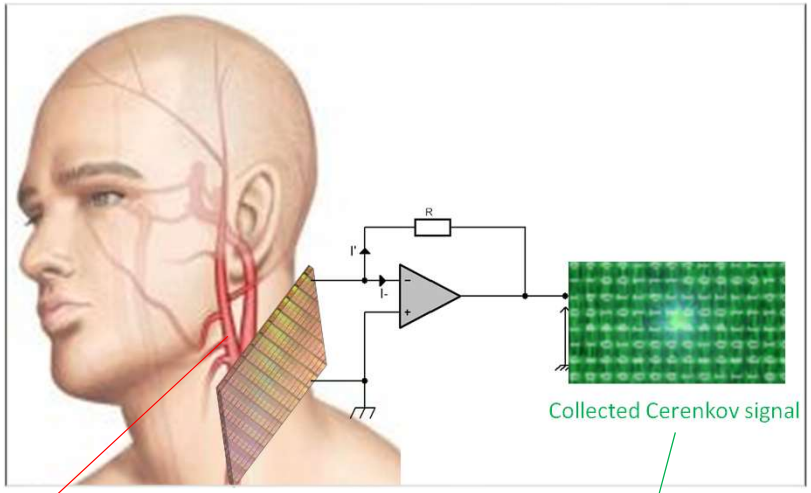
For ^{18}F & ^{11}C β^+ energy spectrum
If Ve+ > C/n (material with n>1)

Cerenkov Photon Emission in a λ range [250 nm ; 1250 nm]

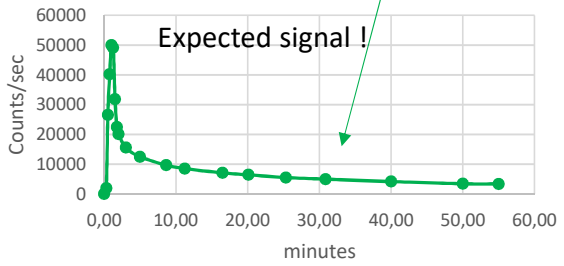
AIF



Detection



Cerenkov Signal



A dedicated device for PET imaging

Define a simulation Set-Up focused on the "Cerenkov" physical process

➢ Physics implementation : trivial !

```
/gate/physics/addProcess Cerenkov
/gate/physics/addProcess OpticalAbsorption
/gate/physics/addProcess OpticalRayleigh
#OR
/gate/physics/addProcess OpticalMie
#AND for surface boundaries
/gate/physics/addProcess OpticalBoundary
```

➢ First question : cut values for Cerenkov production…

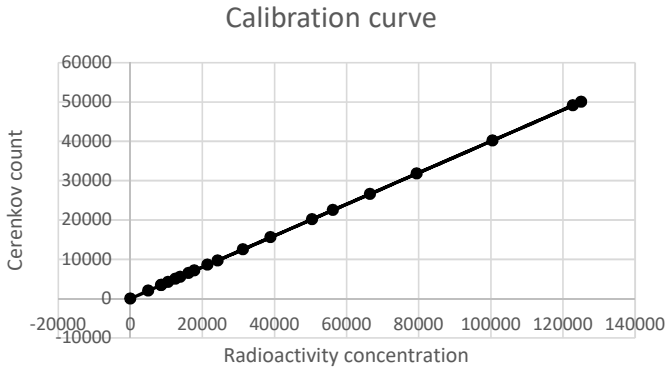
```
/gate/physics/Electron/SetCutInRegion  blood   0.001 mm
/gate/physics/Positron/SetCutInRegion  blood   0.001 mm
```

