Study of Repeatability of a Novel PET Flow Phantom

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I. Introduction

DYNAMIC PET imaging allows quantitative measurements of blood flow by mathematical modelling of the tracer distribution in the myocardium. The quantitated values of myocardium blood flow (MBF) are equal to the blood flow through a mass per unit time.

With the introduction of a commercial PET flow phantom, a validated platform for flow quantification against a known reference flow has been developed [1]. The PET flow phantom provides a reference standard for flow quantification, allowing to evaluate PET system performance and accuracy.

In the study of Boellaard *et al*. [2], a large review of factors affecting the standard uptake value (SUV) quantification was presented. In this study, we used [2] as a basis for minimization of the possible error sources in the flow quantification. However, as no studies about the repeatability of the flow values using the new reference standard have been performed, we set out to investigate the variation and repeatability of the flow values using the phantom with $[^{15}O]H_2O$.

II. Materials and Methods

A. Perfusion phantom

The design and validation of the cardiac PET flow phantom (Shelley Medical Imaging Technologies, Ontario, Canada) is presented in [1]. The flow phantom models myocardium perfusion in terms of input function and tissue activity curve. The input chamber in the phantom is directly correspondent to the left ventricle blood pool in the heart, whereas the exchange cylinder represents the myocardium tissue and capillaries.

Water flows from the input chamber to a perforated tube located inside the exchange cylinder. Water is allowed to flow in the perforated tube with a flow rate Q_{tube}. From the perforated tube, water is perfused to the exchange cylinder. Water flow out of the exchange cylinder is marked as Q_{cyl}. Q_{tube} and Q_{cyl} are fixed during the study to maintain a certain flow rate. Reference flow Q_{ref} is measured using flow meters.

B. Data acquisition

To study the repeatability, we fixed the acquisition and reconstruction parameters specified in [2], which could affect the image-derived flow values. The imaging protocol was as follows: the radiowater dispenser (Hidex OY, Turku, Finland) was calibrated against a dose calibrator (VDC-404, Veenstra Instruments, The Netherlands). The perfusion phantom was set-up on the scanner table and the phantom pump calibration was performed as recommended by the phantom vendor.

The flow value in the exchange cylinder Q_{cyl} was adjusted to be 60 $\%$ of the pump flow rate 200 mL/min. The Q_{cyl} values were in the range of 120-123 mL/min during the measurements, whereas the Q_{tube} values were in the range of 97-98 mL/min. Q_{ref} values are presented in Table I.

Discovery MI PET/CT (GE Healthcare, Milwaukee, USA) system [3] was used in this study. A CT based attenuation correction (CTAC) scan was acquired before each PET scan. The flow meter readings were recorded between CTAC and dynamic PET scan. The protocol was repeated 4 times after the first test scan leading to in total of 5 scans (N $= 5$), including one test scan (N $= 1$) and 4 re-test scans (N $= 2-5$). Individual administered tracer doses are presented in Table I. Dynamic PET scan was started 50 seconds (N $= 1-4$) or 51 seconds (N $= 5$) after the injection of the bolus. The frame times in the dynamic PET study were 15 x 5 s, 3 x 10 s, 3 x 20 s, 4 x 30 s leading to an individual scan time of 4 minutes and 40 seconds.

All scans were reconstructed using 3D-TOF-OSEM algorithm with point-spread function modelling (vendor name VPFX-S) with 3 iterations and 16 subsets, with an image matrix size of 192×192 and a FOV of 35 cm. A 5 mm post-filter smoothing was applied in the reconstructions.

C. Data Analysis

For data analysis, QuantifyDCE 1.1 (Shelley Medical Imaging Technologies, Ontario, Canada), a phantom-vendor provided data analysis software for phantom flow quantification, was used. The software implements a two-compartment kinetic model to derive image-based estimation of flow values, based on rate constants q_{in} and q_{out}, which can be considered to be analogous to K1 and k2. The details of the implementation are presented in [1]. The derived flow values represent the flow from the perforated tube to the exchange cylinder (Q_{in}) and out from the exchange cylinder (Q_{out}). Q_{in} and Q_{out} are in units of [mL/min], when the rate constants are multiplied with the cylinder volume 160.6 mL [1].

D. Data interpretation and results analysis

The Q_{ref} values were computed from the Q_{cyl} values multiplied with the calibration correction factor calculated

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TABLE I: Scan parameters and perfusion phantom derived flow values.

