# A Realistic 4D Numerical Phantom for Quantitative First-Pass Myocardial Perfusion MRI

Lukas Wissmann[1], Johannes F.M. Schmidt[1], and Sebastian Kozerke[1]
[1]*Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland*

**Introduction:** First-pass cardiac perfusion phantoms for myocardial blood flow (MBF) quantification require anatomical background, adjustable MBF values and optional incorporation of motion. A pig heart model [2] and a flow phantom [3] have been proposed enabling adjustable MBF, but human anatomy and motion options are missing. A whole-body anatomical phantom including motion has been proposed recently for X-ray and CT applications [4]. In this study, the anatomy provided by this XCAT phantom was used to simulate 4D myocardial perfusion MRI. The influence of contrast agent dose and $T_1$ estimation errors on MBF quantification is investigated as a showcase application.

**Methods:** Three-dimensional masks were generated using XCAT [4] and reoriented to short-axis view. Realistic MR signal intensities were applied to all tissue regions in the field of view. The arterial input function (AIF) in the left ventricle was modeled using a γ-variate function. Concentration tissue residue functions were derived from the AIF in analogy to [5], using a Fermi function for convolution. The contrast agent (CA) concentration $c(t)$ was converted to signal intensity $S(t)$ according to equations (1) and (2). $T_{1,0}$ is the $T_1$ in the absence of CA, $R$ the CA relaxivity, $T_D$ is the delay between saturation and acquisition and $S_0$ is the fully relaxed longitudinal magnetization. Gaussian white noise was added to obtain realistic SNR values. Fully sampled acquisition was simulated and reconstructed. AIF and tissue residue signal intensity vs. time curves were extracted using the predefined XCAT masks. After signal intensity to contrast agent concentration conversion, Fermi model deconvolution was employed for MBF quantification. The influence of CA dose variation and T1 estimation deviation on MBF error was investigated. Full dose corresponded to 0.1 mmol/kg body weight.

Simulation phantom parameters were: 30 end-systolic time points, field of view 446x284x80 mm$^3$, spatial resolution: 1x1x5 mm$^3$, MBF = 3.5 ml/g/min, $T_D = 50$ ms , baseline $T_{1,0}$ = 1100 and 1550 ms for the myocardium and LV blood pool, respectively, CA relaxivity $R$ = 5.6 L mmol$^{-1}$ s$^{-1}$. Full, 75%, 50%, 20% and 10% CA dose were achieved by scaling down the full dose AIF and keeping the noise level constant. $T_1$ deviation was varied by +/- 15% in steps of 5% for myocardial and LV $T_1$.

$$\frac{1}{T_1(t)} = \frac{1}{T_{1,0}} + c \cdot R \quad (1)$$

$$S(t) = S_0 \cdot \left(1 - e^{-t/T_D}\right) \quad (2)$$

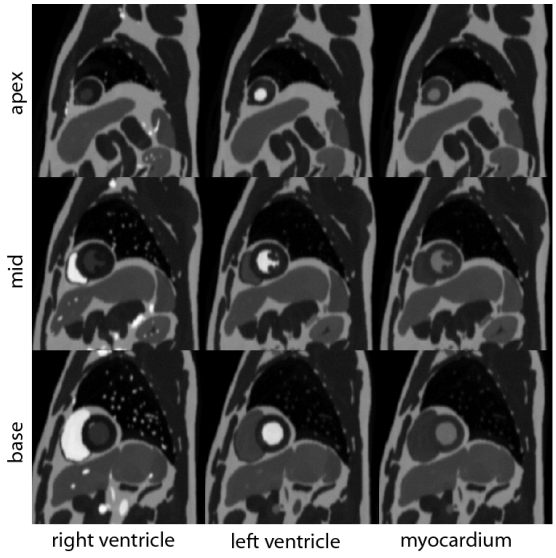


*Figure 1.* Three slices at the three time points of bolus arrival in the right and left ventricle, and myocardium.

**Results:** Fig. 1 shows the numerical phantom at the three bolus arrival time points in the RV, LV and myocardium for apical, mid-ventricular and basal slices. Figure 2 illustrates 100% vs. 10% dose noise-degraded AIF and tissue residue. The reduced magnitudes of the 10% dose curves yield reduced contrast-to-noise ratio for lower dose. Bull's eye plots of MBF values for low and high dose are shown in Fig. 3 together with mean MBF from five realizations for each of the five dose values. Slight underestimation of MBF is apparent for all doses, but stays <5% for 20% dose and beyond. The influence of $T_1$ errors up to 15% upon signal intensity to concentration conversion in both LV and myocardium on MBF outcome is summarized in Fig. 4. Results are comparable for all doses and yield errors up to 30%.

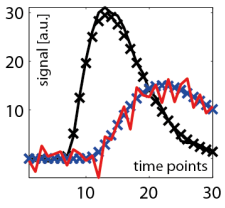


*Figure 2.* AIF and tissue residue function at 100% (x) and 10% dose (solid lines, scaled up 10x for comparison).

**Discussion:** A realistic numerical phantom for quantitative 3D first-pass myocardial perfusion MRI has been implemented in this study. It has been shown that CA dose reduction and erroneous T1 values employed in signal intensity to concentration conversion yield significant MBF errors. The appropriate choice of CA dose is therefore crucial for MBF quantification.

The 3D myocardial perfusion phantom proposed in this study may be extended to include accelerated acquisition, breathing and cardiac motion, hence supporting the development of new acquisition strategies and motion correction algorithms. Furthermore, numerical phantoms for various cardiac MRI applications such as cine or flow imaging may be devised.

**Acknowledgement:** The authors thank William P. Segars for providing the XCAT2 software to generate the underlying phantom anatomy.

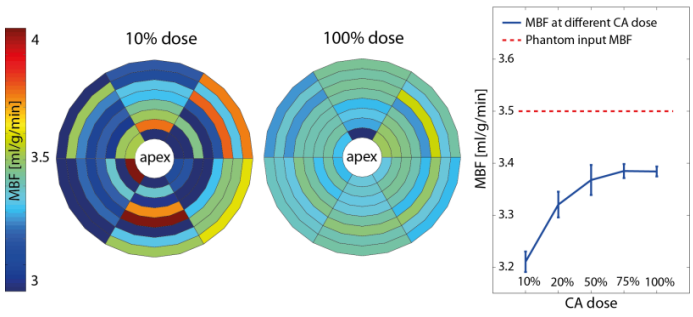


*Figure 3.* Bull's eye MBF plots of 6 sectors in 8 slices from apex to base for 10% dose (left) and 100% dose (center). Mean MBF and standard deviation for five realizations of the phantom for all five doses is shown on the right.

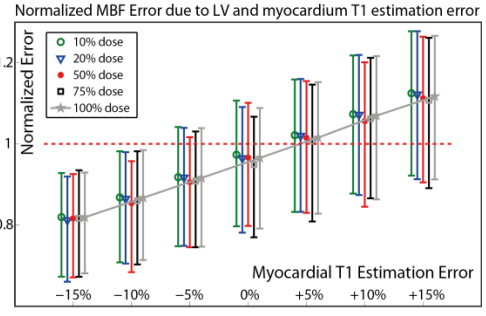


*Figure 4.* Myocardial blood flow error as a function of $T_1$ estimation error during signal intensity to contrast agent concentration conversion. Error bars indicate true left-ventricular $T_1$ ± 15%.

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