Analysis of Time-Varying Images Using 3D Vascular Models

Elizabeth Bullitt and Stephen R. Aylward
Departments of Surgery and Radiology, University of North Carolina, Chapel Hill, NC

Abstract

A medical image traditionally represents a "snapshot" of a portion of the patient's anatomy at a particular moment in time. However, the appearance of image objects often varies between images taken at different times. Such changes may occur because of differences in the image acquisition techniques employed, because of shifts in the positions of organs, or because of development, progression, or regression of pathology.

We have developed a method of defining vessel "trees" from 3D image data. These vessel trees can then be registered with any type of 2- or 3D image data obtained from the same patient and that show the vasculature. Changes in vascular configuration can then be used not only to clarify vascular changes over time, but also to help determine the location and/or change in other image objects. As vessels are present throughout the body, the approach is applicable to any anatomical region.

1: Introduction

Medical images generally provide a "snapshot" of a portion of the patient's anatomy at a particular moment in time. A second image, taken at a later time, may show obvious differences. Such changes may occur for at least four reasons. First, some image acquisition techniques are dynamic, resulting in a sequence of related images each of which differs from the others. Second, changes between images may result from changes in the image acquisition process, as may occur if the two studies are of different modalities or employ different parameter settings. Third, organs may shift or deform between images as a result of change in the patient's position, respiratory motion, or an external force such as intraoperative retraction. Finally, changes in image objects over time may occur because the patient's anatomy has itself changed, as may happen with progression or regression of pathology, or as may occur with operative resection of tissue.

Clinically, it is often important to map one image to another for diagnostic and interventional purposes. Such registration may be useful, for example, in tracking the progression of known pathology, in automated identification of new pathological lesions, or in mapping an intraoperative image of low informational content to a higher quality preoperative image. Such mapping can be difficult, however, when the image pairs contain different objects, and/or when the positions, sizes, shapes, and image intensities of common objects may all have changed when the first image is compared to the second.

One approach to the problem is to use vascular anatomy as a roadmap. Vessels are ubiquitous throughout the human body, and provide a network that surrounds and penetrates almost all anatomical structures. Moreover, distortion and stretching of anatomical objects is mirrored by similar deformations of the associated vasculature. Vascular registration therefore has the capacity not only to help track changes in vascular lesions over time, but also to help locate and track changes in other image objects.

We are developing methods of defining connected vascular "trees" from 3D image data, and of registering these vessels with any 2- or 3D data set that also shows the vasculature. The resulting registrations appear not only helpful in following vascular changes over time, but also in placing or comparing other objects visualized in the first image with those seen (or not seen) in the second image. The purpose of this report is to provide an overview of the approach, and to outline some of the clinical applications for which it may prove useful.

2: Vascular segmentation and description

The initial step is to define vessel "trees" from some form of 3D image data. Previous publications have described the protocols for vessel segmentation and graph description [1], [2], [7], [9]. The methodology is applicable to any type of 3D data in which the image intensity of tubular objects is different from that of background. Although our predominant experience is with magnetic resonance angiography (MRA), we have also applied the approach to computed tomography (CT), 3D digital subtraction angiography (3D-DSA), ultrasound, and confocal microscopy.

In brief, each vessel is provided an initial seed point. The program then automatically defines an image intensity ridge representing the vessel's 3D skeleton curve, with a subsequent automatic, scale-based calculation of vessel width at each skeleton point. Graph description is performed largely automatically in a post-processing program. The final output is a set of vessels, each of which is comprised of a set of 3D skeleton points with an associated radius. Each vessel also possesses information about its relationship to other vessels.

Previous work has addressed both the accuracy and the completeness of these methods. The extraction method appears highly resistant to noise both in computer-generated phantoms and in actual patient data [2], [9]. Monte Carlo experiments demonstrate that the approach is largely independent of both initial seed point placement and initial width estimate. Indeed, the maximum variation in 3D skeleton point placement was less than 1/10 voxel and the maximum difference in width estimate was less than 1/5 voxel for all input parameters tested [2]. Clinical evaluations indicate high accuracy of the vessel trees when evaluated against DSA data obtained from the same patient [9]. It takes approximately 15 minutes to extract all discernible vessels from an MRA of the head. We have incorporated display of these vessel trees into a surgical planning program [10].

