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Combining Time-resolved and Single-phase 3D Techniques in Contrast-enhanced Carotid MR Angiography

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We established an easy-to-use technique for performing contrast-enhanced carotid MR angiography (MRA) with a commercial scanner. Twenty-three patients with suspected carotid or vertebral arterial lesions were prospectively studied. Two techniques were applied in the study. After performing sagittal time-resolved acquisitions, we undertook a coronal single-phase 3D acquisition, in which the injection timing was estimated from the preceding images. In each case, we obtained multidirectional images with sufficient venous suppression. The combined use of time-resolved and single-phase 3D MRA is a feasible technique for obtaining selective arterial images without the use of special applications or hardware.

Keywords: *magnetic resonance angiography, internal carotid artery, contrast enhancement*

Introduction

During contrast-enhanced MR angiography (MRA) of cervical arteries, it is necessary to synchronize data acquisitions with the arrival of contrast agents to avoid subsequent venous enhancement, which degrades arterial conspicuity.^{1,2} Recently, several techniques have been proposed to optimize injection timing, such as a test injection of contrast agents^{3,4} and fluoroscopic monitoring with manual/automatic triggering.^{5,6} However, these techniques require complicated procedures or novel scanners with special applications. Another approach for obtaining arterial images selectively is the time-resolved technique.^{7,8} This technique is easily achieved with any MR unit, but its spatial resolution is limited because of the short acquisition time per frame. Although echo-sharing techniques and an ultrashort repetition time can improve image resolution,^{9,10} they also require special equipment. In this study, we performed both time-resolved and single-phase 3D acquisitions on the same subjects and sought to establish an easy-to-use technique for contrast-enhanced MRA, which can be performed with ordinary commercial scan-

ners and requires no troublesome and time-consuming procedures.

Materials and Methods

Twenty-three consecutive patients with clinically suspected steno-occlusive diseases of the carotid or vertebral arteries were prospectively evaluated with contrast-enhanced MRA after their informed consent had been obtained. The patients, 9 women and 14 men, were aged 46-85 years (with a mean age of 67.9 years). Seven patients underwent intra-arterial digital subtraction angiography (IADSA) for preoperative evaluation of carotid or vertebral artery lesions.

All patients were examined with a 1.5T superconductive MR scanner having a gradient-switching capability of 23 mT/m and a slew rate of 120 mT/m/msec (Signa Horizon Lx 8.2, GE, Milwaukee). A neurovascular coil and a commercially available 3D fast spoiled GRASS (FSPGR) sequence with a sequential k-space order were used for the MRA studies. Our sequence parameters were 6.6/1.1 (repetition time msec/echo time msec), a flip angle of 40 degrees, a readout bandwidth of 64 kHz, a matrix of 256 × 192 (interpolated to 512 × 512 by zero filling), and a field of view of 240 × 120 mm. Additional parameters in

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time-resolved and single-phase MRA were partition sizes of 10 and 24 (interpolated to 48 by zero filling), slice thicknesses of 16 and 3.4 mm (interpolated to 1.7 mm by zero filling), and acquisition times of 6.5 sec and 15 sec. The voxel size in the single-phase 3D acquisition was $0.47 \times 0.47 \times 1.7$ mm.

Six consecutive sagittal time-resolved images were obtained at a 0.5 sec interscan interval and each with a 6.5-sec exposure. The images were taken starting at the initiation of the bolus injection (1.8 ml/sec flow rate) of 7 ml gadopentetate dimeglumine (Magnevist, Schering, Germany) and subsequent injection of 20 ml saline from the right antecubital vein by a power injector. Three minutes after the time-resolved acquisition, the single-phase 3D images were obtained, followed by acquisition of mask images with the same parameters, with the bolus injection of 7 ml gadopentetate dimeglumine and 20 ml saline. The total dose of the gadolinium agent was 0.1–0.15 mmol/kg.

When k-space schemes are sequential and mask images are obtained, the delay time [Δd] before start of acquisition of the single-phase 3D-MRA after initiation of gadolinium injection was deter-

mined by the following equation:

$$\Delta d = (Ts(2Fp - 1) - 3Tc)/2$$

where T_s , T_c are acquisition time per frame in sagittal time-resolved and coronal single-phase MRA, respectively (Fig. 1). F_p is the frame number of time-resolved MRA in which peak arterial enhancement can be obtained. When peak arterial enhancement is observed in two consecutive frames, F_p is determined as a number between them. To more easily determine injection timing, we prepared a table describing injection timing calculated with the above-cited equation as follows: F_p : 3, 3.5, 4, 4.5, 5; Δd : -5, -1.5, 2, 5.5, 9. Examinations of all patients were completed within 20 minutes.

