Magnetic Resonance Angiography of the Aorta

Yasuo Takehara, MD, DMSc,1 Shuhei Yamashita, MD, PhD,2 Harumi Sakahara, MD, PhD,2 Takayuki Masui, MD, PhD,3 and Haruo Isoda, MD, PhD4

Magnetic resonance angiography (MRA) is capable of imaging arteries in the half to whole body by a single acquisition without a nephrotoxic contrast medium, and acquired images can be reconstructed into a specific cross-sectional view in an arbitrary direction. MRA is applicable for vessels non-reachable by a catheter approach, and collateral vessels can be fully visualized. Since MRA is minimally-invasive with no exposure to ionized radiation, it can be repeatedly applied for follow-up. However, there are also disadvantages: the temporal and spatial resolutions are inferior to those of X-ray angiography, and, at present, it cannot be used as a guide for intervention. Moreover, gadolinium administrations may cause NSF in patients who have lost renal function, as a new risk. Accordingly, strict consideration is required for an indication of its application. Development of non-contrast MRA and evaluation of the wall itself may draw more attention in the future. Plaque imaging is being routinely performed nowadays, and the measurement of vascular wall shear stress, which has a close association with arteriosclerosis, may become possible by utilizing the time-resolved phase-contrast method capable of measuring the time-resolved velocity vectors of blood flow throughout the body. (*English Translation of J Jpn Coll Angiol, 2009, 49: 503-516.

Keywords: contrast-enhanced MRA, non-contrast MRA, flow analysis, atherosclerosis

Advantages of MR Angiography

The current modalities to evaluate aortic pathologies include digital subtraction angiography (X-ray DSA), X-ray CT, Doppler ultrasonography (US), and intravascular ultrasonography (IVUS). Of these, magnetic resonance angiography (MRA) is recommended for the following reasons:

1) MRA is a modality without nephrotoxicity

Generally, patients requiring imaging of the aorta have underlying diseases likely to lead to renal dysfunction, such as diabetes and arteriosclerosis, for which the risk of X-ray angiography using iodinated contrast media. X-ray contrast media employs iodinated contrast media, which have been reported to be one of the major factors of hospital-acquired renal insufficiency.1) Many patients indicated for lower limb X-ray angiography are complicated by diabetes and renal stenosis due to arteriosclerosis and have renal dysfunction, and the risk of iodinated contrast medium-induced renal failure is greater than that in patients with other diseases.

The nephrotoxicity of gadolinium contrast medium is very low,2 and moreover, non-contrast imaging may also be selected if necessary, although the image quality may not be satisfactory. MRA and US are the only imaging
methods applicable for vascular evaluation without a concern for renal function in patients at risk of a declining renal function. MRA is superior for maintaining the renal function among contrast imaging methods.

After the non-nephrotoxicity of gadolinium became widely known, X-ray DSA with the arterial administration of a large amount of gadolinium chelates had been attempted. It has been reported that intravenously administered gadolinium is mostly non-nephrotoxic, but, considering its high osmolality, it has been controversial whether it is completely non-nephrotoxic when intra-arterially administered.\(^3\)

Nephrogenic systemic fibrosis (NSF) is the additional concern when a large amount of contrast medium is administered for X-ray DSA or MRA, because a dose-dependent risk is known for NSF.\(^4\)

2) No requirement of catheter approach to the target artery

MRA is capable of imaging blood vessels in any region of the body even in patients with bilateral femoral arterial obstructions and bilateral brachial and axillary arterial obstructions for which the Seldinger’s technique is not applicable. Translumbar aortography with direct puncture of the abdominal aorta (Dos Santos method), which is very invasive and high-risk, was previously applied for patients with obstructions of the femoral, brachial, and axillary arteries in which the Seldinger technique was non-applicable.

3) Three-dimensional data collection by a single acquisition (possible to observe an arbitrary section)

Since MRA is capable of 3-dimensional display, observation from various directions is possible on single contrast medium injection. To acquire images in various directions on X-ray angiography, contrast medium has to be injected each time (imaging of each region is necessary when imaging with table-moving acquisition is not possible), which is unfavorable because it affects renal function but also leads to an extra cost.

4) Collateral vessels are not missed

Since contrast-enhanced MRA is performed through transvenous contrast administration, all collateral vessels and bypasses can be depicted (Fig. 1). In the catheter method, only downstream blood vessels from the injected site are imaged. For example, in patients with obstruction of the abdominal aorta through the common iliac artery, collateral vessels through the thoracic wall (internal mammary artery) and abdominal walls (inferior epigastric artery) are important, but individual imaging of all these vessels employing the catheter method requires approaches to many blood vessels, which is very complex and requires repeated catheter approaches, contrast medium administration, and exposure to ionized radiation.

5) Simple post-processing

In MRA, high-intensity regions are mostly limited to vascular lumens, which can be easily processed after acquisition. This is a marked advantage of image reconstruction compared to CT, which requires the removal of high density structures, such as bone and severe calcification of vascular walls.

