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Time-Resolved MR Angiography of the Legs at 3 T Using a Low Dose of Gadolinium: Initial Experience and Contrast Dynamics

Gurpreet Singh Sandhu^{1,2}, Rod P. Rezaee³, John Jesberger^{1,2}, Katherine Wright^{1,4}, Mark A. Griswold^{1,2,4}, and Vikas Gulani^{1,2,4}

¹Department of Radiology, University Hospitals of Cleveland, Case Western Reserve University, 11100 Euclid Ave, 123 Bolwell Bldg, Cleveland, OH 44106

²Department of Internal Medicine, Western Reserve Care System, Youngstown, OH

³Department of Otolaryngology-Head and Neck Surgery, University Hospitals of Cleveland, Case Western Reserve University, Cleveland, OH

⁴Department of Biomedical Engineering, University Hospitals of Cleveland, Case Western Reserve University, Cleveland, OH

Abstract

OBJECTIVE—This article describes our initial clinical experience with time-resolved MR angiography (MRA) of the legs using the time-resolved imaging with stochastic trajectories (TWIST) technique with a half dose of gadolinium.

MATERIALS AND METHODS—Thirty-four patients underwent a TWIST examination of the legs at 3 T. Thirty-three patients also underwent a bolus-chase MRA examination in the same setting. Times elapsed between the start of contrast injection and the appearance of contrast material (t_A) and peak enhancement of the arteries in the legs (t_B) were analyzed. The number of patients with examinations affected by venous contamination was determined. The differences in t_A and t_B between cases in which venous contamination was present or absent were evaluated using a two-tailed Student t test.

RESULTS—The TWIST technique using a half dose of gadolinium provided diagnostic-quality images of all patients. The mean t_A was 35.5 ± 8.8 (SD) seconds (range, 17.8–60.4 seconds), and the mean t_B was 59.1 ± 15.1 seconds (range, 31–98.8 seconds). Venous contamination was observed in bolus-chase MRA images of 52.9% of patients. The relationship between venous contamination and t_A was not statistically significant ($p = 0.13$). The incidence of venous contamination was higher in patients with lower values of t_B ($p = 0.01$).

CONCLUSION—The described low-dose clinical experience with TWIST and the contrast dynamics information gained from this study could aid radiologists in planning protocols for leg MRA examinations.

Keywords

contrast dynamics; leg MR angiography; lower extremity; time-resolved MRA; TWIST

Peripheral arterial imaging is often performed using MR angiography (MRA), a noninvasive method that provides high-resolution 3D images without ionizing radiation exposure. The most common technique for MRA is bolus-chase contrast-enhanced MRA. During a bolus-chase MRA examination, a gadolinium contrast bolus is injected IV and data are sequentially acquired from various stations in a timed or triggered manner to capture the arterial phase of contrast enhancement. However, data acquisition often lags behind the movement of the contrast bolus [1], leading to venous filling with contrast material at the time of data acquisition, particularly at the distal-most station. This lag results in venous contamination of the bolus-chase MRA images of the legs [2–4] and reduces their diagnostic utility. A number of strategies such as subtraction techniques [5], venous compression [6, 7], alternate contrast bolus injection schemes [8, 9], data postprocessing [10, 11], and parallel imaging [12, 13] have been used to help alleviate venous contamination from leg bolus-chase MRA images with varying success. Alternatively, distal-station MRA can also be performed using time-resolved contrast-enhanced MRA in which multiple datasets are acquired in quick succession after injection of a contrast bolus. This strategy allows acquisition of a set of images in which the arterial phase of contrast enhancement is virtually guaranteed to be captured.

Various time-resolved MRA techniques have been described in the literature [14–18], one of which is time-resolved imaging with stochastic trajectories (TWIST) [19, 20]. In TWIST, the process of data acquisition is accelerated using a combination of view sharing of undersampled k-space data, parallel imaging, and partial-Fourier reconstruction. The k-space is fully sampled only once during data acquisition. At other times, a cylindric region in the center of the k-space is fully sampled and the peripheral region of the k-space is partially sampled with each pass. Data from adjacent frames are combined to fill the remaining points in the peripheral region. The proportion of the central region with respect to the total k-space volume and the sampling fraction of the peripheral region in 1 frame are specified by the user [19, 20].