➢ "Basic" validations…

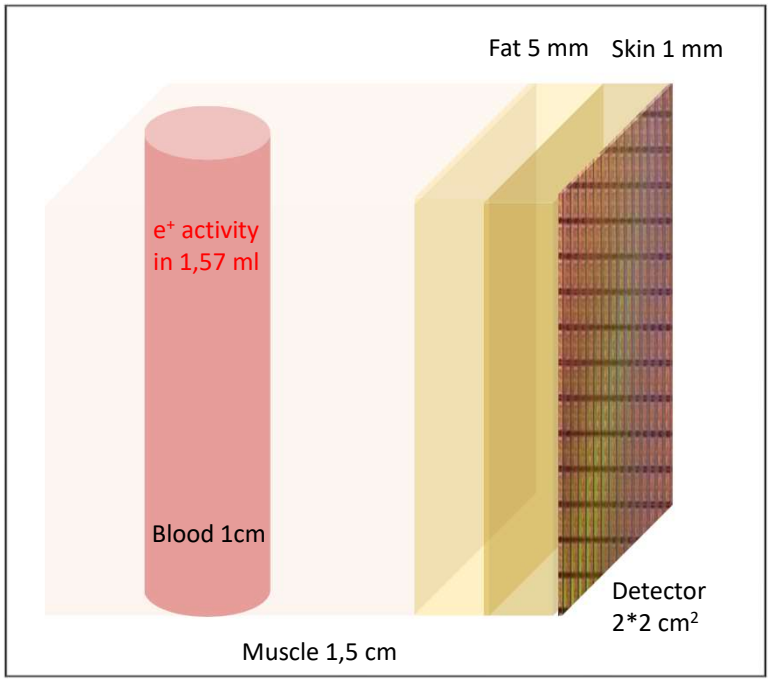
- Validation on the ***number of Cerenkov photons produced*** *(highly dependant about optical material properties)*
- Experimental data : publications *(not feasible for every materials in our case)* or dedicated experiments *(reflexions on that point)*

➢ Which questions are addressed to the simulation ?

1/ Can we expect to have a Cerenkov signal outside the patient ?
2/ If YES, can we quantify the signal ?
3/ In case of a very realistic simulation, can we define a calibration curve ?



Simulation study



- Analytical phantom
  - Cylinder for the artery
  - Tissue layers for :
    - Muscle
    - Fat
    - Skin
- Detector model
  - Perfect contact to the skin
  - Perfect efficiency
  - Small active field of view (4 cm^2)
- e+ activity flow
  - ^{18}F & ^{11}C β^+ spectrum or G4 RadioActive module
  - Time Activity Curves based on real AIF measurements

- Data expected for analysis
  - Cerenkov production in the blood volume *(and other volumes)*
  - StepLength & TrackLength for Cerenkov photon
  - Number of Cerenkov photon detected

Simulation study

Cerenkov photon production and tracking

- Optical photon processes
  - Bulk absorption
  - Rayleigh Scattering
- Material properties
  - Refractive index

Need to customize the Materials.xml file

- ABSLENGTH: Average distance traveled by a photon before being absorbed by the medium
- RAYLEIGH: Average distance traveled by a photon before it is Rayleigh scattered in the medium
- RINDEX: Refractive index of the material

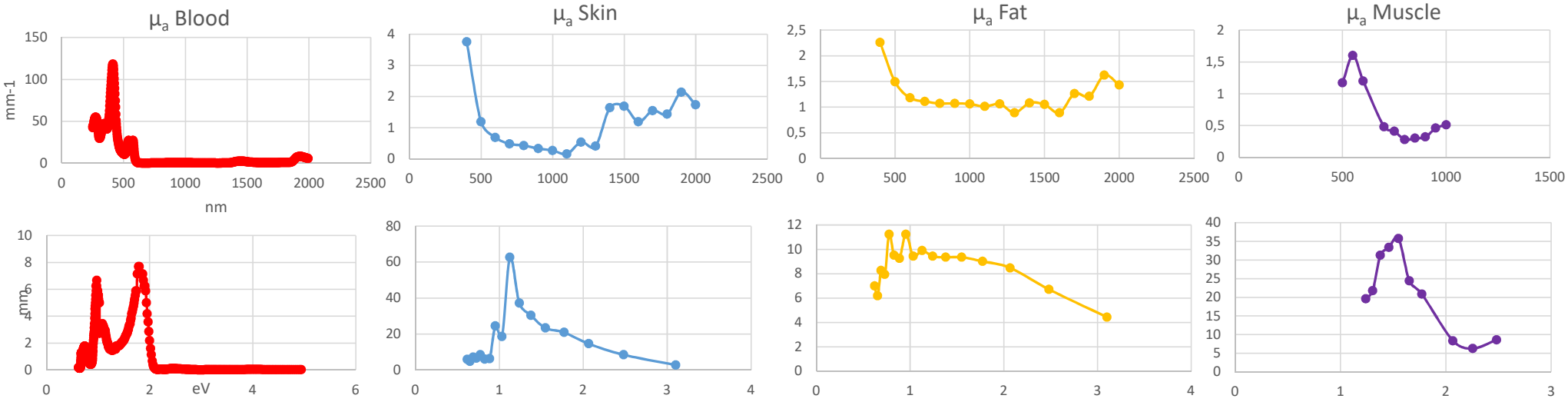
```
<material name="Blood">
<propertiestable>
<propertyvector name="RINDEX" energyunit="eV">
<ve value="1.39" energy="0.6"/>
<ve value="1.38" energy="5"/>
</propertyvector>
<propertyvector name="ABSLENGTH" energyunit="eV" unit="mm">
<ve value="0.17" energy="0.6"/>
<ve value="0.02" energy="5"/>
</propertyvector>
<propertyvector name="RAYLEIGH" energyunit="eV" unit="mm">
<ve value="0.8" energy="0.6"/>
<ve value="0.8" energy="5"/></propertyvector></propertiestable></material>
```

