# Simulation of Bolus Dispersion in Quantitative Contrast-Enhanced Myocardial Perfusion MRI: Impact of a Coronary Bifurcation

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**Target Audience**: Researchers in the field of perfusion MRI and computational fluid dynamics (CFD) simulations, in particular of the heart

**Purpose:** Myocardial blood flow (MBF) can be quantified via T1-weighted contrast-enhanced first-pass MRI. This requires the measurement of the arterial input function (AIF), which should be estimated inside a supplying vessel as close as possible to the tissue of interest (TOI). For technical reasons, the AIF is estimated from the blood pool signal of the left ventricle (LV) during MR-perfusion-measurement. Dispersion of the contrast agent bolus might occur between the LV and the myocardium. Dispersion corresponds to a deformation of the contrast agent bolus. Mathematically, the dispersion can be described as convolution of the AIF of the LV and a vascular transport function (VTF): $AIF_{TOI}=VTF\otimes AIF_{LV}$. The variance of the VTF $\sigma^2$ can be used as a quantitative measure of the dispersion. The negligence of dispersion would result in a systematic error of the MBF estimate and the myocardial perfusion reserve (MPR). Graafen *et al.* found an underestimation of the MBF and an overestimation of the MPR in idealized geometries of a single coronary artery considering steady [1] and pulsatile flow [2]. The aim of this study was to investigate bolus dispersion inside an idealized coronary bifurcation using CFD simulations, and to determine the associated error in MBF and MPR.

**Methods**: An idealized bifurcation of the left main coronary artery (LMCA) to the left anterior descending (LAD) and the left circumflex (LCX) was created using the software package GAMBIT (Ansys, Darmstadt, Germany). Typical dimensions were used for diameter (LMCA: 4.5 mm, LAD/LCX: 3.56 mm), length (LMCA: 10 mm, LAD/LCX: 100 mm) and bifurcation angle (80°). A stenosis was placed inside the LAD 25 mm behind the bifurcation (cf. Fig.1). Two sets of simulations were performed to investigate two different outflow conditions through the stenotic branch: First, full autoregulation of the pressure drop across the stenosis by vasodilation of the downstream vessels, and second, limited autoregulation and therefore reduced flow through the stenotic branch. This reduced flow was based on the results of Segal *et al.*, who measured the velocity proximal to a stenosis before and after angioplasty and who estimated the coronary flow reserve for stenotic and normal vessels [3]. Each simulation set consisted of four simulations (rest and stress, pulsatile and constant flow). As inlet boundary condition a pulsatile plug flow velocity pattern was used [4], which was scaled in amplitude to account for stress and different outflow conditions through the stenotic vessel. CFD simulations were performed using Fluent software package (Fluent 14, Ansys, Darmstadt, Germany) at the High Performance Cluster ‚Elwetritsch' (RHRK, TU Kaiserslautern, Germany). The errors in MBF and MPR due to dispersion were estimated via a two step procedure using the MMID4 model. At first, a myocardial concentration-time curve was generated using the dispersed AIF received at the CFD simulations. Second, the simulated experimental MBF value was determined with $AIF_{LV}$ and the generated myocardial concentration-time curve. With this data, the deviation of MBF and MPR from the simulated values was calculated.

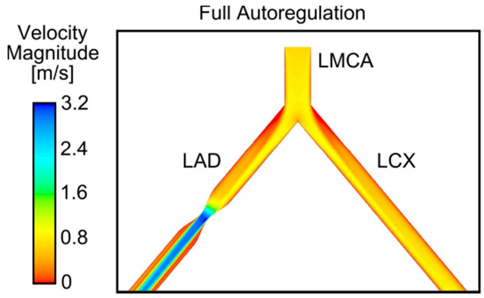


Figure 1: Velocity magnitude inside the bifurcation region represented in false colors for maximal velocity from pulsatile simulations at stress and for full autoregulation.

**Results:** The variance of the VTF as measure of dispersion shows that the increase of dispersion is slightly reduced in the region behind the bifurcation. For most cases the dispersion is larger inside the stenotic LAD compared to the normal LCX (cf. Fig. 2). Furthermore, Figure 2 shows that the dispersion is smaller considering pulsatile flow in comparison to the results for constant flow inside the stenotic vessel, whereas inside the healthy branch almost no difference was observed. For limited autoregulation condition the dispersion is significantly larger than for the full autoregulation condition. A not negligible systematic underestimation of the MBF up to -19.1% for steady flow and up to -16.1% for pulsatile flow was found with the help of the MMID4 model. The larger underestimation for rest compared to stress results in an overestimation of the MPR up to 7.5%.

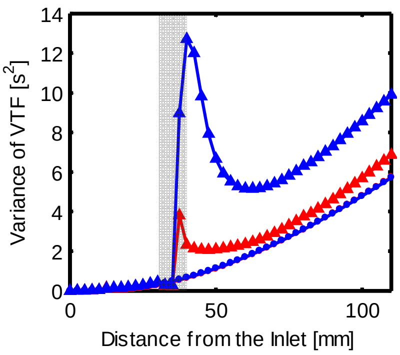


Figure 2: The variance of the VTF as function of the distance from the inlet for pulsatile rest (red) and constant rest (blue) for the condition of limited autoregulation. Symbols represent different branches (▲, stenotic LAD; ●, normal LCX). The data representing the healthy LCX for pulsatile flow is covered by the corresponding data of constant flow. The position of the stenosis is highlighted in grey.

**Discussion and Conclusion:** In general, a negative correlation can be observed between velocity and dispersion. In the region directly behind the bifurcation the velocity profile is deformed and displaced and a laminar parabolic velocity profile does not form (cf. Fig.1). Thus, dispersion is relatively smaller in this region. Pulsatility of the blood flow leads to a reduction of the dispersion and a smaller MBF error in the stenotic vessel. However, the MPR is more overestimated under pulsatile conditions in the stenotic branch. Therefore, pulsatility should not be neglected in dispersion study. The MBF errors found in this study are in the order of the interquartile range of myocardial perfusion MRI of about ±20% in healthy volunteers [5]. Therefore, bolus dispersion should not be neglected during quantitative MBF determination.

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