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Using time-of-flight information for PET, PET/CT and PET/MRI reconstruction

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Summary. — The timing resolution of PET detectors is rapidly improving thanks to new developments in detector design. As a result, the time of flight (TOF) measurement in PET systems is becoming more accurate as well. It has been shown that the TOF measurement supplies information that is not present in non-TOF PET emission data. Because TOF reduces the uncertainty associated with each measured coincidence event, it improves the signal to noise ratio of the reconstructed images. For the same reason, the convergence of iterative reconstruction algorithms is faster and more uniform as well, which also benefits the quality of the reconstructed images. When the TOF resolution is sufficiently high, one can estimate from the TOF-PET data not only the activity distribution, but also the attenuation coefficients. This enables attenuation correction in stand-alone PET scanners and the correction of the available attenuation map in hybrid PET systems. This correction may be valuable, because the CT-based attenuation maps in PET/CT and the MR-based attenuation maps in PET/MR can be degraded by motion, metal artefacts and/or conversion errors. It is observed that for the estimation of the attenuation (or detector sensitivities) from TOF-PET emission data, accurate timing calibration and scatter correction is mandatory. When the calibration and the scatter estimates are accurate, we find that attenuation correction based on the TOF-PET data themselves produces activity images that differ only up to a few percent from the activity images obtained with reference CT-based attenuation correction. With improving TOF resolution, the power of the attenuation estimation algorithms increases, but the accuracy requirements for the timing calibration become more stringent as well.

The timing resolution of PET detectors is rapidly improving thanks to new developments in detector design. As a result, the time of flight (TOF) measurement in PET systems is becoming more accurate as well. It has been shown that the TOF measurement supplies information that is not present in non-TOF PET emission data [1].

Because TOF reduces the uncertainty associated with each measured coincidence event, it improves the signal to noise ratio of the reconstructed images [2]. This is illustrated in fig. 1 using simple 2D simulations. In the first simulation, discs with the

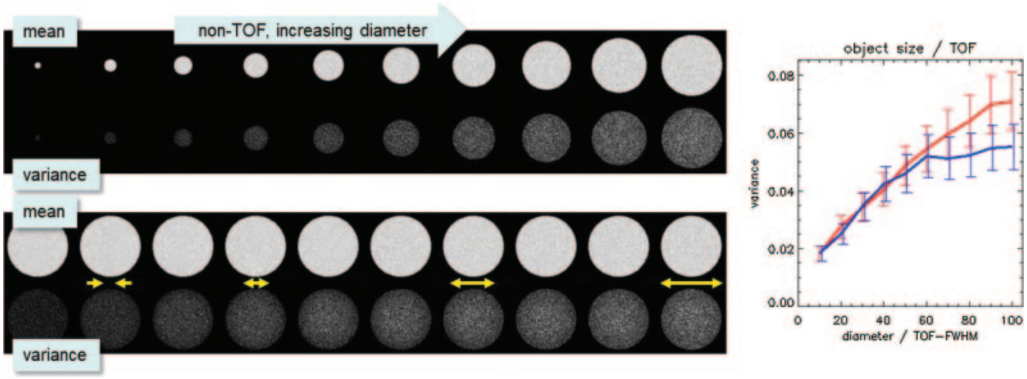

Fig. 1. – Top: in non-TOF PET, the variance in the reconstructed image increases with increasing disk size. Bottom: similarly, in TOF PET, the variance in the reconstructed image increases with increasing TOF uncertainty. In both cases, the first set of images shows the mean activity in every pixel, and the second set shows the variance in every pixel, as estimated from 100 noise realisations. The plot shows the variance as a function of the diameter of the disk for non-TOF (red) and as a function of the TOF kernel width (blue).

same tracer concentration and different diameters were considered. Attenuation-free PET projections were computed, Poisson noise was added and the images were reconstructed iteratively and post-smoothed to obtain the same image resolution for all images. As can be observed in the figure, the reconstructions become noisier for larger disks. This is because, for larger disks, there was more overlapping activity in the projections, and therefore less information about where exactly those photons were emitted. This higher amount of uncertainty translates into higher noise in the reconstructed images. In the second simulation, the same disc is considered, and attenuation-free TOF PET projections of it were computed, using different TOF resolutions (indicated by the size of the yellow arrows). As the TOF resolution is poorer, there is more uncertainty about where the detected photons have originated. Again, this makes the reconstruction problem harder and, as a result, the variance on the reconstructed images increases. This shows that TOF improves the effective sensitivity. For the same reason, with TOF, the convergence of iterative reconstruction algorithms is faster and more uniform as well, which also benefits the quality of the reconstructed images.

