Time-Resolved Contrast-Enhanced MRA Using Cartesian Techniques

Stephen J. Riederer, Ph.D.
Department of Radiology
Mayo Clinic
Rochester, MN 55902 USA

INTRODUCTION

The last decade has seen major advances in the performance capabilities of time-resolved contrast-enhanced (CE) magnetic resonance angiography (MRA). Today, for example, it is possible to generate 3D time-resolved image sets with higher spatial resolution, wider anatomic coverage, better temporal fidelity, and improved image quality while using smaller acquisition times than what was the standard just five years ago. The reasons for this are multifold. Technical developments include improved data acquisition strategies, the evolution of parallel acceleration methods, and improved receiver coil arrays. The effectiveness of many of these developments is enhanced by the use of standard, grid-like "Cartesian" sampling patterns in k-space. In this work we briefly discuss these key elements of Cartesian-based CE-MRA, describe performance characteristics and present representative results.

METHODS

k-Space Sampling Patterns. 3D MRI necessarily requires that three-dimensional k-space be sampled and the resulting data then be reconstructed via Fourier transformation to generate the final image. With Cartesian sampling the readout is solely along one direction (X), and phase encoding is performed along the two orthogonal directions (Y and Z). Slab selection is also performed along Z. It is convenient to describe data acquisition in terms of the k_Y-k_Z phase encoding plane, illustrated in Figure 1. As a reference, Fig. 1A shows a sampling pattern commonly used for non-time-resolved MRA. Each point corresponds to a possible measurement as made in an individual repetition of the 3D acquisition. The rectilinear grid-like nature of the points illustrates the Cartesian nature of the sampling. Only those points falling within either the orange center or black vanes are actually measured. The sampling starts at the orange center. Each TR interval a new point is sampled, with points sampled in the order of their distance from the center. This is a so-called "elliptical centric" view order. This can be converted into a time-resolved view-shared sequence (B) by decomposing the vanes into individual colored groups. In this case the data acquisition is performed using the temporal playout of (D). An individual 3D image is

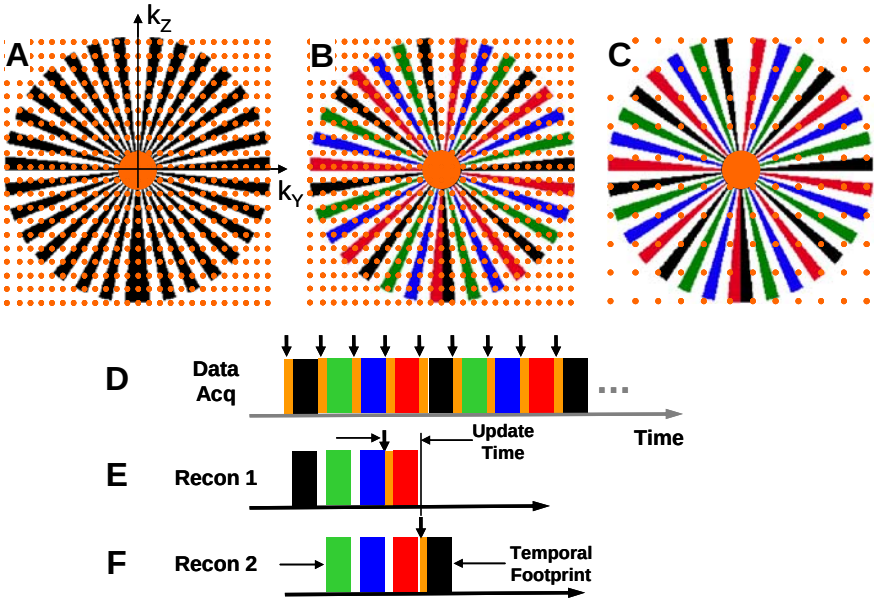

Figure 1. Sampling pattern, temporal sampling of data, and data sorting used in view-shared time-resolved Cartesian CE-MRA.

formed from one sampling of the central orange region and one sampling of each colored vane set; e.g. (E). The next image (F) is formed a short time later after the orange region and one vane set have been freshly sampled, data from the other three vane sets being shared from the previous frame. This shows the distinction between the image update time, defined as the time between consecutive frames, and the temporal footprint, defined as the time over which data are acquired for image formation. The sampling pattern in Fig. 1 is referred to as CAPR (1). Other Cartesian patterns have also been reported (2).

