

HEMODYNAMIC CHARACTERIZATION OF THE TRANS-THORACIC CIRCULATION BY CONTRAST-ENHANCED MAGNETIC RESONANCE IMAGING

M. Mischi¹, H. C. van den Bosch², J. A. den Boer³, J. Verwoerd⁴, R. J. Grouls², and H. H. Korsten^{2,3}

¹Eindhoven University of Technology, Eindhoven, Netherlands, ²Catharina Hospital, ³Eindhoven University of Technology, ⁴Philips Healthcare

Introduction

The analysis of the trans-thoracic circulation (TTC) is an important procedure to assess the cardiovascular condition. Congestive heart failure is usually related to an increase of cardiac preload, influencing the TTC hemodynamics.^{1,2} As a result, a quantitative characterization of the TTC can be valuable for diagnosis and follow-up of cardiovascular dysfunctions. The only TTC-related parameter that is currently measured in the clinical practice is the intra-thoracic blood volume (ITBV), which is assessed by invasive indicator dilution techniques that require a double central catheterization.² An indicator dose is injected in the pulmonary artery and detected in the aorta. The mean transit time (MTT) of the indicator between the injection and detection sites, derived by analysis of the measured indicator dilution curve (IDC), is multiplied by the cardiac output (CO) for the estimation of the ITBV.

In this study, we present a minimally invasive method for the estimation of the dilution impulse response of the TTC by contrast-enhanced magnetic resonance imaging (MRI). The method is based on the measurement of two IDCs in the right ventricle (RV) and left ventricle (LV).³ The estimated impulse response is then interpreted by the local density random walk (LDRW) model, providing a physics interpretation of the transport-dispersion process⁴ and permitting the derivation of relevant hemodynamic parameters characterizing the TTC, such as the ITBV⁵ and the Peclet number,⁶ which is a measure of the ratio between contrast convection and dispersion. An *in vitro* validation of the method is presented together with a clinical feasibility study in healthy volunteers.

Methods

The proposed approach for the identification of the TTC dilution system consists of a peripheral intravenous injection with a low dose (0.1 mmol) of Gadoteridol® (Bracco, Milan, Italy) and its subsequent MRI detection in the RV and LV in a four-chamber view. Two regions of interest (ROIs) are placed in the RV and LV for the measurement of two IDCs (Fig. 1). The dose was determined on basis of *in vitro* measurements and aimed at a concentration range for which the relation between MR signal and contrast concentration is approximately linear, therefore facilitating the IDC analysis.³

The adopted MRI scanner was a 1.5 T Gyroscan Intera (Philips Healthcare, Best, the Netherlands) equipped with a multi-element coil. The designed MRI pulse sequence was a triggered dynamic single-shot single-slice spoiled turbo-field-echo (T1-TFE). Parallel imaging using Sensitivity Encoding (SENSE) was used.⁷ After each R-peak, a non-selective saturation prepulse (90 degrees) was given, followed by a TFE shot after a delay that was adjusted to produce the desired T1-weighting. A large pixel size (3.5×3.5 mm²) and thick slice (10 mm) were adopted to obtain the signal-to-noise ratio (SNR) required for the IDC measurement, while a small flip angle (7 degrees) reduced the signal enhancement from rotation of the blood in the ventricles. The CO was measured by phase contrast angiography across the aorta.⁸

The derived IDCs were used for the estimation of the TTC dilution impulse response, with the RV IDC and LV IDC representing the input and output of the TTC dilution system, respectively. The TTC impulse response was described and parameterized by the LDRW model. This permitted the implementation of a parametric deconvolution by minimization of the mean squared error between the measured LV IDC and that estimated by the convolution between the measured RV IDC and the modelled (parametric) impulse response.⁹ The MTT and the Peclet number of the TTC system can simply be derived by the LDRW parameters representing the estimated impulse response. The ITBV can be obtained from the MTT by multiplying it by the CO.