---

Fig. 1 Three-dimensional contrast-enhanced MRA of a middle-aged woman with coarctation of the aorta. There is a short segment of stenosis at the proximal portion of the thoracic descending aorta (→) after it branches to the left subclavian artery. Note numerous collaterals that developed in the thoracic wall are well depicted in this contrast-enhanced MRA, which cannot be entirely delineated by a simple catheter technique.

MRA: magnetic resonance angiography
6) Appropriate for follow-up after interventional treatment

Generally, vascular imaging is repeated after treatment to evaluate and follow the effect of various interventions (surgical, radiological, and pharmacological interventions), but repeated angiography employing the invasive catheter method is unfavorable regarding the QOL of patients as well as medico-economic viewpoint. MRA should be employed for follow-up because of its applicability for outpatients, reasonable cost, and low risk.

DISADVANTAGES OF MRA

1) Poor spatial resolution

The spatial resolution of MRA is poor compared to other imaging methods, and subtle stenosis and irregularities of the walls may not be identified.

2) Walls cannot be visualized with routine MRA

Since MRA is a luminography, lumens are visualized, but walls are not. The addition of IVUS may be necessary to evaluate the vascular wall before intervention. The importance of imaging the wall in MR has been increasingly recognized, and plaque imaging has been attempted, but no general plaque evaluation method has been established yet. Recently, for the coronary artery, evaluation of not only narrowing of the vascular lumen but also atheroma of the wall has been attempted to identify whether atheroma is likely to rupture. Although it is less necessary for the aorta compared to that for the coronary artery, cerebral infarction caused by rupture of atheroma of the aortic arch has been reported. Therefore, it is useful to know the severity of aortic atheroma before stenting. In the current situation, at least axial T1-weighted images (fat suppression imaging is desirable) should be additionally acquired (before and after contrast imaging), and black blood technique or diffusion-weighted images should also be acquired, if possible.

3) The presence or absence of wall calcification cannot be identified

CT may be employed for diagnosing aortic dissection, where deviated calcified intima or media may be a clue to its diagnosis, but it is less likely that information on calcification is essential for enhanced MRI.

4) Evaluation of the stent-placed region is impossible

When a metal stent is placed, local signals of the stent-contacted arterial wall are lost. The patency of the stented region can be evaluated only by assessing the upstream or downstream regions of the stent and based on collateral vessel formation.

5) Contraindications of MR

There are contraindications characteristic to MR, such as placement of a cardiac pacemaker or other metal devices.

6) Direct transition to intervention from imaging is impossible

At present, MR guided stenting and balloon angioplasty remain at an animal experimental level.

7) Caution is necessary for applications in renal failure patients

There is a risk of nephrogenic systemic fibrosis (NSF) in contrast-enhanced MRA, although it is small. In Japan, the incidence of NSF is one in 100000 administration of gadolinium chelates, estimated from the consumption of gadolinium contrast media. Although single dose has routinely been used in many Japanese institutions, a double dose, triple dose or more contrast medium has been used mainly in Western countries for contrast enhanced MRA with gadolinium chelate, aiming at high-quality imaging with less artifacts. Whole body MRA has also become applied with improvement of the performance of MR devices. However, enhancement cannot be maintained in the lower limbs by a single dose as larger field of view was required, for which a large volume, such as 40–60 mL, of contrast medium was administered in some cases in Western countries. The problem of NSF occurred in the midst of this trend and held off administration of high-dose gadolinium.

Since chelated gadolinium preparation is mostly non-nephrotoxic as long as it is intravenously administered, chelated gadolinium contrast media should be prioritized over iodinated contrast media for patients with a predisposition to renal dysfunction. Inversely, for patients who have completely lost renal function, examination using an iodine contrast medium should be prioritized, rather than gadolinium.
The incidence of NSF may be very low as long as administration at the normal dose (0.1 mmol/kg) is complied with.\(^7\) The risk of NSF increases when eGFR is 30 mL/min/1.73 m\(^2\) or lower.

**MR Imager**

Since the static magnetic field strength is proportional to the expected signal-to-noise ratio (SNR), high-field devices are desirable for MRA. It has been reported that the SNR of MRA images acquired using a 3-Tesla device, which has recently been introduced, is more favorable than that acquired using a 1.5-Tesla device. Since shorter repetition (TR) and echo (TE) times are desirable, a high-performance gradient system is desirable. When TR is short, longitudinal magnetizations of the background tissue are not given time for relaxation. Thus, the background signal is almost 0, increasing vascular contrast, and a short TE reduces the phase disruption of blood flow in voxels of acquired images and retains blood flow intensity.

