# Automatic Segmentation of 3D Phase Contrast MRI using Velocity Guided Gradient Vector Flow

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## Introduction

Hemodynamic measurements using phase contrast (PC) MRI in mouse models of atherosclerosis provide insight into the molecular mechanisms of the disease. Delineation of the vessel wall is a requisite step prior to calculation of hemodynamic parameters such as wall shear stress. Manual segmentation is a tedious, time-consuming process subject to intra-observer and inter-observer variability. The use of automatic segmentation algorithms could eliminate the need for manual delineation and increase study throughput.

Active models, termed snakes, have been applied extensively to medical imagery. A snake is a contour or surface that deforms to capture a region of interest through minimization of an energy functional[1]. The energy functional can be cast as a force balance equation with an internal force, which acts to smooth the snake, and an external force, a vector field that points towards object boundaries. A common external force is the gradient of an edge map. Although this simple external force pushes the snake towards edges in the image, its effect is local and as such has a limited capture range. Gradient vector flow (GVF) is a method that increases the capture range by diffusing the external force into regions with weak edges. Although GVF increases the capture range, long, thin structures remain troublesome. Traditionally external forces have relied exclusively on the image magnitude. Phase based external forces have recently been introduced that look at changes in the vector orientation of phase contrast data[3]. We propose a new external force: velocity guided GVF (VGG). VGG directly incorporates the velocity field as an additional constraint in the GVF framework that acts to expand the active surface along the direction of flow.

## Methods

For ease of notation, all equations describe the two-dimensional case. However, all equations are extendable to three-dimensions. Given an edge map $\mathrm{f(i,j)}$, GVF constructs a vector field, $\mathbf{V}(\mathrm{i,j}) = [\mathrm{u(i,j)}, \mathrm{v(i,j)}]$, by minimizing the energy functional $J_{GVF}\,(u,v) = \iint g(|\nabla f|)(|\nabla u|^2 + |\nabla v|^2) + h(|\nabla f|)|\mathbf{V} - \nabla f|^2 dxdy$. The weighting function $g(|\nabla f|)$ controls the smoothness of the resultant vector field, and the weighting function $h(|\nabla f|)$ controls the fidelity of the resultant vector field to the edge map gradient. The weighting functions proposed by Xu et al were, $g(|\nabla f|) = \exp(-|\nabla f| \,/\, \kappa)$ and $h(|\nabla f|) = 1 - g(|\nabla f|)$ where $\kappa$ is a user selectable parameter which control smoothness of the vector field. The weighting functions' dependence on the edge map magnitude encourages smoothing to preferentially occur in regions with weak or no edges.

To incorporate the velocity data into the GVF framework, an additional term is added to the original GVF energy functional, $J_{VGG}(u,v) = \iint g(|\nabla f|)(|\nabla u|^2 + |\nabla v|^2) + h(|\nabla f|)|\mathbf{V} - \nabla f|^2 + k(|\nabla f|, \mathbf{\Psi})|\boldsymbol{V} - \mathbf{\Psi}|^2 dxdy$. The weighting function $k(|\nabla f|, \mathbf{\Psi})$ controls the fidelity of the vector field to the velocity data, $\mathbf{\Psi}(i,j) = [\Psi_{\bar{x}}(i,j), \Psi_{\bar{y}}(i,j)]$. The weighting function is designed such that the velocity data only influences the vector field when the image gradient is low and the phase quality is high. To achieve this, the VGG weighting function is defined as the multiplication of the phase quality map, $\mathrm{Z(i,j)}$ and $\mathrm{g(|\nabla f|)}$, $\mathrm{k(|\nabla f|, \Psi) = \rho g(|\nabla f|) Z(i,j)}$, where $\rho$ is a user selectable parameter that controls relative weight of the velocity data in regions with low edges and high phase quality. The phase quality map is defined as the exponential of the standard deviation of the partial derivatives of phase[4]. The phase quality map varies between 0 in regions with poor phase quality and 1 in regions with high phase quality.

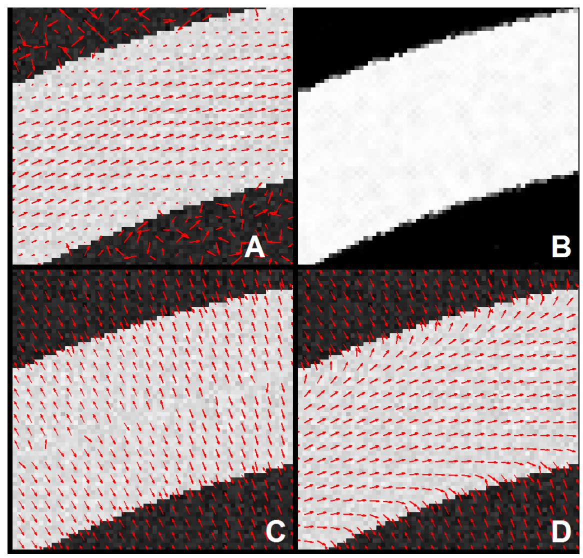


**Figure 1.** Results of VGG on synthetic vessel. (A) Synthetic vessel magnitude image with velocity field overlaid in red. (B) Phase quality map where bright intensities corresponding to high phase quality. (C) GVF external force and (D) VGG external force. The GVF external force point only towards the vessel wall, while the VGG force points towards the vessel wall and along the direction

## Results:

Fig. 1 shows the results of GVF and VGG for a synthetic vessel. The magnitude image and velocity field assuming Poiseuille flow is shown in Fig. 1A. Fig. 1B shows the phase quality map, with high phase quality inside the vessel lumen where phase is smoothly varying. Fig. 1C shows the external force using GVF. The vector field points towards the wall, but little force attracts the snakes along the length of the vessel. After incorporation of the velocity data using VGG, Fig. 1D shows the external force pointing along the direction of flow in addition to towards the vessel wall. Fig. 2 shows the results of an active surface on a 4D PC-MRI dataset of the mouse aortic arch using GVF and VGG initialized at the aortic root. The downstream edge of the active surface is held constant. GVF fails to capture the entire vessel, while VGG successfully captures the aortic arch along with the principal branches. Both methods used the same number of iterations, smoothness constraints, and update weights.

## Conclusions:

An external force was proposed that incorporates velocity data into the GVF framework. VGG alters the external force in regions with high phase quality and weak edges to point along the direction of flow. VGG acts to push an active surface along the direction of flow and was shown to improve segmentation results when compared to GVF.

[1]Kass et al. IJCV, 1987; 1:321-331
[2]Xu et al. Trans. IP, 1998; 7:359-369.
[3]Cho et al. CMIG, 2006; 30:31-41
[4]Ghiglia et al. Two-Dimensional Phase Unwrappping, Wiley; 1998.

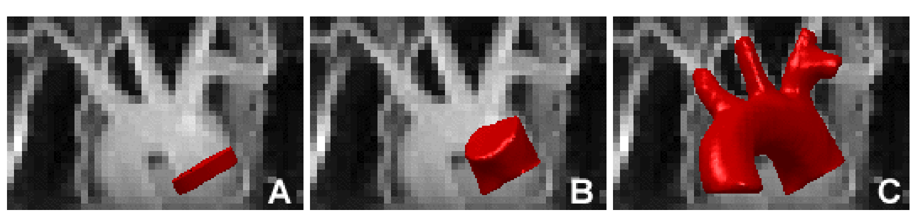


**Figure 2.** Automatic segmentation of the mouse aortic arch. (A) Initial surface at the aortic root. Segmentation results using (B) GVF and (C) VGG. Incorporation of the velocity field enables segmentation of entire aortic arch along with principal branches.