In the past, patients undergoing evaluation for distal arterial abnormalities at our institution underwent a bolus-chase MRA examination and an additional low-dose time-resolved MRA of the distal station (legs). In this study, our experience with TWIST for distal-station time-resolved MRA using a low contrast dose is described, and the time-resolved TWIST datasets are used to investigate contrast dynamics of the legs.

Materials and Methods

This study is HIPAA compliant and was approved by the institutional review board. Retrospective image analysis of 34 consecutive patients (mean age, 61.5 years; age range, 16–88 years; male-female ratio, 25:9) whose leg arterial tree was examined using MRA between July 1, 2008, and April 1, 2009, was performed. The protocol at our institution included a TWIST examination of the distal station and a bolus-chase MRA examination, with both being performed during the same setting. One patient underwent a TWIST examination only.

Data Acquisition

Data were acquired at 3 T (Magnetom Verio, Siemens Healthcare) using a peripheral angiography coil for signal acquisition. The TWIST examination was performed first. This acquisition was followed by a 10-minute delay to allow contrast equilibration, and then the bolus-chase MRA examination was performed. The TWIST and bolus-chase MRA examinations were performed using 0.05 and 0.10 mmol/kg of gadobenate dimeglumine (MultiHance, Bracco Diagnostics), respectively. The contrast agent was injected at a rate of 2 mL/s and was followed by a saline flush (20 mL; rate, 2 mL/s) during both examinations.

The high-dose study was conducted second to minimize the effect of circulating contrast material on the examination.

TWIST data were acquired in the coronal orientation using a T1-weighted 3D FLASH sequence (TR/TE, 2.5/1.0; alpha, 22°; bandwidth, 1115 Hz/pixel; FOV, 313 × 400 × 96 mm; matrix size, 203 × 320 × 64; partial-Fourier, 6/8; generalized autocalibrating partial parallel acquisition [GRAPPA] factor, 2; 25 frames; temporal interpolation factor, 2). The size of the fully sampled central region of k-space (termed A) was kept at 20% of total k-space for all examinations, and the fraction of the remaining k-space sampled with each pass (termed B) was fixed at 50%. These settings yielded an acquisition time of 2 minutes 55 seconds per frame at a spatial resolution of 1.54 × 1.25 × 1.5 mm. Two baseline frames were acquired, and contrast material was then injected at the start of acquisition of the third frame. Bolus-chase MRA data from the leg station were acquired in the coronal orientation as part of an abdominal angiography and lower extremity runoff examination using a T1-weighted FLASH sequence (TR/TE, 3.2/1.2; alpha, 25°; bandwidth, 700 Hz/pixel; FOV, 350 × 400 × 96 mm; matrix size, 369 × 448 × 96; spatial resolution, 0.94 × 0.89 × 1 mm). This examination was performed over 3–4 stations depending on patient height and was triggered by the technologist at the arrival of the bolus in the abdominal aorta.

Data Analysis

The data were analyzed on a satellite console. The maximum-intensity-projection (MIP) technique was used for postprocessing and analysis. Subtraction images were used for analysis in all but two patients who moved during data acquisition. In these two patients, unsubtracted source images were analyzed.

The contrast dynamics were analyzed from TWIST images to study individual variations in enhancement of the leg arterial tree after contrast injection. The number of patients in whom the contrast material appeared in both legs in the same frame was tallied. For patients in whom the contrast agent did not appear in the same frame, the lag between acquisitions of the frames in which the contrast agent appeared in each leg was determined. The times elapsed between the start of contrast injection and appearance of the contrast agent (t_A), start of contrast injection and peak enhancement (t_B), and appearance of contrast agent and complete enhancement (t_C) were calculated for individual patients. Because contrast bolus injection started with the commencement of acquisition of the third frame, this point was taken as the start of the contrast injection. The time at which the contrast material first appeared was defined as the point at which signal increased above baseline in the popliteal artery. The time to complete enhancement was defined as the time at which the bolus reached the distal ends of all arteries of both legs to the level of the tibiotalar joint. The mean, SD, and range of each of the three measurements were calculated. The numbers of patients for whom the values of t_A , t_B , or t_C were outside ± 5 seconds and outside ± 10 seconds of the respective mean values were determined for each of the three times. The relationships between t_A , t_B , and t_C and the age of the patients were analyzed by calculating Pearson correlation coefficients. The significance of the difference between values of the three times for male and female patients was tested using the Student *t* test (two-tailed, $\alpha = 0.05$).