The creation of a 3D, patient-specific, vascular model provides a description of the patient's vascular anatomy at one moment in time. Registration of the vessel model to a variety of other 2- or 3D images of the same patient can provide the basis for interpreting or analyzing a variety of changes in the image data.

3: 3D-2D registration: Endovascular surgery

Endovascular operations involve guidance of a catheter through a vascular network in order to deliver therapy to a specific target. A difficulty with the approach is that endovascular procedures are typically guided only by flat projection images. While advancing the catheter, the clinician periodically injects contrast material and obtains a projection view. These images show only the connected portions of the vasculature "downstream" of the catheter tip. The interventionalist thus cannot simultaneously visualize other important anatomical structures or even other parts of the vascular anatomy.

The ability to register a 3D, patient-specific vascular model with each 2D projection image provides a basis for aiding the interventionalist in a variety of ways.

3.1: Registration of 3D vessels with 2D DSA data

Dr. Liu [11] designed our vascular 3D-2D registration method. The approach uses as primitives 4-8 2D curves extracted from the DSA and an equivalent number of 3D curves extracted from a 3D data set. The program then optimizes a viewplane based disparity measure based on the iterative closest point paradigm between the DSA skeletons and the projections of the 3D skeletons. Newton's method on the pose parameters in 3D is used to iteratively refine the solution.

Tests using synthetic DSA data, created from projections of vessels segmented from MRA, indicated that, under conditions in which a perfect solution was possible, the maximum 3D point placement error was always subvoxel [11]. Clinical evaluations that compared the approach to manual registration, using vessels segmented from MRA and DSA images of the same patient, indicated the method of vascular registration to be both faster and more accurate [8].

Figure 1 illustrates vessels extracted from an MRA of the head and registered with a DSA image obtained from the same patient. The distal vasculature is not shown, as the MRA did not cover the entire head.

Figure 1. Vessel skeletons (white) extracted from MRA of the head and projected upon a DSA image of the same patient.

3.2: Dynamic imaging in endovascular surgery

Images obtained during endovascular interventions are dynamic, and change from moment to moment during the procedure for a variety of reasons. For example, a sequence of images is obtained after each contrast injection, and this sequence shows the advancing wave front of the contrast material. As the catheter is guided through a vascular tree, the group of vessels opacified by contrast will change, since each contrast injection opacifies only the vessels "downstream" of the catheter tip. If the position of the fluoroscopic imager changes, the configuration of opacified vessels will change on projection.

One of the difficulties in using projection images to guide the endovascular treatment of complex vascular lesions is that projection overlap can make it difficult to determine the proper connected vascular path to reach the desired target. Figure 2 provides an example, using the projection of a 3D-DSA of a patient with an intracranial arteriovenous malformation (an abnormal tangle of blood vessels; AVM). The plethora of abnormal vessels and extensive projection overlap make it difficult to perceive how a catheter should be guided in 3D to reach the desired target. However, use of a 3D, connected vascular model can disambiguate the situation, as a single "point and click" can selectively turn off any desired 3D subtree. Registration of a 3D vessel model with a DSA, and subsequent selective "turning off" of desired subtrees in the 3D model, can thus help interpret the 2D image data.

