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Software challenges and opportunities in multimodality PET/CT and PET/MR imaging

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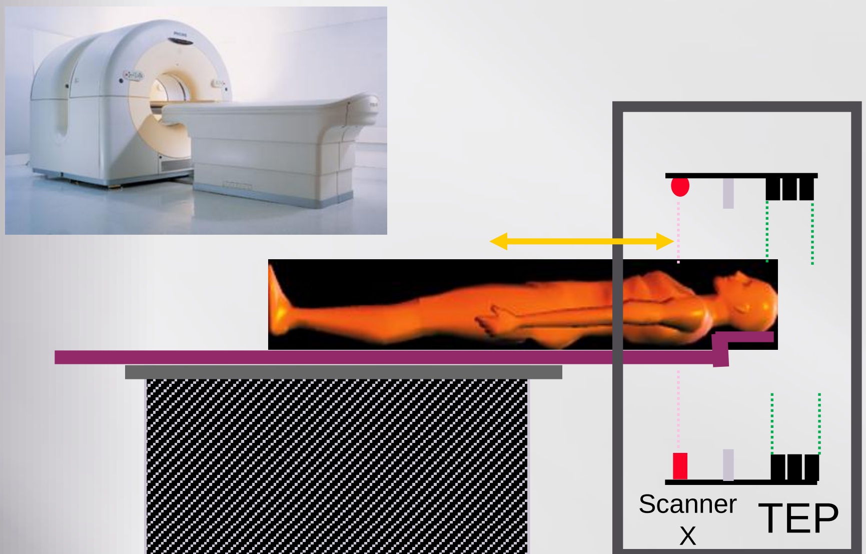
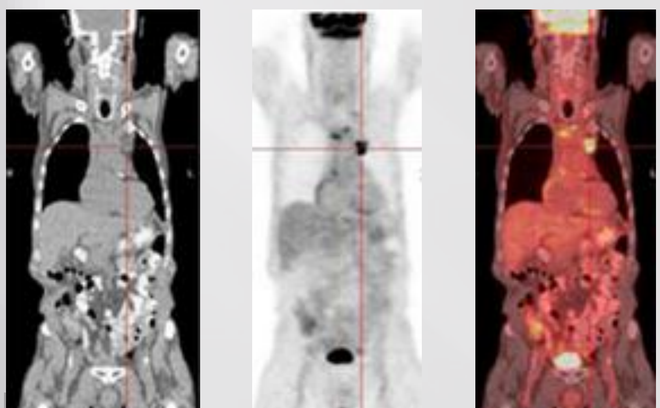
Multimodality imaging: PET/CT

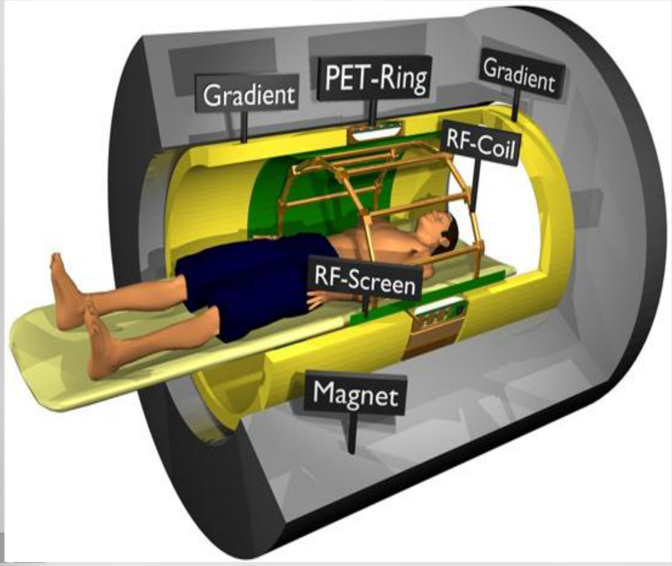


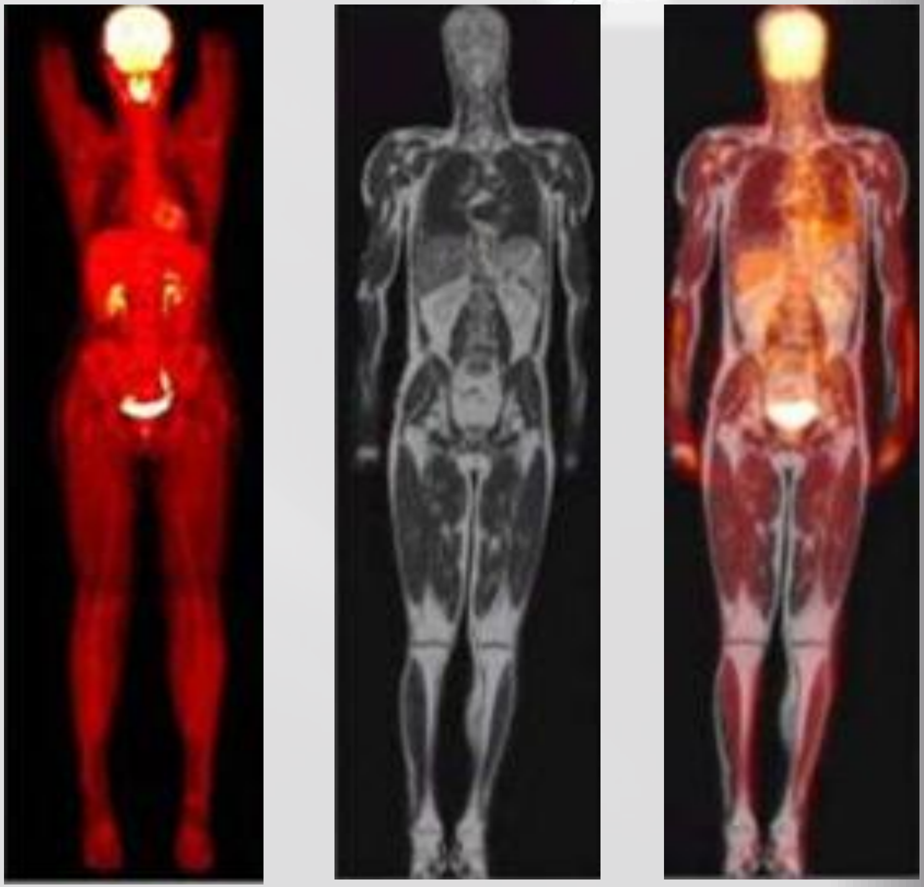


Medical Imaging revolution

- ✓ Combination of anatomy and function
- ✓ Increased patient throughput

Multimodality imaging: PET/MR





Multimodality imaging: software developments

Question Combining anatomy and function: challenge or opportunity?

From a software point of view: a little bit of both

1. Corrections:
    - physics principles of the detection process (scatter, attenuation, partial volume effects, noise)
    - association of anatomical and functional images (physiological organ motion)
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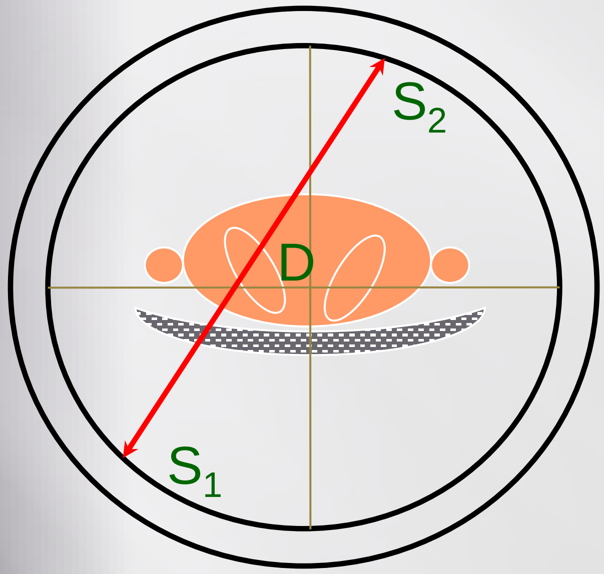
PET attenuation correction

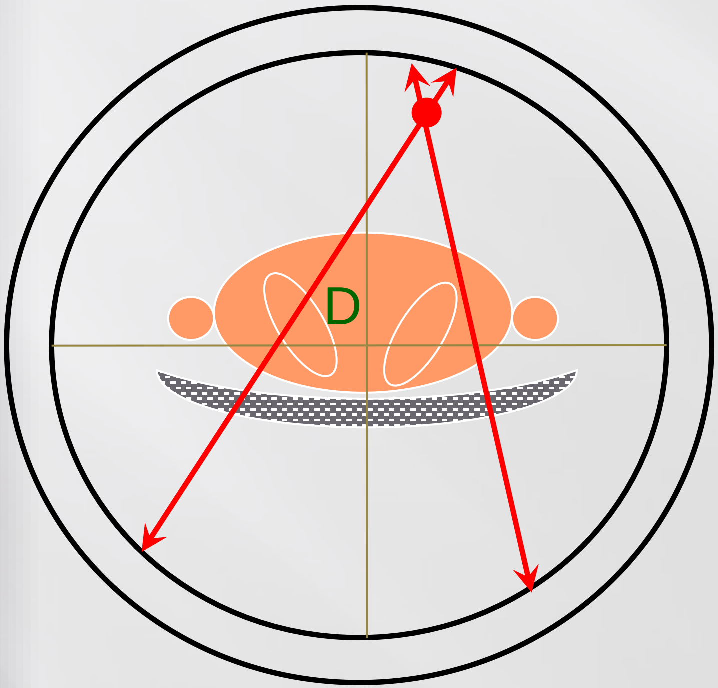


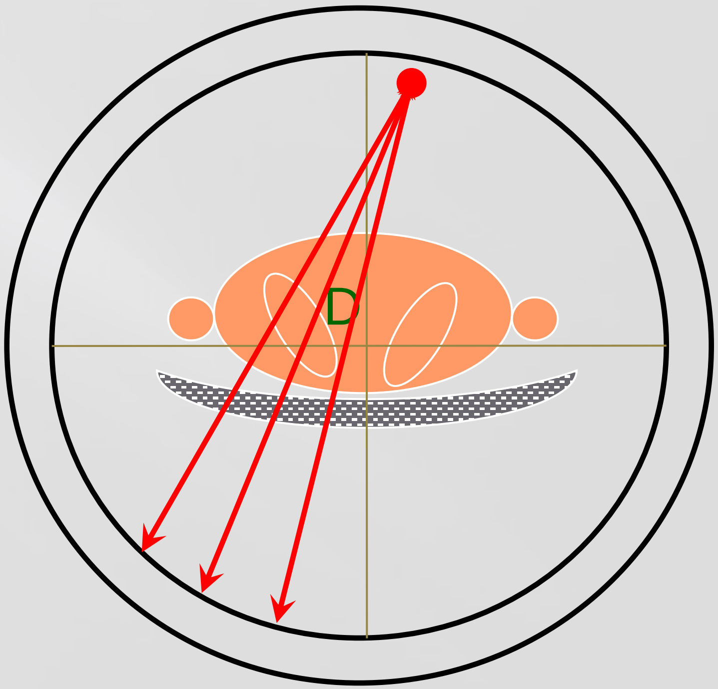
- Need to know the distribution of the attenuation coefficients
- Attenuation independent of the position of the annihilation along the line of response
- No need to know the activity distribution for the calculation of attenuation as it is the case in SPECT