Parallel Acquisition. Approximately ten years ago several methods for parallel acquisition were first described in the literature (3-5). With such methods the MRI signal is simultaneously detected by multiple receiver elements. This redundancy in information allows the total number of k-space samples to be reduced up to a factor as large as the number of receiver elements. The actual factor by which the acquisition time is reduced is referred to as the acceleration, R. Initially, parallel acquisition was applied along the single phase encoding direction of 2DFT acquisition. However, a modification showed how this could be further adapted to the two phase encode directions of 3DFT acquisition (6). The undersampling allowed by parallel acquisition is illustrated in the more sparsely sampled k-space points in Fig. 1C. Several groups early on adapted 2D parallel acquisition to 3D CE-MRA (7, 8) with accelerations in the range of R = 2 - 4. More recently, it has been shown that combined with homodyne, 2D accelerations of 10x can be routinely obtained in some specific applications (9). This advance in speed can be used advantageously to reduce acquisition time and improve spatial resolution compared to previous methods. An example of this is the plot of temporal footprint vs. frame time shown in Figure 2. All curves correspond to a fixed Y x Z spatial resolution, in this case 320x132. Assuming SNR is adequate, the ideal operating point is as close to the origin as possible. Increasing the degree of view sharing to provide increased frame rate moves the operating point left and upward along a given curve. However, as the acceleration factor R increases, a lower curve is created and the overall performance improves in that the temporal footprint and frame time are both reduced. Cartesian sampling in the k_Y-k_Z phase encoding plane of 3DFT acquisition is ideally matched to 2D parallel acquisition, readily allowing large R values and good performance.

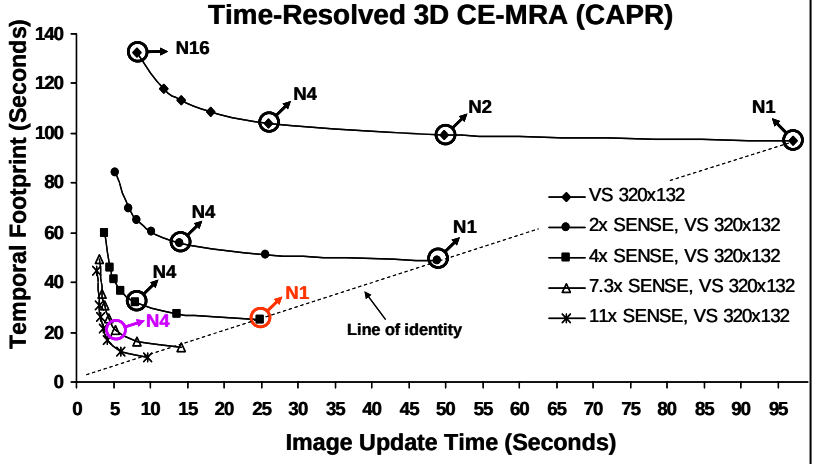

Figure 2. Plot of temporal footprint vs. image update time for fixed spatial resolution. Each curve corresponds to a distinct acceleration factor due to parallel acquisition.

Receiver Coil Arrays. The reconstruction algorithm for parallel acquisition involves inverting a system of equations in which the coefficients are related to maps of the sensitivities of the individual receiver coil elements across the field of view. In order to more readily invert the equations, it is desirable that the coil sensitivities be markedly dissimilar from each other. To address this, coil arrays have been designed which circumscribe the patient and which in effect see the axial phase encoding plane from multiple directions (9). The area of each individual element is designed to provide good falloff along the field-of-view.

Also, such arrays can be made modular, with individual elements inserted or removed to match the overall array circumference to the specific patient, thus providing high SNR.