Rep.	Injected Activity [MBq]	Q_{ref} [mL/min]	Q_{in} [mL/min]	Q_{out} [mL/min]	Error Q_{in} to Q_{ref} [%]	Error Q_{out} to Q_{ref} [%]
Test	495.0	139.8	134.6	136.5	-3.786	-2.377
Re-test 1	487.0	139.8	133.8	138.9	-4.425	-0.7337
Re-test 2	490.0	138.7	132.6	137.7	-5.414	-3.216
Re-test 3	463.0	142.1	134.4	137.5	-5.410	-3.220
Re-test 4	491.0	138.7	132.8	137.6	-4.271	-0.7888
Mean	485.2	139.9	133.6	137.7	-4.451	-1.552
STD	12.74	1.357	0.8853	0.8624	0.5941	1.175

from the flow meter calibration. The time-activity curves (TACs) of the input function and tissue were derived from the 3D ROIs specified for the input chamber and exchange cylinder. All TACs were plotted using MATLAB R2017a. In addition, the relative errors of Q_{in} and Q_{out} to Q_{ref} were calculated. The mean values and standard deviations (STDs) of the injected activities, Q_{ref}, Q_{in}, Q_{out} and error values were calculated to quantify the factors affecting the precision of the repeatability.

III. Results

In Table I the injected activities and quantitative values calculated from the flow phantom are presented. The phantom derived TACs, in addition to the flow values Q_{in} and Q_{out} derived from the TACs, are presented in Fig. 1. The TACs showed no significant variation. Q_{in} and Q_{out} varied between subsequent repeats, with a range of 1.9 mL/min and 2.4 mL/min and with STD of 0.89 mL/min and 0.86 mL/min, respectively. Similarly, the error of Q_{in} and Q_{out} to Q_{ref} varied between subsequent repeats with STD of 0.59 $\%$ and 1.2 $\%$, respectively. The variations in the error values were due to the fluctuations in Q_{cyl}, Q_{tube}, injected activities and scan start times. Overall, the relative error values of Q_{in} and Q_{out} to Q_{ref} were less than 5 $\%$ on average (Table I). The modelled perfusion curves produced high goodness-of-fit (R^2) values ($>$ 0.99) suggesting high modelling accuracy in the derived flow values. Altogether, results showed $<$ 2.5 mL/min variation in flow values, in addition to $<$ 5.5 $\%$ difference between the image-derived flow values to the reference flow values within all subsequent repeats.

IV. Discussion

In this study, the repeatability of the novel PET flow phantom was confirmed. We fixed the parameters specified in [2] to ensure the repeatability of the phantom derived flow values. The repeated scans with flow phantom showed high repeatability and precision in the derived flow values. The errors in the derived flow values with respect to the reference flow were not significant and are due to the slight variations in injected activities, varying flow values of Q_{cyl} and Q_{tube} and scan start times.

The differences in injected activities are due to the automatic [^{15}O]H_2O dispenser system. Small changes in Q_{cyl} and Q_{tube} between the test-retest scans were due to the bolus injection, which increased the flow rate briefly between the scans.

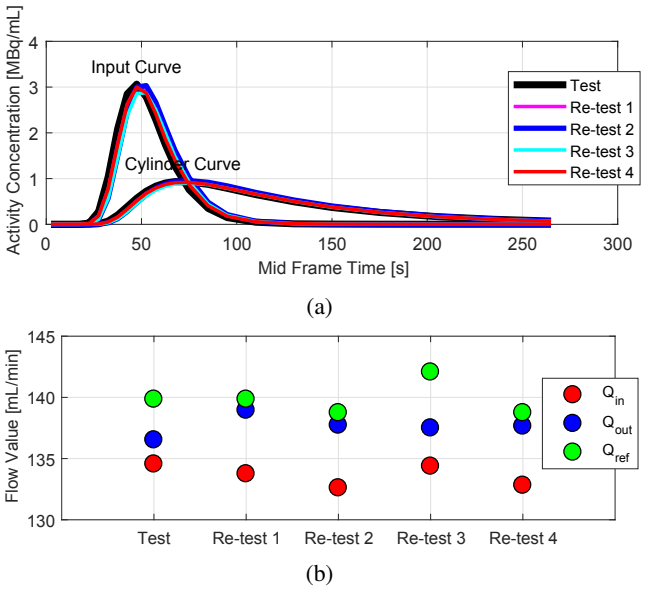

Fig. 1: a) Time-activity curves measured from the input chamber and exchange cylinder of the flow phantom. b) The flow phantom derived flow values.

Gabrani-Juma *et al*. [1] performed a validation study with the perfusion phantom, but the reproducibility study was excluded. Their study showed high accuracy and precision over high range of flow values, what is in agreement with this study. In the future, further studies of the phantom flow rate reproducibility will be performed with several PET/CT systems, scanner/dose calibration rates as well as with different reconstruction techniques.

V. Conclusions

This study confirms that the newly introduced PET perfusion flow phantom produces reliable and repeatable flow values with minimal variations between test-retest scans when using similar protocol and reconstruction parameters. Based on the results, the phantom provides precise flow values where the largest error sources are originating from the variations in the administered activities.

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