PET attenuation correction

b+ emitter
(Ga-68/Ge-68)

γ emitter (Cs-137)

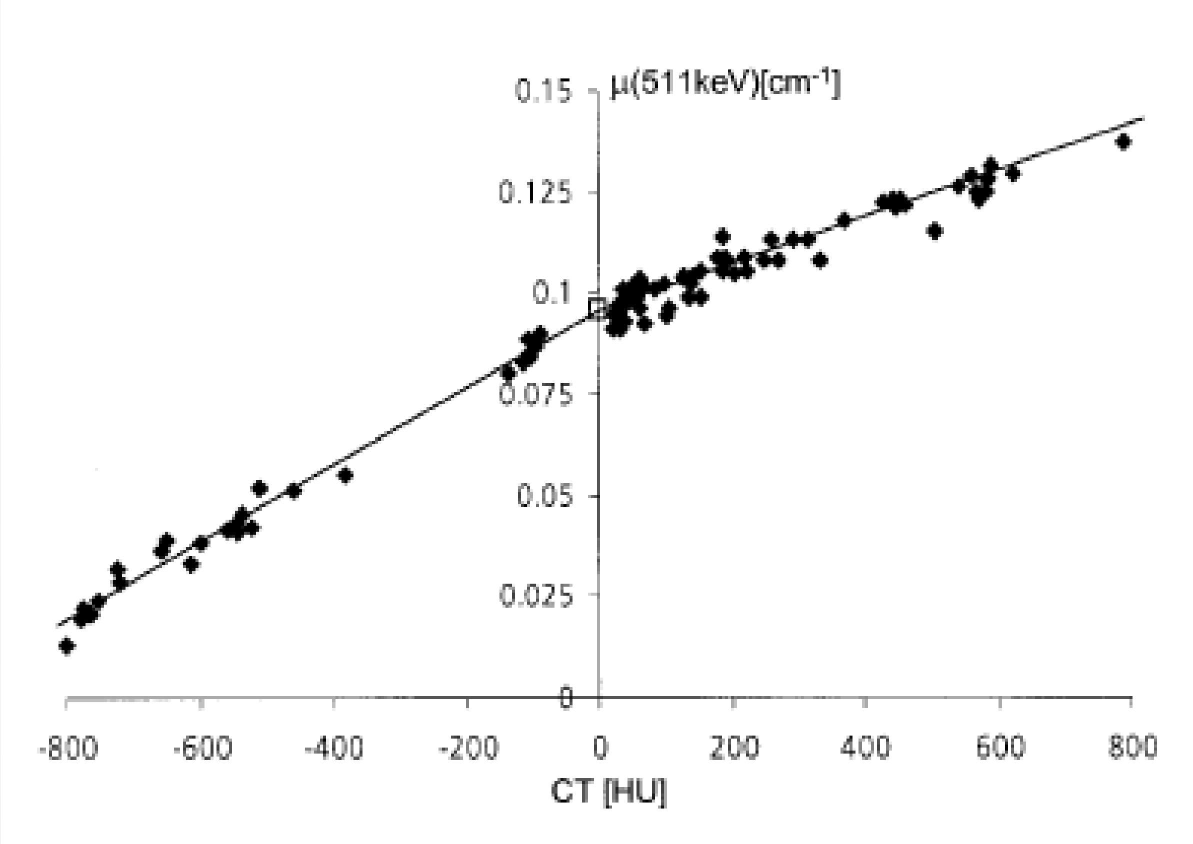




PET attenuation correction

- Noisy
- Need for segmentation
- Long acquisition times (15-20mins)

PET/CT attenuation correction

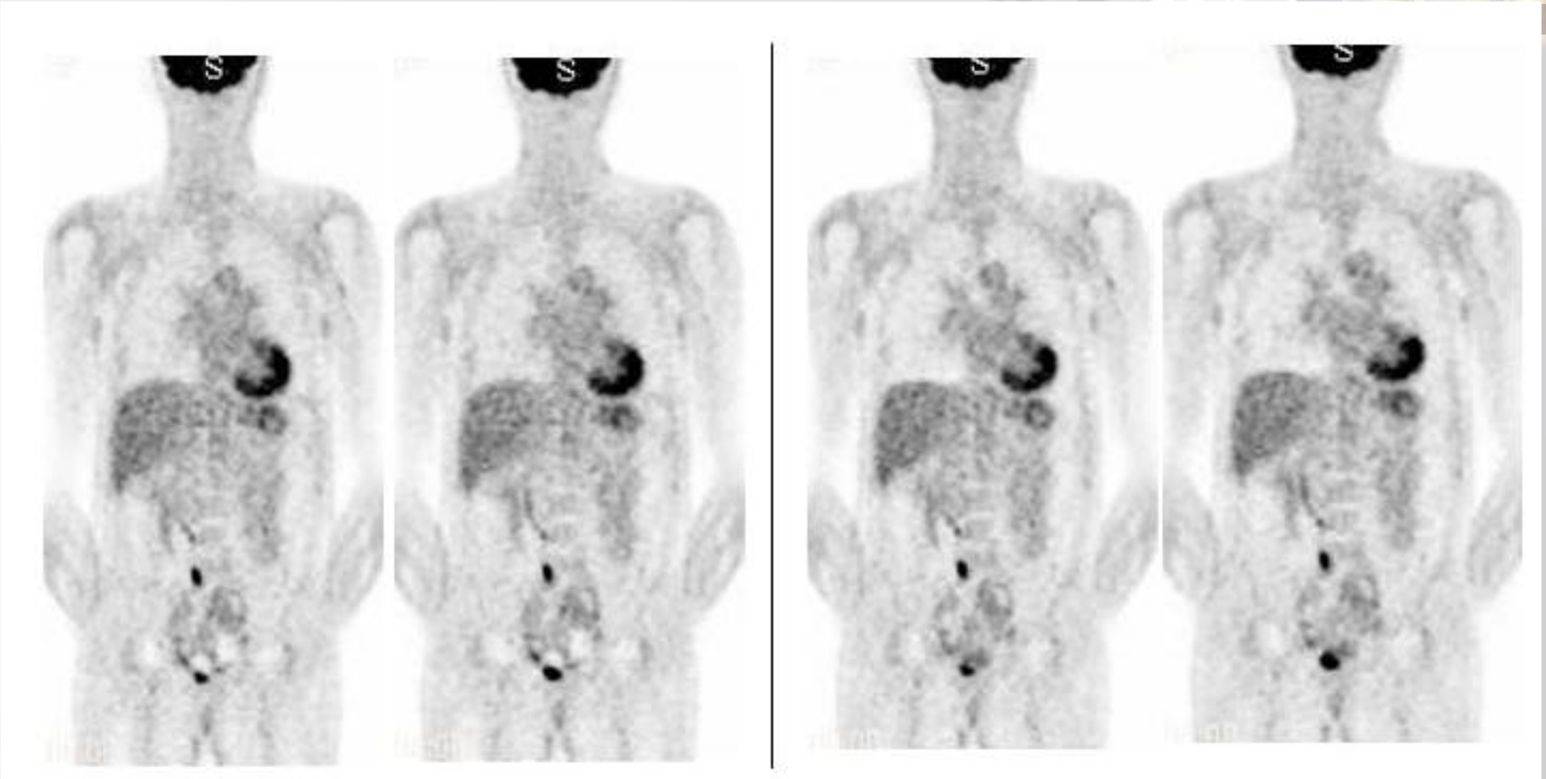


$$\mu = \mu_{H2O} \frac{(HU + 1000)}{1000}$$

$$\mu = \mu_{H2O}^{PET} + HU \frac{\mu_{H2O}^{CT}(\mu_{bone}^{PET} - \mu_{H2O}^{PET})}{1000(\mu_{bone}^{CT} - \mu_{H2O}^{CT})}$$

Burger et al EJNM 2002

PET/CT attenuation correction



Standard AC

CT based AC

- Equivalent quantitative accuracy
- > 20% superior contrast

Visvikis et al EJNM 2003

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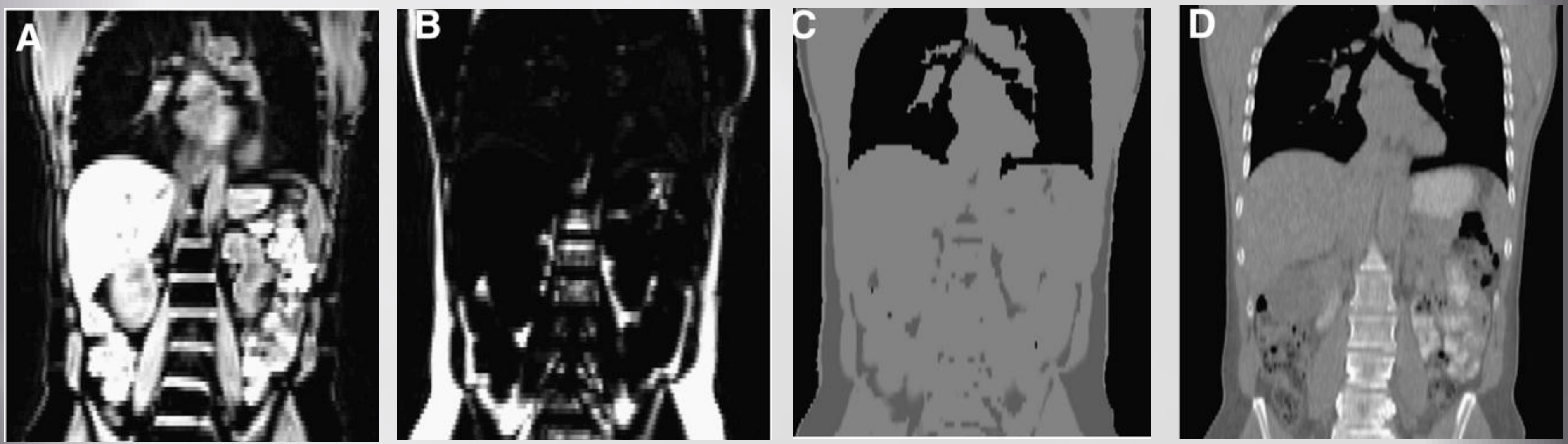
PET/MR attenuation correction

