Detection of Small Vessels in Magnetic Resonance Angiograms by Grey-Scale Skeletonization

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Introduction

Magnetic resonance angiography (MRA) in its numerous variations has become a primary method for the radiologic evaluation of vascular pathologies and for surgical planning. While much attention has been given to MRA acquisition techniques, post-processing techniques used for improvement of visualization, quantification and interpretation have received less attention and promise to play an increasingly central role. A new approach to solving these and other problems is presented here; skeletonization based on the ordered region growing (ORG) connectivity whereby the central axes of the vessels are extracted in a semi-automated manner. Improvements in radiologic evaluation of MRA's in comparison with the maximum intensity projection (MIP) visualization will be demonstrated.

Background

High level techniques, primarily associated with discrete detection of the vessels have been found which produce reasonable results. Methods of vessel tracking have been proposed whereby a pathway is traced through the image along the central axis of a vessel, according to the 2nd order derivatives of the image intensity function, along the central axis of the vessel (S. Aylward *et al*, Proc. of IEEE Workshop, Mathematical Methods in Biomedical Image Analysis, June, 1996). However, vessel tracking is problematic in the vicinity of bifurcations due to inherent ambiguities of direction. Others have proposed segmentation methods which, due to the universal decrease in pixel intensity as vessels taper, can never be entirely accomplished by simple threshold-based region growing. These include the method of McInerney and Terzopoulos (Proc. CVRMed '97, Grenoble, France, March, 1997) and others. These methods are, however, unsuitable for the detection of the smaller vessels where regional nature of the vessels, necessary for segmentation, is almost insignificant.

An ORG method for determining the central axes of the vasculature is discussed in this presentation. This method applied equivalently to the bifurcating and non-bifurcating regions of the vasculature. The method is conceptually simple and allows for high-speed implementation. The ORG is a growth process whereby a region grows outwards from the most intense point on its boundary. If points within a growth region at a given point in the growth process are R_n, points along the boundary are B_n and the new points added to the region are G_n:

$$G_n = \text{Neighbor}(\text{Max}(B_n)) \setminus R_n \qquad (1)$$
$$B_{n+1} = (B_n \hat{E} G_n) \setminus \text{Max}(B_n)$$

Connectivity within the image is then simply the set of all paths along which the above growth process occurred as shown in figure 1.

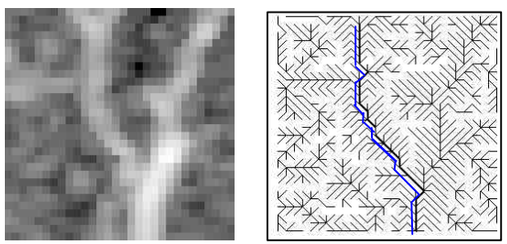


Figure 1. *Endpoint-based skeletonization. The ORG algorithm is applied to a 2D test image. ORG connectivity is established based on a seed point indicated by an arrow in (a) so as to produce a connectivity "tree" whereby each point in the image is connected to all others as shown in (b). The central branches of this tree follow the centers of the prominent bright lines or "ridges" in the image intensity structure which would correspond to vessels in the MRA. A second point is then selected and the path along the connectivity tree was extracted (blue line).*

Materials and Methods

Image Acquisition:
The hepatic MRA's were acquired with gadolinium enhancement from intravenous bolus injection with the 3D spoiled gradient echo (SPGR), 3D time of flight sequence. Image was acquired during single breath hold at a an average of 1.5x3.0x3.0 mm resolution and zero-fill interpolated to 0.7x0.7x1.5 mm resolution.

The COW MRA's were obtained in this region by SPGR 3D time of flight, flow compensated magnetization transfer background suppression, superior flow saturation, 22-cm field of view 1.4-mm thick slices on a 256x224 matrix interpolated to 512x512 and 2X in axial direction.

Hepatic MRA skeletonization and visualization:
Points at the base of the hepatic, the superior mesenteric, and the gastric arteries are chosen as seed points for the ORG algorithm. These are indicated on the maximum intensity projection (MIP) within edited slice ranges from which the 3D locations of the points are inferred based on the origins of points in the 2D MIP. Once the connectivity pattern has been established, , the operator specifies in a similar manner, *distal* points on the vascular tree from which the vasular paths to one of the specified proximal points is produced and superimposed on the MIP in real-time. All such paths are accumulated and at any time an option is provided to "undo" the last branch, which is also carried out in real-time, if an unsatisfactory path is produced due to either inaccurate specification of the endpoint, non-existence of the vascular path due to the limited field of view of the image or other problems causing errors in the connectivity structure. 3D models were created directly from the skeletons with smoothing applied to the vascular paths.

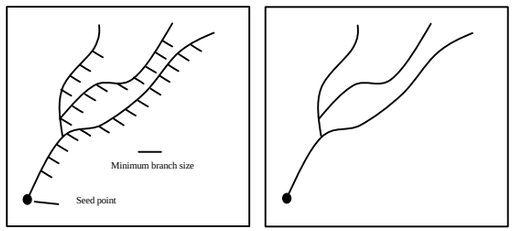


Figure 2. *Branch-length based skeletonization. Raw ORG connectivity tree (left) is trimmed such that no terminal branch has less than a given length to produce skeleton shown on right. The stopping point of the ORG growth can thus be specified as a given number of significant bifurcations.*

Circle of Willis MRA skeletonization:
COW MRA's were skeletonized by application of the ORG connectivity algorithm combined with a trimming algorithm shown schematically in figure 2. In this algorithm, branches are trimmed based on branch length, and bifurcations can only exist if the downstream length of both branches is greater than a given value. Skeletonization is produced by the specification of a single seed point, a given number of desired bifurcations and a cutoff branch length. Also, the image immediately upstream of the seed point must be nulled.