Venous contamination in the distal station and contrast dynamics of the legs were studied. Venous contamination was defined as any degree of venous enhancement in full-thickness MIPs impeding visualization of any of the popliteal, anterior tibial, posterior tibial, and peroneal arteries of either leg. Bolus-chase MRA images were analyzed to find patients whose images showed venous contamination, and the number of patients with examinations showing venous contamination was determined. A similar evaluation of the time-resolved MRA data showed that no TWIST examinations showed venous contamination. The number

of patients in various ranges of t_A , t_B , and t_C (in increments of 5 seconds) who had venous contamination was determined. The differences in t_A , t_B , and t_C between cases with and those without venous contamination were evaluated using a two-tailed Student t test ($\alpha = 0.05$).

Results

In 31 of the patients (91.2%), the contrast agent appeared in both legs in the same TWIST frame. In the remaining three patients (8.8%), the contrast agent in one leg lagged behind that in the other leg by 5.1, 26 (Fig. 1), and 5.1 seconds, respectively. The measured t_A , t_B , and t_C values for all patients are shown in Figure 2. The mean values $\pm$ SD of t_A , t_B , and t_C were 35.5 ± 8.8 seconds (range, 17.8–60.4 seconds), 59.1 ± 15.1 seconds (range, 31–98.8 seconds), and 23.5 ± 9.4 seconds (range, 6.7–53.3 seconds), respectively. The observed t_A , t_B , and t_C values were outside ± 5 seconds of the mean in 17 patients (50%), 25 patients (73.5%), and 18 patients (52.9%), respectively, whereas these values were outside ± 10 seconds of the mean in six patients (17.5%), 13 patients (38.2%), and seven patients (20.6%), respectively.

There were positive correlations between the values of t_A and t_B ($r = 0.82$, $p < 0.005$), t_B and t_C ($r = 0.84$, $p < 0.005$), and t_A and t_C ($r = 0.38$, $p = 0.02$) (Fig. 3). However, there were no correlations between the age of the patients and t_A ($r = 0.27$, $p = 0.13$), t_B ($r = 0.09$, $p = 0.61$), or t_C ($r = -0.11$, $p = 0.55$). Similarly, no significant difference between male and female groups was found for t_A (mean $\pm$ SD, 36.3 ± 9.1 vs 33.3 ± 7.9 seconds, respectively; $t = -0.89$, $p = 0.37$), t_B (59.0 ± 13.1 vs 59.3 ± 20.7 seconds; $t = 0.58$, $p = 0.95$), or t_C (22.7 ± 9.1 vs 26.0 ± 14.5 seconds; $t = 0.67$, $p = 0.52$).

Venous contamination was observed in bolus-chase MRA images of 18 patients (52.9%) (male-female ratio, 15:3). The distributions of the numbers of patients with venous contamination over the periods of t_A , t_B , and t_C are shown in Figure 4. The likelihood of venous contamination was higher in patients with smaller values of t_B ($p = 0.01$) and t_C ($p = 0.008$), whereas its relationship with t_A was not significant ($p = 0.13$).

Discussion

The major clinical strengths of time-resolved MRA include the possibility of using a low contrast dose, elimination of a test bolus, and virtually guaranteed imaging in the arterial phase of contrast enhancement. The hemodynamic information available from a time-resolved MRA dataset is useful for analysis of high-flow lesions, such as arteriovenous fistulas; lesions with retrograde flow; and collateral circulation. The value of this information is seen, for example, in the time-resolved MRA image set of a patient who had severe stenosis of the tibioperoneal trunk in one leg. In this patient, TWIST images enabled the depiction of the collateral supply to the peroneal and posterior tibial arteries of the leg (Fig. S5, which can be seen in the *AJR* electronic supplement to this article, available at www.ajronline.org). Bolus-chase MRA fails to provide clinically useful information in such cases.

