Virtual Dye Angiography: using endogenous contrast to visualize blood flow in MRI-guided interventional procedures

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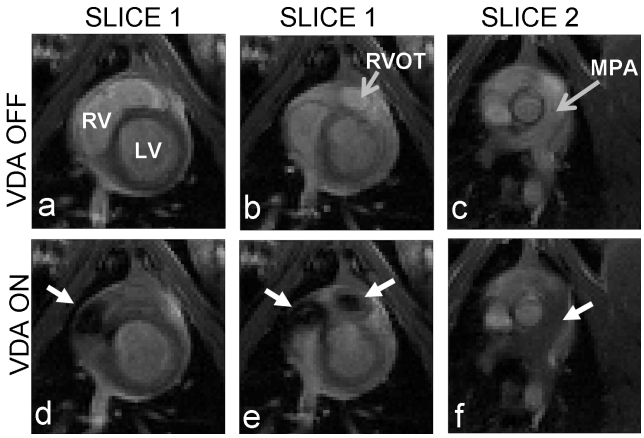
Introduction: In MR cardiovascular examinations and interventional procedures it may be valuable immediately and interactively to visualize blood flow in highly selective regions. Phase-contrast velocity mapping (PC) is not always well suited for this purpose. The acquisition time is generally too long in PC and the image contrast (and thus the image guidance quality) is compromised compared to the preferred SSFP sequence. Additionally, the operator does not necessarily need the quantitative information provided by phase-contrast. We present a novel flow visualization method, that we call Virtual Dye Angiography (VDA). It enables visualization of blood flow analogous to selective catheter angiography and to arterial spin labeling. The method employs interactive, intermittent, targeted saturation of a localized region (using multidimensional RF pulses) in the real-time MR imaging sequence. The modular nature of the technique allows for easy and seamless integration into a real-time interactive, imaging system with minimal overhead. We present initial results in animals.

Methods: In VDA, a target volume is labeled by employing a spatially-selective 90º excitation followed by a spoiler gradient. This VDA module is played before imaging the slice of interest in a single shot real-time acquisition. The 2D spatially-selective excitation [1] sequence consists of a shaped RF pulse played concurrently with a spiral gradient. In general, the shape of the target volume can be controlled with the RF pulse envelope and in this study a cylindrical excitation was used. The location of the saturation column can be chosen freely in an interactive manner such that it can be placed upstream of a structure of interest and the direction of blood flow is visualized by the movement of saturated spins. The operator can either observe the blood flow directly by following the saturated spins in the real-time slice (direct visualization mode) or the visualization can be enhanced by background subtraction (subtraction mode). In the latter case an ECG synchronized frame without VDA is retrieved from a buffer and subtracted from a VDA enabled frame in a manner similar to X-ray digital subtraction angiography.

Experiments were performed on healthy animals on a 1.5T Clinical MR scanner (Espree; Siemens). A real-time, interactive, multi-slice balanced SSFP imaging sequence (TR=2.7 ms / TE=1.35 ms / 45º flip-angle) was used. The sequence was modified to include the ability to turn VDA (in standard mode) on and off interactively. The location and size of the saturation column could also be modified in real-time. The length of the VDA saturation module was 13 ms --- 12 ms for the 2D RF excitation and 1 ms for the spoiler gradient.

