Contrast-Enhanced Magnetic Resonance Angiography

First-Pass Arterial Enhancement as a Function of Gadolinium-Chelate Concentration, and the Saline Chaser Volume and Injection Rate

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Objective: To evaluate the effect of the contrast medium (CM) concentration and the saline chaser volume and injection rate on first-pass aortic enhancement characteristics in contrast-enhanced magnetic resonance angiography using a physiologic flow phantom.

Materials and Methods: Imaging was performed on a 3.0-T magnetic resonance system (MAGNETOM Trio, Siemens Healthcare Solutions, Inc, Erlangen, Germany) using a 2-dimensional fast low angle shot T1-weighted sequence (repetition time, 500 milliseconds; echo time, 1.23 milliseconds; flip angle, 8 degrees; 1 frame/s × 60 seconds). The following CM concentrations injected at 2 mL/s were used with 3 different contrast agents (gadolinium [Gd]-BOPTA, Gd-HP-DO3A, Gd-DTPA): 20 mL of undiluted CM (100%) and 80%, 40%, 20%, 10%, 5%, and 2.5% of the full amount, all diluted in saline to a volume of 20 mL to ensure equal bolus volume. The CM was followed by saline chasers of 20 to 60 mL injected at 2 mL/s and 6 mL/s. Aortic signal intensity (SI) was measured, and normalized SI versus time (SI/T_n) curves were generated. The maximal SI (SI_{max}), bolus length, and areas under the SI/T_n curve were calculated.

Results: Decreasing the CM concentration from 100% to 40% resulted in a decrease of SI_{max} to 86.1% (mean). Further decreasing the CM concentration to 2.5% decreased SI_{max} to 5.1% (mean). Altering the saline chaser volume had no significant effect on SI_{max}. Increasing the saline chaser injection rate had little effect (mean increase, 2.2%) on SI_{max} when using ≥40% of CM. There was a larger effect (mean increase, 19.6%) when ≤20% of CM were used. Bolus time length was significantly shorter ($P < 0.001$), and area under the SI/T_n curve was significantly smaller ($P < 0.01$) for the CM protocols followed by a saline chaser injected at 6 mL/s compared with a saline chaser injected at 2 mL/s.

Conclusion: With 40% of CM and a fast saline chaser, SI_{max} close to that with undiluted CM can be achieved. An increased saline chaser injection rate has a more pronounced effect on aortic enhancement characteristics at lower CM concentrations than at higher CM concentrations.

Key Words: contrast-enhanced MR angiography, gadolinium-based contrast agent, saline chaser

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Since the introduction of contrast-enhanced magnetic resonance angiography (CE-MRA) in 1990,[1,2] many studies have shown that CE-MRA is an acceptable noninvasive substitute for digital subtraction angiography, the standard of reference for the evaluation of vascular pathology.[3–5] During the past 2 decades, imaging parameters, such as acquisition time and resolution, have been improved, and faster sequences with high spatial resolution and image contrast are now available.[6–8] However, the quality of the CE-MRA is not only determined by the imaging parameters but also by the contrast media (CM) and saline chaser injection protocol. Together with physiological factors like cardiac output, the CM volume, CM dose, CM injection rate, and the saline chaser characteristics, all contribute to the shape of the enhancement profile. Since the association was made between nephrogenic systemic fibrosis (NSF) and the administration of gadolinium (Gd)-based paramagnetic contrast medium in patients with advanced renal failure,[9] there has been a focus on strategies for CM dose reduction in magnetic resonance imaging (MRI).[10,11] Some studies reveal a dose dependence of NSF risk that grows to a consistent level only when using total Gd amounts that are higher than those routinely adopted for body MRI or CE-MRA (0.1 mmol/kg).[12–15] A recently published study suggests that the presence of NSF-like fibrosing dermopathy in rats is dependent on the injection interval and not on the amount of Gd in tissue.[16]

Therefore, we performed this study with the purpose of evaluating the effect of the CM concentration and the saline chaser volume and injection rate on first-pass aortic enhancement characteristics in CE-MRA using a physiologic flow phantom. Our hypothesis was that a faster injection rate of the saline chaser would result in superior arterial contrast enhancement at a given CM concentration.