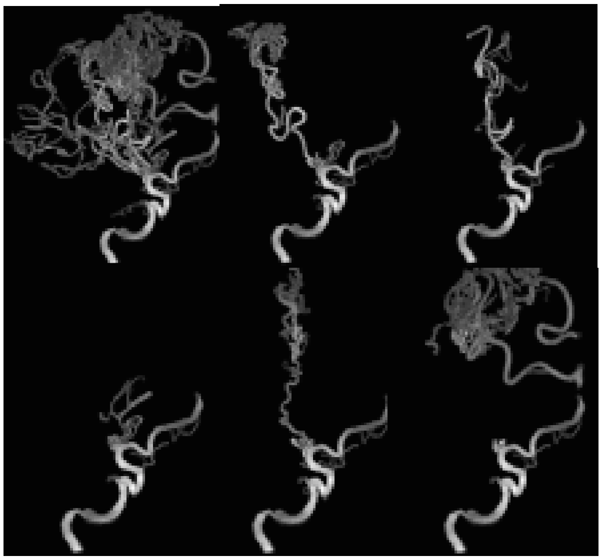

Figure 2. Use of a 3D, connected vascular tree can disambiguate projection overlap.

.

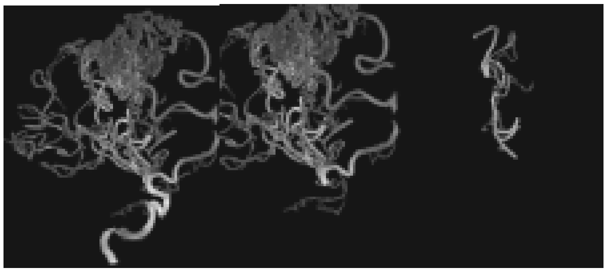

Figure 3. Simulation of catheter passage.

The connected, 3D vascular model can also be used to simulate passage of a catheter through the vascular network. A single "point and click" can turn off all vessels except for those downstream of the click point. This ability allows preliminary assessment of various possible pathways, some of which may be suboptimal, without actually performing the procedure on the patient Figure 3 illustrates this ability. The vessels and point of view are the same as those shown in Figure 2.

An advantage of a 3D vascular tree is that it can be examined from any arbitrary point of view. In such case, it is often desirable to reconstruct the catheter, as seen on a pair of projection images, into 3D so that the catheter can be shown in 3D relative to the 3D vessel tree. We have developed methods of reconstructing tubular objects into 3D from their projections on pairs of fluoroscopic images [5], [6]. Error analysis indicates that reconstruction accuracy is dependent upon a variety of factors including the relative angle of the two projection views, the course of the catheter relative to epipolar planes, and the amount of registration and image distortion error [6].

Figure 4. Reconstruction of a catheter into 3D from a pair of projection views.

Figure 4 shows a 3D vessel tree of the portal veins, segmented from an abdominal CT, and registered with a pair of DSA images (top). The projection of a catheter can be seen entering each DSA image from above (arrows) and penetrating the vessels below. These two projections can be used to reconstruct the catheter into 3D, thus placing it within the same coordinate system as the 3D vessels. The lower pair of images show the 3D vessels together with the reconstructed, 3D catheter (arrows) from two arbitrary points of view.

3.3: Addition of image objects

A disadvantage of procedures guided by DSA images is that DSA tends to show only the set of vessels "downstream" of the vessel in which the catheter lies. Neither other portions of the vasculature nor soft tissue structures, either or both of which may be important to the procedure, can be seen by DSA. During tumor embolization, for example, the margins of the tumor may be invisible by DSA, sometimes making it difficult to determine which vessels supply the tumor and which vessels supply normal tissue. Similarly, the procedure "Transjugular, Intrahepatic, Portosystemic Shunt Formation" (TIPS) involves creation of an artificial pathway between two disconnected portions of the venous system of the liver. During TIPS, the interventionalist must insert a needle through the liver and towards a vascular target that cannot be visualized during needle passage!