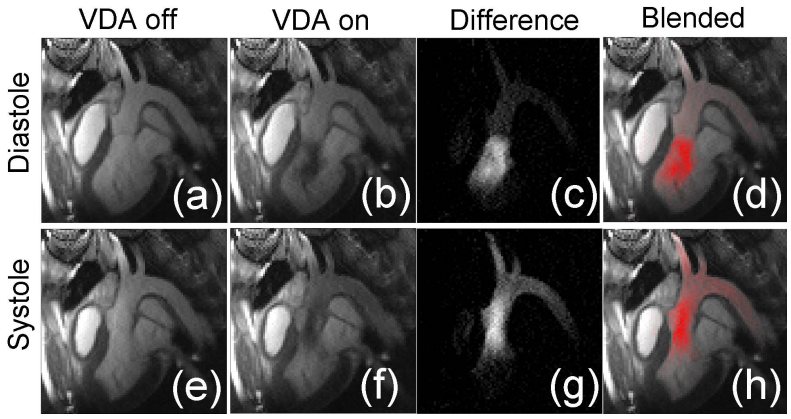


In experiment #1 (direct visualization mode) blood flow from the right ventricle to the pulmonary vessels was visualized. Two slices (slice 1 and 2) were imaged using a real-time bSSFP sequence. The VDA saturation module was played before the acquisition of slice 1. A sequence of images, with VDA turned both on and off, was reconstructed.

In experiment #2 (subtraction mode) blood flow from the left ventricle to the aorta was visualized. A single slice was imaged using parallel-imaging (GRAPPA, rate 4). Several image frames, with VDA turned both on and off, were reconstructed. Additional concurrent ECG data was recorded. ECG data was used to re-interpolate each of the two sets (VDA on and VDA off) of images onto a temporally-uniformly-spaced set of images corresponding to 40 phases within a heart cycle. The difference between corresponding images between the two sets was computed.

Results: Figure 1 shows the results of Experiment #1. It shows two slices and three phases in the cardiac cycle with VDA off (top row) and on (bottom row). The saturation column was oriented perpendicular to slice 1 and through the RV. The white arrows point to the location of the saturated spins: first in initial saturation in the RV (Figure 1(d)), then exiting the RV (Figure 1 (e)), and in the main pulmonary vessel (Figure 1 (f)).

Figure 2 shows the results of Experiment #2 for a systolic and diastolic heart-phase. The saturation column was oriented perpendicular to slice #1 and through the LA. The columns of the figure show, respectively from left to right, the slice when VDA is off, VDA is on, the difference image and the difference image, in red, blended in with the VDA-off image. During systole the tagged spins are seen to have moved farther from the point of saturation than in diastole.



Discussion: We have implemented a novel method of visualizing blood flow in a real-time MR display system and demonstrated it in a large animal. The modular nature of our method allows for the minimal modification of the existing multi-slice imaging sequence and a seamless integration into the existing workflow. Specifically, the operator has the ability to enable VDA directly in the sequence used for image guidance during the intervention without the need to switch to a PC sequence for flow visualization.

VDA employs the principle of spin labeling and is also related to work by Stuber et al [2] where spatially selective excitations were used to perform noncontrast projection MRAs of the coronaries. Here we have demonstrated that by enabling interactive controls of 2D selective excitations in a real-time imaging sequence, the arterial spin labeling principles can be used for flow visualization to help guide interventional MRI.

The contrast of the difference images decays roughly exponentially, with a time-constant on the order of T1 (but which depends [3] also on T2, flip-angle, and blood mixing). Experiment #1 demonstrates that the saturation persists *in vivo* for at least two image frames i.e. more than 500ms (~1.5 frames x 2.7ms TR x 128 echos). This is longer than the 200 ms *in vivo* persistence time reported by comparable methods [4] that are more constrained by T2.

While we have demonstrated the excitation of a cylindrical column (i.e. with a disc-like cross-section), the cross-section of the column can be made of arbitrary shapes, and possibly adapted to the anatomy of the subject, by simply modifying the 2D RF pulse. Physical limitations (gradient limitations and the shortness of T1) make the use of 3D spatially selective pulses currently infeasible. But the use of parallel transmission systems in the future will allow for the saturation of compact 3D shapes using short RF pulses.

Other future refinements of the method that we envision include synchronization with cardiac cycles to ensure consistent and optimal placement of the saturation column. Additionally we plan to explore constrained reconstruction methods to enable higher frame rate visualization when operating VDA in subtraction mode.

References: 1. Börnert, MAGMA,7:166-178 (1998) 2.Stuber MRM 47:322–329 (2002) 3.Ibrahim JMRI 24:1159–1167 (2006) 4.Rehwald Nat. Med. 10:545-549 (2004)