MATERIALS AND METHODS

Institutional review board approval was not required for this study.

Phantom Setup

A custom-made, previously validated physiologic flow phantom (Fig. 1) was used.[17] The phantom was milled from a solid block of polycarbonate. The phantom simulates the cardiovascular system of a 70-kg adult. The design of the phantom is based on a computer-based compartmental model by Bae et al.[18]

The phantom had 3 input ports representing the subclavian vein, the internal jugular vein, and the remainder of the body, as well as 1 output port representing the thoracic aorta (diameter: 24.5 mm). The cavity of the phantom holds 1045 mL of water. Three peristaltic hose pumps (Masterflex model LS [2 pumps] and model IP [1 pump], Cole-Parmer Instrument Company, Vernon Hills, IL), which were calibrated to reflect flow rates in a normal adult, were attached to the 3 input ports with the following physiologic flow rates: upper extremity, 162 mL/min; neck, 975 mL/min; and remainder of the cardiovascular system, 5363 mL/min.[6]

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The pumps derived water (23.9°C) from a reservoir that was constantly filled by a tap water source. After sequentially flowing through the 3 mixing chambers (representing the right heart, the pulmonary circulation, and the left heart) and the simulated thoracic aorta, the water exited the phantom via a polymer hose attached to the distal portion of the descending aorta. Water and contrast material exited the phantom through this hose and were disposed into a nearby sink. The phantom was built for first-pass circulation; neither water nor CM was recirculated.

A 16-mM $CuSO_4$ solution was placed adjacent to the phantom as a standard of reference to allow for correction of measured signal intensities (SI) in the phantom, with regard to differences in field shimming and signal intensity scaling between contrast injections.

Contrast and Saline Injection Protocols

Saline Chaser Volume and Injection Rate Variations

To define the combination of volume and injection rate of the saline chaser that has the largest effect on maximal aortic SI, 2 mL of Multihance (Bracco Diagnostics, Inc., Princeton, NJ) diluted in saline to a volume of 20 mL injected at 2 mL/s were followed by 20, 40, and 60 mL of saline injected at 2, 4, and 6 mL/s. Flow rates greater than 6 mL/s were not tested, given that such flow rates are not routinely used in CE-MRA in human subjects. Analysis of the results (Table 1) demonstrated that it was the injection rate of the saline chaser, rather than the volume, that had the largest effect on maximal aortic enhancement. Therefore, we chose a saline chaser of 20 mL injected at 2 mL/s and a saline chaser of 20 mL injected at 6 mL/s for the main part of this study.

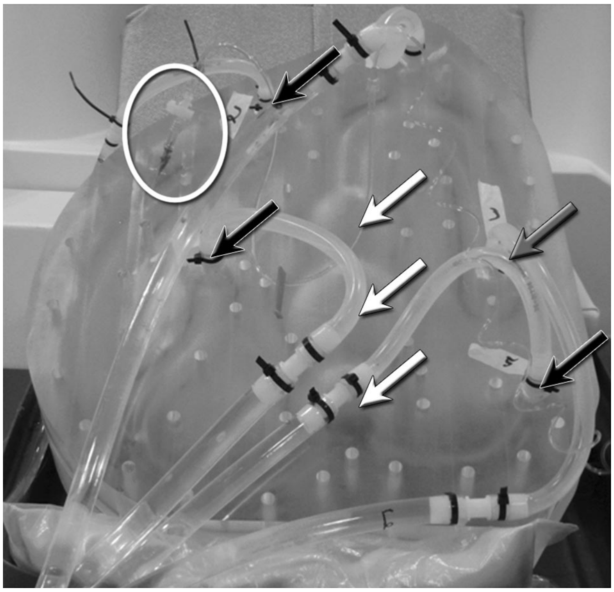

FIGURE 1. Photograph of physiologic flow phantom. A, Input ports represent subclavian vein, internal jugular vein, and remainder of body (black arrows). Mixing chambers represent right heart, pulmonary circulation, and left heart (white arrows). Output port represents thoracic aorta (gray arrow). The angiocatheter is marked by the white oval.