To improve SNR, it is desirable to combine surface coils possessing independent receivers. The first purpose of this is to improve SNR, but it is also useful to increase temporal resolution by combining parallel imaging and reduce SAR at 3 Tesla, mainly by reducing RF power. Some recent models of MR acquisition systems are equipped with surface coils covering a long range in the cephalocaudal direction, in which coil attachment and detachment are not necessary even when images are acquired while sliding the table. Installed coils are sequentially activated from the upper toward the lower region with table movement. Combining multichannel surface coils with the recent high-speed acquisition technique, parallel imaging (such as SENSE and SMASH), the acquisition time can be shortened, or favorable spatial resolution can be obtained even if the acquisition time is the same.

As the latest technique, a system to reduce signal interference through several transmitting and receiving coils using RF with different wavelengths (parallel transmission) has been published.

**Acquisition Technique**

MRA are roughly divided into 2 types: contrast and non-contrast MRA. Previous standards of non-contrast MRA included time-of-flight method and phase contrast method, however; investigations of the practical use of non-contrast methods has recently been making progress, such as a method utilizing cardiac phase shifts of systolic and diastolic phases and a method utilizing spin labeling. Previously, providing reliable and stable vascular visualization by employing contrast-enhanced MRA was the main trend, and various modifications have been made, but physicians came to hesitate to apply contrast-enhanced MRA to patients who had lost renal function after the problem of NSF emerged. In this context, non-contrast MRA has recently been attracting attention.

Since arterial diseases are systemic diseases, it is desirable to include all arteries in the body including the aorta in the field of view.

1) Contrast-enhanced MRA (field of view and temporal resolution)

a) **Table-moving MRA (also termed moving bed MRA, smart step MRA, or bolus chase MRA)**

In this procedure, contrast-enhanced MRA of a large field of view can be acquired on a single injection of contrast medium while shifting the field of view from the abdominal through the pelvic, femoral, and calf regions. Bolus injection of contrast medium is necessary for imaging the abdominal region. When the intra-arterial contrast medium concentration reaches a specific level after this injection, contrast medium is then additionally administered at a dose to maintain the intra-arterial concentration level for subsequent imaging of the lower limbs. Infusion can be set at a low rate of 0.5–1.0 mL/s. It is possible to acquire an arteriogram of almost the whole body by connecting images of several regions, but this method is basically capable of acquiring MRA of only a single time phase. Thus, the patency of visualized arteries can be confirmed with this method, but non-visualized arteries is not necessarily proved occluded. Information concerning the flow direction is also impossible for this single-phase imaging.

b) **Multiphase contrast MRA (repetitive acquisition of high-speed MRA in a specific region)**

To acquire favorable images of contrast-enhanced MRA, it is necessary to maintain the intra-arterial contrast medium concentration above a certain level at least during low-frequency data filling in the k-space. When the acquisition time of a single phase was long, such as 20–30 seconds, the method to identify the contrast medium arrival time to the artery was important, but, with the improvement of MR devices and speed-up of
acquisition, time-resolved-MRA, in which 3-dimensional
data collection is repeated and subtracted from those be-
fore contrast imaging, has become the main procedure,
and the optimum contrast timing is no longer missed.
Since temporal resolution is added to 3-dimensional
imaging in this method, it is also termed 4D MRA or 3D
MRDSA. For the pulse sequence, the sequence employed
for contrast-enhanced MRA of the aorta is normally used.
Field of view is shifted toward the caudal side after multi-
phase acquisition of the abdominal through pelvic region
employing subtraction, and contrast medium is separately
injected to visualize the lower limbs, the influence of the
firstly injected contrast medium can be mostly eliminated.
In multiphase contrast MRA, the optimum acquisition
timing in the time-course intra-arterial contrast medium
concentration is not missed, but a small matrix has to
be inevitably set to increase temporal resolution, which
may reduce spatial resolution due to trade-off. Attention
should be paid to this when evaluating subtle collateral
vessels and narrowed regions. This time-resolved method
added temporal resolution to MRA and enabled identifica-
tion of the blood flow direction, distinguishing true and
pseudolumens of arterial dissection, from which arteries
of organs branch, and the entry and re-entry positions and
their patency. This is important information for surgi-
cal procedures and stenting. Procedures for closing the
pseudolumen may not be applicable when a blood vessel
of a vital organ, such as the renal artery, branches from
a pseudolumen.

c) Contrast medium administration method

On contrast-enhanced MRA, higher contrast images
can be acquired as the dose of contrast medium increases,
if the cost or indications are not considered.8 In Western
countries, double-dose (0.2 mmol/kg) and triple-dose
(0.3 mmol/kg) are adopted in many cases. Our facility
performs multiphase imaging employing the 3D TRICKS
method using contrast medium at 0.1 mmol/kg when only
the lower limbs are imaged. When an extensive region
is included, such as the abdominal through the pelvic
region and lower limbs, gadolinium preparation is used
at 0.15–0.2 mmol/kg up to a maximum volume of 20 mL
in many cases. In the injection program employing the
smartstep or moving table method, 0.1 mmol/kg of contrast
medium is infused at 1 mL/s for the abdominal through
pelvic region, followed by infusion of the remaining
0.05–0.1 mmol/kg of contrast medium at 0.5 mL/s for the
lower limbs to maintain the intra-arterial concentration.
However, only a single time phase can be imaged using
this smartstep or moving table method. When multiphase
contrast MRA is applied in two regions: upper (pelvic-
feemoral region) and lower (femoral-calf region), bolus
injection of 0.075–0.1 mmol/kg of contrast medium at
1 mL/s is applied to each region, and multiple phases
are imaged.