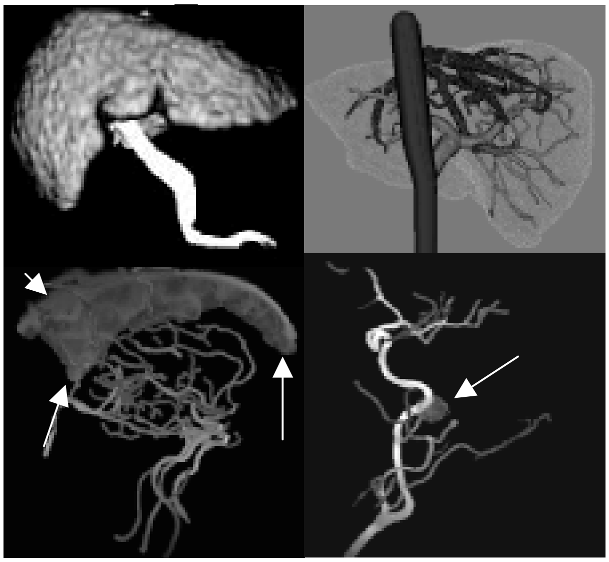

Figure 5. Simultaneous display of other 3D objects with the vasculature.

2D-3D vascular registration allows "insertion" of additional segmented image objects, contained in the initial 3D dataset but not in the DSA image, into a surgical system whose updates are guided by DSA images. Figure 5 illustrates this capacity in 4 different patients. In each case, the projection of one or more additional 3D object(s) is shown in relationship to the 3D vessels which are registered with DSA.

At upper left, the same portal venous system is shown from the same angle of view as in the upper left picture of Figure 4, but the margins of the liver, extracted from the same CT data set from which the vessels were defined, can now also be seen in relationship to the vessels. At upper right, an arterial tree, both venous systems, and the liver boundaries are shown as extracted from the CT of a different patient. The locations of all of these structures are important to TIPS, but normally only a small portion of connected vasculature can be seen at one time by DSA. The lower two images illustrate simultaneous display of the intracranial vasculature with a tumor (arrows), so that the tumor boundaries can be used to help determine which vessels can be safely occluded during endovascular surgery. This kind of additional information is not normally available during endovascular intervention, and can permit better interpretation of the DSA images during the procedure.

4: 3D-3D vascular registration

Dr. Aylward is developing a method of 3D-3D vascular registration [3], [4] which has the potential to address a variety of difficult clinical problems. This section provides an overview of the approach and a brief summary of the kinds of clinical problems for which we believe it will prove useful.

4.1: 3D-3D vascular registration method

The approach to 3D-3D vascular registration performs an initial, rigid-body registration followed by deformable registration. The deformable registration metric is under development, and is not discussed further here.

Rigid-body vascular registration requires a set of tubes extracted from one 3D image and a second image whose image intensities indicate that it contains at least some subset of the same vessels. The method then applies a coarse-to-fine strategy in order to align the tubes defined from the first image with image intensity profiles indicative of vessels in the second image [3], [4]. It takes less than a minute for the process to converge. Monte Carlo experiments indicate that the approach provides extremely consistent (0.1-0.2 voxel and 0.004-0.01 radian standard deviation) registrations of vascular images from different modalities, of different organs, and even if the images contain naturally occurring and surgically induced vascular network changes and localized non-rigid deformations [4].

4.2: Clinical applications

Dr. Aylward's primary motivation in developing the 3D-3D vascular registration metric was to define an

