Partial volume effect issue: Instrumental and biological components

Irène Buvat
Imaging and Modeling in Neurobiology and Cancerology lab
UMR 8165 CNRS - Paris 7 and Paris 11 Universities
Orsay, France
buvat@imnc.in2p3.fr
http://www.guillemet.org/irene

Outline

- Understanding partial volume effect: instrumental and biological components

- Reducing partial volume effect through instrumental developments

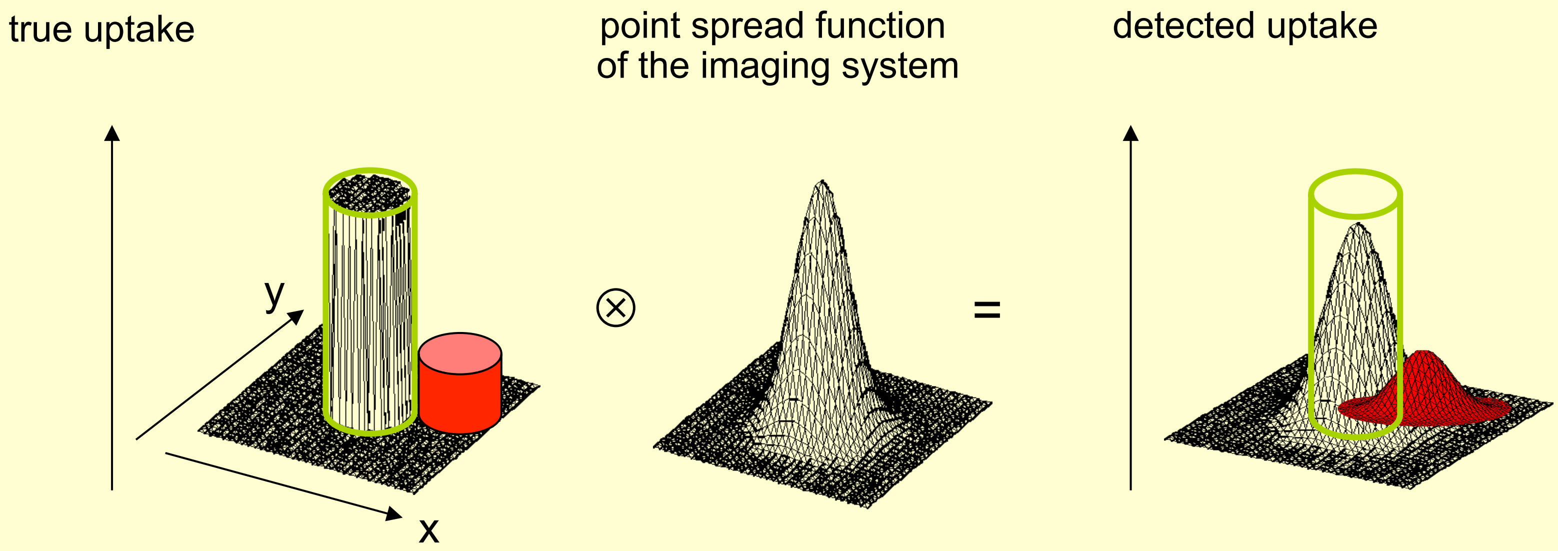
- Reducing partial volume effect through data processing

- Partial volume: friend or foe?

Understanding partial volume effect (1)

- General wording, actually covering 2 effects:

1/ limited spatial resolution of the imaging system (instrumental component)



Spill-out of the hottest object into surrounding structures

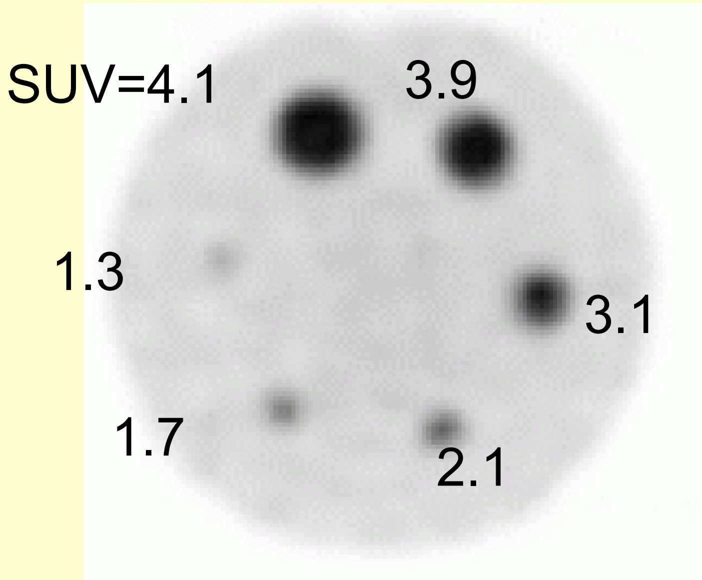
Spill-in the hottest structure of the activity in neighboring regions

The balance between spill-out and spill-in depends on:

- the object size
- the spatial resolution
- the activity levels.

