Peripheral MR Angiography

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30.1 Introduction

Dynamic three-dimensional (3D) contrast-enhanced magnetic resonance angiography (CE-MRA) has evolved over the past decade from an experimental imaging modality to a highly accurate technique that is now routinely used in clinical practice. CE-MRA is the current standard-of-reference MRA technique for non-invasive evaluation of the upper and lower extremity vasculature (Yucel et al. 1999; Ho et al. 1999, 1999). The recent clinical introduction of parallel imaging has significantly advanced the field of peripheral CE-MRA because it can be used in concert with and amplifies other recent improvements such as centric k-space encoding and view-sharing techniques (Pruessmann et al. 1999; Sodickson et al. 1997; Weiger et al. 2000). The high signal-to-noise ratio available in CE-MRA techniques can be used to increase scan efficiency through parallel imaging by acquisition of higher-resolution volumetric datasets free from disturbing venous overlay in shorter imaging times. This chapter provides considerations on how parallel imaging can be applied to optimize image quality of upper and lower extremity 3D CE-MRA.

30.2 Theoretical Background

30.2.1 General MR Angiographic and Physiological Considerations

In general, the choice of imaging parameters for 3D CE-MRA acquisitions is governed by the following antithetical constraints: (1) the desire for high vessel-to-background contrast, (2) the desire for time-resolved imaging, and (3) the desire for high reso-
olution images in three dimensions. In conventional X-ray angiography, the first two of these constraints are easily reconciled because of the very high spatial and temporal resolution of the technique. The typical acquisition duration for an image with a 1,024×1,024 matrix is about 50 ms. Although high vessel-to-background contrast is easily achieved by injecting MR contrast media, the MR imaging process is, however, inherently slow. This is in contrast to X-ray angiography where image acquisition is virtually instantaneous. In MR imaging, acquisition duration is directly proportional to the desired spatial resolution, volumetric coverage and hardware performance. This is the result of the fact that MR data acquisition occurs in a sequential order, i.e., point by point or line by line. For example, acquisition of a single image using a Cartesian readout with 256×256 matrix and TR of 5 ms takes 1.28 s. A volumetric acquisition covering 20 slices would take over 25 s when using the same imaging parameters. Consequently, MR imaging acquisition speed is fundamentally limited by the maximum switching rates of gradients and pulses, and in the current era of ultra-fast hardware, physiological constraints resulting from the need to avoid neuromuscular stimulation and excessive deposition of RF power in biological tissues.

Since the maximum field of view (FOV) of commercially available MR imagers is typically around 40-45 cm, an additional constraint is the fact that two or three consecutive acquisitions are needed to image the entire upper or lower extremity peripheral vascular tree. Because of the inherently slow MR imaging process, one of the major limitations of 3D CE-MRA is simultaneous depiction of arteries and veins, which often hampers image interpretation, especially of small distal arteries.

Another limitation of conventional CE-MRA is the limited spatial resolution. In order to accurately describe degree and length of arterial stenoses it is paramount that the resolution of the 3D CE-MRA dataset needs to meet minimal standards. It is known from the work by Hoogeveen et al. (1998) and Westenberg et al. (2000) that at least three pixels are needed across the lumen of an artery to quantify the degree of stenosis with an error of less than 10%. When this constraint is kept in mind, it is obvious that higher resolution is needed to accurately characterize stenoses in small forearm or lower-leg arteries as opposed to the subclavian or iliac arteries. In general, voxel dimensions should be kept as close to isotropic (equal length in all dimensions) as possible to avoid blurring when viewing vessels in projections with lower spatial resolution. In addition, non-isotropic voxels are suboptimal for the detection and characterization of eccentric stenoses.

Given the considerations above, it is clear that the attractiveness of parallel imaging lies in the fact that it is a versatile tool that can be applied not only to reduce scan time, but also to increase acquired spatial resolution within the conventional scan duration, or to increase volume coverage per unit time.

### 30.2.2 Parallel Imaging in CE-MRA

Parallel imaging uses the spatial variation in coil sensitivities of multi-element phased-array surface coils to increase phase-encoding step size and consequently the number of phase encodings required to reconstruct a set of images. In conventional Cartesian Fourier encoding, reducing the density of phase-encoding steps decreases the reconstructed FOV. If the imaged object is larger than the reconstructed FOV, aliasing results. However, parallel imaging removes the potential aliasing and reconstructs the full FOV, thus delivering full-FOV images with fewer phase encodings in a shorter scan time (Wilson et al. 2004). The reconstruction process required to make up for k-space undersampling can either occur in k-space (Sodickson et al. 1997; Jakob et al. 1998; Kyriakos et al. 2000; Heidemann et al. 2001; Griswold et al. 2002), or in image space (Pruessmann et al. 1999), cf. Chap. 2. All major MR hardware manufacturers currently market coils capable of parallel imaging for neurovascular, thoracic, abdominal and upper and lower extremity applications, cf. Chap. 14. For further details and in-depth discussion of the physical and mathematical principles of parallel imaging, the reader is referred to the first three chapters of this volume.

In clinical practice parallel imaging is a versatile tool that can be used to amplify other strategies aimed at decreasing disturbing venous enhancement and increasing spatial and temporal resolution. The most important of these tools are centric k-space encoding and partial k-space updating strategies, cf. Chaps. 7 and 11. A basic understanding of these techniques is needed to understand how parallel imaging can be used to improve image quality.

Centric k-space encoding is based on the principle of acquiring views close to the origin of the $k_x$-$k_y$ plane first. In other words, contrast-determining central k-space views are acquired first, followed by...