The smartstep or moving table method is applied to
determine the timing,9 in which the contrast medium
concentration upstream of the target artery is detected,
and the MR device automatically starts the main scan
when the intensity level within the aorta exceeds a spe-
cific point. In the fluoro-trigger method, high-temporal
resolution prescan is repeated, the level in the target artery
is visually observed in the image, and the main scan is
started when an operator think the signal in the target
vessel exceeded aspecific level. This method adjusts the timing so that the main
scan starts at the measured time after contrast medium
administration. However, when temporal resolution is
high, the above methods are unnecessary because MRA
acquired at the optimum timing can be selected after
imaging several phases.

2) Non-contrast MRA

Even though the cost and safety are considered, it is
the best to visualize blood vessels without a contrast
medium if possible, but the problems are reliability and
stability. It is difficult to optimize many factors to achieve
favorable visualization, and in some cases, non-contrast
MRA has not been successful with several trials. As de-
scribed above, the visualization capability of non-contrast
time-of-flight MRA was insufficient in either 2D or 3D,
but with the ECG-gated 3D half-Fourier fast-spin-echo
method, visualization of the peripheral arteries has been
accomplished by subtracting the dephasing from the
rephasing image (by concomitantly using spoiler-pulse).
In addition, arterial spin labeling utilizing inversion
recovery pulse has been attempted with the use of bal-
anced FFE, another acquisition method for MRA due to
recent improvement of the gradient system performance.

Contrast-enhanced MRA is capable of selectively
visualizing arteries by combining bolus intravenous in-
jection of contrast medium to visualize early perfusion.
To apply non-contrast MRA to the trunk and extremi-
ties, selective visualization of arteries and veins should
be accomplished with a principle different from that of contrast-enhanced MRA. Selecting and combining several non-contrast MRA methods in consideration of the magnetic field homogeneity, vascular distribution, and blood flow velocity enable vascular imaging of the whole body without a contrast medium (Fig. 2). There are diverse non-contrast MRA methods. Of these, several general methods involving 1.5T MRI of GE Healthcare (GEHC) and its application software are introduced below:

**a) Flow preparation (flop prep) method**

Arteries and veins are separated based on differences in the blood flow velocity and direction. The maximum in-flow effect can be obtained by applying RF pulse at the time of the maximum arterial blood flow velocity, visualizing arterial blood with a high signal intensity. In contrast, venous blood with a slow flow velocity is excited to only a low level, resulting in a low signal intensity. Arteries and veins can be separated utilizing this difference in the signal intensity (Fig. 3). In clinical settings, firstly, the maximum flow velocity in the target blood vessel and the time required for reaching the maximum flow velocity after the R wave (delay time) are determined employing the phase contrast cine method (FAST card) (acquisition time: 15–20 seconds), followed by determining the optimum velocity encode (VENC). In the abdominal region, respiratory gating is also employed, and the acquisition time is about 2–4 minutes. This acquisition method is capable of vascular imaging over a broad range in a coronal section, and aneurysms, the abdominal aorta without dissection, and the common iliac, internal and external iliac, celiac, and renal arteries can be visualized (Fig. 4). When the blood flow is extremely slow in aortic aneurysm and dissection, and when different blood flow velocities exist at the same time, imaging employing the conventional flow prep method is difficult, and modified acquisition methods, such as addition and subtraction, are necessary to achieve a total view.

**b) In-flow inversion recovery (IFIR) method**

The name of this method was recently changed to the inherent enhancement inflow inversion recovery method (inhanse inflow IR). This method utilizes the in-flow effect of blood (Fig. 4). The Time-slip method is well known as a preceding technique utilizing the same principle. Inversion pulse is applied to a selective region including the target blood vessel to reduce the intensity of the background and non-imaged blood vessels. Selective imaging is possible by observing the in-flow effect of blood without inversion pulse in the target vessel. Devising setting of the inversion pulse in consideration of imaged vascular distribution, the blood flow velocity-independent selective imaging of arteries and veins is possible. However, the duration of an in-flow effect is limited. Imaging of a broad range is possible for blood vessels with a high flow velocity, but the range is narrowed when blood flow is slow because the distance reached per unit time is short. The distance reached by blood can be extended by setting a relatively long delay.
time after inversion pulse application, but the contrast to blood vessels is reduced due to trade-off because the background intensity recovery increases in a time-dependent manner. This method is applicable for both Fast Imaging Employing Steady-State Acquisition (FIESA) and FSE of the SSFP system (Fig. 5), and differentially employed depending on the magnetic field homogeneity and blood flow velocity.