Baseline Enhancement Characteristics and Optimized Saline Chaser Injection Protocol

Contrast material variables tested were as follows: 20 mL of 3 different 100% (undiluted) contrast agents (Multihance, Gd-BOPTA, Bracco Diagnostics, Inc., Princeton, NJ; Prohance, Gd-HP-DO3A, Bracco Diagnostics Inc., Princeton, NJ; Magnevist, Gd-DTPA, Bayer HealthCare, Inc., Berlin, Germany), and 80%, 40%, 20%, 10%, 5%, and 2.5% of the full amount of contrast agents. All CM amounts were diluted in saline to a volume of 20 mL and injected at a rate of 2 mL/s to ensure equal bolus lengths. Each CM concentration was followed by a saline chaser of 20 mL injected at 2 mL/s and a saline chaser of 20 mL injected at 6 mL/s.

The contrast material and normal saline solution were administered using a dual-chamber mechanical power injector (Spectris, MedRad, Indianola, PA). The power injector was connected to the phantom via an 18-gauge angiocatheter (Insyte Autoguard Winged, Becton Dickinson and Co., Franklin, NJ), which was inserted into the peripheral portion of the phantom representing the arm vein. The volume of fluid contained within the coiled tubing was 4.5 mL. Contrast material and normal saline (0.9% sodium chloride) were administered at room temperature (23.0°C). Each CM and saline chaser combination was repeated 3 times for statistical purposes.

Magnetic Resonance Protocol

Imaging was performed using a 3.0-T magnetic resonance (MR) system (MAGNETOM Trio, Siemens Healthcare Solutions, Inc, Erlangen, Germany). A single-slice fat-suppressed fast low angle shot T1-weighted sequence on a coronal view with 1 frame/s for 60 seconds was started with each CM application (repetition time [milliseconds]/echo time [milliseconds], 500/1.23; flip angle, 8 degrees; matrix, 192 frequency × 108 phase; NEX 2; section thickness, 20 mm).

Quantitative Analysis of MR Images

Aortic SI was measured by placing 3, 115-mm^2 (17 pixels) large regions-of-interest within the compartment of the phantom representing the descending thoracic aorta on a workstation (Leonardo, Siemens Healthcare Solutions, Inc., Erlangen, Germany) (Fig. 2). The workstation's copy-and-paste function was used to measure SI at the same locations in each image and series. The 3 values were normalized against the reference standard (16-mM $CuSO_4$ solution) using the following formula: $SI = \dfrac{100 \times SI\,[ROI\ aorta]}{SI\,[reference\ standard]}$ on each image and averaged. Average values were calculated for the 3 repeats of each CM and saline injection protocol. Next, the mean of the baseline SI (values from second 1–12) was subtracted from the SI of the following images to determine aortic enhancement for each frame ($SI_{n\,[frame\,x]} = SI_{[frame\,x]} - mean\,SI_{[frame\,1–12]}$). These normalized SI values were plotted against time to derive the normalized SI versus time (SI/T_n) curves. Based on these values, a 50%, 75%, and 90% level related to the SI_{max} (peak intensity of each protocol) was

TABLE 1. Evaluation of the Normalized Signal Intensity Versus Time (SI/T_n) Curves Using 2 mL of MH Diluted With Saline (18 mL) to a Total Volume of 20 mL (10%) and Saline Chaser Volumes of 20, 40, and 60 mL (Injection Rates: 2, 4, 6 mL/s)

Saline chaser injection rate (mL/s)	2			4			6		
Saline chaser volume (mL)	20	40	60	20	40	60	20	40	60
SI_{max}	22	23	23	26	25	26	27	28	28

SI_{max} indicates maximal signal intensity; MH, Multihance.