Simulation study

Data collection about tissue properties for $\lambda_{Cerenkov} \in [250\ nm\ ;\ 1250\ nm]$

- **ABSLENGTH…..** μ_a *for Blood, Muscle, Fat, Skin…not easy to find published value on the full Lambda range*

Convert in mm Vs eV for the G4MaterialPropertiesTable

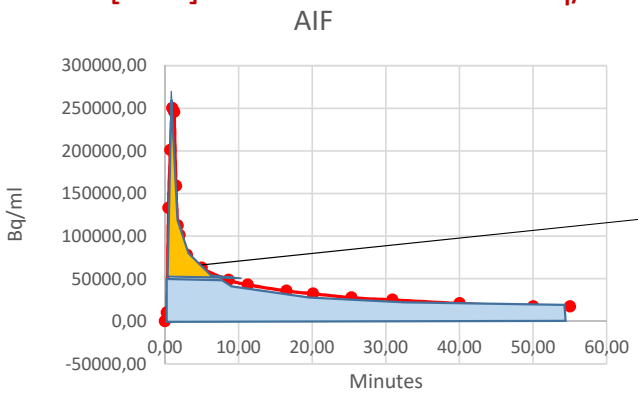


Same approach for :

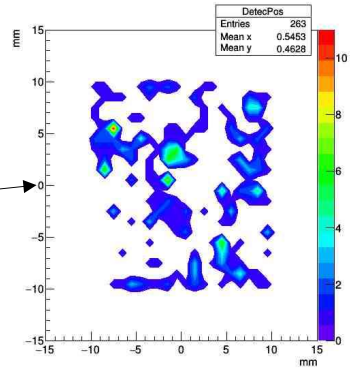
- **RAYLEIGH…..** μ_s
- **Rindex…..***Optical index "n"*

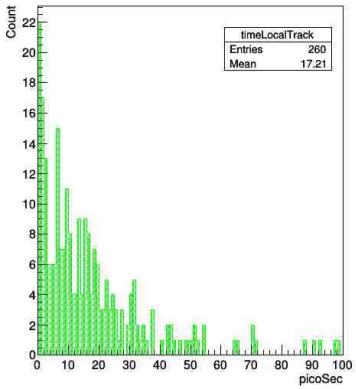
Simulation study

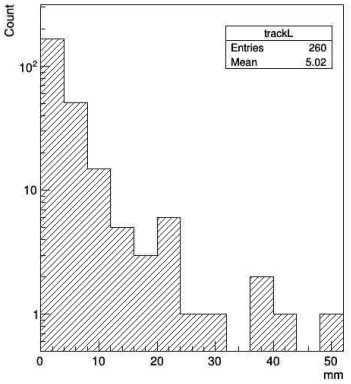
^{18}F-[FDG] concentration : 60 kBq/cc



263 Cerenkov Photons detected







- 555000 Cerenkov photons produced in the blood compartment
- 96% are absorbed in the blood compartment !
- Sensitivity : Cerenkov detected / Activity = 0,3 %

- Positive potential for the “pic” detection

- Question for the tail detection…
- And to estimate the area under the curve
- Limit of the sensitivity for this approach ?