c) Fresh blood imaging (FBI) method

This method utilizes differences in blood flow intensity between the systolic and diastolic phases. Only arteries are visualized by subtracting the systolic-phase venous image from the diastolic-phase arteriovenous image. This
is relatively common as a non-contrast MRA method.\textsuperscript{15} When the blood flow velocity shows downstream of the stenosis region, blood vessels may not be accurately imaged. The absence of a need to be concerned with the adverse effects of contrast medium is an advantage of non-contrast MRA, as described above. In contrast-enhanced dynamic MRA, images can be acquired only at a single timing per test, and when the timing is missed, imaging fails and reading and diagnosing may be difficult. In contrast, in non-contrast MRA, acquisition can be repeated while changing the optimum condition during a single test, resulting in reducing non-assessable cases. It has also been reported that the separation of arteries and veins and background inhibition independent from the timing of contrast medium circulation achieved favorable imaging of the renal artery compared to contrast-enhanced MRA.\textsuperscript{11, 13} Furthermore, the acquisition methods of non-contrast MRA realize the visualization of flow, which may image not only blood vessels but also flowing fluids. The proposition of the development of non-contrast MRA in the future is shortening of the acquisition time while imaging blood vessels in a broad range, for which the development and devising of acquisition methods and operation are expected.

**Reconstruction**

Generally, acquired images of contrast-enhanced MRA are reconstructed after subtracting the mask images (original images before enhancement) from the enhanced images. The images after subtraction are reconstructed employing the maximum intensity projection (MIP) or sliding MIP (multiplanar volume reconstruction (MPVR)) methods. Separately, it is necessary to observe the original images before and after enhancement and specific serial cross-sections employing multi planar reformat (MPR).

**Renal Dysfunction and Indications of Contrast-Enhanced and Non-Contrast MRA**

When an arterial or venous disease is suspected but physicians hesitate to use iodinated contrast media because of allergy, or when the Seldinger technique of the catheter approach is not applicable, these cases are appropriate indications of MRA. Indicated diseases include almost all diseases accompanied by vascular lesions, such as arteriosclerosis obliterans (ASO), Buerger disease (thromboangiitis), aneurysm (true and false), arteriovenous fistula, arterial dissection, for which the usefulness of contrast-enhanced MRA and favorable outcomes have been reported by many researchers.\textsuperscript{16–22} When renal function is lost, contrast-enhanced imaging using an iodinated contrast medium or non-contrast MRA should be selected on the condition of dialysis, but when renal dysfunction is moderate or milder, for the remaining renal function to be conserved; contrast-enhanced MRA should be selected. When aortitis or inflammatory aneurysm is suspected, contrast enhancement is obviously essential.

**Vascular Wall Imaging**

The techniques discussed above are luminographic techniques, regardless of contrast-enhanced or non-contrast MRA. Studies on responsible arteries for myocardial and cerebral infarctions have clarified that there are stenoses with favorable and poor prognoses (stable and unstable plaques, respectively) in arteriosclerotic stenosis, and differentiation of the plaque type in the vascular wall is necessary to differentiate these. The vascular wall cannot be observed employing luminography, and the black-blood method is basically used for this evaluation. For vascular wall imaging, the method in which data collection is started from the null-point of blood employing the non-selective IR preparation pulse is widely employed.\textsuperscript{23} USPIO accumulated by macrophages and other tissue-specific contrast media are also utilized in laboratory experiments.

**Relationship between Blood Flow and The Vascular Wall (Importance of Flow Analysis)**

As a characteristic of MRI, the flow velocity can be quantitatively evaluated, in which the magnetic field gradient is spatially loaded, and flow-induced phase shifts of spin are measured as changes in signal intensity. Data were previously collected only in the 2-dimensional cross-sections, but, employing 3-dimensional data collection and ECG gating for all phases of the cardiac cycle, the flow velocity can be measured in all phases in all intravascular regions within the region of interest in-vivo by collecting data in all phases. Time-resolved 3-dimensional phase-contrast MRI (4D Flow) capable of collecting blood flow data in 3-dimensional space and time, 4 dimensions in total, has been developed and facilitated the application of blood flow analysis in various blood vessels.\textsuperscript{24, 25} By analyzing data of 4D Flow using flow analysis software, flow visualization and analysis (Flova), for example, blood flow measurement in vital
The presence of flow velocity data in time and space indicates that endothelial shear stress can be measured in the vascular wall. Various factors are related to the development and progression of vascular lesions. In addition to vascular wall vulnerability associated with hyperlipidemia, diabetes, cigarette smoking, and Marfan syndrome, hemodynamic factors are also present. On the other hand, there are regions likely to develop vascular lesions. Arteriosclerotic changes frequently occur in the coronary artery, bifurcations of the carotid artery and abdominal aorta at peripheral sides from the renal arteries. Cerebral aneurysms also have predilection sites. These facts suggest the importance of hemodynamic factors. Of hemodynamic factors, the association between vascular wall shear stress and vascular lesions has been widely studied. In the velocity distribution of intravascular blood flow, the speed is high in the central region, but slow near the vascular wall, forming a velocity gradient (shear rate). The friction force that the vascular wall receives from blood is called shear stress, presented with the following equation:

\[ \tau = \mu \left( \frac{dv}{dx} \right) \]

