CONTRAST-ENHANCED MR ANGIOGRAPHY : PRINCIPLES, IMPLEMENTATION, AND APPLICATIONS

Stephen J. Riederer, Ph.D.

Magnetic Resonance Laboratory; Department of Radiology; Mayo Clinic
200 First Street SW; Rochester MN 55905 USA
Phone: 507-284-6209; Fax: 507-284-9778; email: riederer@mayo.edu

Introduction

Within the last decade the technique of contrast-enhanced MR angiography (CE MRA) has grown in importance so that today it is now used routinely worldwide for clinical applications. This rapid growth reflects the identification of the technique's promise in the initial feasibility studies, the addressing of various technical issues by numerous investigators, and the successful performance of CE MRA in comparison to various standards, as done by numerous clinical investigators. In spite of this wide degree of clinical acceptance, there are still numerous areas for further technical development and optimization. The purpose of this work is to attempt to briefly review the basic principles and technical issues of CE MRA, identify what means have been developed to address a number of these issues, describe current clinical applications, and present areas for future development.

Basic Principles

There are a number of review articles and monographs available which provide a comprehensive description of the basic principles and applications of MRA (1,2). The reader is referred to these to get more detailed background information than is provided here.

The basic idea of contrast-enhanced MR angiography is to intravenously administer an MRI contrast agent which significantly alters either the T1 or T2 relaxation time. For CE MRA these are generally gadolinium based, paramagnetic agents used in a way to provide shortening of T1. The contrast-enhanced blood then passes through the cardiovascular system. Depending upon the agent, it may stay in the intravascular but extracellular space, pass into the extravascular space, or attach to specific molecules. This work is confined to the use of Gd-DTPA, an agent in the first of these categories which is excreted by the kidneys. The concept of CE MRA is generally to image the first pass of contrast agent through the vascular region of interest. So-called "intravascular" agents have also been developed which attach to the albumen and are retained in the blood stream for extended periods. However, their routine use is limited.

Technical Issues and Implementation

The various technical issues of CE MRA are summarized in Table 1. A number of these were identified very early in the development of the technique, and various means have been identified to address them. For example, when it appeared clear in the mid-1990s that 3D acquisition would be desirable, the relatively long 10 msec minimum repetition times of the gradient echo sequences used were identified as a significant limitation and targeted as something to be further reduced.

Other issues identified in the table have fostered totally new technical developments. Examples of this include fluoroscopic triggering and the elliptical centric view order (3). Previous to CE MRA there was no commonly used procedure in MRI which required the triggering of a high resolution scan based upon real-time visualization of some phenomenon in a series of 2D images. However, precise matching of the potentially long duration, 3D scan to the arterial phase of the contrast bolus is a critical issue in CE MRA, and fluoroscopic triggering is one means for addressing this. Similarly, prior to CE MRA there was no clear application in MRI in which it was desirable to discriminate distinct temporal phases based on phase encoding view order. However, the characteristic of the elliptical centric order to intrinsically suppress venous signal while still permitting long acquisition times has proven to be critical in acquiring high resolution CE MRA data sets.

Table 1. Summary of Issues in Contrast-Enhanced MR Angiography		
Issue	*Explanatory Question*	*Solutions*
Spatial resolution	Is the spatial resolution adequate to permit diagnosis, with the target of being competitive with x-ray angiography?	Short TR (<5 msec); Minimized FOV; Extended acquisition time; Projection reconstruction; Multi-coil multi-reconstruction
Timing	Can the 3D acquisition be matched to the arterial phase of the contrast bolus?	Test bolus; Real-time fluoroscopic triggering; Time-resolved 3D imaging
Venous suppression	Can the interfering signals from contrast-enhanced veins be avoided?	Acquisition time restricted to arterial phase; Centric phase encoding orders
Reliability	Does the method routinely allow diagnostic interpretation?	Adequate contrast, timing, and MRI technique
SNR	Is the signal level in the arteries of interest adequately large compared to background noise?	Rapid (several ml/sec) delivery of contrast bolus; Suitable receiver coils
Temporal resolution	Can time-varying phenomena be well seen, such as asymmetric filling in the lower extremities?	Time-resolved acquisition, possibly with view sharing

As discussed below, there is a considerable ongoing research in a number of the areas listed in Table 1, particularly further improvements in spatial resolution and time-resolved acquisition.

Applications

It is will beyond the scope of a short communication such as this to indicate in any detail the clinical applications of CE MRA. This is given to some extent in the monograph (2). There have been a considerable number of clinical studies investigating the performance of CE MRA in imaging of the extracranial carotid arteries, the aorta, the renal arteries, and peripheral vascular disease, and in some instances meta-analyses have been performed.

In considering clinical applications it is perhaps worthwhile to consider how specific applications might be well matched to the strengths of CE MRA. For example, imaging of the carotid bifurcation can generally be performed without the need for breathholding, and hence acquisition times of 20 sec or more are feasible. This is an anatomic region in which good venous suppression is important, and a centrically encoded MR acquisition can achieve this whereas a potentially competing CT angiography acquisition does not. Finally, the current

Figure 1. Comparison of subvolume from 3D intravenous CE MRA study of the carotid bifurcation (left) and intraarterial x-ray angiogram (right).

