Particle Trace Visualization of Cardiac Flow Patterns using 3D Phase Contrast MRI: An in vitro Comparison with Streamlines Created using Dye.

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Introduction
Intracardiac flow patterns can be visualized by particle traces obtained from three-dimensional phase contrast MRI. Good results have been shown for stationary [1] and time-resolved data [2]. New off-line retrospective gated 3D phase contrast techniques, providing high resolution time-resolved 3D velocity data, have improved the accuracy of the calculated particle traces [3]. While previous studies have investigated phase contrast MRI velocity measurements and particle path integration algorithms separately, this investigation is performed as a combined comparison with dye.

Methods
Particle traces calculated from phase contrast MRI velocity data were compared with streamlines obtained by injection of dye. A Plexiglas phantom was constructed to study curving and coexisting flow patterns. Different steady flows were produced by a computer controlled pump (UHDC Flow System, Shelly Medical Imaging Technologies, London, Ontario, Canada). All velocity measurements were performed on a 1.5 Tesla imaging system (General Electric Medical Systems, Milwaukee, WI) using a 3D phase contrast pulse sequence (TR=22 ms, TE=7.2 ms, flip angle=20º, FOV 30x30x25.6 cm). All three velocity components were acquired in 32 slices directed perpendicular to the in and outflow direction. The resulting spatial resolution of 1.2 mm \times 3.3 mm \times 8.0 mm is similar to that used for studies of intra-cardiac flow [3]. All velocity data was corrected for eddy current [4] and concomitant magnetic field [5]. The data was transferred to a commercial software package (Ensight, CEI inc., NC, USA) for streamline visualization of the flow, using the 4th order Runge-Kutta numerical integration method.

Streamlines were also created by using dye with the same viscosity and density as water. The dye was injected slowly in the phantom via a catheter. Digital images of the phantom were stored at 25 Hz by a SGI Indy workstation (Silicon Graphics Computer Systems, Mountain View, CA, USA). Calculated streamlines were superimposed on the dye images for comparison.

Results
For laminar flow the calculated streamline in the curving flow phantom showed a good correlation with the dye line (fig. 1). In the bend a small disparity can be seen between them, although their shapes are similar. In the outflow region, both lines show a swirling motion, which is difficult to see in the 2D images. For turbulent flow the dye line is, as expected, less defined. The dye roughly approximates the particle trace, but it is more spread out. For laminar flow in the coexisting flow phantom, the dye and particle trace visualization gave similar results (fig. 2 and 3). For turbulent flow, mixing effects present in the dye visualization could not be seen in the particle trace visualization.

Discussion
The results from particle trace visualization of phase contrast MRI data showed good agreement with the dye visualization. Laminar mixing due to diffusion was negligible in the dye measurements. This agrees with the theory that diffusion is a slow process to assure micro mixing. In turbulent flow, distributive mixing is also induced by the oscillating velocity. The dye visualization showed that this increases the mixing considerably. Due to low spatial and temporal resolution, this effect on the streamline calculation is negligible, which results in a false impression of non-mixing.

Conclusions
In laminar flow conditions, particle trace visualization of 3D phase contrast velocity data gives a good representation of mixing effects and flow patterns. For turbulent flow, the particle trace method visualized the flow patterns correctly, but gives a false impression of non-mixing.

References