\( \tau \): Shear stress, \( \mu \): viscosity (about \( 3.9 \times 10^{-3} \) Pa·sec in human blood), \( dv/dx \): shear rate

Vascular endothelium reacts with the vascular wall shear stress in various ways. Morphologically, loading an about 1.5-Pa shear stress on the vascular epithelium increases NO in the vessel wall and, thereby, dilates vessels and, at the same time, increases PGI2, which inhibits platelet coagulation, and decreases VCAM-1, which inhibits monocyte adhesion. These are anti-arteriosclerosis factors. For the integrity of the vessel wall, wall shear stress should be maintained at an appropriate level of not less than 1.5 Pa. A low shear stress below 0.4 Pa promotes atherosclerosis and the apoptosis of smooth muscle in the vessel wall.
induced by low vascular wall shear stress with aneurysm rupture is also discussed. For long-term prospects, the investigation of arterial wall health by analyzing shear stress and prediction of the long-term progression of arterial lesions are considered (Figs. 6 and 7).

If hemodynamic analysis can be applied to predict sites at which arteriosclerosis occurs in the future, it is possible to predict vascular lesions beforehand. The previous paradigm was the discovery and removal of already formed vascular lesions and its follow-up, but if the association between the shear stress and development of vascular lesions can be sufficiently elucidated in vivo, the prediction and prevention of arterial lesions may become the future trend.

**Reading and Interpretation of MRA**

Firstly, images reconstructed employing MIP are observed in many directions to outline blood vessels. Dilated and narrowed segments are then evaluated in detail employing MPR and MPVR to confirm the presence or absence of collateral blood vessels, which may facilitate the accurate evaluation of collateral blood vessels and narrowed regions undetectable by employing MIP alone.

For bypass surgery, PTA, and stenting, confirmation of the presence or absence of run-off is necessary (Figs. 8 and 9). Multiphase MRA is acquired in as many phases as possible to avoid overlooking findings. It is also necessary to observe the upstream aorta. The original
Magnetic Resonance Angiography of the Aorta

When an aneurysm is present, mural thrombus is investigated, and the stent position is confirmed based on the presence of metal artifacts. It is needless to say that reviewing CT and surgical records is also necessary.

Furthermore, inflammatory aneurysm (Fig. 10), aortitis (Fig. 11), and Bechet’s disease, IgG 4-related diseases, and wall inflammation can be detected as enhancement by contrast medium by adding fat-suppressed T1-weighted cross-sectional imaging subsequently to contrast-enhanced MRA.

MRA displays its power in postoperative follow-up, such as tracing the presence, enlargement, and shrinkage of ULP (Fig. 12) and PAU (Fig. 13).

For aortic dissection, true and pseudolumens and the blood flow condition of the branching arteries can be investigated by high-temporal resolution imaging (Figs. 14 and 15).
**Fig. 11** Middle aged female patient with aortitis syndrome (3D MIP projection image using contrast-enhanced MRA). There is a short segment of stenosis at the infrarenal segment of the abdominal aorta (→) followed by distal post-stenotic dilatation.

MIP: maximum intensity projection;
MRA: magnetic resonance angiography

**Fig. 12** Contrast-enhanced MRA (left anterior oblique view; 3D MIP projection) of a patient with thrombosed-type Stanford B aortic dissection. There are several ULP at the distal portion of the aortic arch (→).

MIP: maximum intensity projection;
MRA: magnetic resonance angiography;
ULP: ulcer-like projections

**Fig. 13**

a: Growing PAU (→) seen in the thoracic aorta of an elderly male patient (left anterior oblique view; 3D MIP projection) Contrast-enhanced MRA. Risk of rupture increased in this case.

b: Coronal source image shows a huge ulcer created due to atherosclerosis in the thoracic descending aorta.

PAU: penetrating atherosclerotic ulcer;
MIP: maximum intensity projection;
MRA: magnetic resonance angiography
Magnetic Resonance Angiography of the Aorta

Fig. 14
a: Enhanced MRA showing dissection in the thoraco-abdominal aorta (3D MIP projection). Three main visceral arteries (→) (the celiac axis, superior mesenteric artery, and left renal artery) stem from the true lumen. Right renal artery branches from the pseudolumen (*) remain unoccluded.
b: Precontrast fat-saturated coronal T1-weighted image. Dissected pseudolumen in the thoracic aorta almost occluded with thrombosis.
MIP: maximum intensity projection; MRA: magnetic resonance angiography.