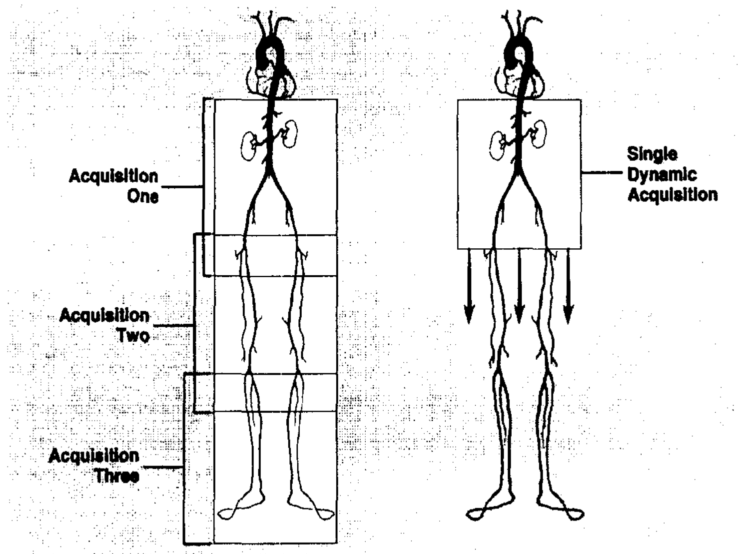

Figure 2. Comparison of conventional multiple, fixed station peripheral MRA (left) with the newly proposed continuous table motion approach (right). (From Ref. 4)

choice of x-ray angiography has nonzero risk, and the replacement of this with a noninvasive procedure having minimal risk, such as CE MRA, is highly desirable. These factors suggest that the application of CE MRA to carotid artery imaging would be particularly well matched. Figure 1 shows a sample comparison of CE MRA and x-ray angiography for carotid imaging .

Similar thought processes may well apply to other anatomic regions. As CE MRA continues to evolve, improved technical performance may well give it more of an advantage in a given clinical application.

Areas of Future Development

Reduction of Acquisition Time. The fundamental tradeoff in MR imaging is general is that of spatial resolution with acquisition time. Reductions in acquisition time generally must be accompanied by reduced resolution unless some fundamental principle can be newly applied. Because of the desirable 3D nature of the data, the acquisition times in CE MRA are generally on the order of ten to several tens of seconds with conventional 3DFT techniques. However, two general technical directions, mutually exclusive, are currently under investigation to attempt to address this issue. One of these is projection reconstruction (PR) acquisition, and the other is the usage of signals from multiple receiver coils. The rationale for PR is that resolution loss is more forgiving for the reduction in azimuthal sampling than rectilinear sampling compared to the theoretical limit. Further, the degree of sampling reduction is even greater in 3D vs. 2D methods. This has been suggested in initial experimental studies, and further work is ongoing. Perhaps the most studied method for scan time reduction using multiple receiver coils is the "SENSE" technique in which the field of view of the acquisition is reduced to the point in which aliasing occurs, but the overlap of signals is reconciled using the multiple reconstructed images, one per coil. The degree of SNR loss caused by the signal processing can potentially be compensated by an increased rate of contrast injection. Work in both of these areas is ongoing.

Improved Time-Resolved 3D Studies. Although some of the earliest technical studies of CE MRA involved the development of time-resolved techniques, in many cases these were limited by the spatial resolution. However, work is ongoing in an attempt to provide a time-resolved 3D image set. This can be particularly important, for example, in imaging the lower extremity in which case asymmetric filling must often be effectively portrayed. A number of methods are being developed to do this. Many involve the use of view sharing or partial updating of k-space. This approach exploits the fact that the central region of k-space dictates the overall appearance of an image, and moreover, in MRI these views can be sampled independently of the more peripheral views. Further, the relative frequency of sampling can also be controlled. Thus, 3D time-resolved studies may well involve multiple image sets in which observeable time resolution is short, allowing accurate portrayal of time-varying phenomena, but time spent accumulating data for the image set is long, providing high spatial resolution.

Extended Field of View Imaging Using Continuous Table Motion. An area of growth in CE MRA is the imaging of the peripheral vasculature. Various means have been developed for doing this using moving table approaches. Virtually all techniques to date image the patient at a set of discrete, fixed table positions or "stations" in the bore of the MRI scanner. Once all desired data have been collected at one table location, the acquisition is interrupted and the table is moved to the next location. To address the loss of data collection efficiency caused by the start/stop nature of these approaches, investigators are studying the concept of data acquisition *during* continuous table motion (4). A comparison of the fixed station approach with the new continuous motion technique is shown in Figure 2. Initial technical studies have demonstrated that data can be combined to form a long FOV image, but accurate knowledge of table position with sub-pixel level of registration is necessary. Initial applications to human imaging are underway. If successfully implemented, this method may allow diagnostic imaging of peripheral vascular disease using patient-specific acquisition parameters. Also, effective implementation of moving table imaging may well require incorporation of the other future developments presented here, scan time reduction using multiple coils and time-resolved acquisition.

Summary

Contrast-enhanced MR angiography has become a widely used method useful for clinical diagnosis. Early studies identified a number of technical issues, and many of these have been addressed with various MRI physics innovations over the last several years. The quality of the results is high enough that CE MRA is replacing conventional x-ray angiography methods at many institutions. Ongoing research is expected to provide further improvements in performance, most notably in additional reductions in examination time, in time-resolved 3D imaging, and in improved imaging of the peripheral vasculature with extended fields of view.

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