Temporal Fidelity. An important development in the assessment of time-resolved sequences is the concept of temporal fidelity. Beyond standard measures such as spatial resolution and frame time, temporal fidelity raises such questions as how well does a given sequence accurately portray the absolute position and velocity of a moving object, how sharply does the sequence portray the leading edge of the advancing contrast bolus, and does the sequence create artifactual signal in advance of or trailing the moving contrast bolus? Cartesian methods with short temporal footprints have been shown to provide highly favorable performance in response to all of these questions (10).

RESULTS

Cartesian time-resolved acquisition has been used effectively in imaging many of the vascular territories of the body. Representative results from the brain are shown in Figure 3 and of the calves are shown in Figure 4.

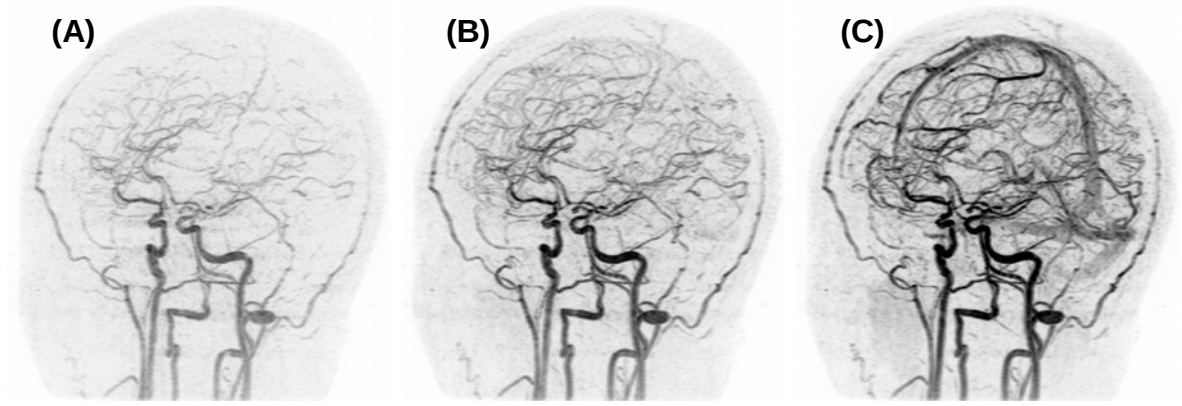

Figure 3. Example of time-resolved Cartesian CE-MRA of the intracranial vasculature. 2.3 sec frame time; 6.9 sec temporal footprint; 1 x 1 x 1 mm^3 spatial resolution. Note in (B) the filling of the arterial vasculature but lack of any signal in the superior sagittal sinus, an indication of the high temporal fidelity.

DISCUSSION

Cartesian-sampled 3D methods, particularly with high acceleration factors, can be used effectively in providing high spatial resolution images of the dynamic contrast bolus with a high level of temporal fidelity. The combination of the approximate 2x acceleration of homodyne sampling, coupled with the 4-12x acceleration of parallel acquisition, has permitted a reduction of the acquisition time per 3D data set by factors in the range of 10 to 20. This allows acquisition times as small as approximately 15 seconds for 1 mm isotropic imaging of the calves and times as small as 1-2 sec for 1 mm isotropic imaging of the brain. These acquisition times are shorter than of any other method. The short temporal footprint, coupled with the centric ordering of the phase encodes, freezes motion and provides high temporal fidelity in depicting the leading edge of the contrast bolus and in providing arterial frames which are devoid of venous contamination. From a practical standpoint, the regular, grid-like pattern of Cartesian k-space sampling allows image reconstruction of a full 3D time-resolved data set to be performed within several tens of seconds of data acquisition.