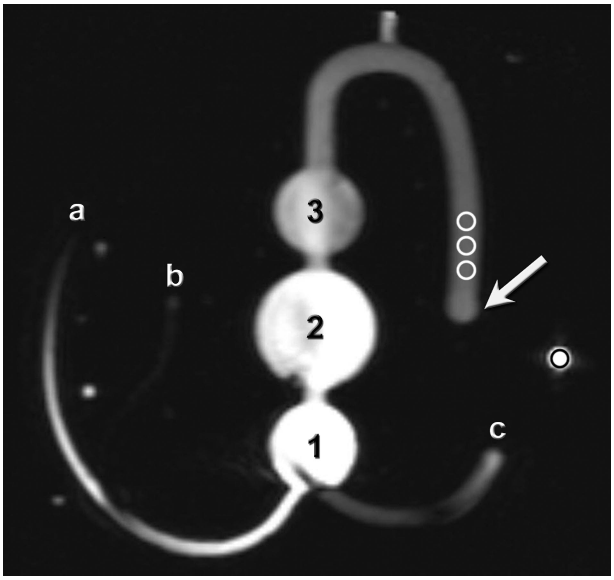

FIGURE 2. Coronal 2-dimensional fast low angle shot T1-weighted image (repetition time, 500 milliseconds; echo time, 1.23 milliseconds; flip angle, 8 degrees) 20 seconds after the initiation of contrast injection (2 mL of Multihance diluted with 18 mL of saline (total volume: 20 mL) [10% CM] injected at 2 mL/s followed by a 20-mL saline chaser injected at 2 mL/s) demonstrating the position of the white regions-of-interest in the compartment representing the descending thoracic aorta and the black region-of-interest in the standard of reference (16 mM $CuSO_4$ solution placed adjacent to the phantom). Input ports represent subclavian vein (a), internal jugular vein (b), and remainder of body (c). Mixing chambers represent right heart (1), pulmonary circulation (2), and left heart (3). Output port represents thoracic aorta (white arrow).

calculated. Duration of 50%, 75%, and 90% peak aortic enhancement (bolus length, BL_{50}, BL_{75}, and BL_{90}) was defined by counting the number of images (seconds) in which SI was greater than or equal to 50%, 75%, and 90%, respectively, of SI_{max}. Finally, the integrals were calculated under the entire SI/T_n curve (INT_{FULL}), as well as during the 50%, 75%, and 90% SI_{max} levels (INT_{50}, INT_{75}, and INT_{90}, respectively).

Statistical Analysis

The effect of the saline chaser injection rate and CM concentration on aortic enhancement characteristics was compared between the different CM concentrations and the different saline chaser injection rates using a paired Student *t* test. A computer software package (SPSS, version 15, SPSS Inc., Chicago, IL) was used for all statistical calculations. A value of $P < 0.05$ was considered significant.

RESULTS

Saline Chaser Volume and Injection Rate Variations

There was no significant difference in SI_{max} between the 3 saline chaser volumes when injected at 6 mL/s (SI_{max} 20 mL: 27.4; SI_{max} 40 mL: 27.6; SI_{max} 60 mL: 27.7). However, increasing the saline chaser injection rate from 2 mL/s to 6 mL/s resulted in significantly higher SI_{max} ($P < 0.01$) for all 3 tested saline chaser volumes (Table 1).

Baseline Enhancement Characteristics and Optimized Saline Chaser Injection Protocol

The maximal signal intensity (SI_{max}) decreased slowly from 100% to 40% of CM and more rapidly at lower concentrations. Increasing the injection rate of the 20 mL of saline chaser from 2 mL/s to 6 mL/s had little effect on undiluted CM (mean increase, 0.4% ± 0.3%) and high CM concentrations, whereas it had a more pronounced effect on lower CM concentrations (mean increase using 10% of CM, 23.7% ± 2.6%). SI_{max} was significantly higher for the CM protocols followed by a saline chaser injected at 6 mL/s compared with the protocols followed by a saline chaser injected at 2 mL/s ($P < 0.001$). See Table 2, column 3 (SI_{max}) and Figure 3 for detailed results.

