Validation of $^{131}$I activity in thyroid phantom using SPECT/CT 3D image based dosimetry

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Abstract. Quantitative imaging gives a better understanding on the distribution of radioactivity that can be used in the estimation of absorbed dose in the specific target organ. The goal of this study was to validate the accuracy of $^{131}$I activity quantification of cumulated activity in thyroid uptake phantom using 3-dimensional (3D) SPECT/CT imaging. In this study, a series of SPECT/CT acquisition of the thyroid uptake was performed. Images of different matrix sizes and iterations number were reconstructed using ordered-subsets expectation maximization (OSEM). Quantification of the activity in the phantom was determined using a Medical Image Data Examiner (AMIDE) software based on the mean value and maximum value. The cumulated activity in the phantom was determined by calculating area under the curve (AUC) in the time-activity curve. The results showed that the mean activity for 256 voxels was underestimated between 6.18% - 13%, and overestimated between 6.156% - 64.66% for maximum value metric. The cumulated activity derived from SPECT/CT showed an error margin of 10%.

1. Introduction
$^{131}$I is a radioisotope that is commonly used to treat thyroid diseases, such as hypothyroidism and hyperthyroidism. Apart from that, thyroid cancer is the most common malignant endocrine tumour, and the incidence is increasing (1). $^{131}$I emits high-energy beta particles (248 - 807 keV) that have good efficacy on treating thyroid diseases. It also emits high energy gamma radiation (364 keV) that can be used in quantification of activity distribution in the body using whole body gamma scintigraphy or Single Photon Emission Computed Tomography/Computed Tomography (SPECT/CT). Measurement of activity distribution is essential to accomplish patient-specific dosimetry in $^{131}$I therapy. Internal radiation dosimetry in nuclear medicine relates to the estimation of the amount and distribution of radiation energies deposited in the tissues by the radionuclides in the body. It has been used in the determination of absorbed dose and related quantities for radiation protection, risk assessment and treatment planning. Medical internal radiation dosimetry (MIRD) using Monte Carlo is a method developed to estimate absorbed dose in a target organ. The method depends on the decay of radioactivity in a target organ, amount of energy deposited in the target organ from the source organ(s), administered activity, mass of target organ and residence time. Residence time is an essential parameter in MIRD calculation. It can be obtained by calculating the cumulated activity in time-activity curve divided by initial activity.
The (3D) image-based patient-specific dosimetry, which couples with patient anatomy and activity distribution allow for patient-specific tumor-dosimetry calculation. In 3D dosimetry, absorbed dose calculation are influenced by SPECT activity quantification and image quality. The previous study showed that it is crucial to have an accurate SPECT reconstruction with compensation for attenuation, scatter and 3D detector response as well as an optimum choice of the number of iterations and the activity calibration geometry (2).

In this study, cumulated activity estimation was determined using multiple 3D SPECT/CT images at different time points compared to the theoretical calculation in phantom setup.

2. Materials and Methods

A thyroid uptake neck phantom (Biodex, Shirley, New York) was used to simulate the patient’s neck. This phantom consists of a solid cylindrical Perspex with a hollow area to fit in a small cylindrical compartment of roughly 30 ml of volume. To image this phantom, a cylindrical bottle was filled with 36 mL of $^{131}$I solution with a total activity of 30.54 MBq. This would produce a total concentration of 610.76 kBq/mL.

2.1. SPECT/CT calibration

Total system volume sensitivity (in cps/MBq) was required in order to convert SPECT counts to activity concentration from the SPECT images (3). This process was carried out using Jaszczak phantom (Biodex, Shirley, New York) with a total volume of 6900 mL that was then filled with an activity of 369.63 MBq of $^{131}$I. The calibration factor for $64 \times 64$, $128 \times 128$ and $256 \times 256$ matrix were 29571.58, 13263.91 and 13228.72 Bq/cps, respectively.

2.2. SPECT/CT data acquisition

All measurements were performed on a GE Discovery NM/CT 670 SPECT/CT (GE Healthcare, Waukesha, USA) system with 16-slice CT capability equipped with a high-energy general-purpose parallel-hole (HEGP) collimator. For each tomographic scan, 60 viewing angles covering 360° and a scatter correction window of 364 keV ±10% was used. Three matrix sizes $64 \times 64$, $128 \times 128$ and $256 \times 256$ with pixel sizes of 8.83, 4.42 and 2.21 mm, respectively, were tested. The phantom was positioned as close as possible to the detector using body contouring detection method. Step and shoot scan mode was set for 40 s/frame. A CT scan with the energy of 120 kVp and tube current of 205 mA was used for attenuation correction as well as to determine the exact location of the subject in the phantom during image processing. The identical SPECT/CT measurements were carried out on day 1, 2, 6, 7, 8, 9 and 23 after administration of $^{131}$I.

2.3. SPECT/CT reconstruction

The acquired SPECT images were then reconstructed using GE Xeleries 3.0 software. Iterative reconstruction was done using 3D ordered-subsets expectation maximization (OSEM) algorithm that included depth-dependent detector response modelling (resolution recovery), scatter, attenuation correction without post-filtering. The iterations number varied from 2, 4, 6, 8 and 10 iterations (i) with a fixed subset (s) of 10. The final reconstructed SPECT images consist of three matrix sizes, $64 \times 64$, $128 \times 128$ and $256 \times 256$.