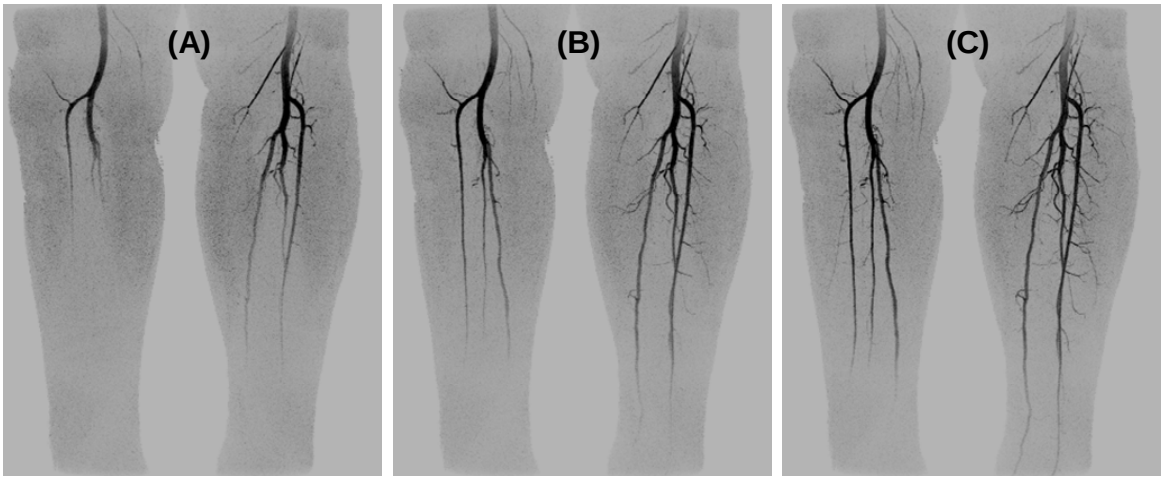

Figure 4. Example of time-resolved Cartesian CE-MRA of the calves. 4.9 sec frame time; 17.0 sec temporal footprint; 1 x 1 x 1 mm^3 spatial resolution. Note the high overall spatial resolution and the clear depiction of the leading edge of the contrast bolus, another indication of the high temporal fidelity.

CONCLUSION

Cartesian sampling for 3D time-resolved contrast-enhanced MRA consistently provides high image quality in multiple vascular territories.

REFERENCES

1. Haider CR, Hu HH, Campeau NG, Huston III J, Riederer SJ. 3D high temporal and spatial resolution contrast-enhanced MR angiography of the whole brain. Magn Reson Med 2008; 60:749-760.
2. Hadizadeh DR, Falkenhausen Mv, Gieseke J, et al. Cerebral arteriovenous malformation: Spetzler-Martin classification ata subsecond-temporal-resolution four-dimensional MR angiography compared with that of DSA. Radiology 2008; 246:205-213.
3. Sodickson DK, Manning WJ. Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. Magn Reson Med 1997; 38:591-603.
4. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. Magn Reson Med 1999; 42:952-962.
5. Griswold MA, Jakob PM, Heidemann RM, et al. Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med 2002; 47:1202-1210.
6. Weiger M, Pruessmann KP, Boesiger P. 2D SENSE for faster 3D MRI. Magma 2002; 14:10-19.
7. Meckel S, Mekle R, Taschner C, et al. Time-resolved 3D contrast-enhanced MRA with GRAPPA on a 1.5-T system for imaging of craniocervical vascular disease: initial experience. Neuroradiology 2006; 48:291-299.
8. Haider CR, Hu HH, Madhuranthakam AJ, et al. Time-resolved 3D contrast-enhanced MRA with 2D homodyne and view sharing for contrast bolus dynamics of the brain. In:14th ISMRM. Seattle WA, 2006; 812.
9. Haider CR, Glockner JF, Stanson AW, Riederer SJ. Peripheral vasculature: high-temporal and high-spatial -resolution three-dimensional contrast-enhanced MR angiography. Radiology 2009; 253:831-843.
10. Mostardi PM, Haider CR, Rossman PJ, Borisch EA, Riederer SJ. Controlled experimental study depicting moving objects in view-shared time-resolved MRA. Magn Reson Med 2009; 62:85-95.