Tissue classification based on 2 point Dixon's MR sequence



Water | Fat | Classify and combine | Corresponding CT

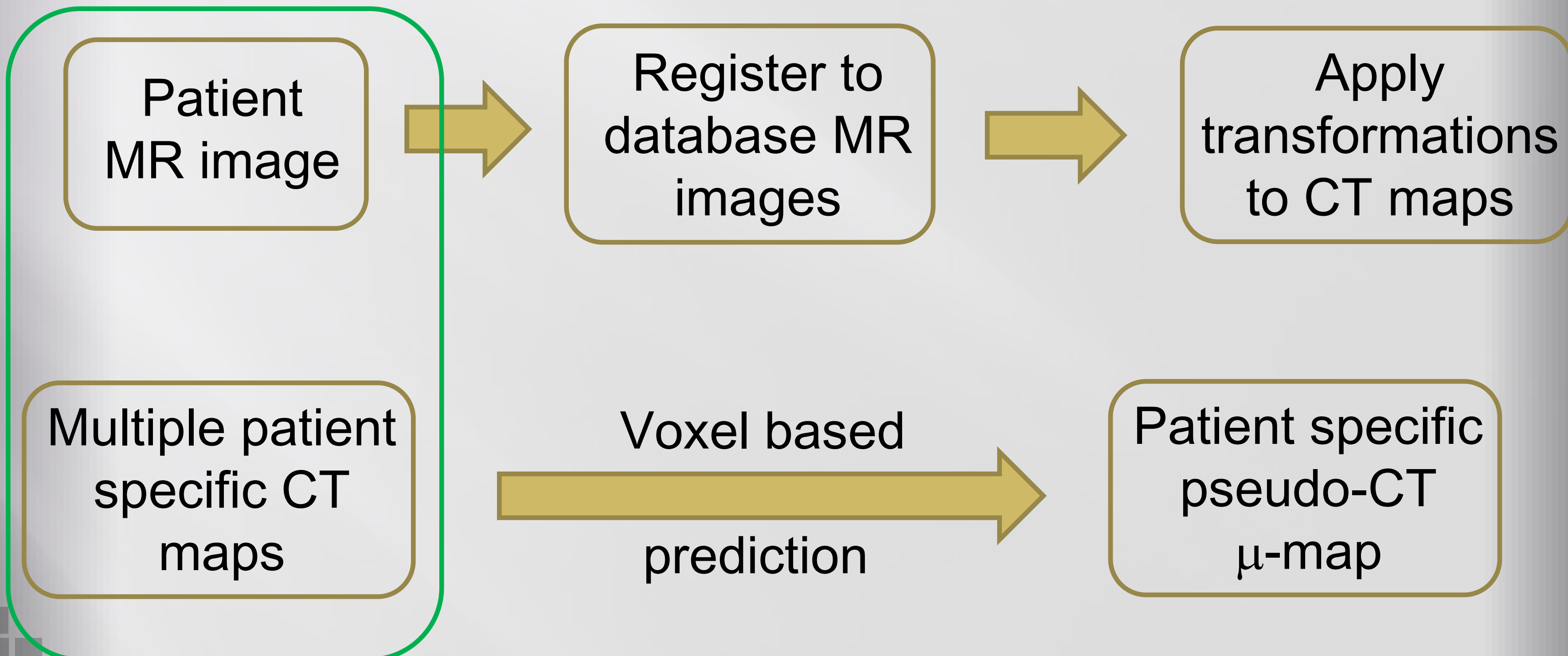
Dixon et al Rad 1984

Martinez-Moller et al JNM 2009

Attenuation correction: atlas based

Machine learning approach: Atlas registration and pattern recognition

(Atlas: Database of registered CT and MR acquisitions)



Hofmann et al JNM 2008

Attenuation correction: comparison

Tissue classification vs Atlas based

Average Relative VOI PET Quantification Errors for Mean SUVs; Results Compared with Those Achieved Using CTAC

Region	CT_{nobone}	CT_{seg}	$PsCT_{MRSEG}$	$PsCT_{AT\&PR}$
Thorax	1.0% ± 0.8%	10.2% ± 7.5%	13.5% ± 10.7%	14.0% ± 11.4%
Abdomen	5.7% ± 8.9%	7.8% ± 10.3%	12.7% ± 10.3%	5.2% ± 4.3%
Pelvis	3.7% ± 4.2%	5.5% ± 5.9%	15.8% ± 9.6%	4.9% ± 5.1%
Average	3.6% ± 6.0%	7.6% ± 8.2%	14.1% ± 10.2%	7.7% ± 8.4%
Lesions	2.8% ± 4.5%	4.0% ± 5.2%	7.5% ± 7.9%	5.7% ± 4.7%

Errors are averaged across all patients for body regions and lesions. Data are mean ± SD.

Hofmann et al JNM 2011

Attenuation correction: improvements

Account for bone structures

Use of Ultra-short Echo Time Triple Echo MR sequence

- ✓ Ultra-short echo time sampling for bone segmentation based on a dual-echo technique (Keereman et al JNM 2010, Catana et al JNM 2010)

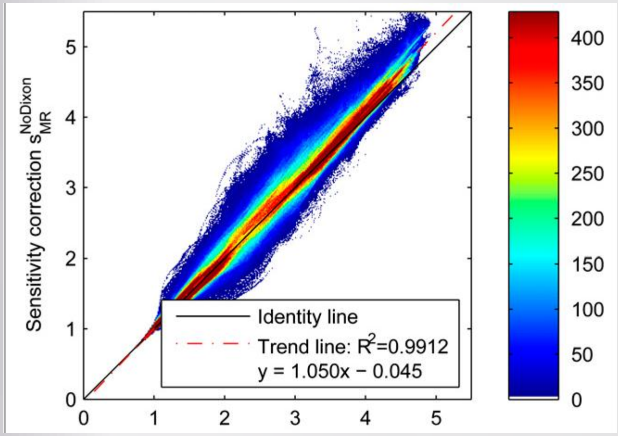
+

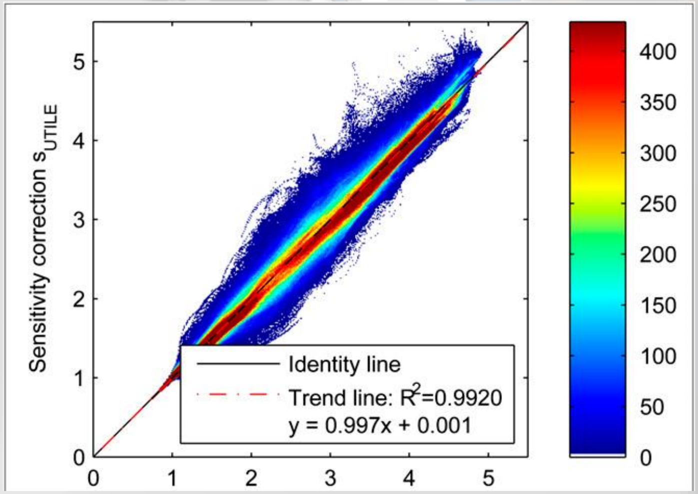
- ✓ Gradient echos for Dixon water-fat separation

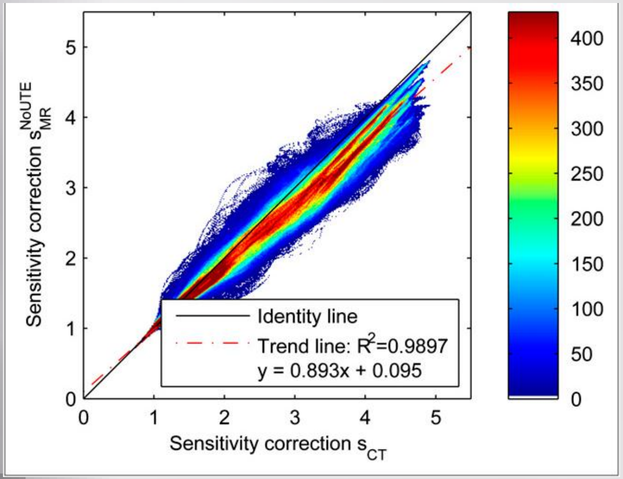
4 tissue classification (air, fat, soft tissue and bone) using predefined attenuation factors

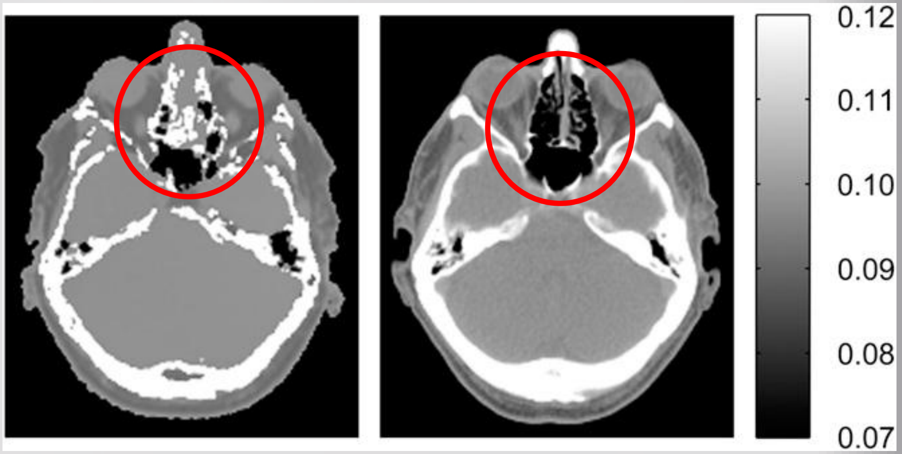
Berker et al JNM 2012

Attenuation correction: improvements





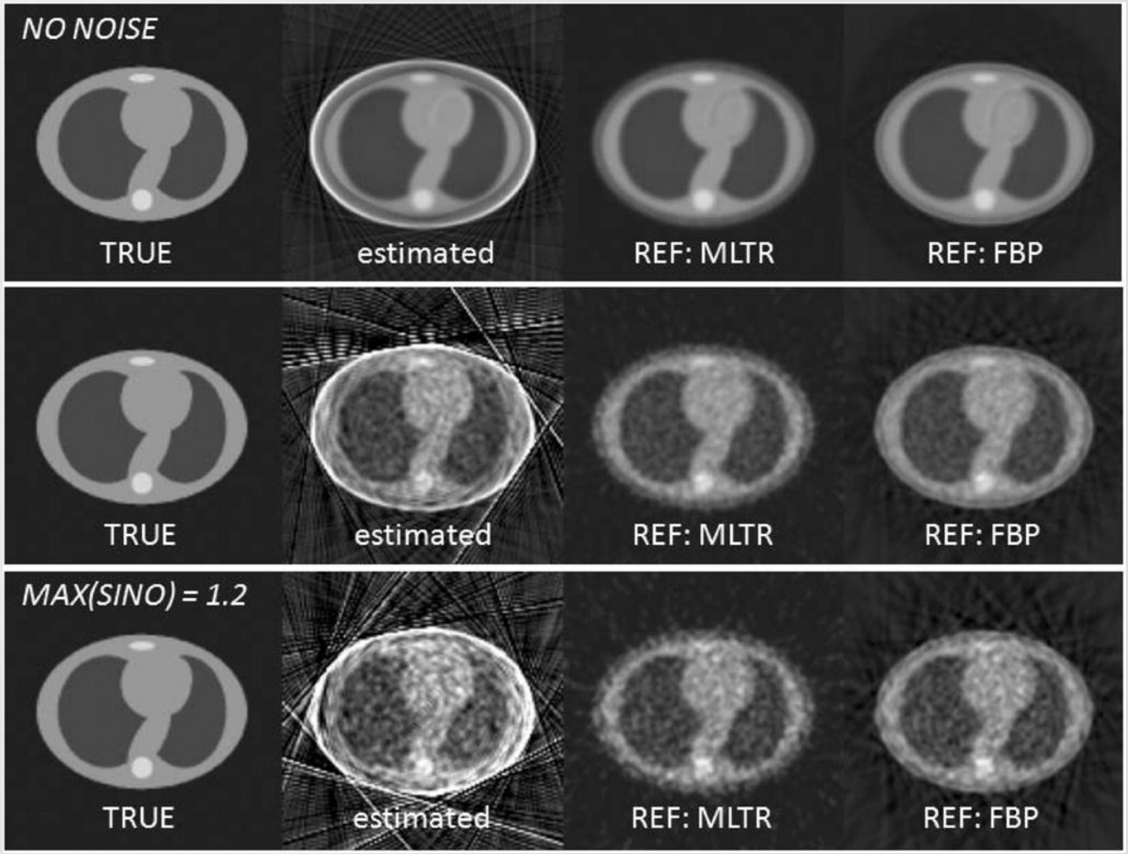




Berker et al JNM 2012

The solution may come from PET

Explore consistency conditions and TOF information to derive the attenuation maps from the non-attenuation corrected emission datasets



