Uncertainty Investigation of PEPT Measurement in the Cardiovascular System

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1. INTRODUCTION

Positron emission particle tracking (PEPT) has been known and used for industrial flow tracking in opaque flow fields such as chemical reactors, food processors, and granulators. Because of its abilities, such as tracking a single or limited number of particles, PEPT has promising potential for biomedical imaging applications.

Both PEPT and positron emission tomography (PET) are based on the annihilation of a positron when meeting an electron, which results in a release of two gamma rays (511 keV) at virtually 180 degrees. By triangulation of the relevant coincidences, the location of the annihilation is calculated (Ingram et al. 2007, Seville et al. 2009).

Cheng et al. (2011) investigated the standard deviations of the position measurements and showed the effect of various factors such as the number of the lines of response (LORs) and relative position of the tracer and the detector on the accuracy of the measurements in a hydrocyclone. The details for labelling the resin spheres as well as the algorithm for the triangulation and elimination of random coincidence was described by Cheng et al. (2011). It has been shown that the conventional PET and PEPT tracking algorithms need improvement to be optimized for a single particle (Jung et al. 2020, Schmitzer et al. 2019) and multiple particles (Langford et al. 2016, Langford et al. 2017) tracking.

To assess the potential of clinical applications of PEPT for coronary disease diagnosis, we investigated the errors associated with the reconstruction of the velocity profile from multiple particles in a vessel with a stenotic obstruction.

2. METHOD

To investigate the uncertainty of the blood velocity measurement using the information from a limited number of particles, computational models with an axisymmetric stenosed geometry and steady flows with various Reynolds numbers (Re=50, 100, 200, and 250) were created. ANSYS FLUENT was used to simulate the laminar fluid flow in the stenosed artery using computational fluid dynamics (CFD) techniques. The total axial length of the stenosis was assumed to be 1 cm. The wall was assumed to be rigid; therefore, no deformation was considered.

Particle tracking was conducted using an in-house Python code. The effects of the number of particles and particle tracking time step were analysed. The particles were randomly seeded into the inlet of the flow field with a uniform distribution. To reconstruct the profile using the particles information, we compared 4^{th} and 6^{th} order polynomial fitting. We modified the fitting procedure to capture the negative axial velocities downstream of the stenosis.

Due to the order of magnitude of the Stokes number, i.e., the relaxation time of the particles over the typical time scale of the flow, the drag force exerted on the particles was neglected. The root-mean-square error (RMSE) between the fitted and the CFD solution was calculated as a metric of the accuracy of the predicted profile. The radioactivity of the tracers bound to the radionuclide (^{18}F) is between 13 and 55 MBq per particle; therefore, gathering the information of the location of the particles is restricted by the particle tracking time step not the radioactivity of the tracer.

3. RESULTS AND DISCUSSION

Figure 1 shows the velocity profile for one of the cases (Re=250) around the stenosis.

The reconstruction of the velocity profile using a limited number of particles showed acceptable agreement, i.e., an estimated error of 1% with 10 particles with Re=250, for the flow before the stenosis. However, recirculation regions were observed. Therefore, we used auxiliary points to improve the fitting of the velocity profile after the stenosis. Figure 2 shows the RMS error for various numbers of particles for the velocity profiles reconstructed with 6^{th} order polynomials. Due to better results, we only present the results corresponding to the 6^{th} order.

The RMS error was less than 3.6% with a standard deviation (SD) of 4.1% for more than seven particles and decreased to 1.5 (SD=0.18%) as the number of particles grew to 30. However, it was observed that the error did not approach zero

for velocity prediction after the stenosis when we increased the number of particles.

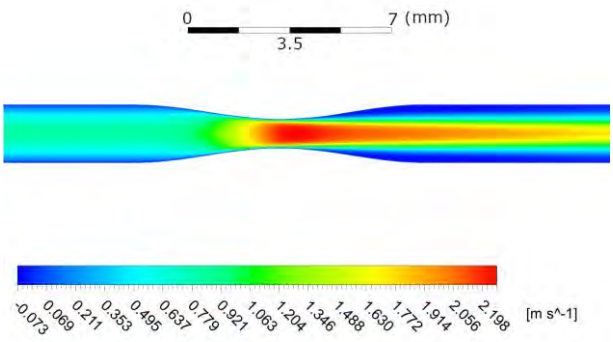

Fig. 1. The velocity contour in the case with 50% stenosis and Re=250

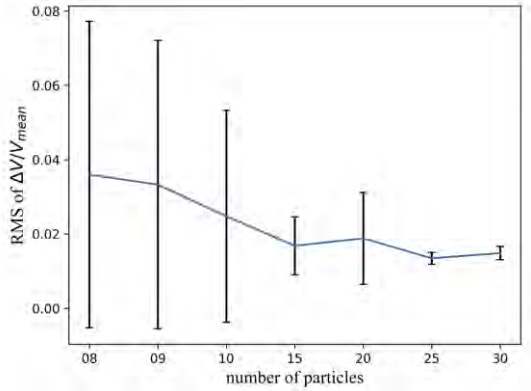

Fig. 2. RMS error between fitted and simulated velocity profiles for different number of particles. The bars show the standard deviation.

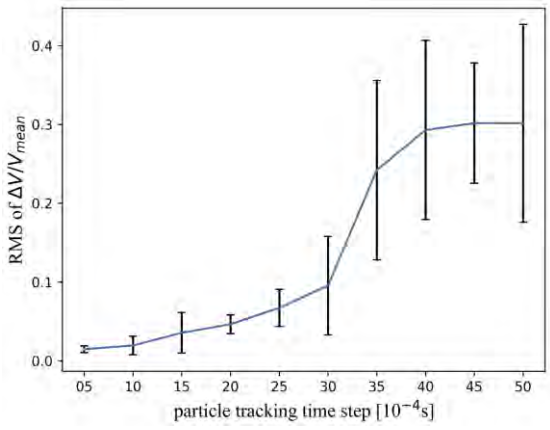

Fig. 3. RMS error between fitted and simulated velocity profiles for different particle tracking time steps. The bars show the standard deviation.

The particle tracking time step was varied from 0.5 ms to 5 ms to investigate its effect on the accuracy of the velocity reconstruction. Figure 3 presents the RMS error of the normalized velocity difference for the different temporal resolutions. The results suggest that the accuracy of the reconstructed velocity profile drops as the particle tracking time step increases. The RMS error was below 10% for tracking time steps less than 25 ms and increased to 30% (SD=12.5%) for tracking time steps larger than 40 ms, respectively. For the untreated 6th order profile, the RMS error of the normalized velocity after the stenosis, increased from 6% (SD=2%) to 39.9% (SD=38%) when Re increased from 150 to 250. However, when the modified fitting was used the RMS error remained below 10% (SD<3%) for all cases.

4. CONCLUSIONS

PEPT is a novel technology with high potential diagnostic impact in clinical applications where non-invasive assessment of blood flow velocity and subsequent derivation of pressure gradients are of critical importance, such as coronary stenosis. To determine the effects of parameters involved in PEPT, we analysed a simplified set-up for stenosed vessels with steady flow at different Reynolds numbers. We investigated the error of this method for velocity profile reconstruction after the stenosis. This methodology is currently being developed for 3D idealised and patient-specific coronary arteries to investigate the correlation of the pressure field and the reconstructed velocity field.

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