3D Modeling of Spatial Resolution Limitations in Contrast-Enhanced MRA Related to the Contrast Bolus Profile using an Analysis of the Modulation Transfer Function

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Introduction Dynamic contrast-enhanced MR angiography (CE-MRA) is an increasingly used and maturing diagnostic imaging modality. Multiple recent advances, such as 3T, faster gradients, improved coils, view-sharing, and parallel imaging/number of receiver channels have driven MRA's growth. Nonetheless, studies comparing CE-MRA to "gold-standard" DSA, while not often performed in the present era due to radiation concerns, tend to show less than perfect results, particularly in the body (1, 2). One explanation for this may be motion, but another likely relates to achieved spatial resolution. Achieved spatial resolution, in turn, has been shown to ultimately depend not just on the resolution prescribed by MR imaging parameters, but ultimately on the shape/duration of the contrast bolus profile (3). It has been recently demonstrated that blood R1 (≡ 1/T1) does not linearly increase with Gd concentration ([Gd]) at higher "first pass" concentrations, instead falling off due to fast water exchange effects (4). In addition, blood R2* (≡ 1/T2*) values are much greater than R2 values due to static dephasing, and can therefore substantially decrease CE-MRA signal intensity (SI) at peak first pass [Gd], particularly at 3T and for longer echo times (TE) (5).

This study applies these new R1 and R2* understandings (which can now be accurately modeled vs. [Gd], and which contribute significantly to the non-linearity of SI during a contrast bolus) to a computerized 3D CE-MRA model. This model considers different bolus injection strategies in conjunction with different prescribed MRA spatial resolutions in order to better understand, visualize, and optimize the competing parameters of spatial resolution, scan time, and bolus injection rate.

Methods A comprehensive computer model simulating 3D CE-MRA was developed (Matlab, Mathworks) allowing input of the following parameters: bolus shape, contrast volume/infusion profile/type (4 commercially available formulations), $FOV_{x,y,z}$, spatial resolution, TR, TE, α, B_o (1.5 and 3T), parallel imaging factors, Hct, serum albumin concentration, noise index, and trigger delay time. The model assumes elliptical centric imaging with standard k-space edge "Gibbs" filtering, and bolus shape is modeled under the assumptions of flow dilution with recirculation, as per other extant CE-MRA data (6, 7). Into this model can be fed any 3D image dataset (synthesized or actual). The "simulated" imaging output is obtained by performing a FFT of the input dataset (zero filled to imaging resolution), adding noise, determining the k-space acquisition order vs. time, calculating the corresponding [Gd] vs. time and associated arterial SI vs. time for contrast type/injection and MR parameters listed above, modulating each k space point $k_{y,z}(t)$ by the appropriate SI(t), and then back-transforming into image space.

We derived a measure of our simulated imaging system's inherent resolution limits, as well as those related to different contrast bolus timing strategies, by measuring modulation transfer function (MTF) in each axis with a sine wave phantom. This phantom, generated in Matlab, spans the gamut of spatial frequencies, with exponentially decreasing wavelengths to well beyond MR resolution. This exponential wavelength decrease maximizes our ability to measure minute differences in imaging systems' performance at their resolution limits while still obtaining information on performance at lower spatial frequencies. Through this derivation of MTF, arbitrary combinations of scan parameters, contrast injection profiles, and contrast agents/doses can be rapidly and systematically evaluated in terms of their true spatial resolution. In addition, promising combinations can be subjectively validated on a more physiologic model of a simulated (or real) renal artery stenosis.

Findings MTF spanning the gamut of modeled spatial frequencies is demonstrated over multiple injection rates in Figure 1 (typical renal MRA parameters). Observe from this and Figure 2 that due to the extremely non-linear behavior of blood [Gd] vs. SI, an appropriately lengthened Gd bolus (less peak Gd concentration but more persistence throughout k-space – red "1 cc/sec" Fig. 1) only minimally decreases low frequency MTF (dictating SI and contrast) without degrading spatial resolution (high frequency MTF). Impact on y and z (phase) resolution may differ slightly depending on geometry and SENSE factors, with x resolution essentially unaffected by injection rate or duration.

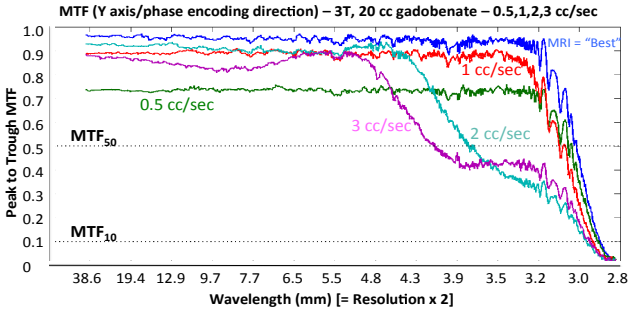

Figure 1. MTF vs. y resolution for different bolus injection rates; gadobenate 20 cc, 21 sec acquisition, 1 x 1.4 x 1.6 mm resolution. Note MTF_{50} (and to lesser extent MTF_{10}) decrease for faster injection rates (i.e. lose resolution). The 1cc/sec and 0.5cc/sec injections have near perfect $MTF_{10,50}$ values, although 0.5cc/sec does lose some low frequency MTF. This suggests 1cc/sec injection (20 sec duration ~ same as acquisition) optimal – faster injection decreases resolution and creates artifacts. Blue "MRI = Best" represents limit of machine resolution.

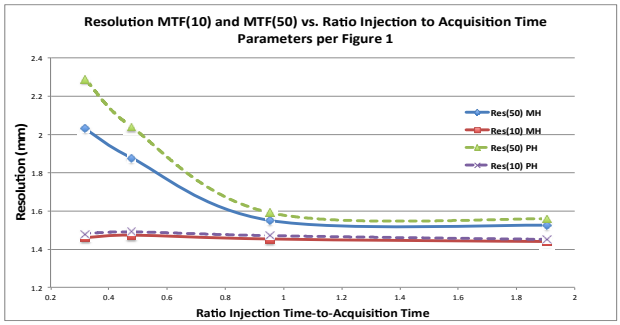

Figure 2. Resolution (as MTF_{10} and MTF_{50}) compared to ratio of bolus injection time (20 cc volume) to acquisition time for parameters per Fig. 1. Gadobenate (high relaxivity) and gadoteridol (conventional relaxivity) compared. Note increasing injection rate (ratio below 1) causes blurring, which is more pronounced for lower relaxivity agents. Suggests optimum ratio ~ 1.

Discussion One benefit of MTF analysis is that global MTF is the product of individual component MTFs – i.e. the MR system (specified resolution), the contrast bolus, and (not yet modeled) motion. Longer bolus duration only minimally decreases SI, yet maintains full resolution when the MTF secondary to the contrast bolus profile most closely approximates that of the imaging system. For CE-MRA under the assumptions of our model, we find that this occurs when the contrast injection duration is approximately equal to the acquisition time of k-space, although this depends on geometry and individual patient hemodynamics, another factor that ultimately needs to be considered. High relaxivity contrast proves advantageous when being injected more slowly due to higher across the board MTF. Changing acquisition parameters with the goal of increasing resolution without choosing contrast injection parameters that satisfy the above condition causes blurring through effective suppression of the periphery of k-space. This phenomenon may explain in part the relative performance of CE-MRA as typically performed versus DSA.

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