2.4. Activity quantification

Total counts in the thyroid neck phantom were determined using Medical Image Data Examiner (AMIDE) software (4). The volume of interest (VOI) was generated using thresholding method with a fixed percentage of 70% from the maximum activity that covered the whole volume of the bottle which was 36 mL. The counts measured were analysed based on mean, maximum, 60% of the maximum, and 70% of the maximum. The total counts for $64 \times 64$, $128 \times 128$ and $256 \times 256$ matrix sizes were converted to activity by multiplying the total counts with the calibration factors determined in section 2.1.

2.5. Data analysis

The changes of $^{131}$I activity over time was represented in time-activity curves (TACs). Since the study involved phantom, only physical half-life was considered as effective half-life. Cumulated activity
\( \tilde{A} \) of the phantom was obtained by measuring the area under the curve, as explained in the following equation:

\[
\tilde{A} = \int_0^\infty A(t) \, dt
\]

(1)

where \( \tilde{A} \) is calculated by integrating the activity (A) administered to the phantom at time \( t = 0 \) to the time of its complete disappearance from the phantom (\( t = \infty \)). In addition, the theoretical activity curve was generated based on a single exponential function with an initial activity concentration of 610.76 kBq/mL. The difference between the estimated value of the cumulated activity and the theoretical data was reported as error percentage, based on the following equation:

\[
\text{Percentage error} \% = \frac{\text{Calculated } \tilde{A} - \text{Measured } \tilde{A}}{\text{Calculated } \tilde{A}} \times 100\%
\]

(2)

3. Results and Discussion

Figure 1(a) represents the calculated (theoretical) activity versus the measured activity (from SPECT images) based on the mean value from 256 voxels reconstructed with 2, 4, 6, 8 and 10 iterations (2i10s to 10i10s). The activity within the VOI in the phantom was underestimated by 12.85% for 2 iterations and 6.17% for 10 iterations, respectively. Increasing the number of iterations improves the recovery of counts but also increases the noise (2). Meanwhile, in Figure 1(b), the measured activity based on the maximum value from 256 voxels were overestimated by 61.56% for 2 iterations and 64.66% for 10 iterations, respectively. The number of iterations and count analysis methods (mean and maximum) play a significant effect on the activity estimation (5). For 60% of maximum and 70% of maximum, the measured activity show overestimation between 10% and 20%.

![Figure 1](image1.png)

**Figure 1.** Correlation between measured activity versus calculated activity based on (a) mean and (b) maximum value for 256 voxels with lowest (2) and highest (10) iterations number used. The \( y = x \) trendline represents the line of identity (LOI)

Figure 2 shows the result of time-activity curves for voxel size of 256 with mean and maximum values. As can be seen in Figure 2(a), shows how the measured (different iteration) data were fitted to the model compare to calculated (theory) for mean value. There was a significant increase in measured mean activity for 256×256 matrix compared to the calculated activity. In Figure 2(b), the maximum analysis value introduces a higher bias due to the maximum peak value affected by noise. Smaller voxel size (128×128 matrix) handles the noise better than larger voxel (64×64 matrix) size as the count per voxel is much higher and thus has better count statistics. The 64×64 matrix size shows the worst results and it is not advisable to utilise this matrix size for this kind of study.

It can be seen from Table 1, the mean voxel size of 128 gave a percentage error of 15% for 2i10s. The values of the error percentage decreased when the iterations number increased. The maximum count analysis metric provides an estimation with an error up to 88% relatives to the actual calculated
value. In this study, we only used the physical half-life for the estimation of cumulated activity and thus, only mono-exponential fitting was used. In clinical settings, the biological half-life must be taken into account and thus, bi-exponential fitting is more accurate in estimating the area under a curve of the time-activity curve (5). The determination of accurate AUC/accumulated activity ($\tilde{A}$) in MIRD is crucial as it plays a significant role in estimating the residence time of the radiotracer in the organ of interest within the body (6).

![Figure 2. TACs of (a) mean and (b) maximum value for 256 voxels for various iterations number](image)

| Voxel size | Iterations          |
|------------|---------------------|
|            | 2i10s   | 4i 10s | 6i10s | 8i10s | 10i10s |
| 256 mean   | -13.4   | -7.0   | -7.2  | -6.6  | -7.6   |
| 128 mean   | -14.9   | -5.9   | -6.2  | -6.2  | -9.9   |
| 256 max    | 78.3    | 75.6   | 75.1  | 77.5  | 80.2   |
| 128 max    | 88.3    | 84.6   | 78.8  | 77.9  | 80.9   |

4. Conclusions
This study found that increasing the number of iterations in OSEM reconstruction gave better activity quantification in the final reconstructed images. The mean activity should be used rather than maximum activity in the estimation of cumulated activity. The 3D SPECT/CT reconstructed with adequate iterations number is capable in estimating cumulated activity for internal radiation dosimetry of $^{131}$I therapy within 10% error margin in phantom study.

5. References
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