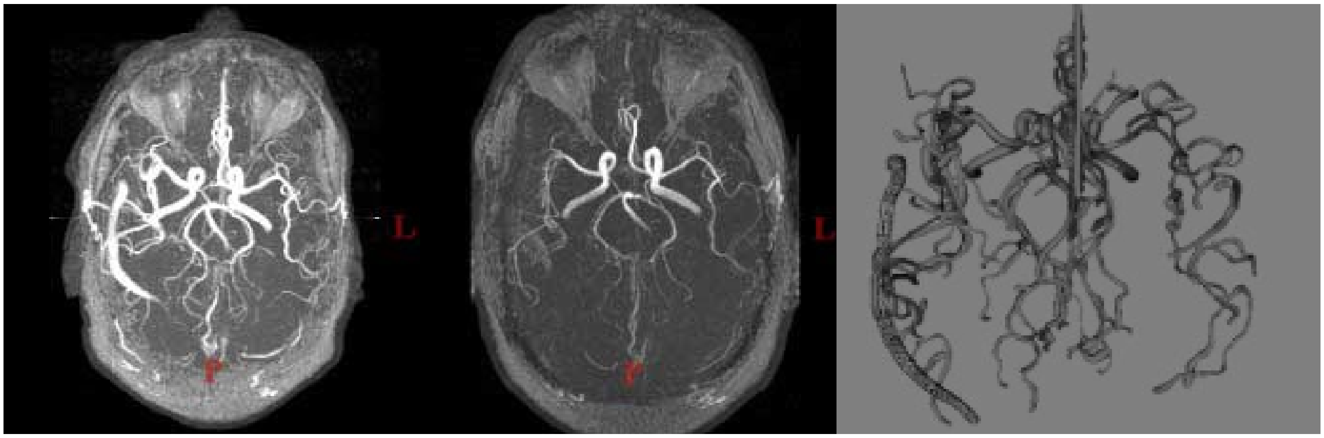

Figure 6. 3D-3D tubular registration of MRA data showing an AVM before (left) and after (center) surgery.

effective means of registering preoperative and intraoperative images. The goal of such registration is interpretation of the generally lower quality intraoperative images within the context of preoperative images of higher informational content. Importantly, anatomical structures depicted by intraoperative images are likely to exhibit deformation as a result of surgical retraction or resection.

A very useful ability would be the capacity to insert anatomical structures defined from the preoperative image into the coordinate system of the intraoperative image, which may not be able to visualize such objects directly. For example, an intraoperative 3D ultrasound image captures vessels well, but may not be capable of localizing a tumor. Vascular image registration permits registration of an intraoperative ultrasound image with preoperative CT data that show both the vessels and a tumor. Dr. Aylward's group is actively pursuing this approach in order to increase the number of liver lesions that can be treated percutaneously.

The same approach can also be used to combine information from different preoperative images. A brain tumor patient, for example, may undergo both MRA, which shows the arteries well but may not show a tumor, and gadolinium enhanced MR, which shows tumors well and will also show some of the arteries and veins. Following 3D-3D vascular registration, the tumor can be displayed in 3D together with the vessels extracted from MRA (see Figure 5). This kind of imagery can be useful in determining which vessels can be interrupted safely during operation [10].

A number of additional projects are under active development in Dr. Aylward's laboratory. One such project uses the tubular registration method to track changes in vascular lesions over time. Figure 6 illustrates registration of MRA images of a patient with an arteriovenous malformation before and after surgery. A distance map can then be used to identify regions of deformation and change [3], [4]. The effectiveness of different surgical techniques, drug treatments, and radiation therapy can thus be quantitatively evaluated, and collateral deformations can be quantified.

Another such project uses the registration method as an aid to automated tracking of growth or change in other objects whose relationship to the vasculature is known. Automated identification of lung nodules using longitudinal multi-detector chest CT data is one such application. Figure 7 shows the ribs, bronchi and vessels extracted from CT data.

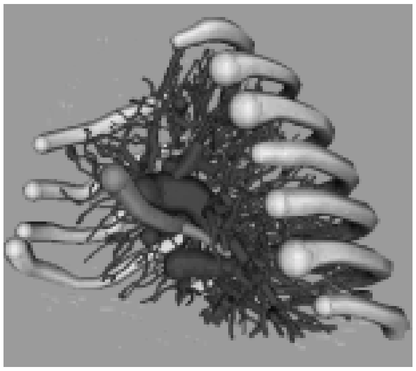

Figure 7. Vessels, bronchi and ribs extracted from chest CT.

It is worth noting that, as shown by Figure 7, neither the tubular object extraction method nor the tubular object registration metric are restricted to blood vessels per se. Indeed, the approach is applicable to any type of tube within 3D image data. Although this paper has concentrated upon vascular applications, the approach is thus also applicable without modification to other kinds of tubular structures such as long bones or ribs, the bronchi, the bowel, and nerves.