Fig. 15
a: Pseudoaneurysm (contrast leakage into the pseudolumen) seen in the elderly male patient, which was created at the orifice of the celiac axis after graft replacement (left anterior oblique MIP projection of the contrast-enhanced MRA).
b: Oblique coronal reconstruction of the source image shows the pseudoaneurysm outpouching from the celiac axis.
MIP: maximum intensity projection; MRA: magnetic resonance angiography.
Dissemination of dissection to branching arteries and multiple aneurysm development with aortic lesions have recently been frequently encountered. MRA also plays an important role in planning interventions for these lesions and later evaluation.

**PITFALL IN OBSERVATION OF MRA**

When a metal stent is placed in a blood vessel, signals in the stented region are lost and may be perceived as a pseudostenosis. Moreover, MRA normally visualizes only lumens because of subtraction. A mural thrombus may be overlooked when only MRA following MIP reconstruction is observed. Observation of multiple cross-sections of the original images before subtraction should be routinely performed. It is also necessary to confirm the procedure applied before MRA in patients after bypass surgery, otherwise bypass graft near the body surface may be excluded from the field of view. Furthermore, as described above, when the optimum acquisition timing is missed, non-visualized blood vessels may be misidentified as obstruction. This can be avoided by multiphase acquisition.

There are reasons why noninvasiveness is desirable for the imaging of vascular lesions. Firstly, repeated examination is necessary for patients with vascular lesions. Arterial lesions are exposed to blood flow stress daily and go through dynamic morphological changes. When a vascular lesion is already present, it is necessary to not only pay attention to its progression, but also follow the course after surgical treatment by imaging because such changes progress, for which invasiveness and the nephrotoxicity of contrast medium are not desirable. For example, when an arterial lesion is surgically repaired, reportedly, an aneurysm is formed at a site distant from the surgically repaired site within 18–24 months in 17%–25% of cases. It has also been pointed out that an ulcer-like projection may cause recurrence of dissection and aneurysm formation, and become a starting point of rupture. It is also known that the enlargement of an abdominal aortic aneurysm is accelerated when the diameter exceeds a certain size (0.6 cm or greater enlargement after the diameter exceeds 6 cm).^{29}

**CONCLUSION**

Contrast-enhanced MRA has been refined with the advancement in MR technology, and images with high temporal as well as spatial resolutions have been acquired. Cases in which X-ray angiography is non-applicable, high-risk cases, and cases requiring frequent follow-ups are appropriate indications of MRA. Non-contrast MRA techniques have also recently advanced, for which safe MRA for patients with renal failure can be expected. Development of the 3D cine PC method facilitated application of hemorheological analysis for the evaluation of shear stress of the wall. The prediction and prevention of arteriosclerotic lesions as vascular wall lesions may become possible in the future.

**ACKNOWLEDGMENT**

We are grateful to collaborators at the First and Second Departments of Surgery, Hamamatsu University School of Medicine and Department of Radiology and Surgery, Iwata City Hospital for their cooperation in treatment and research of vascular diseases.

**REFERENCES**

1) Nash K, Hafeez A, Hou S. Hospital-acquired renal insufficiency. Am J Kidney Dis 2002; 39: 930-6. [Medline] [CrossRef]
2) Prince MR, Arnoldus C, Frisoli JK. Nephrotoxicity of high-dose gadolinium compared with iodinated contrast. J Magn Reson Imaging 1996; 6: 162-6. [Medline] [CrossRef]
3) Nyman U, Elmstahl B, Leander P, et al. Are gadolinium-based contrast media really safer than iodinated media for digital subtraction angiography in patients with azotemia? Radiology 2002; 223: 311-8, discussion 328-9. [Medline] [CrossRef]
4) Bridges MD, St Amant BS, McNeil RB, et al. High-dose gadodiamide for catheter angiography and CT in patients with varying degrees of renal insufficiency: Prevalence of subsequent nephrogenic systemic fibrosis and decline in renal function. AJR Am J Roentgenol 2009; 192: 1538-43. [Medline] [CrossRef]
5) Fayad ZA, Fuster V. Clinical imaging of the high-risk or vulnerable atherosclerotic plaque. Circ Res 2001; 89: 305-16. [Medline] [CrossRef]
6) Maki JH, Wilson GJ, Eubank WB, et al. Utilizing SENSE to achieve lower station sub-millimeter isotropic resolution and minimal venous enhancement in peripheral MR angiography. J Magn Reson Imaging 2002; 15: 484-91. [Medline] [CrossRef]
7) Prince MR, Zhang H, Morris M, et al. Incidence of nephrogenic systemic fibrosis at two large medical centers. Radiology 2008; 248: 807-16. [Medline] [CrossRef]
8) Mitsuzaki K, Yamashita Y, Ogata I, et al. Optimal protocol for injection of contrast material at MR angiography: study of healthy volunteers. Radiology 1999; 213: 913-8. [Medline]
9) Foo TK, Saranathan M, Prince MR, et al. Automated detection of bolus arrival and initiation of data acquisition in fast, three-dimensional, gadolinium-enhanced MR angiography. Radiology 1997; 203: 275-80. [Medline]

10) Miyoshi M, Tsukamoto T. Flow preparation pulse for abdominal non-contrast-enhanced MR angiography, 2006 ISMRM.