Defrise et al PMB 2012

Multimodality imaging: software developments

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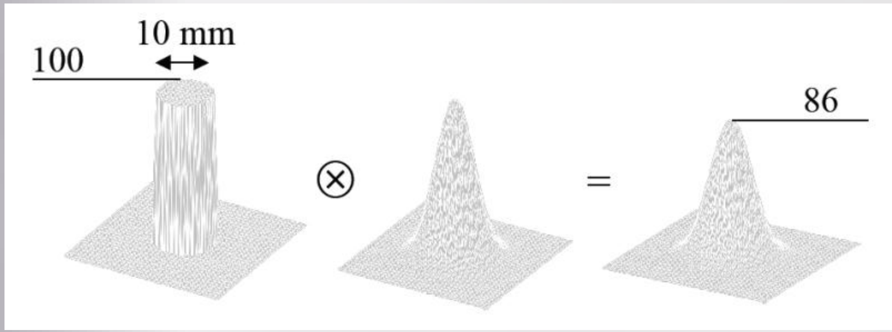
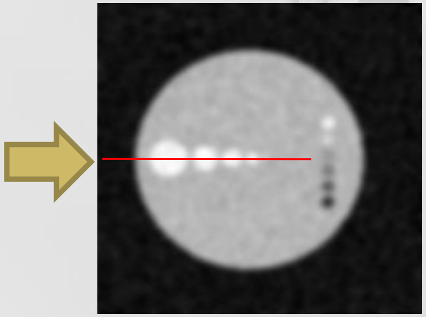
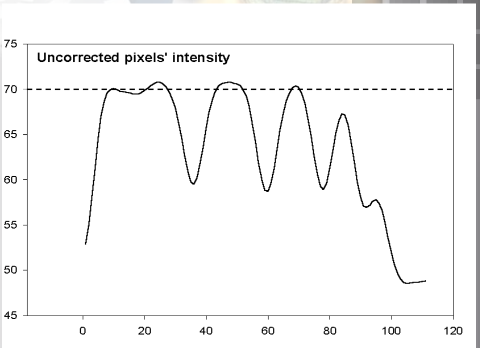
Partial volume effects correction







Different classifying categories may be identified

(i). Emission only or anatomical detail based

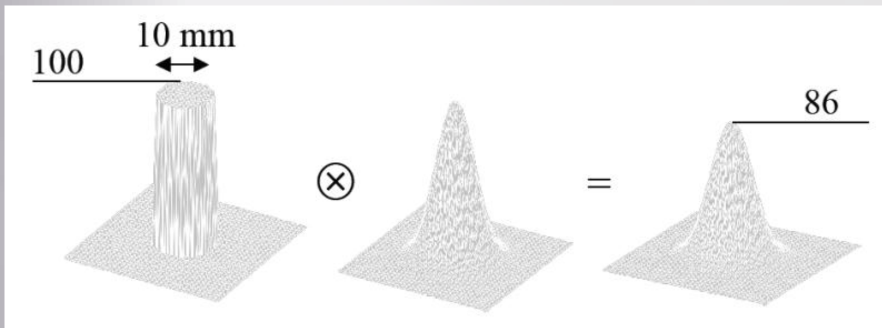
(ii). Region of interest or voxel-wise based

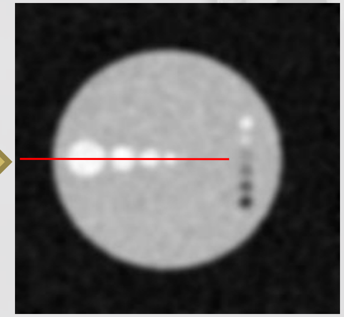
(ii). Segmentation needed or not

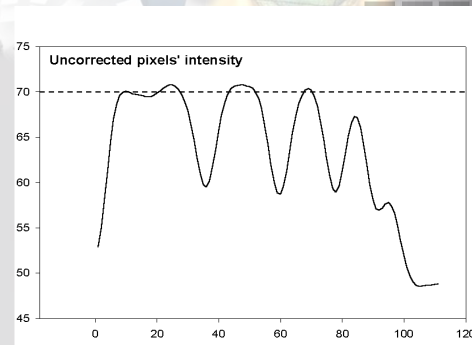
(iii). Assumptions considering regions homogeneity

(iv). Post-reconstruction vs reconstruction based

Partial volume effects correction







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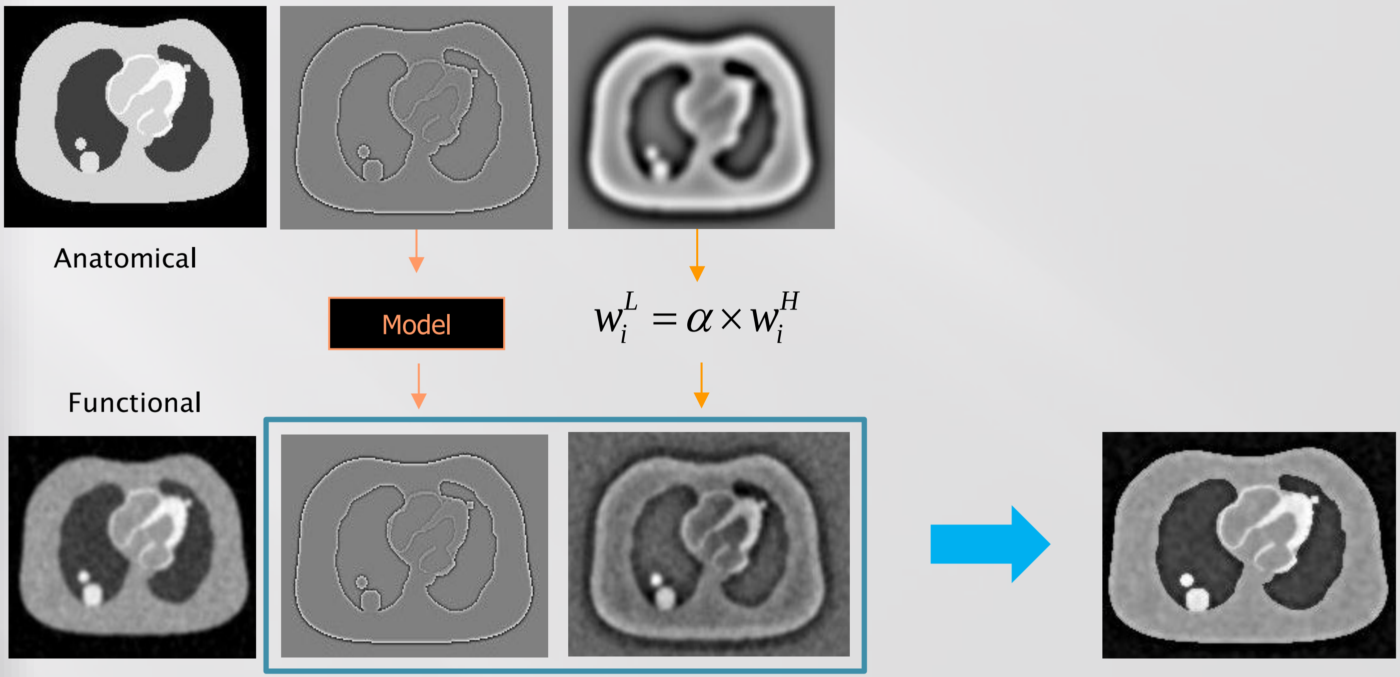
Partial volume effects correction

Post-processing voxelwise approaches (overall image improvement)

Multi-resolution Analysis

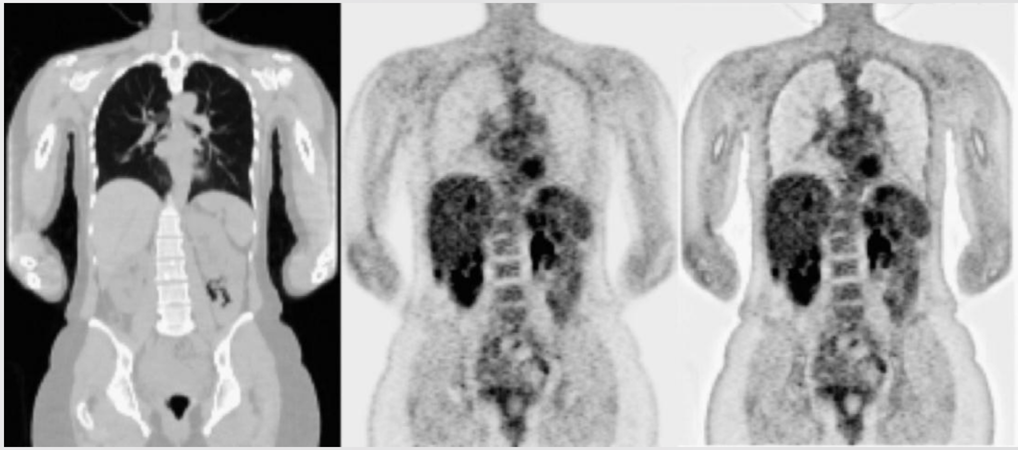


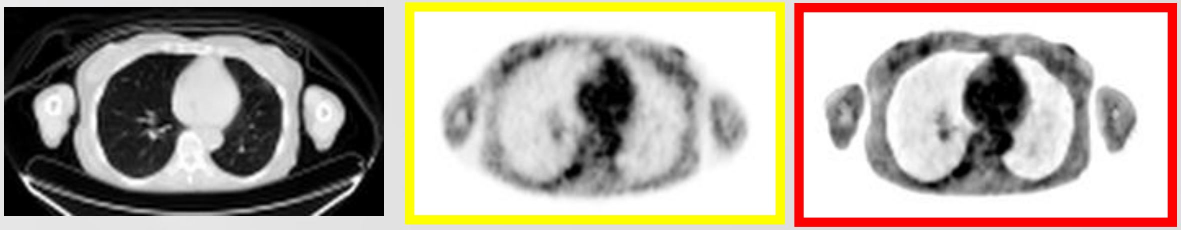
Boussion et al PMB 2006

Le Pogam et al Med Phys 2011

Multi-resolution Analysis: PVC

Oncology:

