Visualizing blood vessel trees in three dimensions: clinical applications

Elizabeth Bullitt*[a], Stephen Aylward[b]
Departments of [a]Surgery and [b]Radiology University of North Carolina, Chapel Hill, NC, 27599, USA

ABSTRACT

A connected network of blood vessels surrounds and permeates almost every organ of the human body. The ability to define detailed blood vessel trees enables a variety of clinical applications. This paper discusses four such applications and some of the visualization challenges inherent to each.

Guidance of endovascular surgery: 3D vessel trees offer important information unavailable by traditional x-ray projection views. How best to combine the 2- and 3D image information is unknown.

Planning/guidance of tumor surgery: During tumor resection it is critical to know which blood vessels can be interrupted safely and which cannot. Providing efficient, clear information to the surgeon together with measures of uncertainty in both segmentation and registration can be a complex problem.

Vessel-based registration: Vessel-based registration allows pre-and intraoperative images to be registered rapidly. The approach both provides a potential solution to a difficult clinical dilemma and offers a variety of visualization opportunities.

Diagnosis/staging of disease: Almost every disease affects blood vessel morphology. The statistical analysis of vessel shape may thus prove to be an important tool in the noninvasive analysis of disease. A plethora of information is available that must be presented meaningfully to the clinician.

As medical image analysis methods increase in sophistication, an increasing amount of useful information of varying types will become available to the clinician. New methods must be developed to present a potentially bewildering amount of complex data to individuals who are often accustomed to viewing only tissue slices or flat projection views.

Keywords: vessels, MRA, surgical guidance, computer-assisted diagnosis, segmentation, registration

1. INTRODUCTION

A complex, connected, plethoric network of blood vessels surrounds and permeates the organs of the human body. Knowledge of the location of individual vessels, the location of branchpoints, the direction of blood flow, the territory supplied by an individual artery, and the shapes of relevant vessels can be critical to a range of surgical applications.

One difficulty when addressing the vascular system, however, is that vessel networks are highly variable. Many pathological conditions (e.g., arteriovenous malfor mations, malignancy, infection, and stroke) may induce ingrowth of new vessels. Other disease states (e.g., atherosclerosis, hypertension, diabetes, and infection) may produce loss of healthy vessels. Both types of disease states, as well as many others, also induce changes to vessel morphology.

To complicate the situation, even healthy subjects exhibit marked variability of vascular patterns. Although a few, large, named vessels can almost always be found in expected locations, there is high variability in the number, location, and feeding territories of child branches, and even in many of the named vessels themselves, which may be absent, present in large or small size, or duplicated[1]. Vessel attributes also are known to change with healthy aging, with a decreased vessel number and an increased vessel tortuosity[2] found in older subjects.

The large variability in even healthy vessel networks means that it is inordinately difficult to define a generic vascular model for more than a few, large, named vessels. The problem becomes increasingly difficult the higher the level of vascular detail required. Unfortunately, surgical planning almost always requires knowledge of much more than the basic level of vascular architecture—indeed, knowledge of the patient-specific, variable portion of the vasculature is often what is MOST important in surgical planning for any particular individual.

Medical Imaging 2005: Image Perception, Observer Performance, and Technology Assessment,
edited by Miguel P. Eckstein, Yulei Jiang, Proceedings of SPIE Vol. 5749
(SPIE, Bellingham, WA, 2005) · 1605-7422/05/$15 · doi: 10.1117/12.604746

A major focus of our group over the last 10 years has therefore been upon the definition of three-dimensional (3D), detailed, patient-specific vascular models from preoperatively acquired image data. The approach is applicable to magnetic resonance angiograms (MRA), computed tomographic angiograms (CTA), 3D-rotational x-ray angiography (3D-DSA), 3D ultrasound, or any other 3D image in which vessels are of higher image intensity than background.

The current paper does not focus upon methods of defining vessel networks, of providing graph descriptions, of registering one vessel network with another, of reconstructing an interventionalist's catheter into 3D from a pair of projection views, or of providing a statistical analysis of vessel shape. The methods employed by our own group have already been described[3-20], and we do not review either our own methods or those of other groups here.

The purpose of the current paper is instead to identify and flag some of the visualization challenges inherent to presenting complex, 3D, vascular information in a way likely to be meaningful to the clinician. Four specific clinical applications are targeted: guidance of endovascular surgery, planning for tumor surgery, intraoperative vessel-based registration, and disease staging based upon vessel attributes. Many clinicians are still only accustomed to viewing 3D slices or 2D projection images from set points of view. As segmentation, registration, and image analysis methods increase in sophistication, new and highly valuable information will become increasingly available to the clinician. How best to present this new and complex information most helpfully is, in many situations, yet unknown. The goal of the current paper is to identify several of the vascular applications in which the development of new visualization methods could be of high clinical utility.

