MAJOR PAPER

Time-resolved Three-dimensional Magnetic Resonance Velocity Mapping of Chronic Thoracic Aortic Dissection: A Preliminary Investigation

Yasuo Amano*, Tetsuro Sekine, Yuriko Suzuki, Keiji Tanaka, Ryo Takagi, and Shinichiro Kumita

1Department of Radiology and 3Coronary Care Unit, Nippon Medical School
1–1–5 Sendagi, Bunkyo-ku, Tokyo 113–8603, Japan

(Received October 12, 2010; Accepted December 8, 2010)

Purpose: The blood flow patterns of chronic thoracic aortic dissection are complicated, and their clinical significance remains unknown. We evaluated the technical and clinical potentials of time-resolved 3-dimensional (3D) magnetic resonance (MR) velocity mapping for assessing these patterns.

Methods: We used data collected from time-resolved 3D phase-contrast MR imaging of 16 patients with chronic thoracic aortic dissection to generate time-resolved 3D MR velocity mapping that included 3D streamline and path line. We investigated blood flow patterns of this disease in the mapping and compared them with the morphological changes of the patent false lumen.

Results: Time-resolved 3D MR velocity mapping visualized rapid flow at the entry and in the true lumen immediately distal to the entry. We observed slower helical or laminar flow in the patent false lumen. In patients with disease progression, slower helical flow following rapid entry jet collided with the outer wall of the false lumen and was also observed in a growing ulcer-like projection.

Conclusion: We showed the potential of time-resolved 3D MR velocity mapping for visualizing pathologic flow patterns related to chronic thoracic aortic dissection.

Keywords: thoracic aortic dissection, velocity mapping, 3D phase-contrast

Introduction

Follow-up of thoracic aortic dissection to show any deterioration is necessary even in chronic phase because mortality and morbidity rates are high in an emergency occurrence and because the growth rate of thoracic aortic dissection is faster than that of abdominal aortic dissection.1–3 Contrast-enhanced computed tomography (CT) or 3-dimensional (3D) magnetic resonance (MR) angiography is the standard technique for diagnosing and classifying thoracic aortic dissection, visualizing mural thrombus, intramural hematoma, and ulcer-like projection (ULP), and following up patients with this disease.3–9 However, the frequent involvement of renal arteries in aortic dissection1,7 precludes the use of contrast agents in some patients with renal insufficiency and risk for contrast-induced nephropathy and nephrogenic systemic fibrosis.

Recently, non-contrast-enhanced 3D MR angiography images with bright blood signals and high spatial resolution have been acquired using steady-state free precession (SSFP) and fast spin-echo imaging, i.e., turbo spin-echo (TSE), such as fresh blood imaging.10–13 The disadvantages of these 3D MR angiography techniques are that they provide limited information regarding blood flow about the entry and false lumen and that distinguishing blood flow from fresh thrombosis may be difficult at high signal intensity.14 Time-resolved 3D phase-contrast MR imaging and velocity mapping analysis may compensate for the disadvantages of non-contrast-enhanced 3D MR angiography. Even after contrast-enhanced 3D MR angiography, time-resolved 3D velocity mapping may be valuable for detailed flow analysis of the true and false lumens of a thoracic aortic dissection. Blood flow analysis may provide information about hydraulic stress and pressure pulse related to progression of aortic dis-
section as well as factors known to affect disease progression, such as Stanford type and size of the false lumen.

Time-resolved 3D MR velocity mapping is currently applied for several diseases of the thoracic aorta, including aneurysm, coarctation, and atherosclerosis. However, this technique has not been employed in detailed investigation of the flow patterns of the true lumen, false lumen, and ULP in chronic thoracic aortic dissection. Its clinical significance for evaluating this disease is also unknown because there has been no comparison of blood flow patterns with morphological changes in the patent false lumen and ULP. Therefore, we evaluated the technical and clinical potentials of time-resolved 3D MR velocity mapping for assessing pathologic flow patterns in chronic thoracic aortic dissection.

Materials and Methods

Subjects
Sixteen patients (14 men, 2 women, aged 49 to 85 years, mean, 65.5 years) with chronic thoracic aortic dissection were enrolled after providing informed consent for participation in the study. In contrast-enhanced CT at presentation with acute thoracic aortic dissection, 4 patients had Stanford type A aortic dissection, and 12 had type B. The interval between initial diagnosis of thoracic aortic dissection and this study ranged from 8 months to 11 years (mean, 4 years 6 months). The dissections comprised 8 cases of double-barrel aortic dissection and 4 cases each of thrombosed false lumen with and without ULP. Five patients underwent graft implantation before this MR imaging study, four with double-barrel dissection of the descending aorta and one with Stanford type A dissection at the present study. The interval between surgery for the thoracic aortic dissection and this study ranged from 2 months to 11 years (mean, 5 years).