Consequences (1)

Same activity concentration in each sphere (10, 12, 16, 22, 28, 34 mm in diameter), uniform background, only the sphere size varied

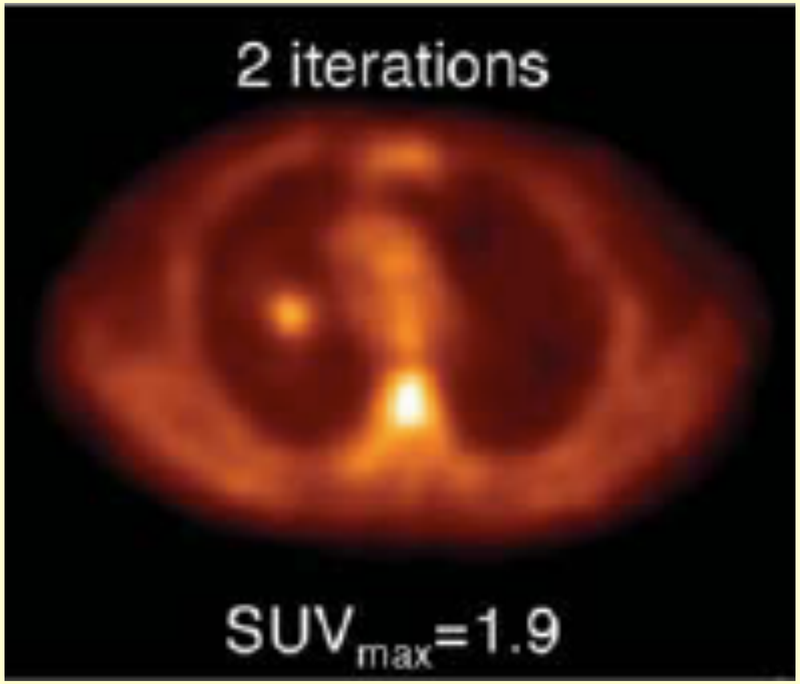


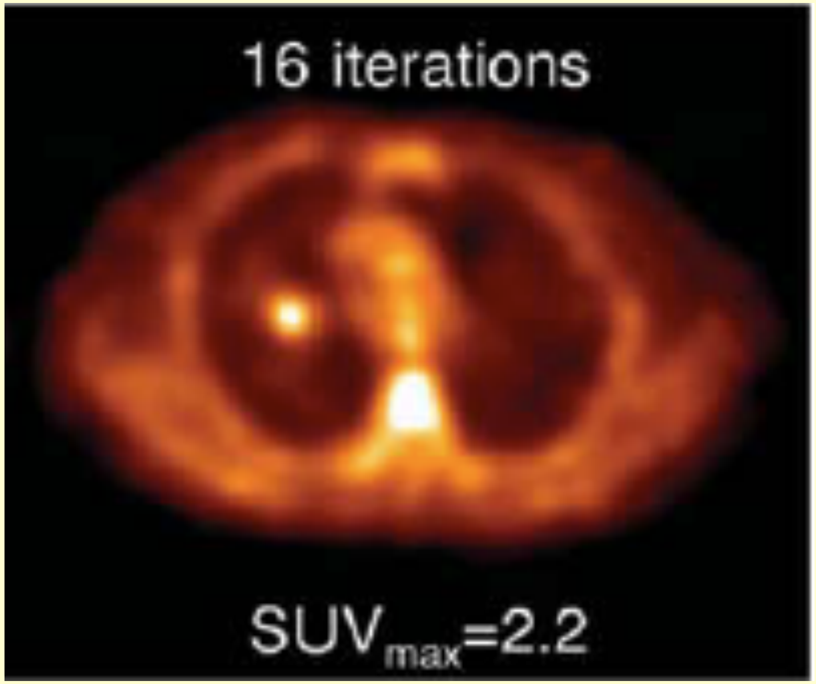
True SUV ~4

Because of PVE, the apparent uptake depends on the object size.
This is true for all objects of "size" ≤ 3 x FWHM in the image

Consequences (2)

Same acquisition system, same data, different reconstruction parameters, hence different spatial resolutions in the images



