Estimation of extraction fraction (EF) and glomerular filtration rate (GFR) using MRI: Considerations derived from a new Gd-chelate biodistribution model simulation

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Introduction

Previous reports have described the use of MRI to non-invasively estimate single-kidney extraction fraction (EF) and glomerular filtration rate (GFR), by measuring the concentration difference of Gd-chelate in the renal artery and renal vein from measurements of the longitudinal relaxation time (T1) of the blood [1-6]. The renal artery has proven to be difficult for accurately measuring blood T1, due to small vessel size, the tortuousness of the vessel, the pulsatility of the blood flow, and artifacts from vessel motion. Descending aorta [Gd] measurements were obtained instead of the renal artery [Gd] measurements; however, these measurements also had significant errors. Measurements of [Gd] in the inferior vena cava (IVC) below the renal vein ostia have been reproducible. The overall goals of this work were to 1. theoretically model Gd-chelate biodistribution within the body's extracellular compartments following an intravenous injection of the agent, and 2. determine the physiological conditions for which the substitution of the IVC [Gd] measurement for the renal artery [Gd] measurement was valid.

Methods

For this study we 1. developed new difference and differential equations for Gd-biodistribution that include vascular transport, finite transit times, and intravenous bolus injection of Gd-chelate; 2. numerically solved the equations for [Gd] as a function of time in the vessels and water compartments; 3. derived algebraic equations based on Gd flux constraints that give upper limits for differences between IVC [Gd] and renal artery [Gd], as well as upper limits for differences between EF calculated using the IVC [Gd] versus renal artery [Gd]. 4. evaluated the assumption that the [Gd] in the IVC is equal to the [Gd] in the renal artery, and determined the pharmacokinetic conditions necessary for the assumption to be true, and or determined that the assumption was untrue and developed an alternative hypothesis. Fig. 1 shows the vascular geometry model, and Fig. 2 shows the mathematical symbols and numerical values used to represent the flow dynamics and [Gd] biodistribution.

Results

The numerical solutions show that following a bolus injection of Gd and subsequent stabilization of the vascular concentrations within 3 minutes, [Gd] in the IVC below the renal ostia will be 3.2%-4.7% higher than the [Gd] in the renal artery (See Fig 3). Consequently, if the IVC measurement is used instead of the renal artery measurement, EF will be overestimated by 14%-20%. The algebraic equations also predict this error in the EF.

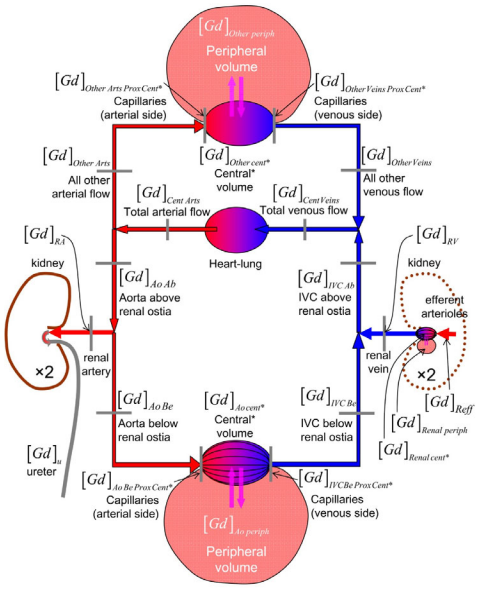

Fig. 1: Vascular geometry model for Gd biodistribution study

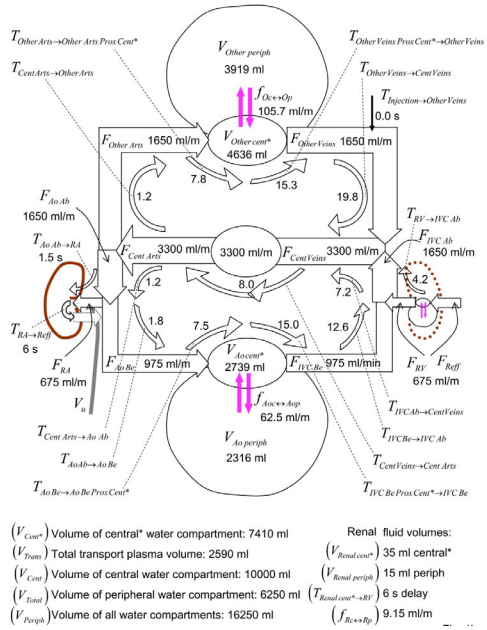

Fig. 2: Numerical values for flow rates, water volumes, and vascular transit times

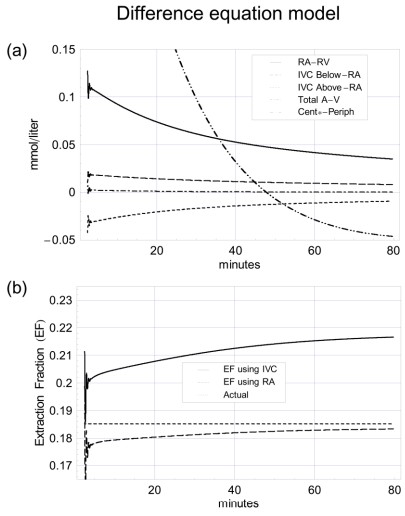

Fig. 3: Numerical solutions showing overestimation of EF using IVC [Gd]

Discussion

The most surprising prediction of the model is that within three minutes following intravenous bolus injection of Gd, the [Gd] in the IVC below the renal ostia becomes higher than the [Gd] in the renal artery. This effect can be understood as a physical consequence of the equality of Gd flux from central veins to central arteries. Because plasma in the IVC below the renal ostia mixes with plasma in the renal vein that has a relatively low [Gd], the equality of Gd flux through the central vessels can be met only if the IVC [Gd] below the renal ostia becomes greater than the arterial [Gd].

References

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