Bolus length at 75% SI_{max} (BL_{75}) demonstrated a constant decrease from undiluted contrast to 10% of CM, and remained constant at lower concentrations. Increasing the injection rate of the 20-mL saline chaser from 2 mL/s to 6 mL/s resulted in a decrease in the bolus length with significantly shorter BL_{50}, BL_{75}, and BL_{90} for the CM protocols followed by a saline chaser injected at 6 mL/s compared with the protocols followed by a saline chaser injected at 2 mL/s ($P < 0.001$). For example, at 75% SI_{max} (BL_{75}), bolus length decreased by 1.2 seconds ± 0.5 seconds. See Table 2, columns 4 to 6 for detailed results for BL_{50}, BL_{75}, and BL_{90}.

The integral under the SI/T_n curve during 75% SI_{max} (INT_{75}) showed a constant decrease from undiluted CM to 0.5% of CM. Increasing the saline chaser injection rate from 2 mL/s to 6 mL/s resulted in a decrease in INT_{75} with high CM concentrations (mean decrease with undiluted CM, 13.2% ± 8.8%), whereas it had the reverse effect with lower CM concentrations (mean increase using 10% of CM, 3.6% ± 1.4%). INT_{50}, INT_{75}, INT_{90}, and INT_{FULL} were overall significantly smaller for the CM protocols followed by a saline chaser injected at 6 mL/s compared with the protocols followed by a saline chaser injected at 2 mL/s ($P < 0.01$). See Table 2, columns 7 to 10 for detailed results for INT_{FULL}, INT_{50}, INT_{75}, and INT_{90}.

DISCUSSION

The aim of our study was to evaluate the effect of the CM concentration and the saline chaser volume and injection rate on first-pass aortic enhancement characteristics in CE-MRA. Our results showed that when using higher CM concentrations, the enhancement curves demonstrated a plateau that is caused by the nonlinear relation between concentration of Gd and MR signal. This nonlinear relation has been demonstrated in other studies as well.[19–21] Depending on the CM used, injecting only 40% of CM will still result in 82% to 92% of SI_{max} compared with SI_{max} using undiluted CM. It should be mentioned, however, that even though we diluted all amounts of CM with saline to a volume of 20 mL to ensure equal bolus length, the bolus lengths at the analyzed levels of SI_{max} were significantly shorter and the integral under the SI/T_n curves was significantly smaller with lower CM concentrations. It is important to acknowledge this when using low CM concentrations for contrast-enhanced MRI. Bolus length should not be shorter than acquisition time.[22] Therefore, the contrast and saline injection protocol should be chosen according to the imaging parameters. The central 20% of k-space acquisition defines vessel contrast in CE-MRA.[22] Gd concentration—as measured with SI_{max} in our study—at the time of central k-space acquisition determines intravascular SI.[23] Ideally, the CM arrives before the central k-space lines are measured, and SI_{max} coincides with the acquisition of the central lines. The sharpness of the vessel contours depends on the presence of CM during the sampling of the peripheral k-space lines.[22] The presence of CM in our study is represented with the area under the SI/T curve (INT), whereas the

TABLE 2. Evaluation of the Normalized Signal Intensity Versus Time (SI/T_n) Curves at 50%, 75%, and 90% Signal Intensity Levels Using Various Concentrations of Gd-BOPTA, Gd-HP-DO3A, and Gd-DTPA Diluted With Saline to a Total Volume of 20 mL Injected at 2 mL/s and Both a 20 mL Saline Chaser Injected at 2 mL/s and 6 mL/s

Gd-BOPTA (mL/20 mL) (% CM)	20 mL Saline Injection Rate (mL/s)	SI_{max}	BL_{50}	BL_{75}	BL_{90}	INT_{FULL}	INT_{50}	INT_{75}	INT_{90}
0.5 (2.5%)	2	4.2	11	6	4	54	36	23	16
	6	4.9	8	5	3	52	32	23	14
1.0 (5%)	2	9.8	10	6	4	115	78	53	37
	6	12.3	8	5	3	120	78	56	36
2.0 (10%)	2	22.1	10	6	4	260	180	122	85
	6	27.4	8	5	4	273	179	127	105
4.0 (20%)	2	44.1	12	8	4	573	430	319	172
	6	49.3	11	6	4	571	429	274	191
8.0 (40%)	2	61.1	15	11	7	979	777	618	414
	6	62.9	14	10	6	928	736	578	368
16.0 (80%)	2	66.4	20	16	11	1368	1172	1002	837
	6	66.7	18	15	11	1292	1071	940	718
20.0 (100%)	2	66.8	22	18	15	1500	1316	1146	980
	6	66.9	21	17	14	1424	1249	1082	916