After data acquisition, the arterial images were subtracted from the mask images, and maximum intensity projection (MIP) images were generated with a workstation (Advantage Windows, GE, Milwaukee).

The image quality of the obtained angiograms was determined through consensus by two neuroradiologists (MS, HO) following their qualitative

Fig. 1. Estimation of timing for initiation of coronal single-phase 3D MRA acquisition after injection of contrast

An appropriate delay time [Δd] for the 3D acquisition can be easily estimated from the frame number with peak arterial enhancement of time-resolved acquisitions (F_p) and acquisition times of the two techniques (T_s , T_c). The illustration indicates the relationships of these parameters under the condition that k-space schemes are sequential and mask images are obtained.

evaluation by means of visual inspection. The qualitative evaluation of the images was based on two criteria: arterial contrast enhancement and venous suppression. Images were assigned the following scores: 0 for poor arterial enhancement or venous suppression; 1 for moderate; 2 for good; and 3 for excellent. The presence of abnormalities such as stenoses, occlusions and collateral circulations was also described. In seven patients who underwent IADSA, the degree of internal carotid stenosis was measured and calculated according to the North American Symptomatic Carotid Endarterectomy Trial (NASCET) criteria¹¹ and Statements of the American Heart Association.^{12,13}

Results

In all the patients, a high arterial contrast (score 3 or 2) was successfully obtained on sagittal time-resolved as well as coronal single-phase images

(Table 1, Figs. 2, 3). The value of Δd ranged between -5 and 5.5 , with a mean value of 0.3 (SD: 2.8). Excellent contrast scores of 3 were achieved by 23 sagittal images and 21 coronal images. No patient demonstrated poor (score 0) arterial contrast. Sufficient venous suppression (score 3 or 2) was obtained in almost all cases. Venous enhancement was absent in 20 sagittal and 17 coronal images (score 3). One case each of faint (score 2) and moderate depictions (score 1) of the internal jugular veins were found in the sagittal images, while the coronal images were judged to have 3 and 2 cases, respectively. Marked venous enhancement (score 0) was observed in one coronal image, attributable to technical errors in the injection of the contrast agent.

We found twenty-one arterial abnormalities in 16 of 23 patients. Abnormalities included ten internal carotid artery stenoses, one near-occlusion, one occlusion, one common carotid artery stenosis, one

Table 1. Arterial enhancement and venous suppression of time-resolved and single-phase 3D MRA

	Excellent (3)	Good (2)	Moderate (1)	Poor (0)
Arterial enhancement				
Time-resolved	23	0	0	0
Single-phase 3D	21	1	1	0
Venous suppression				
Time-resolved	21	1	1	0
Single-phase 3D	17	3	2	1

Fig. 2. Severe stenosis of left internal carotid artery (71-year-old male)
a, d: sagittal time-resolved contrast-enhanced MRA (**a:** right side, **d:** left side);
b, c: coronal single-phase contrast-enhanced 3D-MRA (**b:** AP view, **c:** LAO 30 degree)
 Severe stenosis of the left internal carotid artery is readily depicted in time-resolved and in single-phase 3D MRA (arrowheads).

occlusion, two vertebral artery stenoses, three occlusions, and two subclavian artery occlusions. In five patients, formation of collateral circulations was accompanied by occlusions of the common carotid artery, vertebral artery and subclavian artery.

In fourteen internal carotid arteries of seven patients who underwent IADSA, there was no difference between the numbers of occlusions and severe, moderate and mild stenoses (according to NASCET criteria) discovered through IADSA and those discovered through MRA (Table 2, Fig. 4).

Discussion

The contrast-enhanced carotid MRA has been introduced as a less-invasive technique to demonstrate carotid artery stenoses, especially for preoperative evaluations of carotid endarterectomy

(CEA).^{1,2,14} Previous studies comparing this technique to IADSA have demonstrated its clinical feasibility for determining CEA indications according to NASCET criteria and AHA guidelines.^{5,7,8} In these studies, high-resolution multidirectional arterial images with venous suppression were obtained. However, these images require the use of high-performance scanners with special, sometimes noncommercial, applications and troublesome procedures.¹⁴ For less-invasive evaluation of carotid artery diseases in daily practice, easy procedures must be made available that use ordinary commercial scanners.