In contrast to bolus-chase MRA, which provides only a single 3D dataset, a set of time-resolved MRA images virtually guarantees the acquisition of at least one volume with complete arterial enhancement and without significant venous contamination (Fig. S6, which can be seen in the *AJR* electronic supplement to this article, available at www.ajronline.org). Callback examinations due to venous contamination are completely eliminated with time-resolved MRA of the legs. However, time-resolved MRA provides images from a single station and multiple contrast doses are needed for time-resolved

imaging at multiple stations in the same setting. Finally, the spatial resolution of images produced by time-resolved MRA is typically lower than the spatial resolution of images produced by bolus-chase MRA.

Information about contrast bolus movement through the extremities is often useful in planning bolus-chase MRA examinations, and a rough knowledge of bolus timing is also important for time-resolved MRA. This study shows that the values of t_A , t_B , and t_C are correlated. However, there is greater variability in t_B values than t_A values and the correlation coefficient between t_A and t_C is low. These findings suggest that there is greater variability in the time to fill the distal ends of the arteries than in the time of contrast arrival in the leg station. Few studies have reported the dynamics of a contrast bolus in the lower extremities [4, 21, 22]. In one study, 2D projection MRA examinations of the calf, knee, and thigh of a cohort of 87 patients were performed to estimate the time delay between contrast injection and arrival in various stations of the leg [21]. The value of t_A (mean $\pm$ SD, 35.5 ± 8.8 seconds; range, 17.8–60.4 seconds) is higher in our study than the reported value of 27 ± 6 seconds (range, 16–49 seconds) for contrast arrival in the popliteal artery at the knee in a previous study [21]. The t_B and t_C values were not reported in the previous study.

The results of our study do not show a correlation between age or sex and travel times, although there does appear to be a strong trend toward slower flow with increasing patient age. Increasing age and male sex have previously been reported to be associated with slower contrast flow to the common femoral artery [21]. The differences between the results of study and our results may relate in part to the smaller sample size in our study. The difference in reported travel times may be because of the lower average age of patients in our study compared with the average age of patients in the earlier study (61.5 vs 67 years, respectively). The previous study also showed that abnormalities, such as aortic aneurysm, and a history of myocardial infarction, cellulites, and ulceration can alter contrast travel times to the lower extremities [21]. The influences of these factors on contrast dynamics were not studied here because the sample size is too small for this analysis.

We observed venous contamination in the distal-station bolus-chase MRA images of 18 patients (52.9%). This finding matches that of a previous report in which bolus-chase MRA images of the distal station of 50.6% of patients were reported to have mild-to-severe venous contamination [4]. In our study, the incidence of venous contamination was higher for patients who had lower t_B or t_C values as compared with those who had higher values of the two times (Fig. 3).

Venous contamination is a particularly difficult problem in patients in whom the arrival and movement of the contrast bolus vary between the two legs. For example, significant venous contamination was observed in the bolus-chase MRA images of two of the three patients with differing arrival times in the two limbs. In both cases, arterial phase images could be obtained with TWIST (Figs. 1A–1C and S1D [the latter is available at www.ajronline.org]). We should note that a large fraction of the patients in this study (28/34) underwent MRA evaluation for the purposes of planning fibular free-flap transfer operations. Venous contamination is expected to be a much worse problem in examinations of patients with conditions that directly affect the vascular system and hemodynamics, such as critical limb ischemia. Thus, the fraction of patients in whom bolus-chase MRA results in significant venous contamination is likely to be higher with more varied patient populations.

In the protocol used for all patients in this study, two baseline frames were acquired before the start of contrast injection. Given that the minimum value of the bolus arrival, t_A , was 17.8 seconds, this work shows that contrast injection can be safely started at the initiation of

the first baseline frame itself. The gadolinium dose—half of the standard dose—was found to be sufficient for diagnostic-quality peripheral-station time-resolved MRA examinations.

The spatial resolution of an MRA examination determines its utility for accurate evaluation of any stenotic lesion in the arterial tree [23]. Although the time-resolved MRA examination did provide images with isotropic voxels that help in multiplanar analysis [23], the obtained spatial resolution with time-resolved MRA (voxel dimensions, $1.54 \times 1.25 \times 1.5 \text{ mm}^3$) was poorer than that of bolus-chase MRA ($0.94 \times 0.89 \times 1 \text{ mm}^3$). For the initial implementation of a clinical protocol, a trade-off was made: Some spatial resolution was sacrificed for some temporal resolution. Given that no TWIST examination with this protocol suffered from venous contamination, previous experience suggests that some decreased temporal resolution can be tolerated to obtain better spatial resolution. In patients who underwent the examination for planning a fibula free-flap transfer operation, the lower resolution examination still allowed proper evaluation of the lower extremity vascular branching patterns and lesion localization, although perforator localization is more accurate with a higher-resolution examination. Repeat examinations were not required in any patient [24].