MR imaging (Table 1)
A 1.5-tesla imager (Achieva Nova Dual, Philips, Best, The Netherlands) was used. Four of the 16 patients underwent multi-phase, breath-hold, contrast-enhanced 3D MR angiography (Fig. 1A). Because of renal impairment or lack of consent for the use of gadolinium, the other 12 underwent 3D MR angiography without contrast enhancement, three using 3D SSFP (Fig. 2A) and nine with 3D TSE, both of which used cardiac gating, respiratory compensation, and fat suppression techniques. Respiratory compensation consisted of a navigator gating technique for the 3D SSFP and a respiratory gated technique using a bellow for the 3D TSE, as described previously. Fat suppression involved use of a spectrally selective inversion-recovery pulse in the 3D SSFP and a short inversion time inversion-recovery technique in the 3D TSE. Because the 3D TSE was robust to susceptibility artifacts and magnetic inhomogeneity, it was used more frequently than 3D SSFP. We used 3D SSFP to exclude coronary artery diseases and when the patient’s condition required a shorter scan duration. Thereafter, we performed time-resolved 3D phase-contrast MR imaging with temporal resolution of 22 to 26 ms, 13 to 16 cardiac phases (without view sharing), velocity encoding of 200 cm/s, and scan time of 14 to 26 min, depending on cardiac and respiratory rates. Table 1 shows the imaging parameters of each 3D MR imaging

| Table 1. Imaging parameters of 3-dimensional (3D) magnetic resonance (MR) angiography and time-resolved 3D phase-contrast MR imaging in chronic thoracic aortic dissection |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| TR (ms)         | TE (ms)         | flip angle      | matrix          | slice thickness (mm) | options |
| CE 3D gradient-echo | 5.2             | 1.5             | 30              | 512×180           | 4–6 | breath-hold |
| 3D steady-state free precession | 4.2             | 2.1             | 90              | 272×272           | 3.4–4 | fat suppression |
| 3D turbo spin-echo | 1 RR            | 90              | 90              | 256–272×204       | 3–4 | T2 prep, navigator inversion recovery |
| time-resolved 3D phase-contrast | 4.9–5.4         | 2.4             | 8               | 192×192           | 6–8 | respiratory gating |

CE, contrast-enhanced; RR, interval between two R waves on ECG; TE, echo time; TR, repetition time; T2 prep, T2 preparation pulse.
Field of view was 40×40 cm² in all imaging sequences, except that of 3D phase-contrast MR imaging (35×35 cm²). Sensitivity encoding with reduction factor = 2 was used in all sequences. Cardiac gating was applied to non-contrast-enhanced 3D MR angiography and time-resolved 3D phase contrast MR imaging.
Fig. 1. A 60-year-old man with double-barrel thoracic aortic dissection at chronic stage. (A) Contrast-enhanced 3-dimensional (3D) magnetic resonance (MR) angiography shows chronic thoracic aortic dissection with patent false lumen (arrow). (B) Three-dimensional path line velocity mapping shows rapid jet at the entry (arrow) and in the true lumen immediately distal to the entry. Slower helical flow in the false lumen (arrowhead) coincides with the outer wall in 3D MR velocity mapping. However, this method cannot detect the entire patent false lumen.

Fig. 2. A 61-year-old man with double-barrel thoracic aortic dissection at chronic stage. (A) Non-contrast-enhanced 3-dimensional (3D) magnetic resonance (MR) angiography using 3D steady-state free precession shows thoracic aortic dissection with hyperintense false lumen (arrow) and hypointense thrombosis (arrowhead). (B) Three-dimensional path line velocity mapping shows rapid jet at the entry (arrow) and slower helical flow in the false lumen. (C) Multi-planar reconstruction images generated from non-contrast-enhanced 3D MR angiography are shown. Compared with the images acquired simultaneously with the time-resolved 3D velocity mapping (left), the false lumen was slightly enlarged, from 47 to 49 mm, after 8-months' follow-up.
Fig. 3. A 73-year-old man with postoperative chronic thoracic aortic dissection and patent false lumen after graft surgery. Three-dimensional streamline magnetic resonance (MR) velocity mapping shows slow laminar flow in the patent false lumen (arrow) and faster flow in the smaller true lumen (arrowhead). This patient is clinically stable.