When the TOF resolution is sufficiently high, one can estimate from the TOF-PET data not only the activity distribution, but also the attenuation coefficients [3]. This enables attenuation correction in stand-alone PET scanners and the correction of the available attenuation map in hybrid PET systems. This correction may be valuable, because the CT-based attenuation maps in PET/CT and the MR-based attenuation maps in PET/MR can be degraded by motion, metal artefacts and/or conversion errors. This is illustrated in fig. 2, where a joint reconstruction algorithm (MLAA) was used to estimate the attenuation and activity distributions from a TOF-PET brain scan. This TOF-PET system (GE-Signa) has a TOF resolution of about 380 ps. The estimated attenuation shows details of skull, soft tissues, air and a dental filling, which are not seen in the atlas-based attenuation map.

It is observed that for the estimation of the attenuation (or detector sensitivities) from TOF-PET emission data, accurate timing calibration and scatter correction are

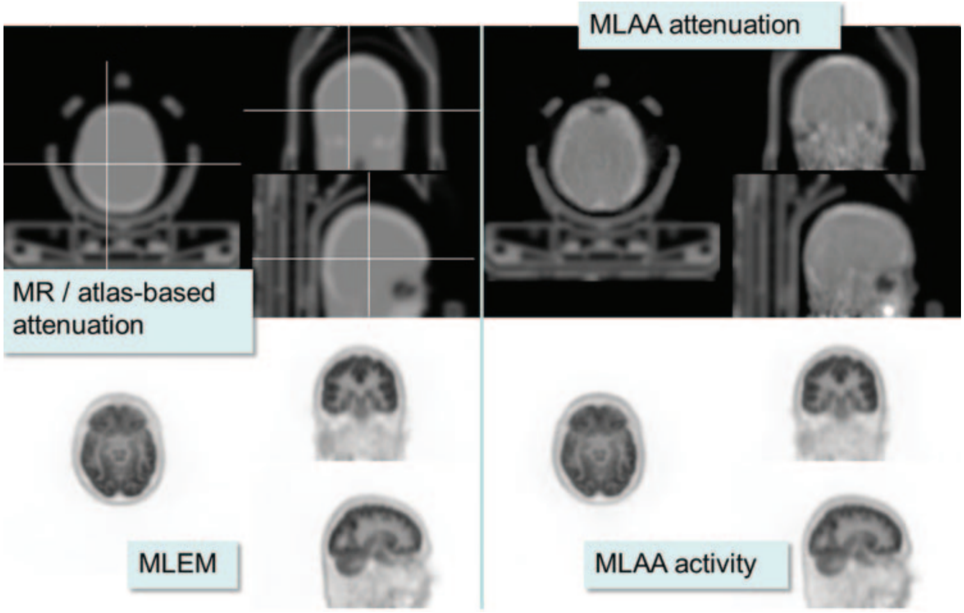

Fig. 2. – Left panel: the MR/atlas-based attenuation map (top) is a combination of a template for the bed and coils with an estimate of the attenuation in the head based on an atlas which is aligned to the patient MR image. With this attenuation map, an activity image is reconstructed with MLEM (bottom). Right panel: result of a maximum-likelihood reconstruction (called MLAA) that jointly estimates the attenuation (top) and the attenuation corrected activity (bottom). The template for the bed and coils was used, MLAA only estimated the attenuation by the patient head.

mandatory [4]. When the calibration and the scatter estimate are accurate, we find that attenuation correction based on the TOF-PET data themselves produces activity images that differ only up to a few percent from the activity images obtained with reference CT-based attenuation correction.

With improving TOF resolution, the power of the attenuation estimation algorithms increases, but the accuracy requirements for the timing calibration become more stringent as well.

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