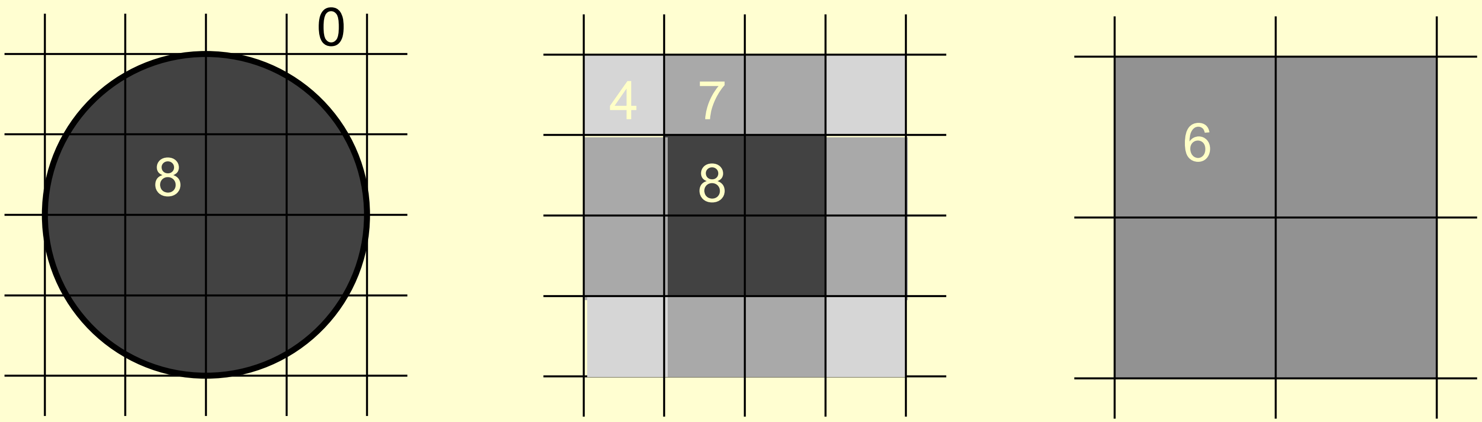


OS-EM, 8 subsets

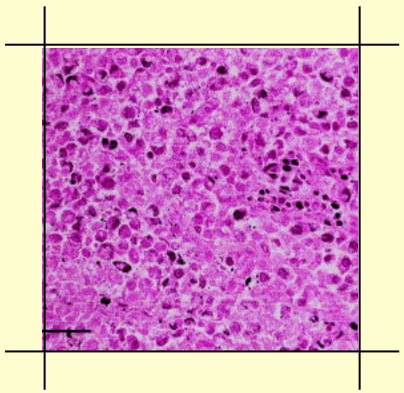
Because of PVE, the apparent uptake depends on the reconstruction, and on the imaging

Understanding partial volume effect (2)

2/ Sampling effect: "tissue fraction effect" (instrumental & biological component)

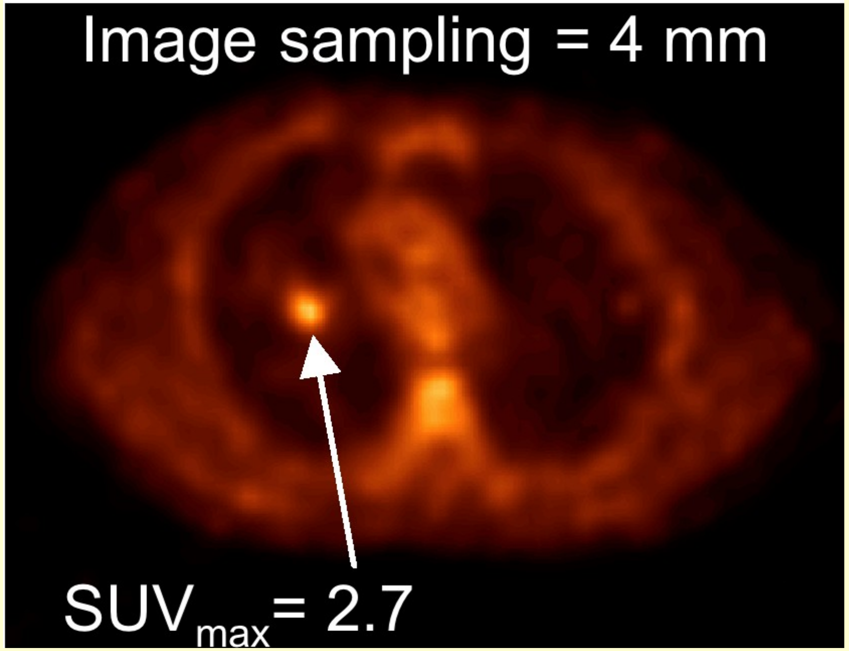


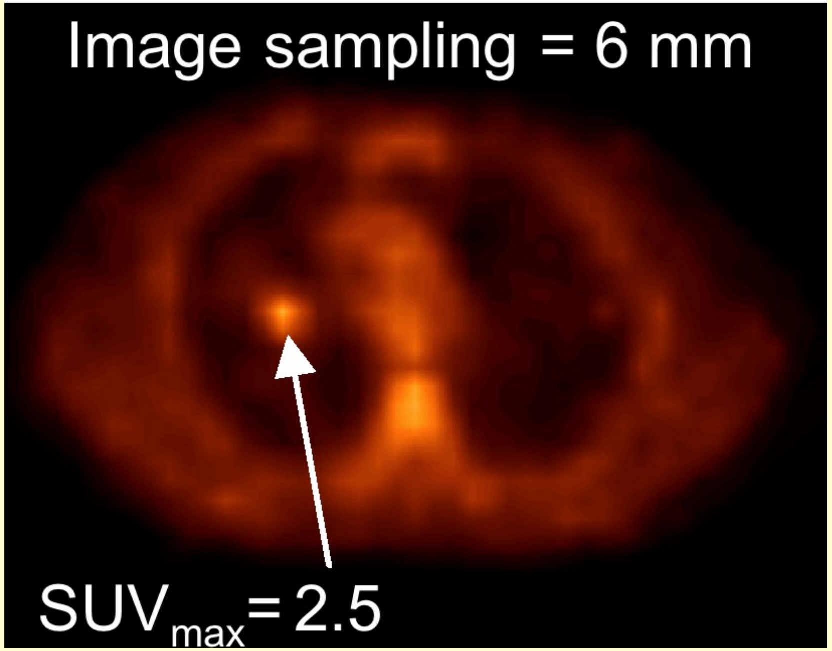
The likelihood to get a mixture of tissues with different uptake in a single voxel increases when the voxel size increases.