Time-resolved 3D MR velocity mapping

The raw data of time-resolved 3D phase-contrast imaging was transferred offline to the computer where GT Flow software (GyroTools, Zurich, Switzerland) was installed, and we generated time-resolved 3D MR velocity mapping from the raw data using the dedicated software.

First, we generated a 2-dimensional (2D) color velocity map overlay that reflected the flow velocity at each slice and cardiac phase. This velocity mapping and 3D MR angiography images were used to determine the locations of the entry and patent false lumen. Thereafter, we generated 3D streamlines and path lines, 2 major methods for time-resolved 3D velocity mapping,15–17 by imaging the “seeding flow particles” at no more than 5 locations: proximal to the entry, distal to the entry of the true lumen, in the false lumen adjacent to the entry, distal to the entry of the false lumen, or proximal to the re-entry. The 3D path lines revealed the paths of particles from the seeding locations in the dynamic flow velocity field (Figs. 1B, 2B), and the 3D streamlines represented continuous lines of velocity vectors at each cardiac phase (Fig. 3).15

Evaluation of time-resolved 3D MR velocity mapping

First, we used the time-resolved 3D MR velocity mapping to investigate the blood flow patterns of the true and false lumens, entries, and ULPs in chronic thoracic aortic dissection. Next, we compared the blood flow patterns of the patent false lumen and ULP with the morphological changes of the chronic thoracic aortic dissection detected by contrast-enhanced CT or 3D MR angiography before or after this study. The interval between this study and the CT or 3D MR imaging studies reviewed ranged from 7 months to 3 years 6 months (mean, 1 year 8 months).

Results

Contrast-enhanced or non-contrast-enhanced 3D MR angiography and time-resolved 3D phase-contrast imaging were completed successfully in all 16 patients. Time-resolved 3D MR velocity mapping images were generated within 20 min from 3D phase-contrast imaging data using the GT Flow software.

Blood flow patterns of chronic thoracic aortic dissection in time-resolved 3D MR velocity mapping

Time-resolved 3D MR velocity mapping depicted blood flow in the false lumen in eight of the 16 patients with chronic thoracic aortic dissection. In three of the eight, contrast-enhanced 3D MR angiography confirmed the patency of the false lumen (Fig. 1). The time-resolved 3D velocity mapping displayed rapid flow (>60 cm/s at systole) at the entry and in the true lumen immediately distal to the entry (Figs. 1B, 2B) in all 8 patients. In six of the 8 patients with double-barrel dissection, slower helical flow (<25 cm/s at all cardiac phases) that was continuous with the jet flow at the entry collided with the outer wall of the patent false lumen, whereas the blood flow in the patent false lumen was not visualized entirely using time-resolved 3D velocity mapping (Fig. 1B). In the other 2 patients, who had undergone surgery, slower laminar flow (<25 cm/s at all cardiac phases) was visualized in the false lumen by time-resolved 3D MR velocity mapping (Fig. 3).

The time-resolved 3D velocity mapping did not show blood flow in the thrombosed false lumen and mural thrombus, both of which showed low signal intensity in 3D MR angiography with or without contrast enhancement (Fig. 2). In the 4 patients with ULP, two showed stagnant blood flow at the ULP, one with ULP larger than 10 mm in diameter showed slower helical flow, and one with a small ULP showed no blood flow.

Blood flow patterns and morphological changes in chronic thoracic aortic dissection (Table 2)

We used contrast-enhanced CT or 3D MR an-
MR Velocity Mapping of Aortic Dissection

Table 2. Comparison between blood flow patterns of the patent false lumen and ulcer-like projection (ULP) and their morphological changes

| Blood flow patterns                        | Enlarge | Stable |
|-------------------------------------------|---------|--------|
| Slower helical flow in the false lumen    | 3*      | 2**    |
| Slower laminar flow in the false lumen    | 0       | 2**    |
| Slower helical flow at the ULP             | 1       | 0      |
| Stagnant flow at the ULP                   | 0       | 2      |

* We included a patient with critically enlarged false lumen in the abdomen who underwent graft surgery. The slower helical flow was below 25 min/s at all cardiac phases and collided with the outer wall of the false lumen following rapid jet at the entry. ** These patients underwent surgery but had stable patent false lumen.

Discussion

This study demonstrated that time-resolved 3D MR velocity mapping visualized the presence or absence of blood flow in the false lumen of a chronic thoracic aortic dissection. This technique can compensate for the lack of flow information in non-contrast-enhanced 3D MR angiography. Time-resolved 3D MR velocity mapping showed blood flow patterns characteristic of the true and patent false lumens, entries, and ULPs in chronic thoracic aortic dissection. This preliminary investigation suggests a possible relationship between slower helical blood flow of the patent false lumen and ULP and disease progression in some patients, especially those who did not undergo surgery.