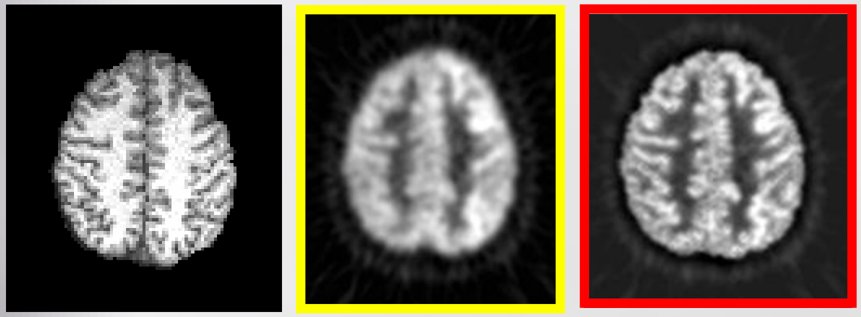




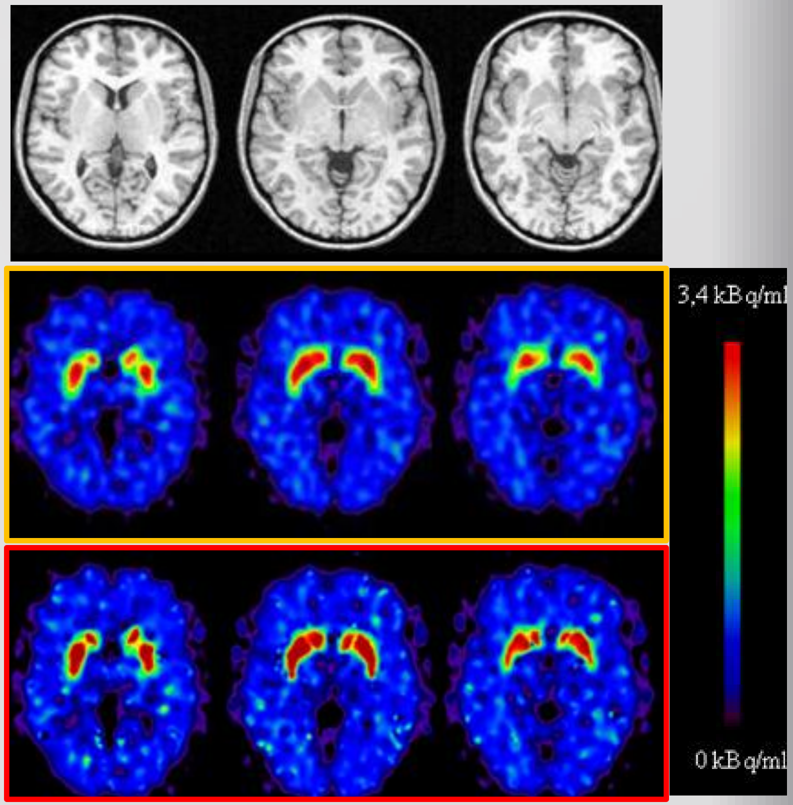
Lung backgd activity +2%
Tumour/Lung activity +20%

Multi-resolution Analysis: PVC

Neurology:



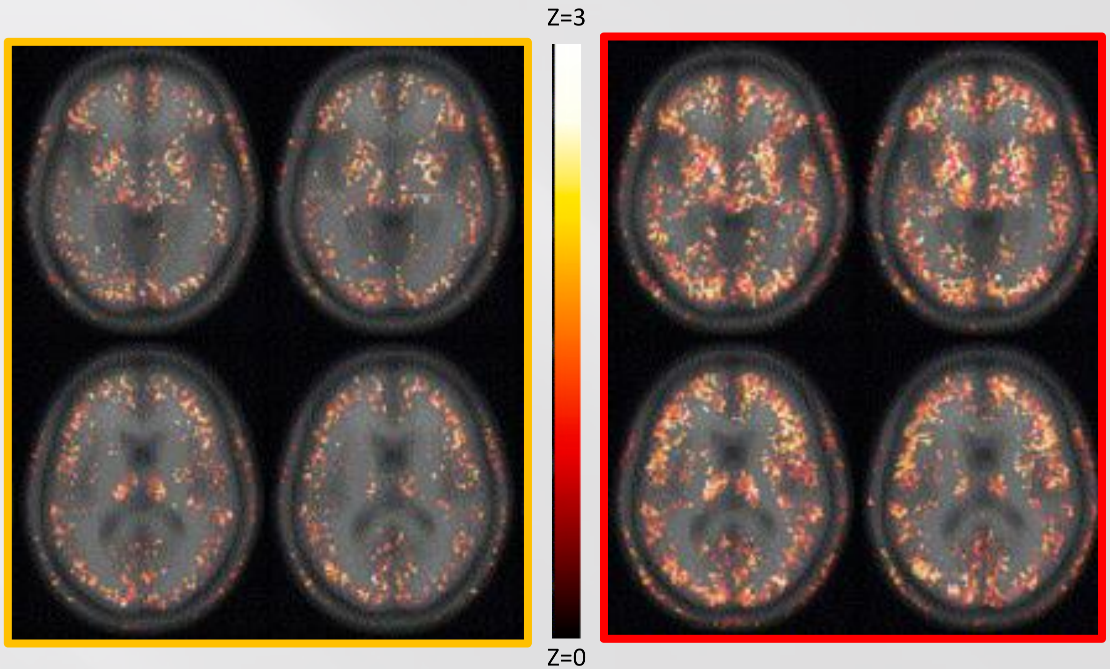
White matter -20%
Grey matter +30%



Boussion et al PMB 2006

Shidihara et al Neuroimage 2009

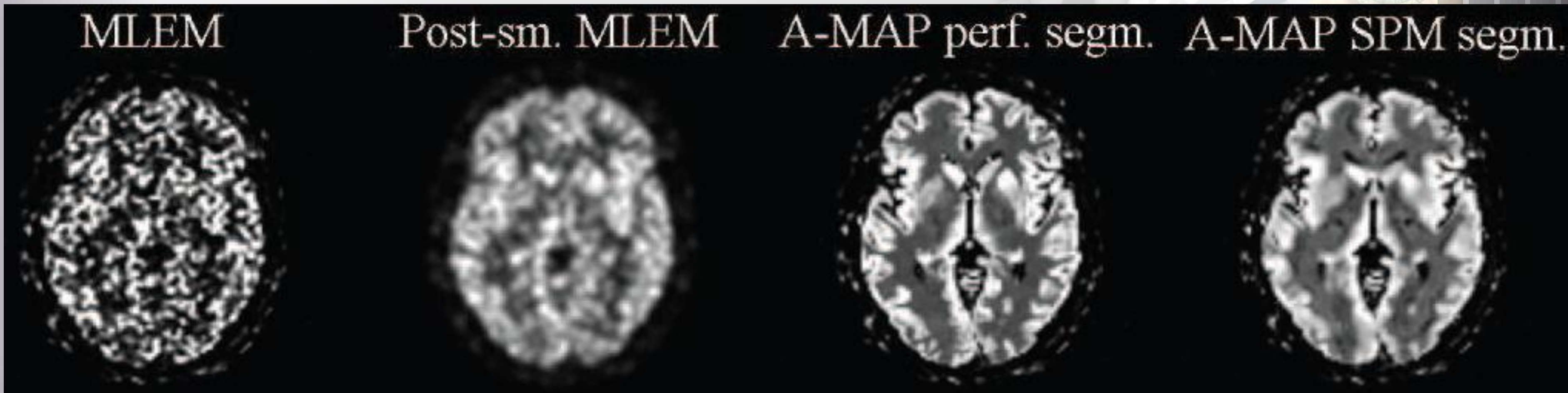
Multi-resolution Analysis: denoising

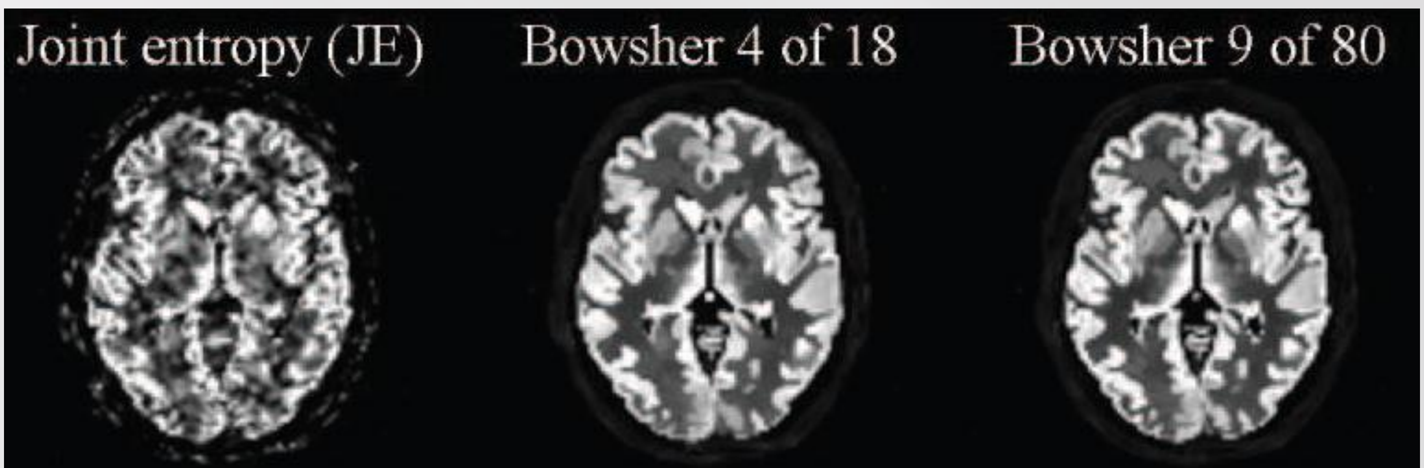


ORIGINAL

DENOISED

Reconstruction based PVC using MR based priors





courtesy J Nuyts

PET/MR: software developments

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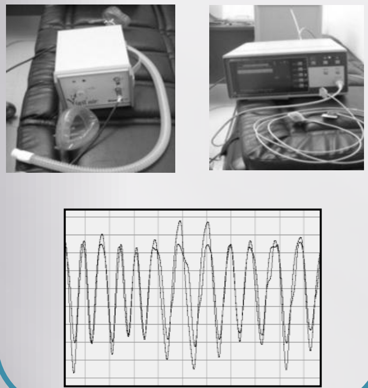
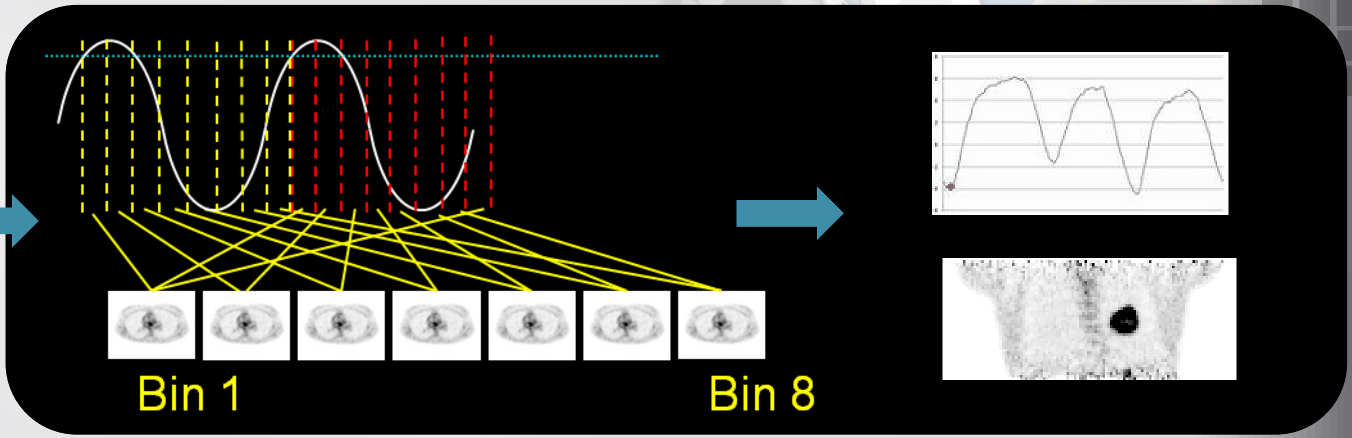
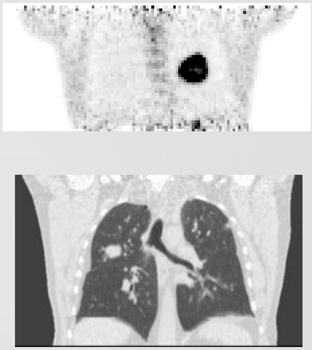
Respiratory motion: PET/CT

