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# A model-based method for myocardium flow estimation

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## 1. Introduction

A model-based method for assessing myocardial perfusion applied to tissue indicator curves (time/intensity, $T/I$), extracted from first pass contrast enhanced MR images is proposed. The $T/I$ curves were obtained by using an intravascular contrast agent (CA). The measurable left ventricular blood pool was defined as the system input delayed with respect to the injection site due to the time course of the CA through the relevant large vessels.

To obtain quantitative information on myocardial blood flow, $T/I$ curves were processed using an appropriate signal filtering technique [1] and interpreted with a model-based simulator as described in [2,3].

In normal operating conditions, the physician fits the $T/I$ curves with a gamma function to eliminate artefacts due to blood pool re-circulation. This is appropriate when a correct estimate of the time course of the intravascular indicator during the first pass through myocardial tissue is feasible. However, the noise contribution on the $T/I$ curves, especially for low-flow experiments, makes this operation very crucial. To overcome this drawback, a wavelet-based denoising operation was introduced on $T/I$ curves before gamma fitting.

The myocardial micro-circulation was modelled as a multiple-pathway system. Within the microvascular system there are $N$ parallel microvascular flow pathways. Each pathway is composed of a small vessel unit in series with an axially distributed capillary unit; except for local flow, all pathways are identical. The total quantity of indicator within the region of interest corresponds to the residue function, experimentally measured by acquiring the time/intensity curve relevant to the region of interest in the MR perfusion images.

In order to fit the model to the experimental residue function data, the contrast agent flow and volume within capillaries (i.e. the pathways) were adjusted.

## 2. Method

The experimental studies were conducted by using intravascular low-dose injections of iron oxide particles in the femoral vein of five pigs. In each pig the first injection was performed in basal conditions, while the subsequent ones were performed after inducing different degrees of stenosis of the left anterior descending coronary. Images were acquired in basal conditions by using a Philips 0.5T system (J5-11 Philips Medical system, Best, The Netherlands), using a wrap-around coil and an Inversion Prepared Fast Gradient Echo sequence (flip angle 17°, TE = 3.2 ms, TR = 7.4 ms). The time course of the intravascular indicator was monitored over 40 s. $T/I$ curves were obtained from multiple regions of interest from the complete image time series, whereas one region of interest was drawn in the left ventricular cavity to provide the vascular input function. A calibration curve was evaluated in each experiment in order to transform the $T/I$ curves to time-content curves and to correct for non-linearity in the relation between MR signal intensity and contrast agent concentration. Calibration curves were obtained using 24 vials containing a range of iron oxide particle

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Table 1
Estimated mean flows and S.D.

| Stenosis degree | Denoised data (mean ± S.D.) | Raw data (mean ± S.D.) |
|---|---|---|
| 30% | 1.27 ± 0.015 | 1.20 ± 0.030 |
| 10% | 1.56 ± 0.035 | 1.51 ± 0.069 |
| 0% | 1.85 ± 0.049 | 1.75 ± 0.111 |

concentrations. One vial was filled with agar–agar. They were imaged using the same acquisition parameters as in the animal experiment. Then, a concentration-signal intensity curve was designed. The same vial with agar–agar was used during animal image acquisition in order to normalise image intensity with the one obtained with the vials.

Reference myocardial blood flow was measured by radiolabeled microspheres injected into the left atrial cavity immediately before each contrast agent injection as shown in [4]. After MRI experiments, the hearts were excised, and the regions relevant to MRI analysis were monitored by using a gamma-counting machine in order to evaluate the microsphere concentration.

The MR first-pass curves were analysed using the model in order to extract absolute flow values. In particular, the method was based on three steps: (a) application of the wavelet-based denoising technique to $T/I$ curves; (b) fitting of the denoised data with a gamma-based model of microcirculation to eliminate recirculation effects; (c) use of the model-based simulator to extract myocardial blood flow values. According to the model defined in [2,3], simulations were performed using the MMID4 program (available from National Simulator Resource, University of Washington, Seattle) with the assumption that an intravascular CA is used and that the LV residue curve is the input function to all pathways. Then, the model residue functions were fitted to the experimental curves in order to derive blood flow estimates.

## 3. Results

The effect of the denoising technique on blood flow estimates was systematically assessed using the described model. The flow values were the result of repeated gamma fitting operations performed on time–content curves when the gamma fitting interval was varied. Table 1 shows the mean values and the standard deviations (S.D.) of the estimated flow results using denoised (left column) and raw curves (right column) for three different stenosis degrees.

Table 2
Comparison between model-based flow estimates and reference measurements[a]

| Stenosis degree | $F_m$ (mean ± S.D.) | $F_e$ (mean ± S.D.) | DIFF (mean ± S.D.) |
|---|---|---|---|
| 30% | 0.35 ± 0.1 | 1.37 ± 0.13 | 0.010 ± 0.003 |
| 10% | 1.72 ± 0.04 | 1.78 ± 0.04 | 0.042 ± 0.017 |
| 0% | 1.855 ± 0.02 | 1.850 ± 0.01 | 0.025 ± 0.016 |

[a] $F_m$, flow evaluated with microspheres; $F_e$, flow estimated with the proposed method; DIFF, absolute difference between $F_m$ and $F_e$.

In Table 2 the mean flow values, the S.D. ($F_m$, flow evaluated with microspheres; $F_e$, flow estimated with the proposed method) and the absolute differences values (DIFF) between model-based and microsphere blood flows estimates for different occlusion degrees are reported.

From the table (see right column) it appears that flow estimates obtained with the proposed method highly correlate with reference data also for different stenosis degrees.

## 4. Conclusions

Results of the present study show that accurate estimates of myocardial blood flow may be obtained using a spatially distributed model of residual curves of an intravascular indicator. In order to improve myocardial blood flow reliability in blood flow estimates, also in presence of background noise in $T/I$ curves, a wavelet-based denoising technique was successfully applied to residue curves.

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