In real applications:
- Blood and myocardial tissue
- Grey matter, white matter, and cerebrospinal fluid
- Tumor tissue and healthy tissue
- Blood inside small vessels in a tissue
- Air in alveoli in lung tissue
- etc

Consequences (3)





Because of PVE, the apparent uptake depends on the image sampling (ie voxel size)

Reducing PVE through instrumental developments

One single approach: improving the spatial resolution of the imaging device (possibly through an improvement of the time resolution in TOF PET)

Tai and Laforest, Ann Rev Biomed Engineer 2006: 255-285

In addition to improving image quality and detail detection, it will always reduce partial volume effect

Reducing PVE through data processing

Two complementary options:

• Improving spatial resolution and sampling so as to reduce PVE

Yet, partial volume effect will always remain present in the images because of limited spatial resolution and image sampling

It also affects MR and CT images !

• Explicitly correcting for partial volume effect, ie estimating uptake values that would be measured without PVE

Many methods: tentative classification

- **Improving spatial resolution**
  - **During image reconstruction**
    - PSF modeling
      - Modeling the PSF within the system matrix
      - *etc*
    - using anatomical priors
      - Encouraging smoothness within anatomical regions and large activity changes between anatomical regions only
  - **Post-reconstruction**
    - deconvolution
      - By the PSF in the reconstructed images
      - *- MLEM*
        Kirov et al 2008
        Barbee et al 2010
        etc
    - using anatomical priors
      - Transferring high frequency information from anatomical data into the PET or SPECT images
- **PVE corrections**
  - **Image-based**
    - 1 ROI, 1 value/ROI
      - Multiplying the value of interest by a recovery coefficient
    - >1 ROI, 1 value/ROI
      - Estimating and inverting spill-over between regions
    - 1 ROI, voxel-based
      - Estimating 1 recovery coefficient per voxel in 1 ROI
    - >1 ROI, voxel-based
      - Calculating a full map of recovery coefficients
  - **Projections-based**
    - ROI reconstruction
      - Reconstruction of the mean value in specific ROIs
    - voxel-based
      - Estimating spill-over in the projection space

Many methods developed for more than 30 years…

Improving spatial resolution

During image reconstruction

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using anatomical priors

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1 ROI voxel-based

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>1 ROI voxel-based

Yang et al 1996
Shcherbinin et al 2010
etc

Projections-based

ROI reconstruction

Huesman 1984
Carson et al 1986
Formiconi 1993
Vanzi et al 2007
Moore et al 2012
etc

voxel-based

Erlandsson et al 2010
Erlandsson et al 2011
etc

Many methods: tentative classification

Partial volume corrections have been developed
over more than 30 years !
Why is the problem not solved yet ?

Attention has first been paid on attenuation and scatter that affect all structures (regardless of their size). Only after that, has PVE attracted more attention (together with motion), probably because it only affects small structures.
Still, biases introduced by PV can be far higher than those introduced by scatter !

This is also because quantitation became only recently a hot topic of interest

Many methods: which methods are provided by vendors?

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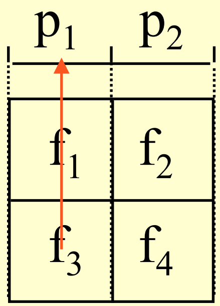
etc

PSF modeling in image reconstruction

without modeling of the PSF

$$p = R\,f$$

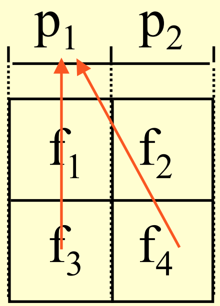
$$\begin{bmatrix} r_{11} & 0 & r_{13} & 0 \\ 0 & r_{22} & 0 & r_{24} \\ r_{31} & r_{32} & 0 & 0 \\ 0 & 0 & r_{43} & r_{44} \end{bmatrix}$$

