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Automated vessel segmentation using cross-correlation and pooled covariance matrix analysis☆

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Abstract

Time-resolved contrast-enhanced magnetic resonance angiography (CE-MRA) provides contrast dynamics in the vasculature and allows vessel segmentation based on temporal correlation analysis. Here we present an automated vessel segmentation algorithm including automated generation of regions of interest (ROIs), cross-correlation and pooled sample covariance matrix analysis. The dynamic images are divided into multiple equal-sized regions. In each region, ROIs for artery, vein and background are generated using an iterative thresholding algorithm based on the contrast arrival time map and contrast enhancement map. Region-specific multi-feature cross-correlation analysis and pooled covariance matrix analysis are performed to calculate the Mahalanobis distances (MDs), which are used to automatically separate arteries from veins. This segmentation algorithm is applied to a dual-phase dynamic imaging acquisition scheme where low-resolution time-resolved images are acquired during the dynamic phase followed by high-frequency data acquisition at the steady-state phase. The segmented low-resolution arterial and venous images are then combined with the high-frequency data in *k*-space and inverse Fourier transformed to form the final segmented arterial and venous images. Results from volunteer and patient studies demonstrate the advantages of this automated vessel segmentation and dual phase data acquisition technique.

Keywords: Contrast-enhanced MR angiography; Time-resolved; Matched filtering; Cross correlation; Pooled covariance matrix analysis; Vessel segmentation

1. Introduction

Conventional contrast-enhanced magnetic resonance angiography (CE-MRA) produces a single image volume properly timed to capture the first pass of a contrast agent for maximal arterial enhancement [1]. Retrograde flow, delayed or asymmetric filling of contrast agent, or cases with fast arterial-venous transit of the agent may result as an adaptation to vessel occlusive disease or produce suboptimal arterial angiography with significant venous contamination [1–4]. Time-resolved acquisitions can resolve these difficulties by acquiring a series of three-dimensional (3D) images to capture the detail of the contrast dynamics of the vasculature system [2–8], but at the cost of reduced spatial resolution and signal-to-noise ratio (SNR) [9]. It is of significant interest to generate dynamic images together with arterial and venous images with high spatial resolution, high SNR and contrast-to-noise ratio (CNR) in a single scan.

Time-resolved CE-MRA provides contrast dynamics in the vasculature. This temporal information can be used to separate arteries from veins using a variety of algorithms such as correlation analysis [10], matched filtering [11–13], eigenimage filtering [14], feature space analysis [15] or Mahalanobis distance (MD) analysis [16–18]. The ability to separate arteries from veins allows extended acquisition at the steady state as well as matched filtering of the whole data to improve both spatial resolution and SNR without significant CNR reduction [17,18]. Segmented arterial images with high SNR and CNR have been demonstrated by several groups [10–18]. However, most of the segmentation algorithms require operator intervention such as thresholding [19]. Improper thresholding may significantly reduce the image quality. Furthermore, the contrast

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dynamics pattern may vary significantly within a large imaging field of view (FOV) due to delayed filling, asymmetric filling or slow blood flow in the tortuous vessels [1–8]. Correlation with single arterial and/or venous reference curves may result in misclassification. A single global thresholding of the correlation coefficients or MD may not work well. Fully automated segmentation with consideration of the contrast variation within the imaging FOV is highly desirable to reduce the labor cost and improve the robustness of the segmentation technique.

In this article, we present a fully automated region-specific segmentation algorithm for effective separation of arteries from veins based on cross-correlation and pooled covariance matrix analysis. This segmentation algorithm is applied to a dual phase dynamic imaging acquisition scheme where low-resolution time-resolved images are acquired during the dynamic phase followed by high-frequency data acquisition at the steady-state phase. Matched filtering of the time-resolved data and steady state is used to improve SNR. The 3D dynamic images are divided into multiple subregions to account for the variation of contrast arrival times. Arteries, veins and background are separated using region-specific cross-correlation and pooled covariance matrix analysis. The segmented low-resolution arterial and venous images are then combined with the high-frequency data in *k*-space and inverse Fourier transformed to form the final segmented arterial and venous images. Results from volunteer and patient studies demonstrate the advantages of this automated vessel segmentation and dual phase data acquisition technique.

