Quantitative multi-pinhole small-animal SPECT with U-SPECT-II/CT

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Aims
Small-animal SPECT plays an important role in biomedical research. Accurate and reliable quantitative imaging with small animal SPECT can help scientists with understanding the behavior of organs, tissues and pharmaceutical in vivo, which is a good motivation for developing accurate correction methods for photon attenuation. Previous phantom assessments¹² show that photon attenuation reduces the measured activity concentration in the center of rat-sized and mouse-sized phantoms by up to 25% and 18% with Tc-99m, respectively. These studies lead to the conclusion that the attenuation compensation, together with correction for other image degrading effects, is required in order to consistently achieve accurate quantitative small-animal SPECT images. We here propose a CT-based modified non-uniform Chang³ method for attenuation correction and evaluate this method with phantom studies in a U-SPECT-II/CT system (with an integrated Skyscan 1178 single-source system)⁴. The necessary information for calculating attenuation correction maps was derived from registered X-ray CT images of the phantom.

Method
First a SPECT scan was made in the U-SPECT-II/CT system of a small drop of a solution containing 57.2 MBq Tc-99m to obtain the calibration factor of the SPECT system. Later on a 30-mm NEMA-small-animal phantom filled with 8.66 MBq/ml Tc-99m solution was scanned with both the SPECT and CT modalities. List-mode SPECT data were acquired and a scatter-corrected SPECT image was reconstructed by using the pixel-based ordered subset expectation maximization (POSEM⁵) algorithm combined with a triple-energy-window (TEW⁶)-based scatter correction. A CT image was also reconstructed in Hounsfield unit (HU) and registered to the SPECT image.

The attenuation coefficient (μ) at the location of each voxel was derived from the registered CT image, by employing a linear scaling of the HU numbers:

$$\mu = \mu_0 \left( \frac{\text{HU}}{1000} + 1 \right),$$

where $\mu_0$ is the attenuation coefficient associated with water and the energy of the photons used in SPECT. In the case of Tc-99m studies, $\mu_0$ equals 0.151 cm⁻¹.

The amount of attenuation was quantified by the transmitted fraction (TF) which is the ratio of detected counts with attenuation to the counts in an ideal attenuation-free situation. In the modified non-uniform Chang³ method, the overall TF of each voxel in a SPECT image is
treated as the average of TFs along different projection trajectories starting from that voxel. Along each projection line, the TF is simply computed as the line integral of the attenuation coefficient on that line. The calculation above is represented as the following equation:

\[
TF = \frac{1}{M} \sum_{m=1}^{M} \exp\left(-\int_{L_m}^{L_m} \mu(l) \, dl \right),
\]

in which \(M\) is the number of projections in acquisition for a certain voxel, \(L_m\) denotes the \(m\)-th projection path of gamma photons, and \(\mu(l)\) is the attenuation coefficient as a function of location \(l\) on that projection line \(L_m\).

With the scatter-corrected image voxels (SC), the calibration factor (CF) and the overall transmitted fraction (TF), the attenuation-compensated image (AC) was given by:

\[
AC = \frac{SC \cdot CF}{TF}.
\]

**Results**

Figure 1(a) shows uniform and non-uniform slices of the NEMA phantom from un-corrected and attenuation-corrected SPECT images. Figure 1(b) shows their corresponded CT slices, and the derived attenuation correction maps (slices of transmitted fraction values) are illustrated in Figure 1(c).

![Figure 1](image1.png)

Figure 1: Slices and attenuation correction maps. (a) un-corrected (UC) and attenuation-corrected (AC) SPECT slices. (b) CT slices. (c) attenuation correction map derived from the CT slices.

The transmitted fraction values in the attenuation correction maps demonstrated about 20~23% attenuation in the center area of the phantom, which is consistent with literature\(^1\text{-}^2\), and indicating that the attenuation correction is important for quantification even in small-animal SPECT. The quantitative errors are visualized more clearly by using line profiles in Figure 2. The average quantification error of the entire phantom volume was \(-16.2\%\) without attenuation correction, and was reduced to \(4.7\%\) with attenuation correction.
Figure 2: Line profiles in (a) uniform slice and (b) non-uniform slice. NC: without attenuation correction. AC: with attenuation correction. GS: gold standard obtained with dose calibrator.

Conclusion
The effects of attenuation in small-animal SPECT can be corrected by using the CT-based non-uniform Chang method in the U-SPECT-II/CT system, with a good accuracy of less than 5% error on average.

References: