A new method to quantify boundary conditions using dynamically scaled *in vitro* MRI for coronary arteries

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Introduction

Computational fluid dynamics (CFD) modelling is commonly used for coronary flow analysis, and advanced boundary conditions are required [1, 2]. This study proposes the novel use of dynamically scaled *in vitro* PC-MRI flow acquisition to measure boundary conditions for true-scale coronary flow CFD.

Methods

Left main coronary geometries

- The left main angles 40°, 80° and 110° were selected, representative of the first principal mode of variation (100 asymptomatic CTA, 54±8 years; 57 females) [3].

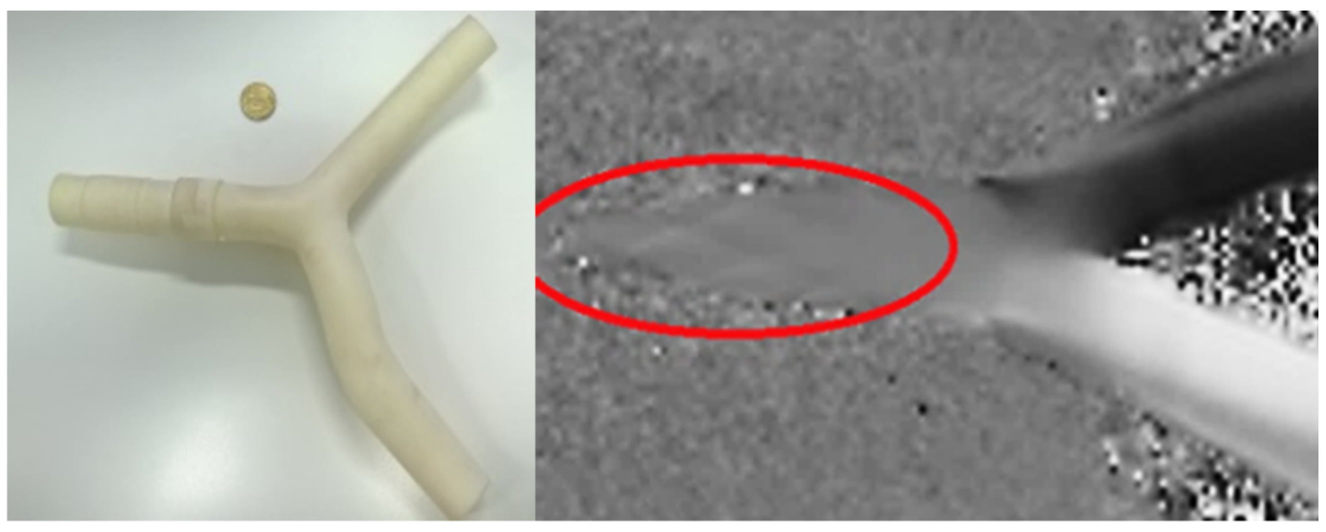

Fig. 1 (i) Flow circuit, (ii) scaled 110° phantom and (iii) PC-MRI left-right acquisition image of the stented geometry showing stent flow pattern (circled, right).

- Two idealised, non-stented and stented, and one patient-specific geometry were reconstructed in AutoCAD (Fig. 1).

Computer simulations (CFD)

- Rigid, steady state, Non-Newtonian, laminar, parabolic inlet, no-slip conditions, static pressure outlet, tetrahedral sensitivity tested mesh, ANSYS CFX 15 [4].

Large-scale *in vitro* PC-MRI

- Rapid-prototyped 6:1 phantoms were connected to a steady-flow, blood mimicking circuit [5] (Fig. 2).
- Viscosity and flow rate we proportionally scaled to maintain a constant Reynolds number .
- Parameters: voxel size 1x1x1mm, TA=27:54min, TR=425.04ms, TE=4.64ms, TI=300.0ms, flip angle= 15°.

Co-registration and comparison

- The PC-MRI data was segmented using intensity thresholds and co-registered with a coherent point drift algorithm [6], where the number of rigid point set *N,M* and the dimension of points *D* gives the equal isotropic covariance:

$$\alpha^2 = \frac{1}{DNM}\sum_{n=1}^{N}\sum_{m=1}^{M}\|x_n - y_m\|^2 .$$

- Natural-neighbour interpolation allowed for direct comparison in custom software written in MATLAB.

Results

- Co-registration covariance error was small: $\sigma^2 < 5.8x10^{-4}$.
- Good flow agreement was found and flow features were captured by both methods.
- Velocity magnitude error <12%, Spearman's correlation coefficient ρ >0.78, Pearson's correlation r^2 >0.87.
- Better agreement was found in regions with high velocities (Fig. 3), with regions being geometry dependent.
- Discrepancies were found in regions of slow flow (lateral walls) and close to the wall (PC-MRI over-estimated wall velocities) (Fig. 4) .
- Best agreement was found for the stented geometry (Fig. 4).

Key Messages

- Dynamically large-scaled *in vitro* PC-MRI measured flow agreed well with true-scale CFD simulations.
- PC-MRI's systematic over-estimation of near wall-velocities was likely introduced due to partial voluming.
- Measuring flow in dynamically scaled 3D prints can assess advanced patient-specific boundary conditions for CFD.

Fig. 2 Experimental setup of *in vitro* PC-MRI (top left) with large 3D printed phantoms (right). Super-computing facility for CFD (bottom left)

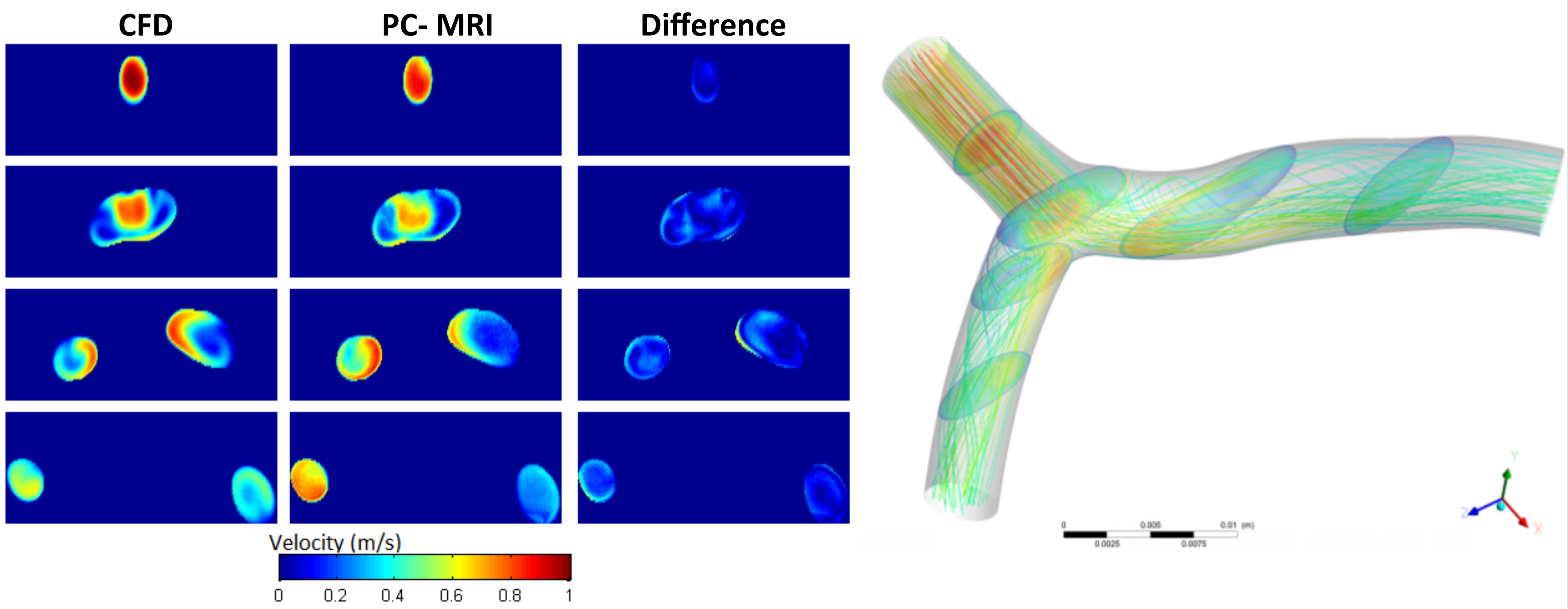

Fig. 3 Patient bifurcation flow contours of CFD (left), PC-MRI (middle) and their difference (right) in four planes of the 3D flow field volume.

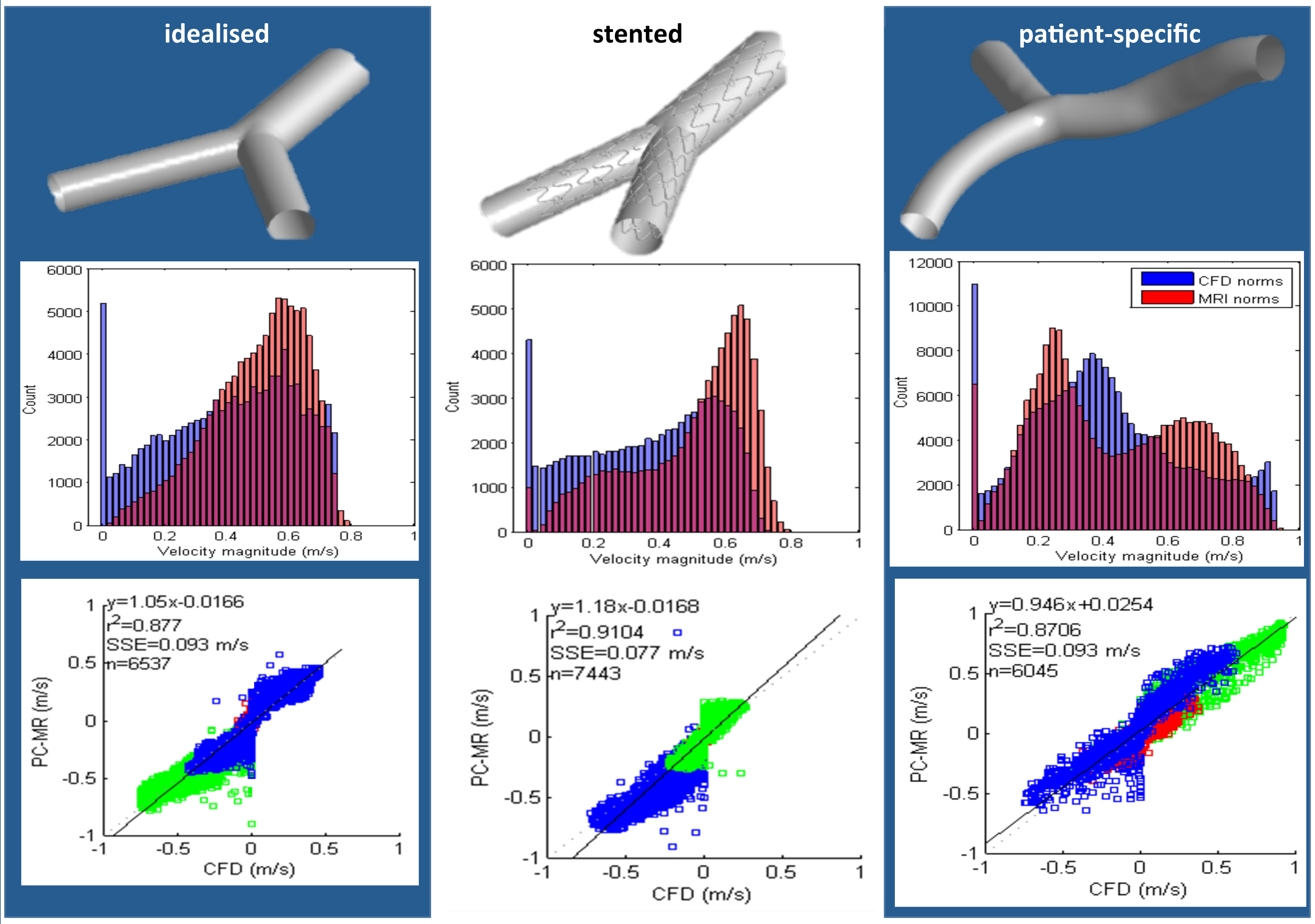

Fig. 4 (i) Bifurcation shapes studied, (ii) Velocity norm counts of MRI (red) and CFD (blue), (iii) 3D flow field comparison (blue - main flow direction; green - branch direction; red - perpendicular direction).

Conclusions

Although regions of low velocities were underestimated by phase contrast MRI, both the real scale CFD and dynamically scaled MRI flow agreed well in both magnitude and direction. Agreement was higher in regions of high SNR, but regions of low and oscillating flow showed larger discrepancies. Dynamically scaled *in vitro* PC-MRI can provide advanced boundary conditions for higher accuracy CFD modelling.

References [1] Zhang, Int J Num Meth Biomed Eng, 2014; [2] Hundley, Circulation, 1996; [3] P. Medrano-Gracia, MICCAI, 2014; [4] S. Beier, Ann Biomed Eng, 2015; [5] Anastasiou, ECCE, 2010; [6] A. Myronenko, IEEE, 2010; [7] Chiastra, J Mech Behav Biomed Material, 2014 ; [8] Mattace-Raso, Circulation, 2006; [9] Marshall, J Biomech, 2004
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