2. GUIDANCE OF ENDOVASCULAR SURGERY

Endovascular operations involve threading a catheter through a vascular network with the goal of delivering therapy to a specific target. This form of minimally invasive therapy has undergone explosive growth over the last 10 years, and is now the procedure of choice for many patients suffering from vascular diseases. A difficulty with the procedure is that it is generally guided only by puffs of contrast injected at irregular intervals through the catheter and captured by an x-ray projection image. The resultant display shows only the connected vascular network downstream of the catheter tip in a flat, projection view. All of the complex, 3D information inherent to the vascular network is thus collapsed into a projection image containing significant vessel overlap. Moreover, relevant additional anatomical structures (tumor boundaries, sensitive structures such as eloquent cortical regions, and other portions of the vasculature) are not depicted.

The ability to provide the interventionalist with useful 3D information about both the connected vascular network and relevant additional structures thus provides an enormous opportunity to improve the clinical standard of practice both in terms of safety and speed. Indeed, the current standard of practice for the treatment of complex intracranial lesions involves a procedure that may last 10 hours or more and may require the acquisition of so many x-ray images from different points of view that the patient may suffer radiation burns.

The following discussion assumes the extraction and effective graph description of a 3D, detailed vessel network from either preoperatively acquired MRA, CTA, ultrasound or other 3D image, or from a 3D rotational angiographic image obtained during the procedure. We also assume both a method of registering the patient-specific vascular model with each new x-ray angiogram as it is acquired, and a means of reconstructing the interventionalist's catheter into 3D from a pair of projection views. The methods employed might be those of our own group, as previously referenced, or those of any other group.

Given the above assumptions, there are at least four display problems inherent to 3D image guidance of endovascular operations. We have found good solutions for the first two but as yet do not have definitive solutions for the others. The problems include:

1) Vessel mismatch between x-ray angiograms and the 3D vessel segmentation,
2) Projection overlap,
3) Choice of 3D vessel display method,
4) Determination of the optimal method to guide catheter advancement.

2.1 Vessel mismatch between x-ray angiograms and the 3D vessel segmentation

Any previously defined 3D vessel segmentation will almost always contain additional vessels not present in a new x-ray projection image, which delineates only the subset of vessels downstream of the catheter tip. Similarly, the new x-ray image will often contain fine vessels not present in the projection of the original 3D segmentation. Figure 1 illustrates the vessel mismatch problem between an x-ray angiogram depicting the connected set of vessels visualized by a selective left carotid injection (Figure 1A) and a projection of a well-registered set of 3D vessels initially defined from a preoperative MRA of the same patient (Figure 1B). Each image contains vessels not present in the other. The resultant display is confusing.

One reasonable solution is to allow the user to “turn off” individual 3D vessels or connected 3D vessel subtrees, enabled by a graph description of the 3D segmented vessels. Figure 1C illustrates the result after two user “point and click” requests to delete the connected 3D trees represented by the portions of the contralateral carotid and the basilar circulations included in the initial segmentation. The x-ray image continues to display some vessels not included in the initial 3D segementation, but the extraneous vessels in the 3D image have been eliminated from view. Interpretation of the resultant display is now much easier. We believe that effective guidance of endovascular surgery based upon predefined 3D vascular models will require both an effective graph description of these 3D models and efficient user control over what is displayed.

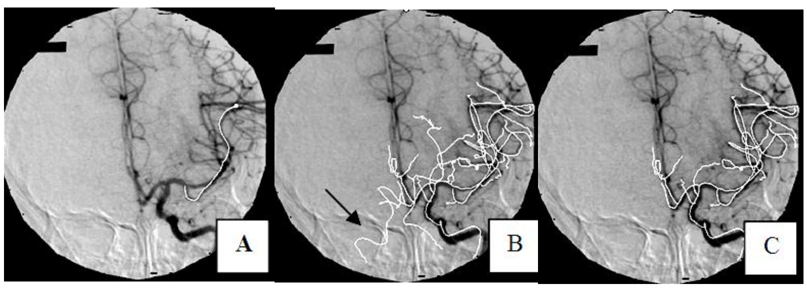

Figure 1. Mismatch between vessels displayed by selective x-ray angiography and well-registered projections of 3D vessels segmented from a preoperative MRA. **A:** Selective left carotid x-ray angiogram shown from an AP view with the skeleton of a single, 3D vessel segmented from a preoperative MRA shown projected in white. **B:** The same x-ray angiogram with the superimposed projections in white of the skeletons of both the contralateral carotid and the basilar circulation as defined in 3D. **C:** A single pair of “point and click” operations have removed the connected trees belonging to extraneous 3D vessels associated with the contralateral carotid and basilar circulations.