11) Masui T, Katayama M, Sato K, et al. Non Contrast MRA of renal artery using Flow-prep FIESTA for evaluation of patients with suspected renal tumor: Comparison of Dynamic contrast MRA, 2008 ISMRM.

12) Masui KM. Miyoshi M, et al. Evaluation of the femoral arteries; before and after tumor treatments using non-contrast MRA using subtraction method based on velocity encoding Technique. 2009 ISMRM.

13) Masui T, Katayama M, Sato K, et al. Evaluation of the renal arteries: comparison of two types of Non-contrast MRA and Dynamic contrast MRA, 2009 ISMRM.

14) Sato K, Masui T, Katayama M, et al. Non-contrast-enhanced MR angiography of the carotid arteries and aortic arch using Inherent Enhancement (Inhance) Inflow IR, adopting peripheral-gated partial-Fourier fast spin echo (FSE) or steady-state Free Precession (FIESTA): A comparison with contrast MRA, 2009 ISMRM15.

15) Miyazaki M, Sugiura S, Tateishi F, et al. Non-contrast-enhanced MR angiography using 3D ECG-synchronized half-Fourier fast spin echo. J Magn Reson Imaging 2000; 12: 776-83. [Medline] [CrossRef]

16) Yucel EK, Kaufman JA, Geller SC, et al. Atherosclerotic occlusive disease of the lower extremity: prospective evaluation with two-dimensional time-of-flight MR angiography. Radiology 1993; 187: 637-41. [Medline]

17) Ralston MD, Dykes TA, Applebaum BI. Verification of lumbar vertebral bodies. Radiology 1992; 185: 615-6. [Medline]

18) Kim D, Edelman RR, Kent KC, et al. Abdominal aorta and renal artery stenosis: evaluation with MR angiography. Radiology 1990; 174(3 Pt 1): 727-31. [Medline]

19) Bland PH, DiPietro MA, Chenevert TL, et al. Tissue characterization of the testes using ultrasonic CT. Work in progress. Radiology 1986; 159: 101-5. [Medline]

20) Glazer HS, Lee JK, Levitt RG, et al. Radiation fibrosis: differentiation from recurrent tumor by MR imaging. Radiology 1985; 156: 721-6. [Medline]

21) Johnson DW, Voorhees RL, Lufkin RB, et al. Cholesteatomas of the temporal bone: role of computed tomography. Radiology 1983; 148: 733-7. [Medline]

22) Herrkens RJ, Higgens CB, Hricak H, et al. Nuclear magnetic resonance imaging of atherosclerotic disease. Radiology 1983; 148: 161-6. [Medline]

23) Song HK, Wright AC, Wolf RL, et al. Multislice double inversion pulse sequence for efficient black-blood MRI. Magn Reson Med 2002; 47: 616-20. [Medline] [CrossRef]

24) Yamashita S, Isoda H, Hirano M, et al. Visualization of hemodynamics in intracranial arteries using time-resolved three-dimensional phase-contrast MRI. J Magn Reson Imaging 2007; 25: 473-8. [Medline] [CrossRef]

25) Markl M, Chan FP, Alley MT, et al. Time-resolved three-dimensional phase-contrast MRI. J Magn Reson Imaging 2003; 17: 499-506. [Medline] [CrossRef]

26) Malek AM, Alper SL, Izumo S. Hemodynamic shear stress and its role in atherosclerosis. JAMA 1999; 282: 2035-42. [Medline] [CrossRef]

27) Ando J, Yamamoto K. Vascular mechanobiology: endothelial cell responses to fluid shear stress. Circ J 2009; 73: 1983-92 Epub 2009 Oct 5. [Medline] [CrossRef]

28) Dyste GN, Beck DW. De novo aneurysm formation following carotid ligation: case report and review of the literature. Neurosurgery 1989; 24: 88-92. [Medline] [CrossRef]

29) Brewster DC, Cronenwett JL, Hallett JW Jr, et al. Guidelines for the treatment of abdominal aortic aneurysms. Report of a subcommittee of the Joint Council of the American Association for Vascular Surgery and Society for Vascular Surgery. J Vasc Surg 2003; 37: 1106-17. [Medline] [CrossRef]