Dynamics of Contrast Agents in MRA: Analytical basis and experimental validation

A. N. Moghaddam[1,2], T. Balawi[1], R. Habibi[1], G. Laub[3], and J. Finn[1]

[1]Radiology, UCLA, Los Angeles, CA, United States, [2]Bioengineering, Caltech, Pasadena, CA, United States, [3]Siemens Medical Solution, United States

Introduction: For MR angiography (MRA), the concentration of Gd in blood determines the magnitude of vascular enhancement. The image quality depends on synchronizing data acquisition with arrival of the contrast bolus in the vessels of interest. Therefore a clear understanding of the first pass dynamics in the vascular system becomes important in high quality MRA. This importance is further emphasized at low-dose contrast protocols, as demanded in patients with severe renal impairment[1], since the useful time window of the contrast bolus is truncated at lower doses. Some studies have simulated the contrast agents' dynamics, using the theory of linear time-invariant (LTI) systems, to predict contrast agents' dynamics in CT angiography[2]. In this study we first analytically verify that the circulatory system can be modeled as an LTI system that responds linearly to the infusion as its input. We further show how the parameters of such a system may be estimated based on physiological parameters. Explaining the relation between the dynamics of contrast agents and the image enhancement, we experimentally quantify this approach for MRA by implementing a software tool that can be easily used in routine daily clinical practice.

Methods:

a) Analytical justification: The circulatory system is modeled as a system whose output is the concentration of contrast agent in the region of interest (ROI) while the infusion rate of contrast agent is its input. It is shown analytically that the output of each compartment, as expected in LTI systems, can be written as the convolution of the input with an impulse response. The impulse response, in turn, is a predictable function of the patient physiologic characteristics.

b) Computational algorithm: Using the theory of LTI systems, we calculated a patient specific impulse response for signal intensity enhancement in a ROI, based on the temporal intensity profile of time-resolved MRA following a small test injection. Our algorithm interpolates the sparse image enhancement data, caused by test bolus, and next uses the long division method to deconvolve the aforementioned impulse response from the signal intensity curve and corresponding test bolus profile. The predicted time attenuation curve in that ROI is then calculated using the convolution of the contrast injection profile with the estimated impulse response. Subsequently the time window encompassing the highest average as well as the plateau intensity is determined on the intensity curve. The algorithm was implemented using Matlab 7.0.4 and validated for absolute numbers on cardiac CT scans in twenty patients[3], whose estimated intensity curves were compared to the corresponding actual scans. The acceptable agreement between the estimated timing and actual scans confirm the validity of the simulation.

c) MRA experiments: Twenty patients (63.5±16.2 years, 9 Males) underwent high spatial resolution contrast enhanced (CE) MRA of the carotids at 3.0T, using a 32 channel system (TIM Trio, Siemens Medical Solutions), following infusion of 0.1 mmol/kg gadopentetate dimeglumine over 15 seconds. Acquisition time was 21 sec and voxel dimensions were 0.7x0.6x0.8 mm. The center of k-space, that characterizes the contrast enhancement, was selectable within the entire acquisition window. In these experiments the time to center was kept fixed at 5 sec and the appropriate timing was applied through the delayed start of acquisition. Initially, a contrast timing run was performed with 1.5 ml Gd, using a spoiled gradient echo with 0.9 sec temporal resolution. Regions of interests (ROI) were placed over the carotid siphons and the straight sinus and time-intensity curves were generated using commercial software (Mean Curve, Siemens Medical Solutions). These curves were input to an algorithm implemented in Matlab which convolved the dynamic vectors with the planned contrast infusion waveform, to generate a predicted time-response curve for ROIs. Our computational algorithm also provided time to peak, time to 85% of peak signal, and the time window when the signal was above 85% peak, both for carotid and venous confluence. All MR angiograms were scored for image quality on a 4-point scale by two independent expert readers.

Results: All MRAs were scored excellent (18) or good (2) for overall image quality. The center of K-Space for all 20 high quality MRAs was positioned within the "85% peak period" for the carotid and prior to the corresponding venous window. For this injection profile the estimated mean ± SD of 85% peak period was 8.23±0.44 s for carotid and 8.15±0.20 s for sigmoid vein, separated by 6.2 sec.

Conclusion: Contrast dynamics for MRA can be modeled as an LTI system whose impulse response can be derived from the time resolved MRA following a test bolus injection. The computational algorithm we implemented to estimate this impulse response as well as the signal enhancement in the high-resolution MRA, predicts stable "85% peak periods" for carotid and venous signal. Timing of these periods showed perfect correlation with scan time at center of K-Space in high-quality MRAs. The algorithm can be implemented as a simple in-line tool for unambiguous positioning of the temporal acquisition window.

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