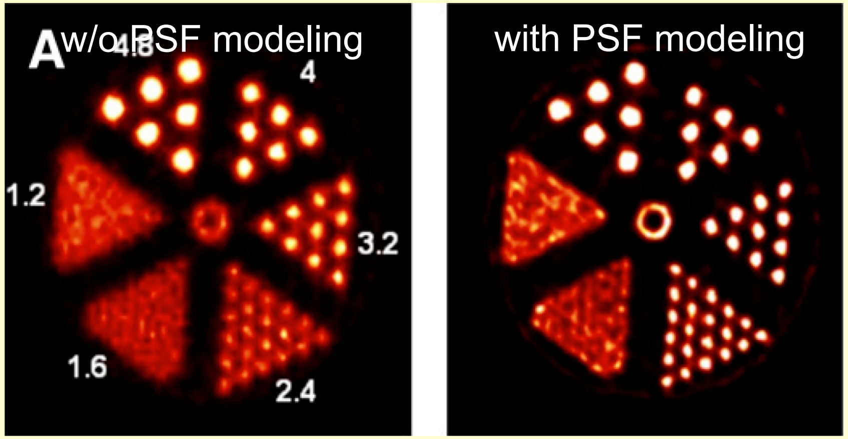


with modeling of the PSF

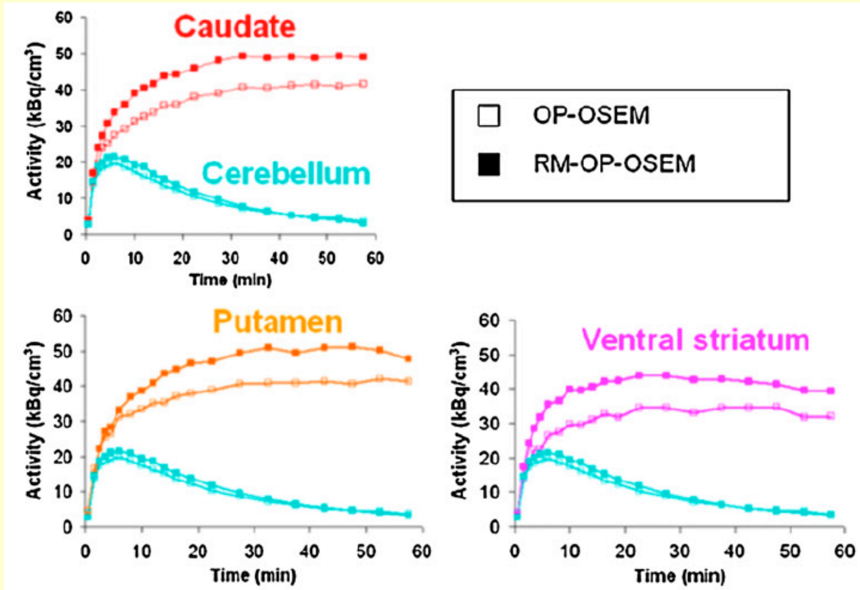
$$p = R_\sigma\,f$$

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix}$$





HRRT PET scanner, *Sureau et al JNM 2008*



Only 1 PV correction strategy available routinely !

Easily accessible, definitely useful, but PSF modeling does not fully compensate for PVE

- The lack of availability of the other PV methods considerably limits their wide assessment and the demonstration of their usefulness in patient scans

- Implementation of more sophisticated PV corrections by vendors is essential to move forward and assess the role partial volume correction should play in clinical practice

Why are the other approaches not available?

Improving spatial resolution

During image reconstruction

PSF modeling

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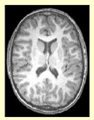
Reader et al 2003
etc

using anatomical priors



Chen et al 1991
Fessler et al 1992
Gindi et al 1993
Ouyang et al 1994
Lipinski et al 1997
Comtat et al 2002
Baete et al 2004
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etc

Post-reconstruction

deconvolution

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using anatomical priors

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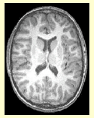
PVE corrections

Image-based

1 ROI
1 value/ROI



-Recovery coefficients
Hoffman et al 1979
Wisenberg et al 1981
Kessler et al 1984
*Srinivas et al 2009 **

>1 ROI
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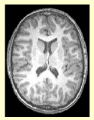
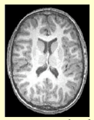
Henze et al 1983
Herrero et al 1988
Rousset et al 1998

1 ROI
voxel-based



Videen et al 1988
Meltzer et al 1990
MüllerGärtner et al 1992
Da Silva et al 1999
etc

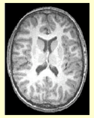
>1 ROI
voxel-based



Yang et al 1996
Shcherbinin et al 2010
etc

Projections-based

ROI reconstruction



Huesman 1984
Carson et al 1986
Formiconi 1993
Vanzi et al 2007
Moore et al 2012
etc

voxel-based

Erlandsson et al 2010
Erlandsson et al 2011
etc

Requiring segmented anatomical images

Improving spatial resolution

During image reconstruction

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Reader et al 2003
etc

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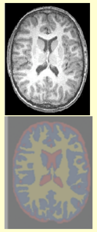

Post-reconstruction

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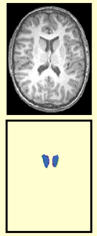

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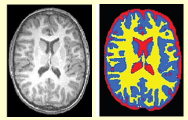

Projections-based

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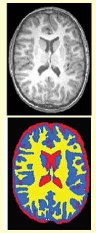

voxel-based

Erlandsson et al 2010
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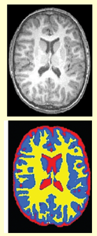
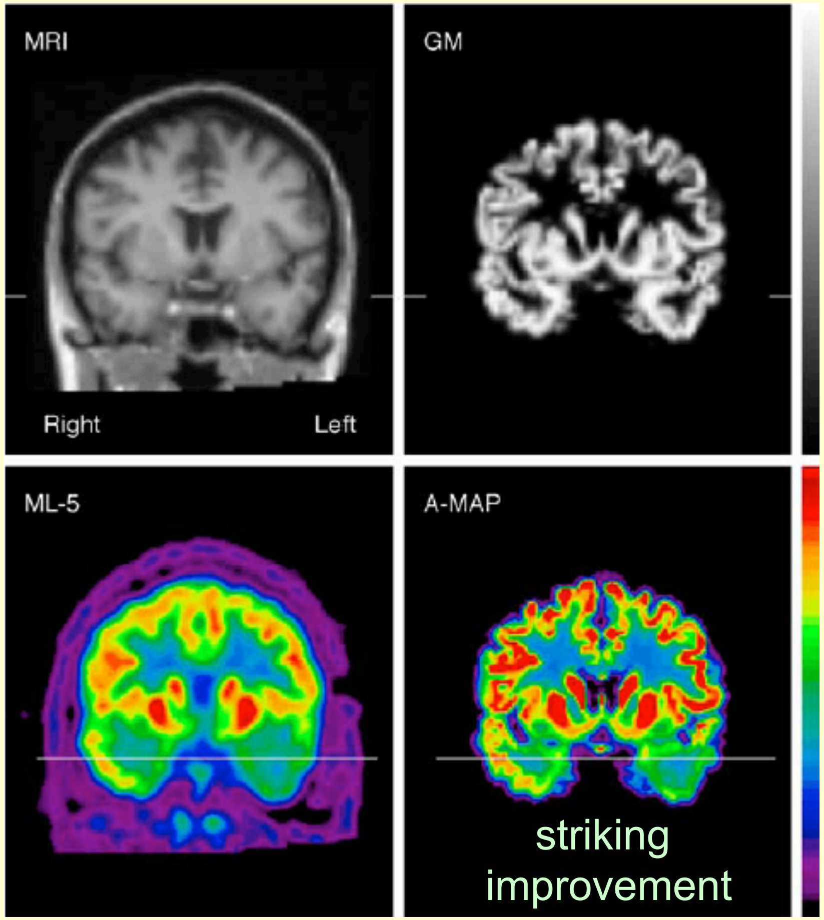