Synchronisation

External detectors





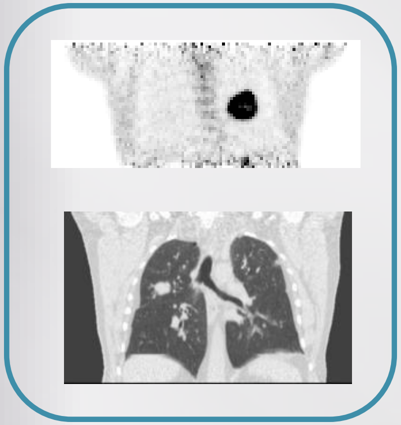


Affine or deformable motion model

Qiao et al PMB 2007

Lamare et al PMB 2007a, b

Respiratory motion: PET/CT



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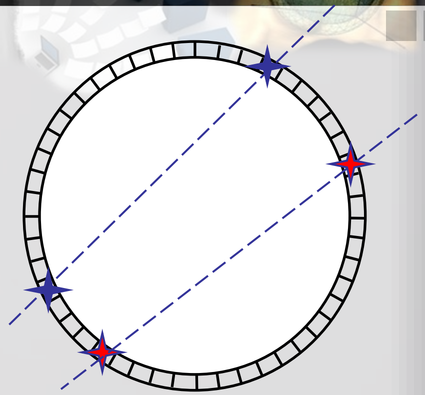
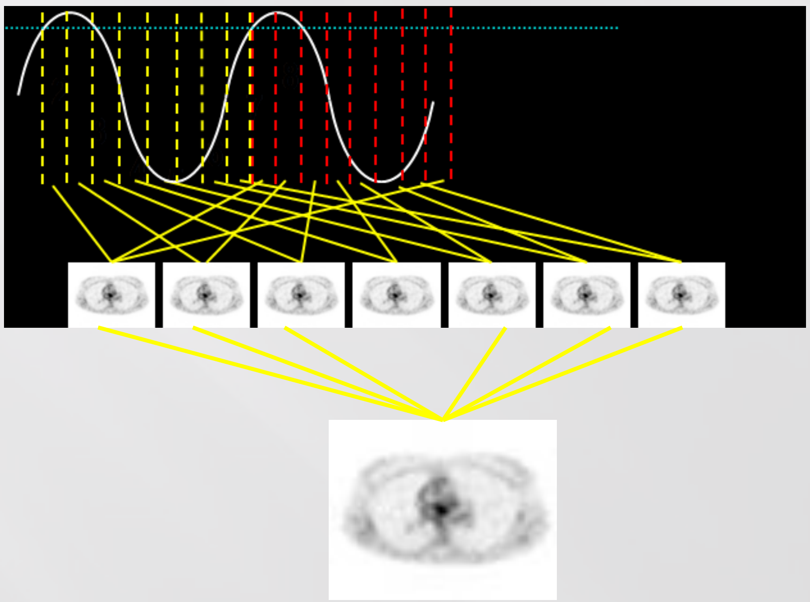
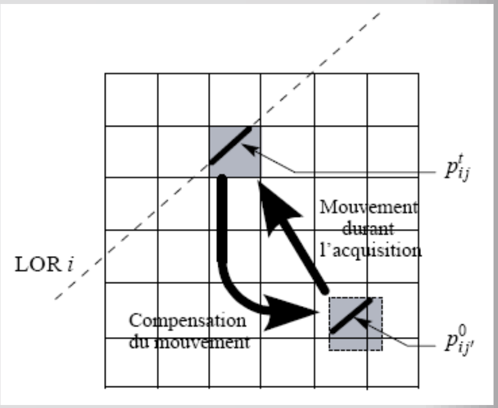






Qiao et al PMB 2007

Lamare et al PMB 2007a, b

Respiratory motion: PET/MR

Can we use the same workflow for motion correction in PET/MR?

YES!

Differences that need to be taken into consideration?

- ✓ Temporal sampling
- ✓ MR sequences that measure motion

Are there any advantages / disadvantages in using MR?

- ✓ No ionising radiation
- ✓ Simultaneous acquisition
- ✓ MR incompatability of different external motion measurement devices

Respiratory motion: MR sequences

Different protocols for motion estimation in MR

- Dynamic 3D T1/T2 acquisitions
- Dynamic 2D T1/T2 acquisitions binned into 4D images (using normalised mutual information or 1D navigators)

Combination with affine or deformable image registration for the derivation of 3D vector fields

Limitation: only applicable to sequences providing anatomical contrast

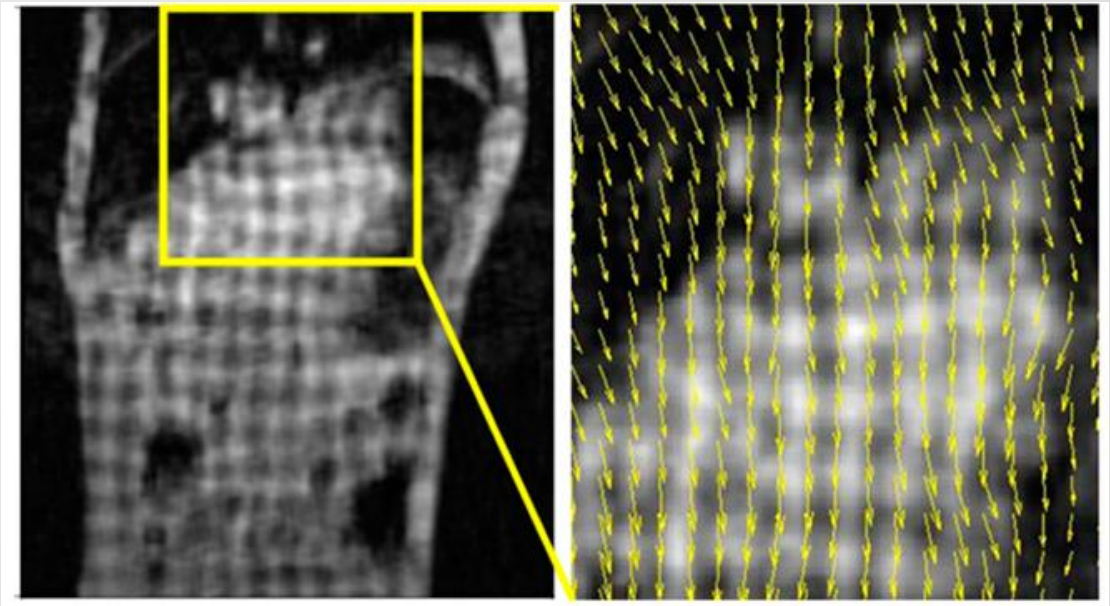
Catana et al JNM 2011

Dikaios et al Eur Rad 2012

Respiratory motion: MR sequences

Different protocols for motion estimation in MR

- Tagged MRI acquisition: superimpose a regular tagging pattern on the object magnetisation distribution (1D, 2D or 3D in the phase or amplitude domains)



Ozturk et al Proc IEEE 2003

Guerin et al Med Phys 2011

Respiratory motion: MR sequences

Different protocols for motion estimation in MR

- Tagged MRI acquisition: superimpose a regular tagging pattern on the object magnetisation distribution (1D, 2D or 3D in the phase or amplitude domains)

  Advantage: Does not require the use of deformable image registration for the derivation of 3D vector fields

  Limitation: Does not allow estimation of motion in the lungs. MR images are usually affected by artefacts.

Ozturk et al Proc IEEE 2003

Guerin et al Med Phys 2011

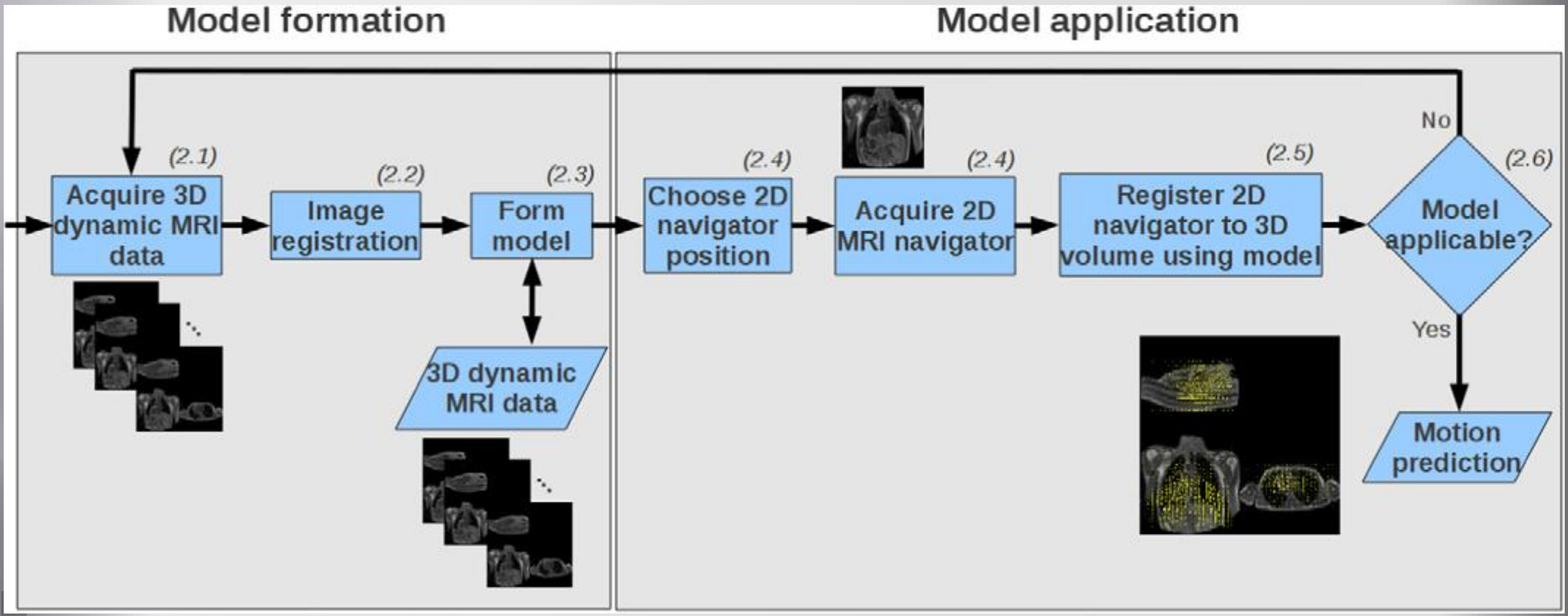
Respiratory motion: motion modelling

Different protocols for motion estimation in MR

- Patient specific motion model based on establishing a relationship between 4D internal structures displacement and diaphragmatic 1D/2D navigators