Gd–HP–DO3A (mL/20 mL) (% CM)	20 mL Saline Injection Rate (mL/s)	SI_{max}	BL_{50}	BL_{75}	BL_{90}	INT_{FULL}	INT_{50}	INT_{75}	INT_{90}
0.5 (2.5%)	2	2.8	12	6	4	36	26	15	11
	6	3.2	9	5	3	35	23	15	9
1.0 (5%)	2	6.4	11	6	4	78	55	35	25
	6	8.0	8	5	3	81	52	37	23
2.0 (10%)	2	15.1	11	6	4	177	130	83	58
	6	19.1	8	5	3	190	124	87	56
4.0 (20%)	2	33.4	11	7	4	408	298	212	130
	6	38.7	9	6	3	411	283	211	114
8.0 (40%)	2	54.4	13	10	6	790	599	493	362
	6	58.0	12	8	5	758	575	427	282
16.0 (80%)	2	65.0	18	14	10	1203	1009	845	630
	6	65.8	17	12	9	1130	951	742	576
20.0 (100%)	2	66.1	20	16	12	1339	1156	992	771
	6	66.6	18	14	11	1264	1058	882	713

Gd–DTPA (mL/20 mL) (% CM)	20 mL Saline Injection Rate (mL/s)	SI_{max}	BL_{50}	BL_{75}	BL_{90}	INT_{FULL}	INT_{50}	INT_{75}	INT_{90}
0.5 (2.5%)	2	3.1	12	7	4	40	29	19	12
	6	3.8	8	5	2	40	24	17	7
1.0 (5%)	2	7.5	11	6	4	92	65	41	29
	6	9.5	9	5	3	97	66	43	28
2.0 (10%)	2	17.5	10	6	4	209	142	96	67
	6	21.1	8	5	3	215	139	98	62
4.0 (20%)	2	39.5	11	6	4	468	348	222	153
	6	41.9	11	6	3	470	337	231	123
8.0 (40%)	2	55.8	14	10	6	841	653	509	324
	6	59.4	14	9	6	836	673	492	345
16.0 (80%)	2	65.1	19	15	11	1263	1077	912	695
	6	65.6	18	14	10	1205	1023	858	639
20.0 (100%)	2	65.9	21	16	13	1393	1248	1004	836
	6	66.2	19	15	12	1318	1117	774	774

SI_{max} indicates maximal signal intensity; BL_{50}, bolus length at 50% signal intensity level; BL_{75}, bolus length at 75% signal intensity level; BL_{90}, bolus length at 90% signal intensity level; INT_{FULL}, integral of the entire SI/T_n curve; INT_{50}, integral at the 50% signal intensity level; INT_{75}, integral at the 75% signal intensity level; INT_{90}, integral at the 90% signal intensity level.