1.1. Theory

The fully automated vessel segmentation algorithm includes the following five steps: (1) automated region-specific regions of interest (ROIs) generation; (2) region-specific matched filtering; (3) region-specific cross-correlation analysis; (4) region-specific pooled covariance matrix analysis; (5) formation of the composite images. Details of each step are given in the following sections.

1.2. Automated region-specific ROI generation

ROIs and reference curves for artery, vein and background are needed for matched filtering and subsequent cross-correlation and pooled covariance matrix analysis [16]. Fig. 1 shows the flow chart for this algorithm. First, the 3D

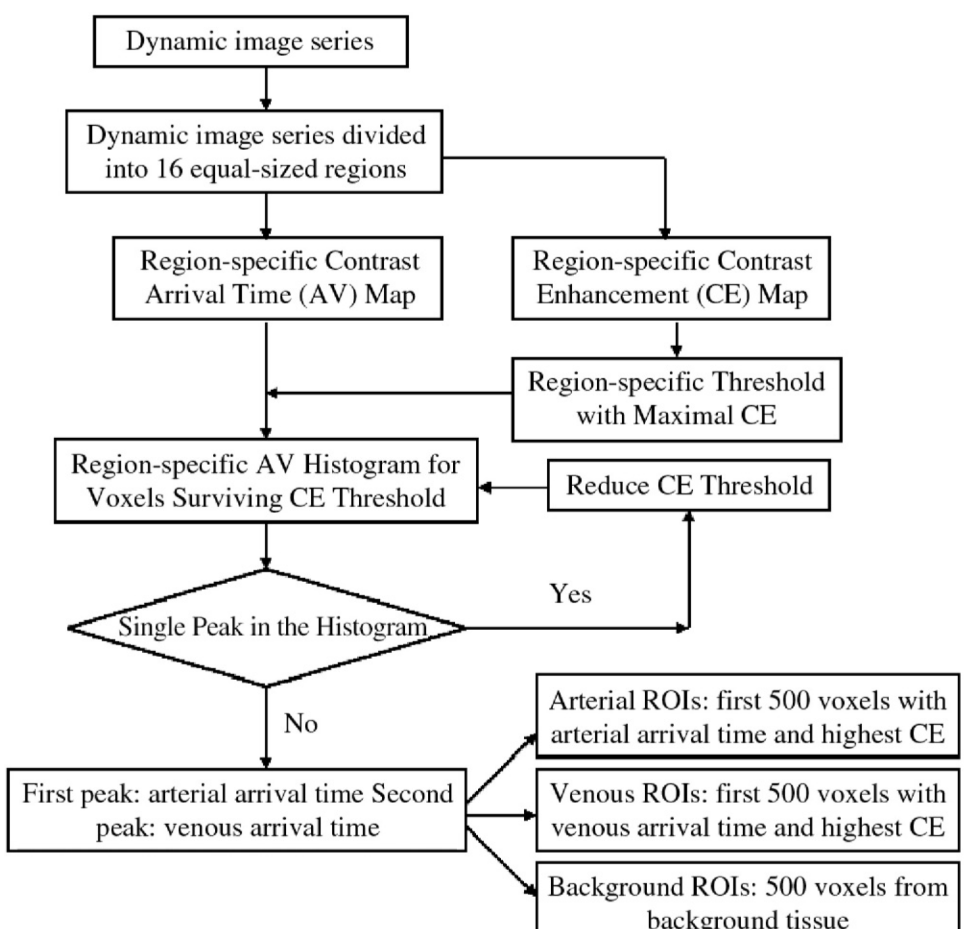

Fig. 1. Flow chart for region-specific ROI generation.