5: Discussion

This paper discusses a means of defining tubular objects from 3D image data and of registering such images with other 2- or 3D images that contain at least a subset of the same tubes. Such registration can provide a means of understanding, interpreting, and analyzing a variety of changes that may occur in images taken over time.

An advantage of the approach is that blood vessels exist throughout the human body. The methods outlined here are therefore immediately applicable to a wide variety of disease processes, to a large range of image modalities, and to almost any anatomical region.

An obvious limitation of the approach is that it depends upon the existence of tubular objects within the image data. The method is therefore not applicable to images that fail to display blood vessels or other tubular objects.

It also should be noted that the amount of vascular detail in the 3D vascular model is dependent upon the resolution of the underlying 3D data from which the tubular objects were extracted. DSA images, for example, can display vessels of much smaller diameter than can MRA images of traditional 1 mm interslice spacing. However, the advent of high-resolution CT and MR imaging, which can provide isotropic voxels at submillimeter spacing, as well as the development of 3D-DSA, provides means of defining 3D vessel trees with a much higher level of detail. Figures 2 and 3 illustrate a vascular tree defined from 3D-DSA data.

An active area of research is that of extension of the 3D-3D registration metric to handle deformable registration. An important feature will be automated determination of where and what type of vascular changes have occurred. Such ability could lead to exciting new applications such as accurate mapping of intraoperative ultrasound images to preoperative MR or CT with indication of how much residual tumor remains, even though the intraoperative image may display distortions due to retraction and although tissue may be missing as a result of resection.

References

1. Aylward S, Pizer SM, Bullitt E, Eberly D (1996) Intensity ridge and widths for 3D object segmentation and description *IEEE Workshop on Mathematical Methods in Biomedical Image Analysis* IEEE 96TB100056, 131-138.
2. Aylward S, Bullitt E (2001) A comparison of methods for tubular object centerline extraction. (Accepted *IEEE-TMI* pending minor revision)
3. Aylward SR, Weeks S, Bullitt E (2001) Analysis of the parameter space of a metric for registering 3D vascular images. Accepted MICCAI 2001.
4. Aylward SR, Jomier J, Weeks S, Bullitt E (2001) Registration and analysis of vascular images (Submitted IJCV).
5. Bullitt E, Liu A, Pizer SM (1997) Three dimensional reconstruction of curves from projection views. I. Algorithms. *Medical Physics* 24:1671-8.
6. Bullitt E, Liu A, Pizer SM (1997) Three dimensional reconstruction of curves from projection views. II. Analysis of error. *Medical Physics* 24:1679-87.
7. Bullitt E, Aylward S, Liu A, Stone J, Mukherji S, Coffey C, Gerig G, Pizer SM (1999) 3D graph description of the intracerebral vasculature from segmented MRA and tests of accuracy by comparison with x-ray angiograms. *IPMI 99; Lecture Notes in Computer Science* 1613:308-321.
8. Bullitt E, Liu A, Aylward S, Coffey C, Stone J, Mukherji S, Muller K, S, Pizer SM (1999) Registration of 3D cerebral vessels with 2D digital angiograms: Clinical evaluation *cademic Radiology* 6:539-546.
9. Bullitt E, Aylward S, Smith K, Mukherji S, Jiroutek M, Muller K (2001) Symbolic Description of Intracerebral Vessels Segmented from MRA and Evaluation by Comparison with X-Ray Angiograms. *Medical Image Analysis* 5:157-169.
10. Bullitt E, Aylward S, Bernard E, Gerig G (2001) Special Article. Computer-assisted visualization of arteriovenous malformations on the home pc (2001) *Neurosurgery*: 48: 576-583.
11. Liu A, Bullitt E, Pizer SM (1998) 3D/2D registration using tubular anatomical structures as a basis. *MICCAI ’98, Lecture Notes in Computer Science* 1496: 952-963