Signal suppression of the internal jugular veins is considered crucial to improving the conspicuity of carotid bifurcation lesions in contrast-enhanced carotid MRA. The contrast agent's transit time from carotid arteries to internal jugular veins is less than eight seconds, too brief for the complete cap-

Fig. 3. Occlusion of left vertebral artery (79-year-old male)

a, d: sagittal time-resolved contrast-enhanced MRA (a: right side, d: left side); **b, c:** coronal single-phase contrast-enhanced 3D-MRA (b: AP view, c: LAO 30 degree)

Occlusion of the proximal left vertebral artery is evident. The distal portion of the left vertebral artery and left ascending cervical artery (arrowhead), dilated as a collateral pathway, is clearly visible. No internal carotid abnormalities are noted.

Table 2. Degree of internal carotid artery stenosis according to NASCET criteria

	Normal	Mild ≤ 30%	Moderate ≤ 70%	Severe < 100%	Occlusion
MRA	7	2	0	4(1)	1
IADSA	7	2	0	4(1)	1

Values in parenthesis represent near-occlusion.

Fig. 4. Severe stenosis of left internal carotid artery (69-year-old male)

a: coronal single-phase contrast-enhanced MRA (AP view), **b:** IADSA (AP view), **c:** sagittal time-resolved contrast-enhanced MRA (left side), **d:** IADSA (lateral view)

Severe stenosis of the proximal portion of the left internal carotid artery is seen in contrast-enhanced MRA as well as IADSA (arrow heads). Configurations of the stenotic segment from MRA corresponded well with those from IADSA.

ture of low-frequency data during 3D imaging.^{3,5} Therefore, special applications are required that are capable of acquiring 3D datasets with venous suppression. Ultrashort repetition time or echo sharing can allow adequate images to be obtained within the limited time window.^{7,9} Elliptical centric k-space ordering can widen time windows to allow for acquisition of volume images.^{5,15,16} The parallel imaging technique can dramatically reduce acquisition time while maintaining spatial resolution.¹⁷ However, without these techniques, obtaining isotropic three-dimensional images seems impossible. Another prerequisite is the appropriate timing of the scan initiation after injection of the contrast agent. Estimating the arrival time of the contrast agent requires a test injection or fluoroscopic monitoring.¹⁻⁶ The test injection can be performed on any scanner, but is troublesome. Manual/automatic triggering during fluoroscopic monitoring requires new hardware and software, and the procedure is complicated.

We used time-resolved MRA instead of test injection or fluoroscopic monitoring to estimate the arterial enhancement time after injection of the contrast agent. With time-resolved MRA, we can obtain sagittal angiograms with sufficient in-plane resolution, as previously reported.^{9,10,18} In addition, injection timing of single-phase 3D coronal acquisition can be easily estimated. Although estimation of arrival timing is not precise, 3D arterial images with no or faint venous overlapping were successfully obtained in almost all cases. These images have sufficient in-plane resolution and can be rotated to some extent,¹⁹ although the z-axis has limited resolution. Blurring of images was also negligible, presumably because the intra-arterial contrast

agent of the previous injection helps to stabilize the intra-arterial signal.²⁰

Multidirectional images make it possible to readily identify arterial steno-occlusive lesions and associated collateral circulations and to correlate them well with findings on IADSA in this study. Moreover, the degree of internal carotid stenosis according to NASCET criteria in MRA corresponded well with that in IADSA, and no disagreement in operative indications was present. This technique may be usable as a preoperative evaluation for CEA.

One limitation of this study is the small amount of contrast agent used. The dose of each injection was only 7 ml. We had to use subtraction techniques to enhance arterial contrast. Use of a double dose of the contrast agent may improve arterial contrast and eliminate the need for subtraction procedures.

Where novel techniques such as elliptical centric view ordering are not available, we proposed a practical approach combining time-resolved and single-phase 3D acquisitions to obtain carotid MRA. This technique allows us to obtain cervical arterial images with sufficient venous suppression and without novel scanners or troublesome procedures.

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