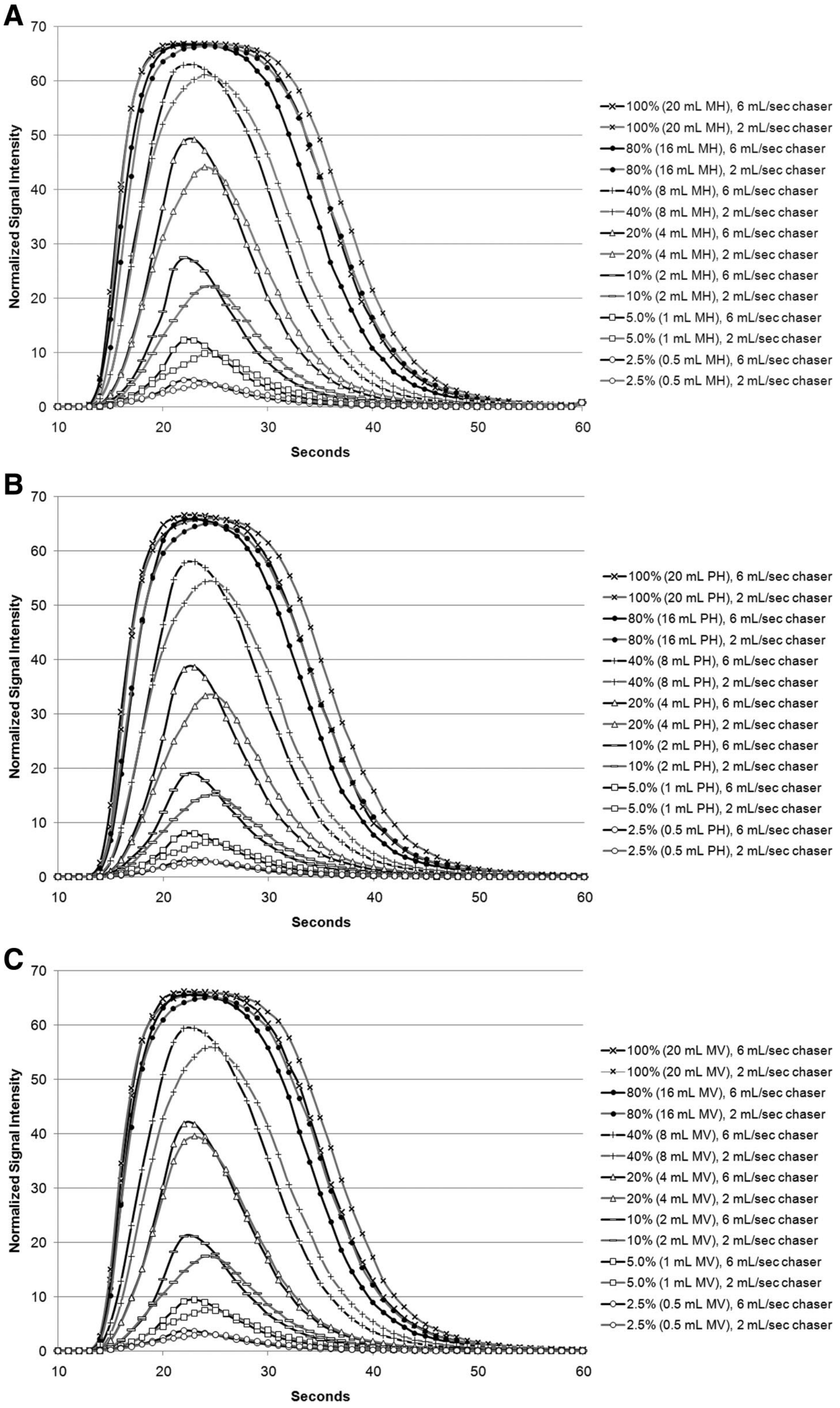

FIGURE 3. Graph demonstrating the normalized signal intensity versus time (SI/T_n) curves for each Multihance (MH) (A), Prohance (PH) (B), and Magnevist (MV) (C) concentration followed by a 20-mL saline chaser injected at 2 mL/s and a 20-mL saline chaser injected at 6 mL/s. Note the plateau that is reached with the undiluted CM (100%, 20 mL) and 80% of CM due to the nonlinear relation between the Gd concentration and the MR signal intensity. Using 40% of CM results in a SI_{max} close to the one with higher CM concentrations. Note, however, the narrower curve demonstrating the shorter bolus length. Also note the increase in SI_{max} when 10% and 20% of CM are followed by the saline chaser with the faster injection rate, whereas at 80% and 100% there is only a minimal increase in SI_{max} due to saturation. In all CM concentrations, a tighter bolus is observed when the CM is followed by a saline chaser with an injection rate of 6 mL/s compared with a saline chaser with an injection rate of 2 mL/s.

length of the bolus is indicated by BL. Our study demonstrates the bolus shapes of various CM concentrations and saline chaser injection rates, which can be carefully selected according to the duration of the sequence protocol and timing of the k-space acquisition.