Results

Implementation:
Computation of the complete ORG connectivity takes approximately 2 minutes on a 500 MHz Pentium processor machine for our hepatic MRA data sets and in general is linearly proportional to the size of the data set. Once the ORG connectivity is determined, vessel paths based on user-supplied endpoints are determined and visualized in real-time with the option for re-selecting points if the results are undesireable.

Computation of skeletons of vascular trees in the COW based on branch sizes takes less than 10 seconds on the R10000 195MHz processor.

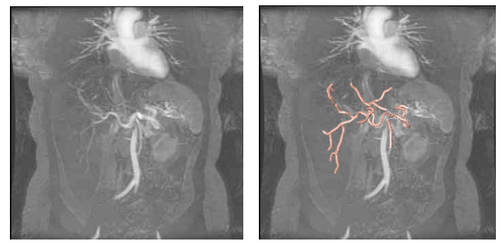


Figure 3. *Comparison of MIP (left) and ORG-skeletonization (right) visualizations of hepatic MRA. One point is supplied by the operator for each terminal point in the skeletonization of the vascular tree.*

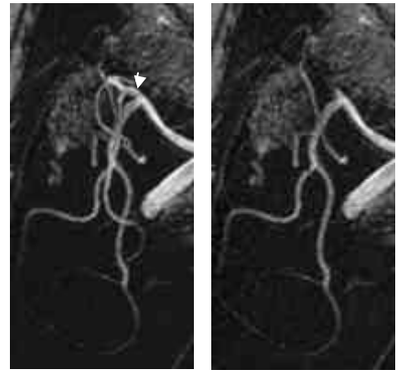


Figure 4. *Disentanglement of vascular trees. Intertwined vascular trees of the COW separated from one another based on a skeletonization. All points within a radius of 2 voxel units of the skeleton downstream from the indicated point (arrow) are nulled in image. MIP of original image is shown on left and MIP of selectively nulled image shown on right.*

Identification of aberrant hepatic arteries in MIP vs. ORG skeletonization:
12 hepatic MRA's were evaluated for number of distinct branches within abdominal arteries with both MIP and ORG skeletonization. Aberrant anatomy was evaluated with both methods and compared with known anatomy determined at surgery. Replaced right hepatic arteries were identified in 3 of 3 cases, all confirmed at surgery. In 10 of 12 cases, more celiac branches could be identified on ORG compared to MIP. In 7 of 12 cases, more superior mesenteric artery branches were identified. In the remaining cases the number of branch vessels was equivalent at ORG and MIP.

Skeletonization of Circle of Willis MRA:
The skeletonization of the COW image was performed with the ORG and the branch-length trimming algorithm. The skeletonization was applied to the middle cerebral arteries and the basilar arteries in 3 COW images with minimum branch lengths of 15 and 25 voxel units and for 5 and 10 bifurcations. Errors in the skeletonization primarily included misconnections of vascular segments such that the downstream direction of a given vascular segment was incorrect. The number of such errors in each skeleton was determined based close visual comparison with the original image and are shown in table 1.

Study Conditions*	Number of Samples	Connectivity Errors (average)
MCA (5,15)	6	2.3±1.5
MCA (10,15)	6	3.0±1.7
MCA (5,25)	6	2.1±1.5
MCA (10,25)	6	3.5±1.4
Basilar (5,15)	3	0.0±0.0
Basilar (10,15)	3	1.0±1.7
Basilar (5,25)	3	0.0±0.0
Basilar (10,25)	3	2.0±1.7

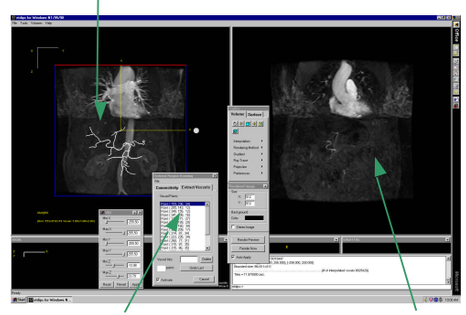
*Format: vessel (bifurcations, number of branches)

Table 1. *Rate of errors in COW skeletonizations. (MCA is middle cerebral artery) Errors are highest in the MCA arterial tree where substantial overlapping of the vessels occurs. Other than these errors, the skeletonization is highly accurate and reliable.*

Conclusions

ORG skeletonization of MRA is a useful method for analysis. Skeletonization of the hepatic MRA allows for clearer visualization of the smaller vessels and is helpful to radiologists both in identifying arteries and in describing the vascular anatomy to others such as for surgical planning. Skeletonization of the COW MRA has significant potential for improving visualization and quantification of the vascular paths provided limited errors can be corrected by other means. The ORG skeletonization process has been implemented within the ETDIPS Windows NT software package (Poster 102, Plug-ins: A Software Model for Biomedical Imaging & Visualization Research) to further the application of this method (figure 5).

3D skeletal lines superimposed on MIP



Vessel segment information

3D selection of points on vessels (within segmented MIP or single slice)

Figure 5. *ORG skeletonization implemented as plug-in to ETDIPS package on Windows NT.*