Introduction

In conventional x-ray digital subtraction angiography (DSA), administration of contrast agent is necessary in order to depict blood vessels. After arterial catheterization and injection of an iodinated contrast agent, two-dimensional projection images of the lumen of the vessel are acquired from chosen angles. For every new projection this procedure has to be repeated. The availability of 3D rotational angiography and CT angiography may help to overcome this problem but at the expense of high radiation doses.

Unenhanced MR angiography (MRA) differs from DSA and other angiographic techniques in that blood vessels are depicted non-invasively in the absence of contrast agent injection. Unenhanced MR techniques allow the acquisition of 3D datasets or stacks of 2D images that contain all vessels in the volume of interest. The acquired images included in the 3D data set are called “source images”. Projectional angiographic displays of the vessel are subsequently reconstructed from the data using the maximum intensity projection (MIP) postprocessing algorithm, which generates angiogram-like images from the entire dataset or a subset from any desired viewing angle without the need for further measurement. Another advantage of MRA versus x-ray angiography derives from the fact that extravascular tissue is depicted together with the vessels, thereby permitting the correlation of blood flow abnormalities with associated soft tissue pathologies (Table 1).

Contrast in MR images depends principally on static tissue parameters: longitudinal relaxation time T1, transverse relaxation time T2, and proton density. In addition, the MR signal is sensitive to flow and movement which frequently leads to artifacts in MR imaging. MR angiographic sequences, however, use flow-induced signal variations to depict blood vessels or even to obtain quantitative information about blood flow in terms of velocity and direction.

Unenhanced MRA comprises those MR techniques that rely solely on flow effects. Unlike contrast-enhanced MRA (CE MRA) and x-ray angiography, which depict the vessel lumen filled with contrast agent, it is just the movement of blood that is seen in the unenhanced MR-angiogram. Flow effects can be grouped into two fundamentally different categories:

- **Amplitude effects (time-of-flight)** Blood flowing into or out of a chosen slice has a different longitudinal magnetization compared to stationary spins, depending on the duration of stay (time-of-flight) in the slice.
- **Phase effects** Blood flowing along the direction of a magnetic field gradient is subject to changes of its transverse magnetization compared to stationary spins.

In principle, both flow phenomena are effective simultaneously leading either to a decrease or an increase of the MR signal depending on the type of sequence used. Appropriate sequence techniques have been developed which emphasize one of the flow effects and suppress the other. Typically, MR angiography techniques are designed in such a way that flowing blood produces hyperintense signal while the background signal from stationary tissue remains largely suppressed (“bright-blood” angiography). Alternatively, flowing spins can be

| Advantages of MR angiography | Unenhanced MR Angiography
|-------------------------------|------------------
| No ionizing radiation         |                  |
| Non-invasive                  |                  |
| Any projection can be reconstructed from 3D datasets |                  |
| Depiction of extravascular tissue |                  |
| Flow quantification in terms of velocity and direction |                  |
made to appear hypointense compared to the stationary background (“black-blood” angiography). In the clinical setting “bright-blood” MRA is the more widely accepted of the two techniques. There are two approaches to performing “bright-blood” MRA: time-of-flight (TOF) and phase-contrast (PC) angiography (Table 2).

Although intravenous contrast administration is not required in TOF and PC MRA, it can be applied in certain situations to improve vessel contrast.

Since unenhanced MRA is based on complex flow phenomena, physiological conditions of flow in the vascular territory of interest are of major importance for the applicability of the method. Advantageous conditions are found especially in the vessels of the brain because of the nearly laminar flow in this territory. Moreover, flow is largely constant during the heart cycle (Fig. 1), making ECG triggering unnecessary for imaging of brain vessels. The high velocity of arterial flow (50–100 cm/sec) provides good vessel-background contrast and moderate acquisition times. In clinical routine, unenhanced MRA has proven to be a robust and versatile method for non-invasively imaging of brain vessels (circle of willis, sagittal sinus). In addition, this technique is also suitable for depicting extracranial carotid arteries and short segments of peripheral vessels (e.g. lower leg).

A major limitation of unenhanced MRA, however, is a susceptibility to signal loss in areas of turbulent or very slow flow. In severe cases, this may lead to a misdiagnosis of the pathologic condition (stenosis, aneurysm). Additionally, TOF and PC angiography are highly sensitive to motion artifacts. Although motion artifacts often arise due to patient movement because of the need for relatively long acquisition times, they may also occur in areas of very pulsatile flow such as that occurring in the carotids, aorta, and especially, in the peripheral arteries, and in the thoracic and abdominal regions due to breathing and heart actions. Whereas ECG triggering may reduce or eliminate those artifacts associated with pulsatile flow, the availability of contrast-enhanced MR angiography (CE MRA) has largely made unenhanced MRA redundant for most vascular territories outside of the brain. However if unenhanced MRA techniques are performed, a thorough understanding of the underlying physical and technical mechanisms is prerequisite to performing imaging and to correctly interpreting the acquired angiograms.

### Understanding Flow Effects

#### Outflow-related Signal Loss

(washout effect, T2 flow void)

When images are obtained with a spin-echo (SE) pulse sequence, blood flowing at a high velocity perpendicular to the imaging plane produces a weaker signal than the surrounding stationary tissue. This phenomenon is caused by the washout of flowing spins from the slice during the imaging process.

Spin-echo techniques are characterized by a sequence of slice-selective 90° and 180° radio frequency (RF) pulses. Only those tissue components that are affected by both pulses can provide an MR signal. Moving material, such as blood in the vessels, flowing through the excited slice at a suffi-

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**Table 2. Techniques of unenhanced MR angiography**

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Time-of-Flight (TOF)</strong></td>
<td>Flow changes longitudinal magnetization</td>
</tr>
<tr>
<td><strong>Phase-contrast (PC)</strong></td>
<td>Flow changes transverse magnetization</td>
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**Fig. 1.** Comparison of flow profiles in the external carotid artery (ECA), the internal carotid artery (ICA) and the middle cerebral artery (MCA). There is very pulsatile flow in the ECA. However, in the intracranial vessels, the variation of flow during heart cycle is much less pronounced [Courtesy of Steffi Behnke, MD, Dept. of Neurology, Saarland University Hospitals]