Time-resolved 3D MR velocity mapping demonstrated rapid blood flow at systole in the entry and in the true lumen immediately distal to the entry in all patients with patent false lumen. A narrow intimomedial tear and true lumen immediately distal to the entry may have contributed to the jet flow. In six of the eight patients with double-barrel dissection, slower helical flow that was continuous with the jet flow at the entry collided with the outer wall of the dilated false lumen. The wide variation of flow velocity and slower helical flow in the dilated lumen may be related to an increase in wall shear stress on the outer wall of the false lumen, which comprises fewer elastic fibers.2,19,21,22 In this study, 3 patients with enlarged patent false lumen in the thorax or abdomen showed this type of blood flow patterns, and one patient with a growing ULP had slower helical flow at the ULP. The false lumens with laminar flow or ULPs with stagnant flow did not enlarge in this study. These results suggest that pathologically helical blood flow, in addition to other risk factors, such as Stanford type, maximum diameter of the aorta, aging, hypertension, and atherosclerosis, may contribute to the deterioration of chronic thoracic aortic dissection.2,3,5,8,21 This study has also suggested that preemptive surgery might prevent disease progression even in cases of slower helical flow in the false lumen. Further studies with a larger patient population are needed to confirm these preliminary results.

The present 3D phase contrast MR imaging and velocity mapping techniques involved lengthy scan time and only incompletely visualized blood flow in the patent false lumen. Improved scan efficiency will require combining time-resolved 3D phase-contrast imaging with techniques that will expedite acquisition, including undersampling data acquisition and radial scan.23,24 Time-resolved 3D MR velocity mapping did not visualize the entire blood flow in the patent false lumen, possibly because of the sudden changes in flow velocity and retrograde or multidirectional blood flow in the dilated false lumen.25,26 Two-dimensional phase-contrast imaging detects an abnormal flow pattern in the false lumen at any slice level,25-27 but this technique cannot comprehensively visualize the 3D blood flow patterns. Extensive visualization of the blood flow in the false lumen requires more attention to the loca-
tions where “seeding particles” are placed. Development of sophisticated software feasible for multidirectional blood flow is also necessary to display flow patterns in the entire false lumen.

Our preliminary study had several limitations. We had a small sample size with various times to follow-up. Thus, we could not determine the effects of the blood flow patterns on their serial expansion in patients with chronic thoracic aortic dissection, although our preliminary investigation indicated some relation between disease progression and slower helical flow in the dilated false lumen and at the ULP. Neither did we compare time-resolved 3D MR velocity mapping and other imaging modalities, including Doppler ultrasonography, flow wire, and conventional angiography, to validate this quantitative result. However, because of the limited view of ultrasonography and flow wire and the invasiveness and contrast injection associated with conventional angiography, these methods are not used to investigate thoracic aortic dissection at chronic stage. Lastly, quantitative analysis of the blood flow patterns may be preferable to our visualization-based analysis, but this would require consensus standards.

In conclusion, time-resolved 3D MR velocity mapping generated from time-resolved 3D phase-contrast imaging visualized blood flow patterns characteristic of the true and false lumens, entries, and ULPs in chronic thoracic aortic dissection. In patients with disease progression, we observed slower helical flow that coincided with the outer wall of the patent false lumen and at the ULP.