Examples of PV corrections using segmented anatomical priors

Image enhancement during image reconstruction

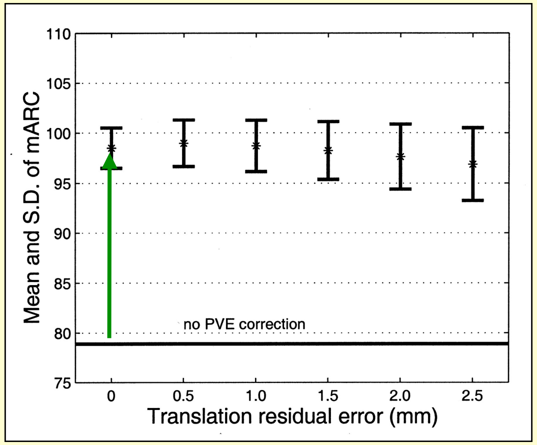
(anatomically-based maximum a posteriori approach, *Baete et al 2004*)



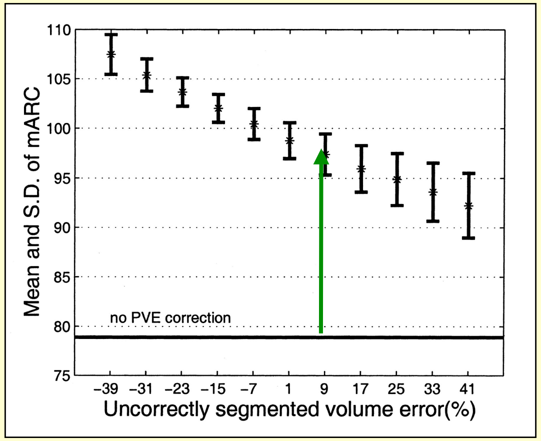
Explicit PVC after image reconstruction

(geometric transfer matrix, *Rousset et al 1998, Frouin et al 2002*)

Impact of PET/ MR registration errors



Impact of MR segmentation errors



Right caudate, F18DOPA PET

Trickiness of structural-based PVC

Extremely promising results, but some significant limitations

- Strong assumption: anatomy has to be highly correlated with function: not always true
- Activity is most often assumed to be uniform in each segmented region
- Segmentation of CT or MR images is a problem in itself (except for brain MR)
- **Practical feasibility in large cohorts of patients** still has to be demonstrated due to a significant number of hyper-parameters to be set in some methods
- Robustness of these methods wrt anatomy-function mismatch, registration errors, and segmentation errors is not widely documented **in clinical studies**

Yielding noisy images

Improving spatial resolution

During image reconstruction

PSF modeling

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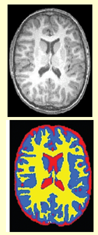

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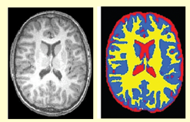

Projections-based

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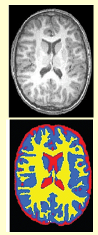

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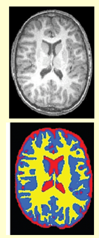
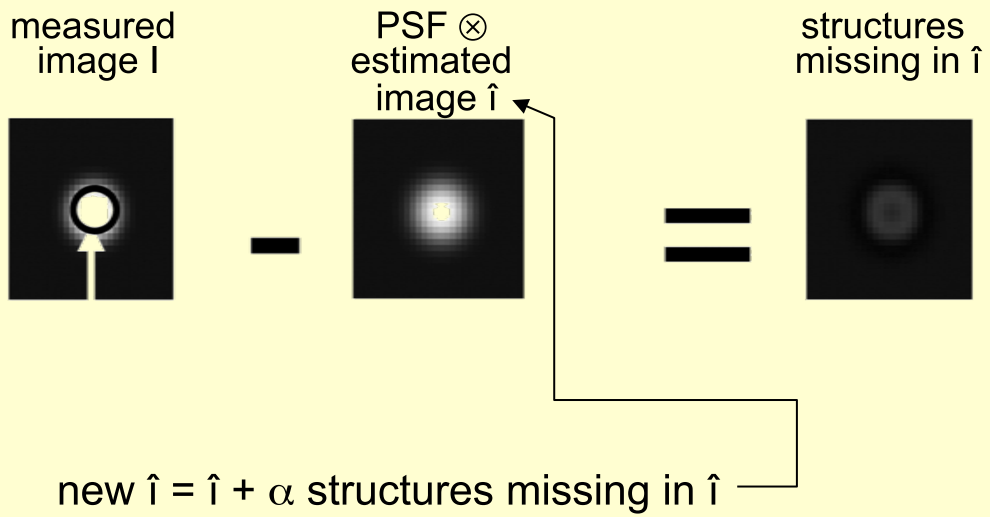
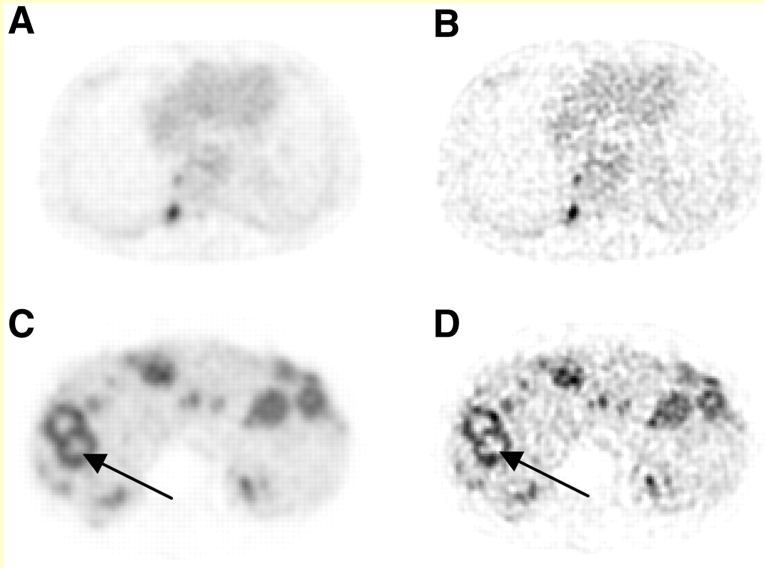