Outcomes to study the potential of this approach

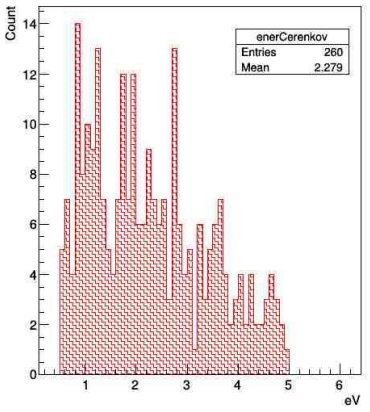
- Photon track length
- Photon energy spectrum
- Photon time tagging
- Scattering distribution
- …

➢ GATE developments

- Method implementations

from G4Step & G4Track to get hit informations

- GateCrystalSD / GateCrystalHits / GateRootDefs
- Probably need to associate a Messenger to select ON/OFF what users want to store



Simulation study

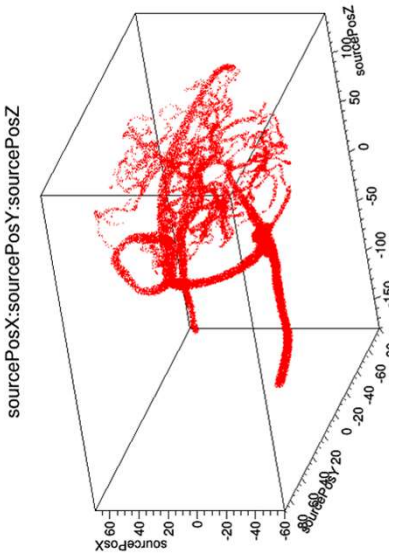
Next steps to improve the sensitivity study ?

- Need to be more accurate in our simulation… two steps :
  - Improve the phantom model : clinical configuration
  - Improve the detector model :
    - including the electronic thresholder
    - photodetection processes & quantum efficiency
    - Interface between the skin and the detector / boundary effect
  - Also need to validate optical material properties and Cerenkov production

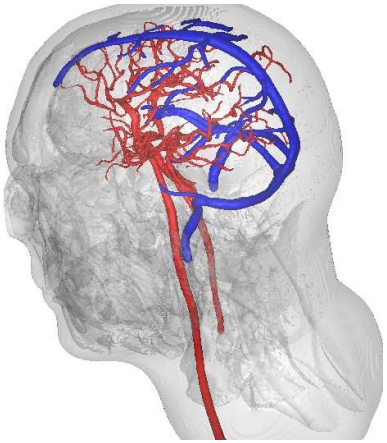
Simulation study – realistic phantoms

➢ First approach : XCAT phantom

e+ dynamic distribution

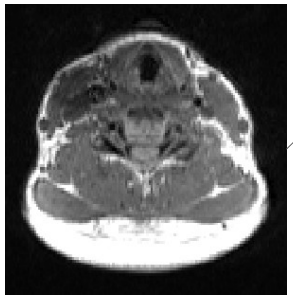


XCAT Phantom for
attenuation label structures



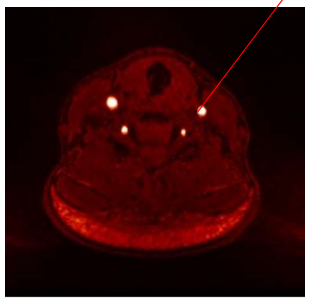
+ : Easy to use
- : Blood compartment and neck structure

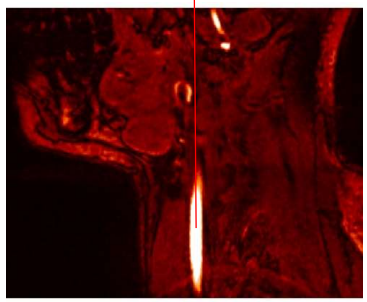
➢ MRI patient data



Basic T1 sequence

Dedicated “TOF” sequence
To have blood flow signal





The main difficulty concern the scanner description in the voxelised volume
- Need to test the hybrid navigator

PERSPECTIVES

➢ **Need to be more accurate in our simulation… two steps :**

- Improve the phantom model : clinical configuration
  - *Use the MRI phantom and work on the scanner description in the voxel matrix*

- Improve the detector model :
  - *including the electronic thresholder*
  - *photodetection processes & quantum efficiency*
  - *Interface between the skin and the detector / boundary effect*

Collaboration with the instrumentation department @ CEA Saclay

- Also need to validate optical material properties and Cerenkov production
  - *Dedicated experiments with same colleagues from CEA Saclay…medium/long term*


THANK YOU !