References

1. DeSanctis RW, Doroghazi RM, Austen WG, Buckley MJ. Aortic dissection. New Engl J Med 1987; 317:1060–1067.
2. Onitsuka S, Akashi H, Tayama K, et al. Long-term outcome and prognostic predictors of medically treated acute type B aortic dissections. Ann Thorac Surg 2004; 78:1268–1273.
3. Sueyoshi E, Sakamoto I, Hayashi K, Yamaguchi T, Imada T. Growth rate of aortic diameter in patients with type B aortic dissection during the chronic phase. Circulation 2004; 110 (11 Suppl 1):II 256–261.
4. McMahon MA, Squirrell CA. Multidetector CT of aortic dissection: a pictorial review. Radiographics 2010; 30:445–460.
5. Blount KJ, Hagspiel KD. Aortic diameter, true lumen, and false lumen growth rates in chronic type B aortic dissection. AJR Am J Roentgenol 2009; 192:W222–W229.
6. Quint LE, Williams DM, Francis IR, et al. Ulcer-like lesions of the aorta: imaging features and natural history. Radiology 2001; 218:719–723.
7. Macura KJ, Corl FM, Fishman EK, Bluemke DA. Pathogenesis in acute aortic syndromes: aortic dissection, intramural hematoma, and penetrating atherosclerotic aortic ulcer. AJR Am J Roentgenol 2003; 181:309–316.
8. Lee YK, Seo JB, Jang YM. Acute and chronic complications of aortic intramural hematoma on follow-up computed tomography: incidence and predictor analysis. J Comput Assist Tomogr 2007; 31:435–440.
9. Liu Q, Lu JP, Wang F, Wang L, Tian JM. Three-dimensional contrast-enhanced MR angiography of aortic dissection: a pictorial essay. Radiographics 2007; 27:1311–1321.
10. Amano Y, Takahama K, Kumita S. Non-contrast-enhanced MR angiography of the thoracic aorta using cardiac and navigator-gated magnetization-prepared three-dimensional steady-state free precession. J Magn Reson Imaging 2008; 27:504–509.
11. François CJ, Tuite D, Deshpande V, Jerecic R, Weale P, Carr JC. Unenhanced MR angiography of the thoracic aorta: initial clinical evaluation. AJR Am J Roentgenol 2008; 190:902–906.
12. Miyazaki M, Sugiura S, Tateishi F, Wada H, Kassai Y, Abe H. Non-contrast-enhanced MR angiography using 3D ECG-synchronized half-Fourier fast spin echo. J Magn Reson Imaging 2000; 12:776–783.
13. Miyazaki M, Lee VS. Nonenhanced MR angiography. Radiology 2008; 248:20–43.
14. Pedrosa I, Morrin M, Oleaga L, Baptista J, Rofsky NM. Is true FISP imaging reliable in the evaluation of venous thrombosis? AJR Am J Roentgenol 2005; 185:1632–1640.
15. Buonocore MH. Visualizing blood flow patterns using streamlines, arrows, and particle paths. Magn Reson Med 1998; 40:210–226.
16. Markl M, Draney MT, Hope MD, et al. Time-resolved 3-dimensional velocity mapping in the thoracic aorta: visualization of 3-directional blood flow patterns in healthy volunteers and patients. J Comput Assist Tomogr 2004; 28:459–468.
17. Harloff A, Strecker C, Dudler P, et al. Retrograde embolism from the descending aorta visualization by multidirectional 3D velocity mapping in cryogenic stroke. Stroke 2009; 40:1505–1508.
18. Hope MD, Hope TA, Meadows AK, et al. Bicuspid aortic valve: four-dimensional MR evaluation of ascending aortic systolic flow patterns. Radiology 2010; 255:53–61.
19. Markl M, Arnold R, Hirtler D, et al. Three-dimensional flow characteristics in aortic coarctation and poststenotic dilatation. J Comput Assist Tomogr 2009; 33:776–778.
20. Spuentrup E, Stuber M, Botnar RM, Kissinger KV, Manning WJ. Real-time motion correction in
navigator-gated free-breathing double-oblique submillimeter 3D right coronary artery magnetic resonance angiography. Invest Radiol 2002; 37:632–636.

21. Williams DM, LePage MA, Lee DY. The dissected aorta. Part I. Early anatomic changes in an in vitro model. Radiology 1997; 203:23–31.

22. Cheng C, Tempel D, van Haperen R, et al. Atherosclerotic lesion size and vulnerability are determined by patterns of fluid shear stress. Circulation 2006; 113:2744–2753.

23. Gu T, Korosec FR, Block WF, et al. PC VIPR: a high-speed 3D phase-contrast method for flow quantification and high-resolution angiography. AJNR Am J Neuroradiol 2005; 26:743–749.

24. Baltes C, Kozerke S, Hansen MS, Pruessmann KP, Tsao J, Boesiger P. Accelerating cine phase-contrast flow measurements using k-t BLAST and k-t SENSE. Magn Reson Med 2005; 54:1430–1438.

25. Chang JM, Friese K, Caputo GR, Kondo C, Higgins CB. MR measurement of blood flow in the true and false channel in chronic aortic dissection. J Comput Assist Tomogr 1991; 15:418–423.

26. Strotzer M, Aebert H, Lenhart M, et al. Morphology and hemodynamics in dissection of the descending aorta. Assessment with MR imaging. Acta Radiol 2000; 41:594–600.

27. Silverman JM, Raissi S, Tyszka JM, Trento A, Herfkens RJ. Phase-contrast cine MR angiography detection of thoracic aortic dissection. Int J Card Imaging 2000; 16:461–470.