Respiratory motion: motion modelling

Different protocols for motion estimation in MR



King et al Med Imag Anal 2012

Respiratory motion: motion modelling

Different protocols for motion estimation in MR

- Patient specific motion model based on establishing a relationship between 4D internal structures displacement and diaphragmatic 1D/2D navigators

Limitation: A dynamic 3D T1 acquisition is necessary for each patient in order to derive the motion model

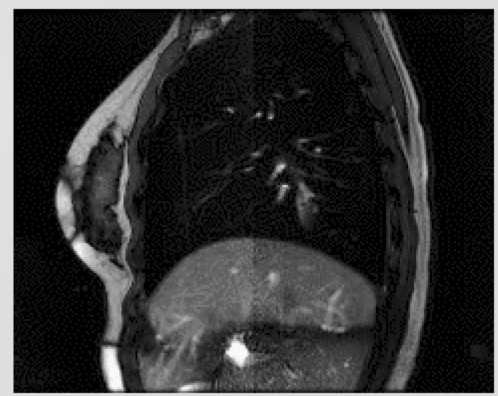
Respiratory motion: motion modelling

Different protocols for motion estimation in MR

- ❑ Generic motion model based on using a patient database of 4D internal structures displacements and associated diaphragmatic 1D/2D navigators

2D Navigator

+ $U(t) = B\,s(t)$ →



Inserm
Institut national de la santé et de la recherche médicale

Fayad et al Med Phys 2012

Fayad et al SNM 2012

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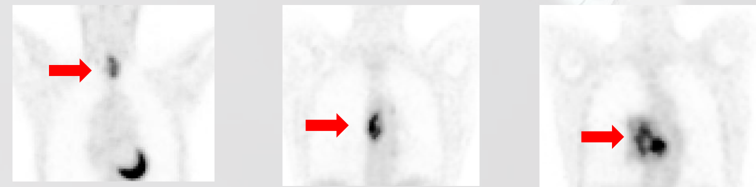
PET image derived parameters

✓Predictive and prognostic value of functional volume for different cancer models

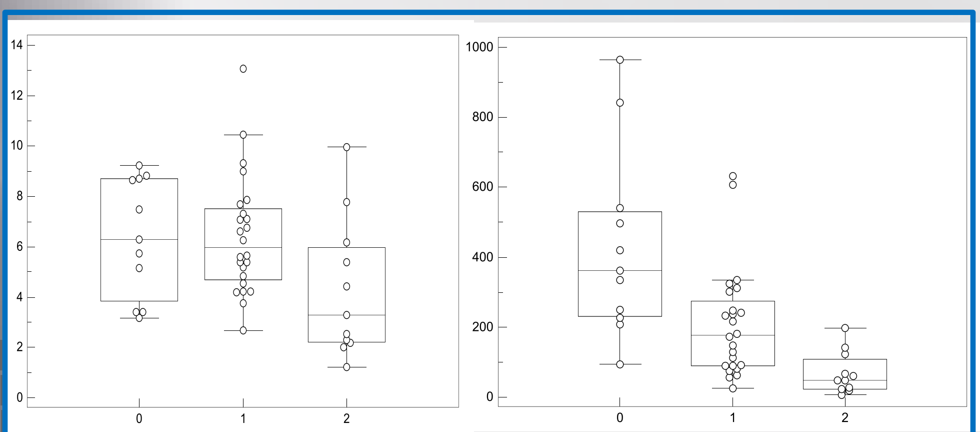
Initial FDG PET scan



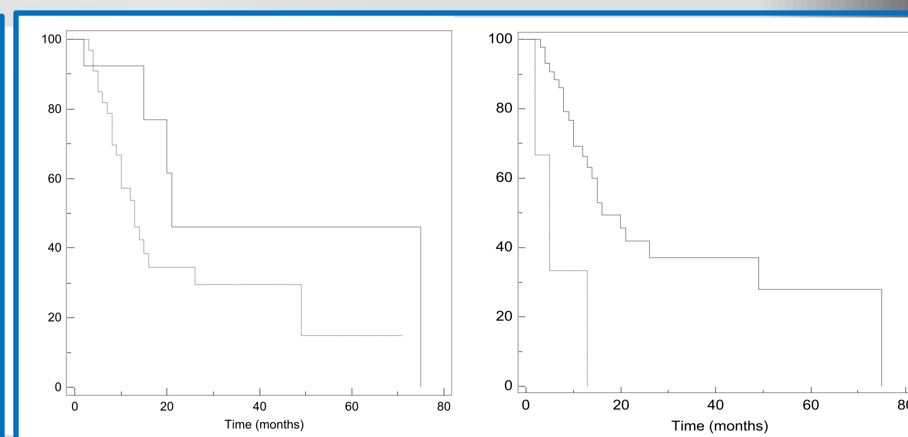
Better patient stratification and management (survival, therapy response)

Example: 45 esophageal cancer patient

Therapy response



Survival



Instituts thématiques Inserm
Institut national de la santé et de la recherche médicale

Hatt et al EJNM 2010

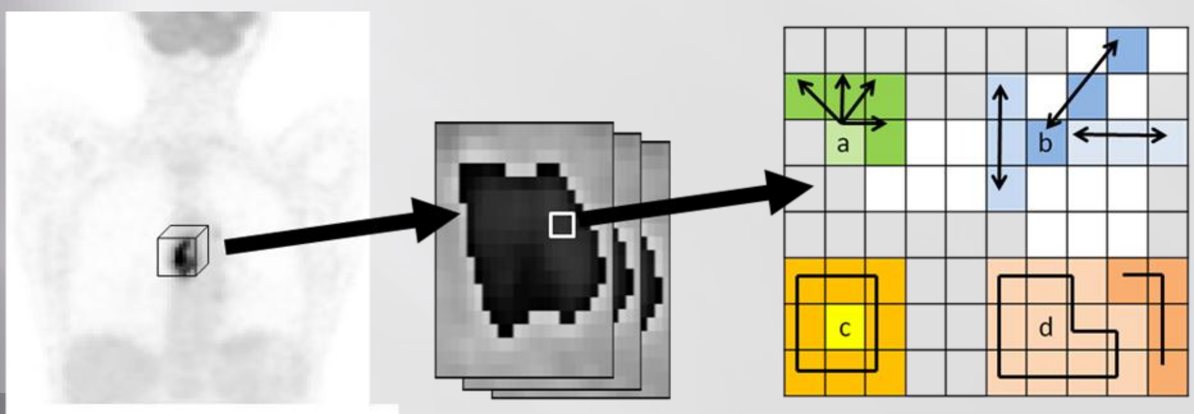
Characterising tracer distribution

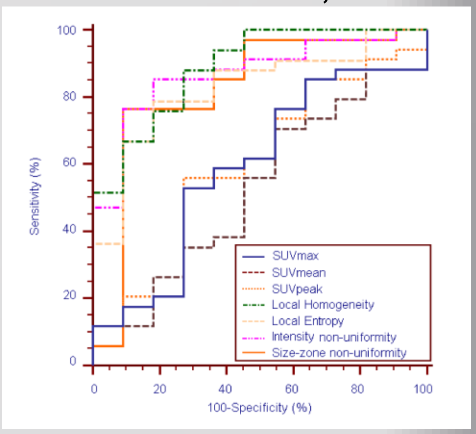
✓Characterisation of tumour activity distribution

Hypothesis: Intra-tumour traceur distribution variability represents a challenge in molecular imaging. Is there any additional information that can be extracted from PET images?

Objectives: Analysis of the activity distribution at local and regional levels

1. Stratification: therapy response, survival, distinction benign / malignant lesions
2. Correlation with molecular and biological measures (genomics)
3. Multi-tracers and multi-modality analysis (ex: αvβ3 Expression, glucose métabolisme, diffusion)

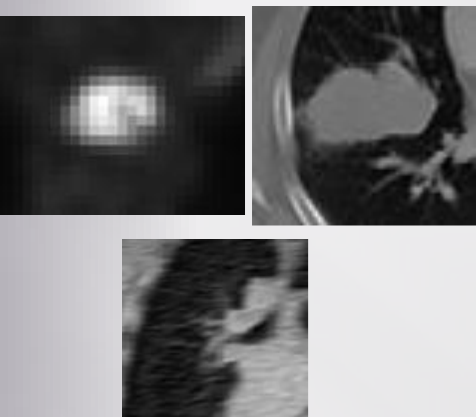




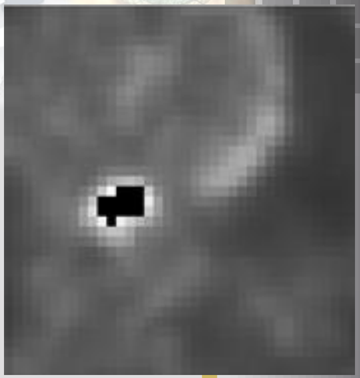
Entropy, Local Homogeneity, Regional Homogeneity

Tixier et al JNM 2011

Multi-modality information paradigm

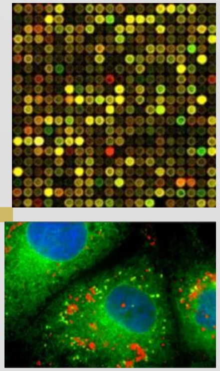


Segmentation



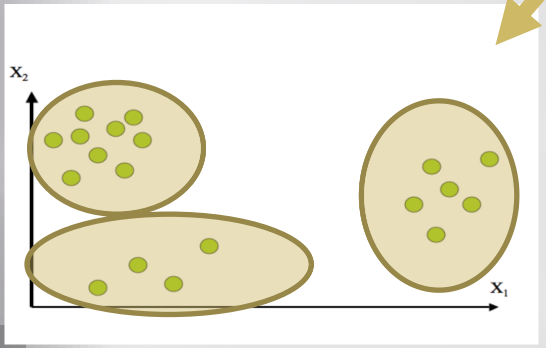
Therapy response prediction, assessment

Extraction of image derived parameters



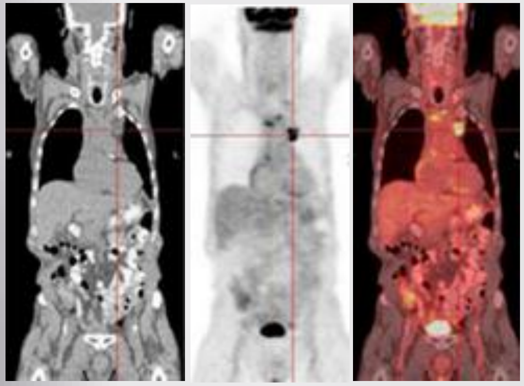
Parameters → Patients ↓	f_1	....	f_k
p_1			
...			
p_n			