Example of deconvolution

Van Cittert deconvolution

(*Teo et al 2004*)





Features of the deconvolution approaches

Improve spatial resolution hence reduce PVE

Yield images (not only one value per ROI)

High noise (MDs don't like noise)

Noise to be controlled through regularization:
- hard to tune regularization well in a broad variety of situations
- the exact impact of regularization on quantitative values is not well known

Incomplete PVE correction as high frequency cannot be recovered

Last but not least: need to properly characterize the PSF

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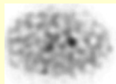

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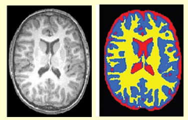

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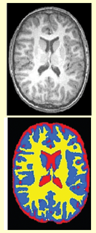
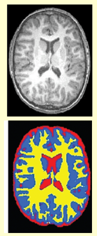
Formiconi 1993
Vanzi et al 2007
Moore et al 2012
etc



voxel-based

Erlandsson et al 2010
Erlandsson et al 2011
etc

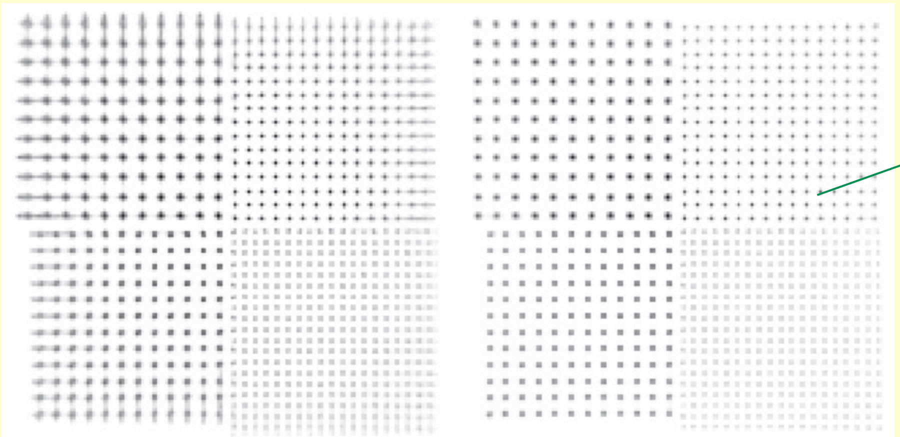


Determining the point spread function

• The best approach to determine the PSF still needs to be identified:

- Analytical approximations *(Rahmim et al 2008, Strul et al 2003, Selivanov et al 2000, Yamaya et al 2005, 2008)*
- Computer simulations *(Rafecas et al 2004, Herraiz et al 2006)*
- Experimental measurements *(Panin et al 2006)*
- Empirical adjustment *(Watson et al 2011)*

• Non-stationary and object dependent: in iterative reconstruction, the reconstructed spatial resolution depends on the convergence rate, which itself depends on the activity distribution.

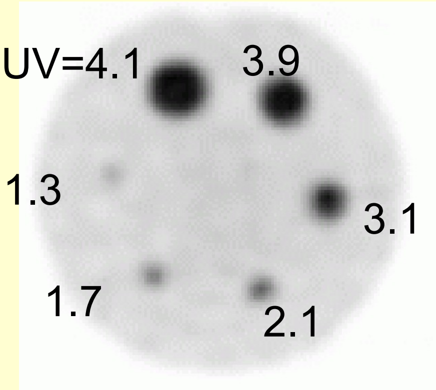


with shift-invariant kernel with shift-variant kernel
PETbox reconstruction *(Pratx and Lewin, PMB 2011)*

Promising approach: reconstruction involving a space-variant PSF results in a far more stationary PSF in the images, which greatly facilitates PVC performed on the reconstructed images