Higher parallel imaging factors (i.e., GRAPPA factors 3–9) and view sharing across more frames have also been successfully used to obtain high-temporal-resolution and high-spatial-resolution distal-station TWIST angiography data [25]. The optimal parallel imaging acceleration and view-sharing settings that still yield clinically interpretable images remain to be determined.

Finally, the lowest contrast dose that can be routinely used for these examinations was not evaluated in the current study. Experimental results have suggested that high-quality MRA images can be obtained with a lower contrast dose [26]. A technique for time-resolved MRA of the legs using 0.03 mmol/kg dose of gadolinium has recently been described in the literature [27]. The authors were able to obtain a TWIST dataset with a spatial resolution of $1.1 \times 1.1 \times 1.35 \text{ mm}^3$ at a frame rate of 5.5 seconds in the leg station. The results of that study showed that TWIST provided images of better quality than MRA examinations performed during continuous table movement of patients with clinical symptoms of peripheral arterial occlusive disease [27].

A possible limitation of our study is that the bolus-chase MRA examination was performed after the TWIST examination and conceivably venous contamination could be related to the half dose of gadolinium contrast injected for the TWIST examination. However, previous reports suggest that the 10-minute interval that we kept between the two examinations is sufficient for contrast equilibration [2, 7, 28]. Because subtraction images were obtained, in our experience, venous contamination from the first study was not a degrading factor in the images.

Conclusion

Our initial experience with time-resolved MRA of the distal station by TWIST technique at 3 T using a low contrast dose and results of contrast dynamics of the legs can help radiologists plan imaging protocols for time-resolved MRA of the lower legs. The imaging protocol could be further optimized in terms of gadolinium contrast dose, view sharing, parallel imaging factor, and temporal and spatial resolution.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Full-thickness coronal maximum-intensity-projection (MIP) images from time-resolved MR angiography (MRA) and bolus-chase data of 83-year-old man. Patient had different times of enhancement of arteries in left and right legs. See also Figure S1D in supplemental data online.

A and B, MIP images from time-resolved MRA show complete contrast enhancement of arteries of left leg (**A**) and of right leg (**B**). Complete arterial enhancement of right leg was delayed from that of left leg by 26 seconds.

C, MIP image from bolus-chase MRA shows significant venous contamination in left leg.

Fig. 2.

Values of t_A , t_B , and t_C by individual patient for 34 patients in study group. Values are defined as follows: times elapsed between start of contrast injection and appearance of contrast agent (t_A), start of contrast injection and peak enhancement (t_B), and appearance of contrast and complete enhancement (t_C). For each patient start, end, and length of bar denotes t_A , t_B , and t_C , respectively. Note wide individual variations of these times. Values of t_A in six patients are greater than minimum value of t_B (31 seconds).

Fig. 3.

Graphs show relationships of times t_A , t_B , and t_C .

A–C, Distribution patterns of t_A and t_B (**A**), t_B and t_C (**B**), and t_A and t_C (**C**) with respect to each other. Values are defined as follows: times elapsed between start of contrast injection and appearance of contrast agent (t_A), start of contrast injection and peak enhancement (t_B), and appearance of contrast and complete enhancement (t_C).

Fig. 4.

Graphs show frequency distributions of patients with venous contamination plotted against ranges of times t_A , t_B , and t_C .

A–C, Bar diagrams show total numbers of patients (*gray bars*) in various ranges of t_A (**A**), t_B (**B**), and t_C (**C**) and numbers of patients with venous contamination in those ranges (*black bars*). Values are defined as follows: times elapsed between start of contrast injection and appearance of contrast agent (t_A), start of contrast injection and peak enhancement (t_B), and appearance of contrast and complete enhancement (t_C). Note that incidence of venous contamination is relatively high in shorter ranges of t_B and t_C and is relatively more evenly distributed with respect to t_A .