Classification

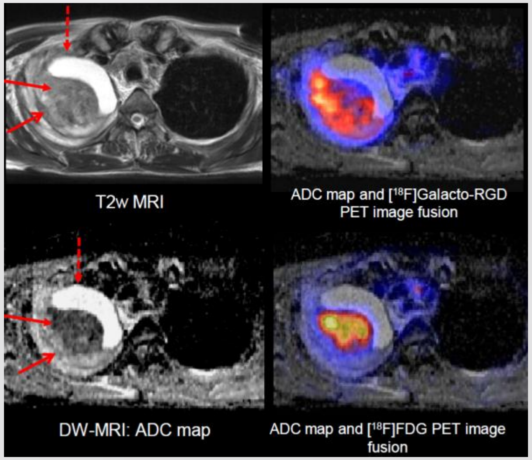


Multi-modality information paradigm

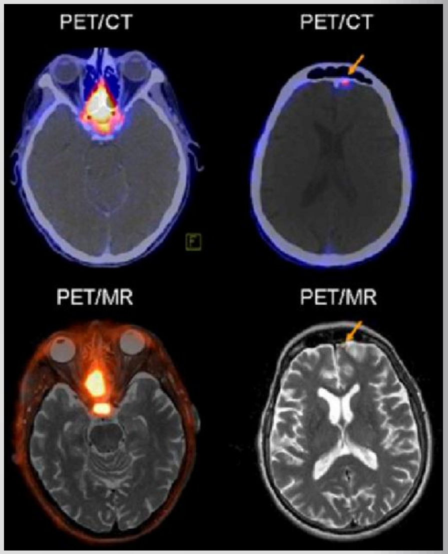
Multi modality / multi tracer imaging: PET/CT, SPECT/CT, PET/MRI…



CT PET/CT PET/CT fusion



A.J. Beer, et al. *SNM annual meeting* 2010



B.J. Pichler, et al. *Journal of Nuclear Medicine* 2010

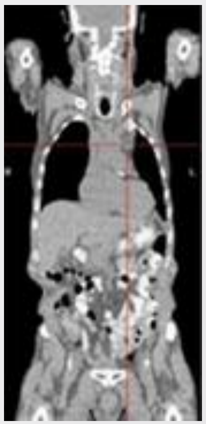
- ✓ Combining function and anatomy
- ✓ Multi modal imaging PET/MRI, multi-tracers, 4D imaging, etc.
- ✓ Towards increasingly large datasets with heterogeneous but complementary information

Multi-modality and temporal evolution

Extraction of pertinent information:

FDG

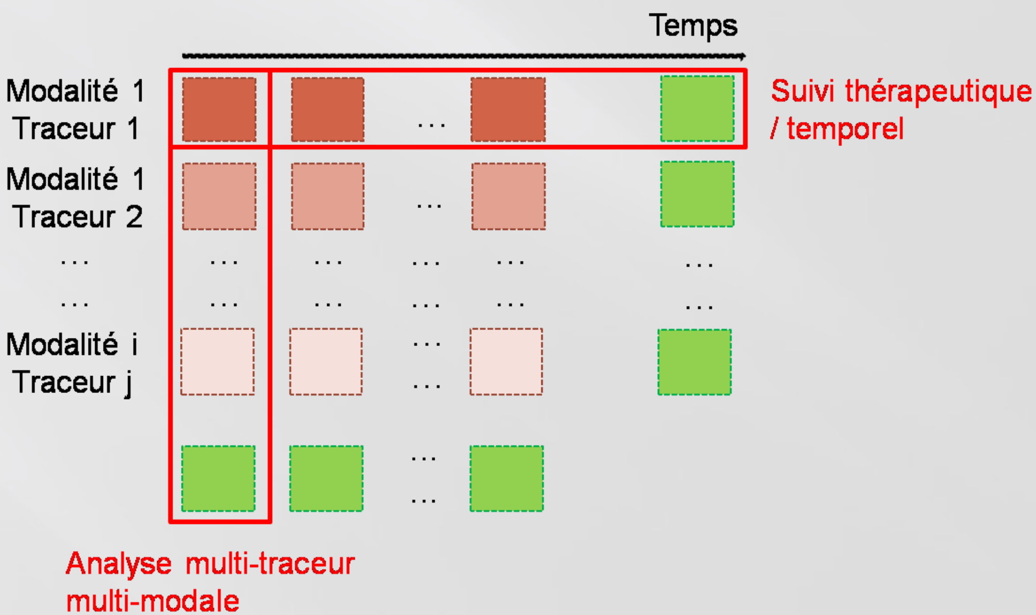
CT



FLT

MRI

- **Information fusion**
- **Segmentation**
- **Classification**

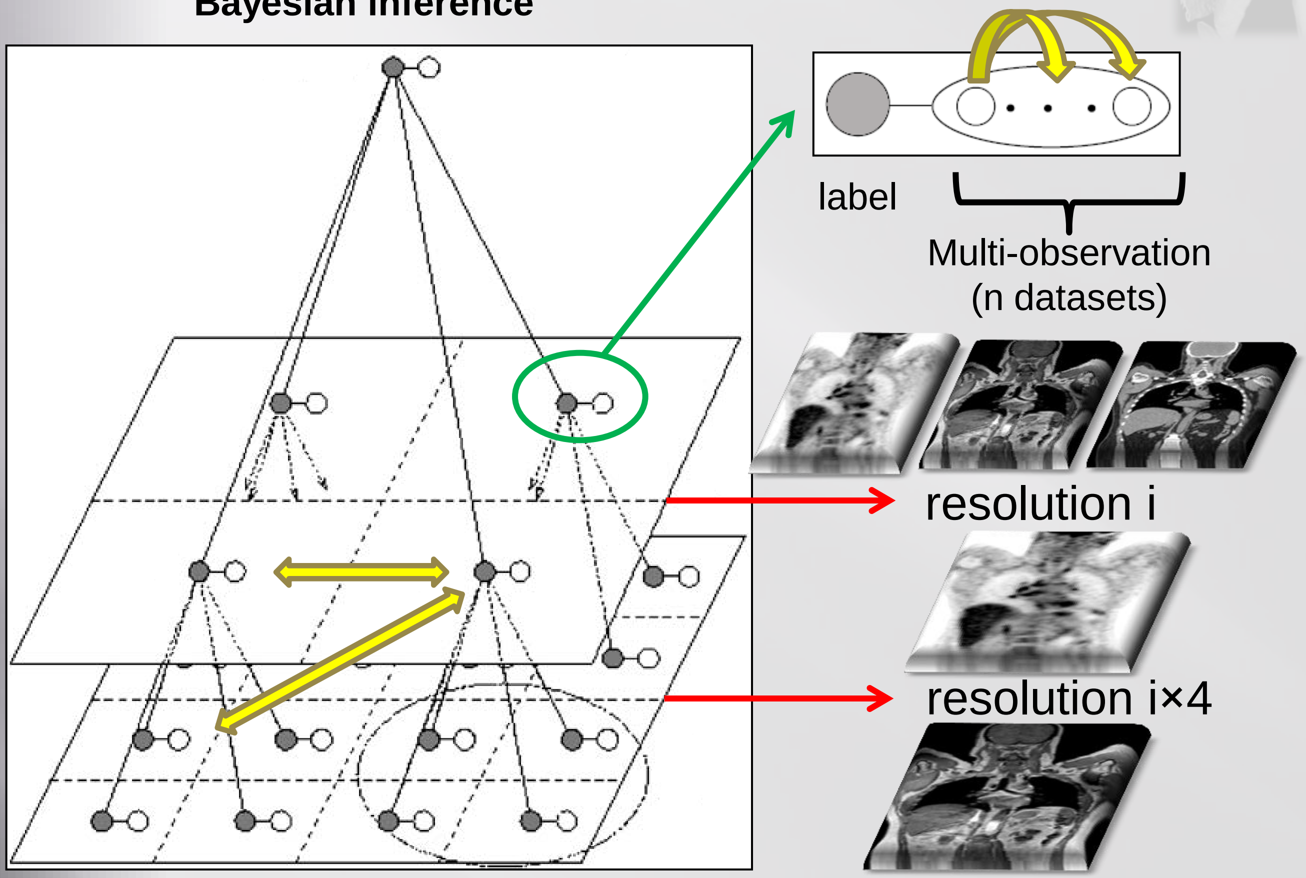


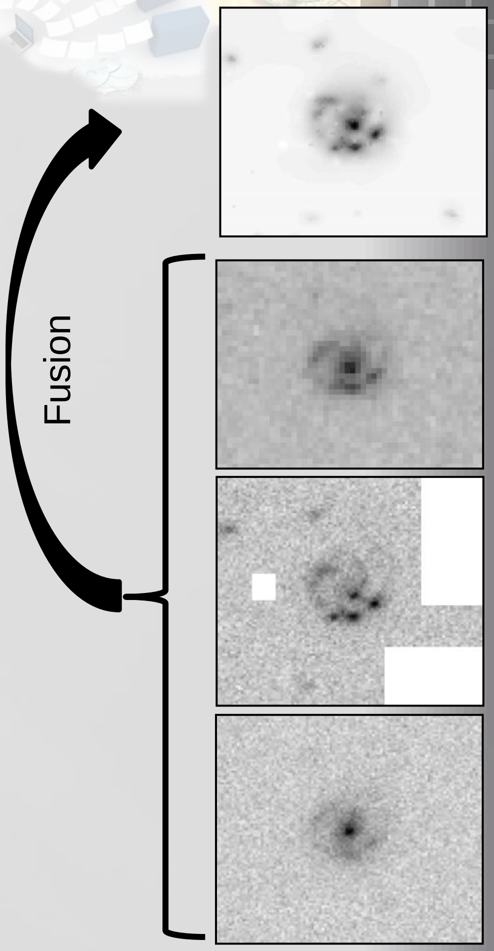
Before treatment

During treatment

Multi-resolution and multi-observation hierarchical models

Bayesian inference





Ex. Astronomy images
(3 observations)

- Handling missing data
- Handling data of variable resolution levels
- Possibility of complex models (correlated noise, fuzzy modeling, etc.)

Conclusions

Multimodality imaging is producing challenges in terms of software development but also plenty of opportunities.

MR sequences is the key for providing answers to a number of challenges associated with PET/MR.

Existing approaches previously developed in PET/CT multimodality imaging may be explored within the PET/MR field.

New software developments are necessary to efficiently explore the multitude of information that may be available from multimodality imaging.

L@TIM