Understanding the clinical usefulness of partial volume correction

• Partial volume effect makes the activity measurement dependent on the metabolically active volume

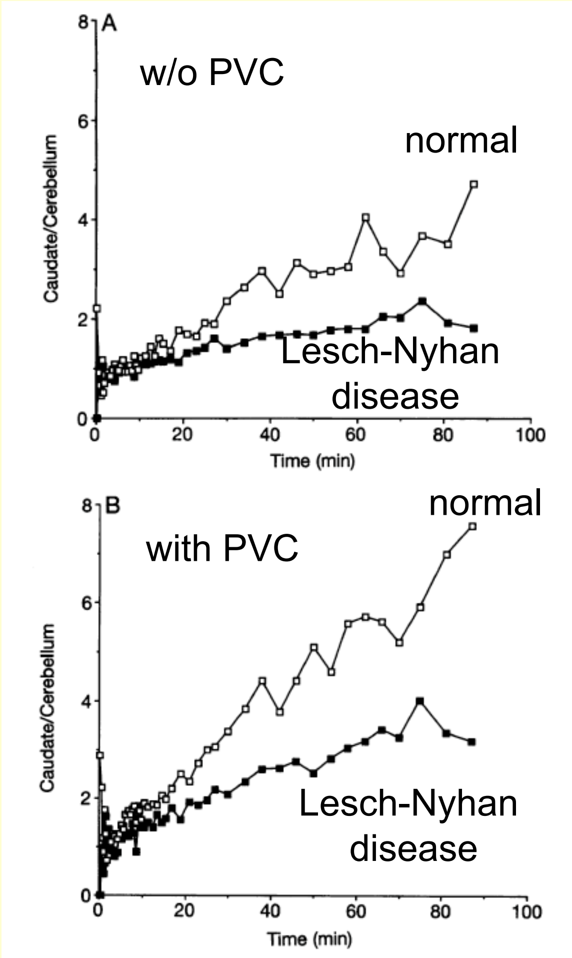


• This might not always be misleading, as often, diagnosis is not only based on metabolic activity, but also on the metabolically active volume (in tumor imaging for instance)

This is probably why it is so difficult to demonstrate the clinical usefulness of PV correction

Partial volume correction: friend or foe?

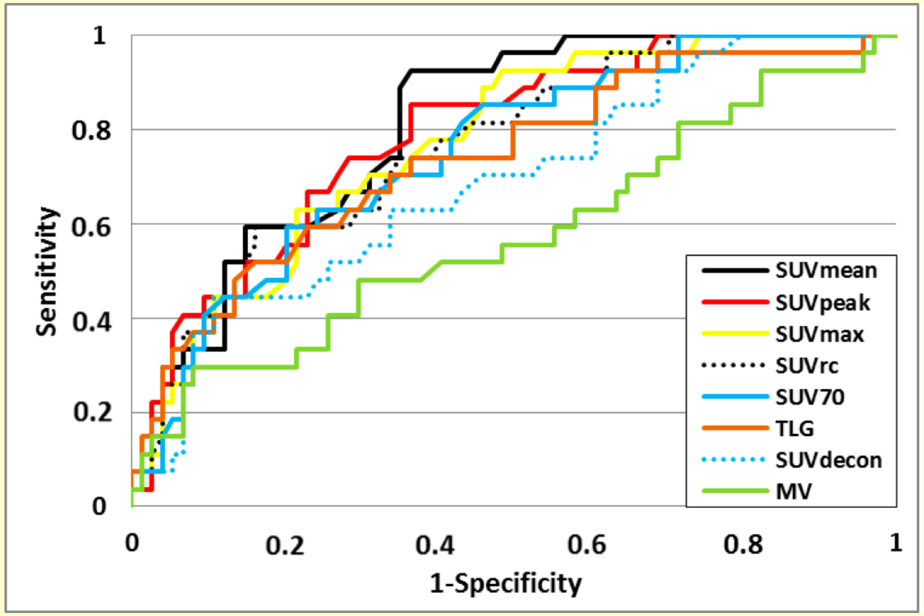
Friend



Wong et al, PNAS 1996
C11 WIN-35,428 (dopamine transporter) dynamic PET

Foe

Distinguishing between responding and non responding lesions in cancer patients (metastatic colorectal cancer) using FDG PET



Maisonobe et al, EJNMMI 2012

Conclusions

• Instrumental point of view: struggle towards enhanced spatial resolution to reduce PVE

• Many PVE correction strategies rely on structural priors: PET/CT and PET/MR should play a key role in further development and assessment of PVE corrections

• Accurate PVE correction requires precise segmentation (difficult in some applications), better understanding of the relationship between anatomy and function, and precise characterization of the PSF: all these points are still active research topics

• There is a huge need for further assessment of the role of PVE correction in clinical applications (cardiac, brain, oncology). Cf historical example of SPECT attenuation correction that took years to be accepted – and is still not by all).

More … (with references and equations !)

Erlandsson K, Buvat I, Pretorius PH, Thomas BA, Hutton BF. A review of partial volume correction techniques for emission tomography and their applications in neurology, cardiology and oncology, Phys Med Biol 2012 (in press)

Rousset OG, Rahmim A, Alavi A and Zaidi H. Strategies for partial volume correction in PET. PET Clin. 2007, 2:235-249.

Soret M, Bacharach S, Buvat I. Partial volume effect in PET tumor imaging. J Nucl Med 2007, 48: 932-945.