The method feasibility was tested with five healthy volunteers (age 28.6 ± 6.3) who gave informed written consent. The measured CO was equal to 6.7 ± 1.4 L·min⁻¹. The measurements were performed during breath hold both after expiration and after inspiration. A simple *in vitro* model of the transpulmonary circulation with a calibrated volume adjustable between 0.4 and 1 L was used for validation of the proposed method.³

Results

The results of the *in vitro* volume measurements were satisfactory, showing a correlation coefficient $R = 0.95 \pm 0.02$ between the real and estimated volumes (Table 1). The Peclet number of the system could also be estimated (Table 1) and, as expected, it showed an inverse relation with the volume ($R = -0.99$). In fact, a larger volume causes an increase of the contrast dispersion. The results in the volunteers showed an average SNR equal to 19.1 and 26.0 for the RV and LV IDC, respectively. Accurate LDRW estimates of the LV IDC were obtained ($R = 0.92 \pm 0.07$). The average indexed¹¹ ITBV estimates were equal to 0.31 ± 0.06 L·m⁻² and to 0.32 ± 0.03 L·m⁻² for the measurements performed after expiration and after inspiration, respectively. Differently from the ITBV, which did not show significant variations after expiration and after inspiration (average absolute variation equal to $10\% \pm 15\%$), the Peclet number showed significant variations (average absolute variation equal to $42\% \pm 32\%$), evidencing the sensitivity of this parameter to different hemodynamic conditions. Fig. 2 shows an example of measured RV and LV IDC together with the estimated LV IDC.

Conclusions

A new method for a minimally invasive characterization of the TTC is proposed. The method was validated *in vitro* and its clinical feasibility was tested in healthy volunteers. The *in vitro* validation produced satisfactory results and the tests in volunteers showed the clinical feasibility of the method. Additional clinical validation is however necessary to validate the ITBV measurements and investigate the clinical value of the TTC Peclet number.

Table 1: In vitro volume measurements.

True volume (L)	Estimated volume (L)	Peclet number
0.41	0.41	328
0.48	0.46	301
0.66	0.63	276
1.05	1.00	164

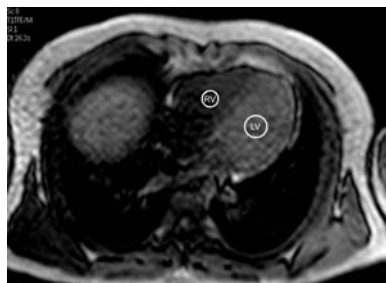


Fig. 1: MRI 4-chamber view. Two ROIs are placed in the RV and LV for the IDC measurement.

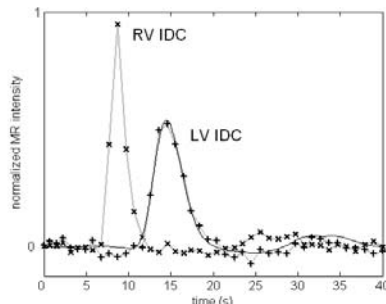


Fig. 2: Measured RV (crosses) and LV IDC (plusses) together with the estimated (black solid line) LV IDC.

References

1. SG Sakka et al, *J Crit Care* 1999;14:78-83.
2. C Wiesenack et al, *J Cardiothorac Anesth* 2001;15:584-88.
3. M Mischi et al, *Magn Reson Med*, in press.
4. CW Sheppard, *Basic principles of the tracer methods*, Wiley, New York, 1962.
5. M Mischi et al, *IEEE Trans on UFFC* 2004;51(9):1137-47.
6. JM Bogaard et al, *Basic Res Cardiol* 1984;79:479-93.
7. KP Pruessmann et al, *Magn Reson Med* 1999;42:952-62.
8. DN Firmin et al, *Magn Reson Med* 1990;14:230-241.
9. M Mischi et al, *Ultrasound Med Biol* 2007;33(3):439-51.
10. D Dubois and EF Dubois, *Arch Intern Med* 1916;17:863-71.