Our results demonstrated no significant difference in SI_{max} between the different saline chaser volumes, even though a larger saline chaser volume has been shown to have an advantageous effect on arterial first-pass Gd-CM dynamics in humans.[24] In our phantom model, the dead space between the injection site and the right atrium is much lower compared with clinical practice with longer tubing plus venous volume from the antecubital fossa to the right atrium. This most likely contributes to the lack of benefit of a larger saline chaser volume and accounts for some of the differences with those reported by Boos et al,[24] where a larger saline chaser volume will result in a better washout of the Gd distributed within the venous system of the upper extremity.

Using high CM concentrations and an increased saline chaser injection rate only minimally increased SI_{max} due to the saturation phenomenon that occurs because of the nonlinear relation between the concentration of Gd and the MR signal. Although the relaxivity of most Gd-based contrast agents is constant between 1.0 and 3 T, with similar R1 effects for T1-weighted imaging, the T2* artifacts induced by an overconcentrated contrast agent bolus in gradient-echo sequences may be substantially increased on 3-T scanners compared with 1.5-T scanners.[25,26] Because we have adopted a fast low angle shot sequence to measure SI over time in our study, our results can be partly affected by T2* effects decreasing the SI in the phantom aorta at increased contrast agent concentrations. When using lower CM concentrations, which yield enhancement effects below this plateau, the effect of an increased saline chaser injection rate is more pronounced and more similar to that noted during computed tomography angiography.[17] In addition to increasing SI_{max}, increasing the saline chaser injection rate also shortens the bolus length, which must be taken into consideration when determining the acquisition time. Additionally, the results may vary when using other pulse sequences and different field strengths.

Although it might be easier to perform faster acquisitions with smaller volumes of contrast agents with a bolus chasing technique or with dynamic time-resolved CE-MRA for the imaging of smaller vessels, such as in the run-off arteries of the calf, using a diluted bolus to image large vessels, such as the aorta at a high spatial resolution, could possibly prove to be preferential.

A previous study demonstrated that using a low concentrated Gd-doped saline chaser compared with a pure saline flush significantly improves vessel contrast in time-resolved CE-MRA.[6] Although these results are promising, we did not investigate a Gd-doped saline chaser in our study. We demonstrate that optimizing a pure saline chaser with low CM concentrations will result in higher SI_{max} without administering additional Gd.

We acknowledge that our study has limitations. A significant limitation lies in the fact that water was used instead of blood or plasma. This is of particular concern for the use of Multihance, which is known to have a low protein binding ability causing a higher relaxivity.[26,27] Therefore, the relaxivity of Multihance was less than that achieved in vivo. However, not only the total volume of more than 700 L of water used during our experiment, but also the entire phantom setup with over 160 m (4 × 40 m) of polymer hose make the use of blood or plasma impossible. Nonetheless, our results serve as a starting point for possible patient studies, most notably due to the increasing need to reduce CM in MRI related to NSF and the administration of high-dose Gd-based paramagnetic CM in patients with advanced renal failure. Moreover, there is no recirculation of the water/CM mixture. However, the aortic enhancement characteristics of the arterial first pass can be reliably investigated, as demonstrated in a previous study using computed tomography.[17] While we did not examine all available MR contrast agents, the homogeneity of the results with the 3 used contrast agents suggests that our results can be extended to other Gd-based contrast agents. In this study, we did not vary the injection rate of the contrast agent. Although the CM injection rate also contributes to the shape of the bolus enhancement profile, we decided to limit the investigation of this study to the chosen CM concentration, the saline chaser volume, and injection rate, as well as 1 cardiac output.

We conclude that with reduced CM concentrations and a fast saline chaser, maximal aortic SI close to that with undiluted CM can be achieved. An increased saline chaser injection rate has a more pronounced effect on aortic enhancement characteristics at lower CM concentrations than at higher CM concentrations.

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