2.2 Projection overlap

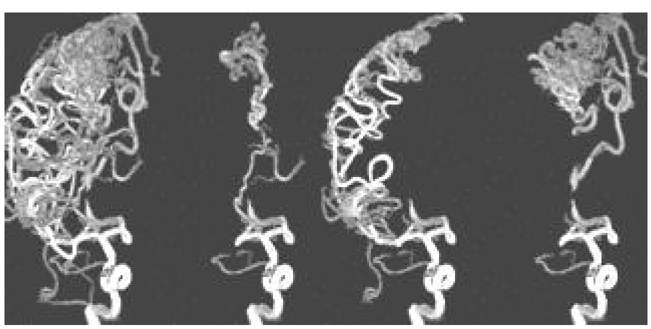

Figure 2. AP view of large arteriovenous malformation. Left: A 3D vessel tree has been segmented from a left carotid 3D-DSA (3D dataset donated by Siemens). Because of the plethora of vessels it is difficult to determine which child vessels are connected to which parent. A 3D, tree-based vessel description allows a single “point and click” to delineate a subtree in a distinctive color or to turn off a selected subtree. The three panels to right illustrate selective visualizations in which various subtrees have been “turned off”, allowing better perception of the 3D, connected vascular anatomy.

A related problem involves projection overlap. As a "reality check" for the clinician, it is essential to first display the 3D segmented vessels registered with each intraoperatively acquired x-ray angiogram. Even when extraneous 3D vessel trees have been hidden using the approach described above, however, there may be large amounts of projection overlap. Figure 2 provides an example, using 3D vessels segmented from a 3D-DSA obtained during treatment of a large arteriovenous malformation. The goal of such operations is to advance the catheter to several critical positions, from each of which it is possible to occlude a subtree supplying the malformation without occluding any vessel branch that supplies healthy brain. A 3D, tree-based display can help greatly in clarifying the connected 3D anatomy since, by a single point and click, one can either color the selected vessel branch and all dependent vessels a distinctive color (not shown) or can delete that branch and associated subtree[13]. Figure 2 illustrates.

2.3 Choice of 3D vessel display method

How most effectively to display a selected subset of 3D vessels superimposed upon an intraoperatively acquired x-ray angiogram is unknown. Figure 1 illustrates one type of visualization, in which 3D vessel skeletons are superimposed upon the x-ray angiogram. This type of visualization allows the interventionalist to view both the x-ray angiographic information and the 3D information simultaneously, but does not include information about the radius of the 3D segmented vessels. Figure 2 illustrates another type of visualization, in which the 3D vessels are shown at full width using selective volume rendering to display each vessel at the image intensity indicated by the original 3D volume[13]. Figure 3 illustrates yet a third type of visualization, in which the 3D segmented vessels have been surface tiled and selectively colored. Many additional visualizations are possible, including surface meshes, elective selection of opacity, and many others. The difficulty is in providing an effective set of rendering methods without offering the clinician a potentially bewildering set of choices. We are currently evaluating a variety of display approaches.

2.4 Determination of the optimal method to guide catheter advancement

An intraoperatively acquired, 2D x-ray projection image can, by definition, only display the patient's anatomy from a single point of view. This image cannot be rotated, and viewing the patient's vasculature from another point of view may require another injection of contrast and an additional x-ray exposure. What the interventionalist requires is, at each moment in time, knowledge of how to best advance, withdraw, or redirect a catheter so as to reach a desired point within a 3D vessel network that is usually shown only as a flat projection image.

An advantage of 3D vessel segmentations is that 3D vessel trees (or user-selected subsets of those trees) can be shown from any arbitrary point of view. We can also reconstruct the position of the interventionalist's catheter from a pair of projection views[8,9] so as to allow a 3D rendering of the current catheter position and projected trajectory relative to the 3D vasculature as shown from any point of view[14, 15]. Figure 3 illustrates a pair of intraoperative, x-ray projection views of the liver vasculature, a set of 3D vessels segmented from a preoperative CTA registered with the 2D image pair, and the inteventionalist's catheter reconstructed into 3D and projected back onto the pair of projection views. The final panel in Figure 3 illustrates the ability to display the segmented vasculature together with the interventionalist's catheter from any arbitrary point of view. The optimal means of presenting complex 3D information to the surgeon is unknown, however.

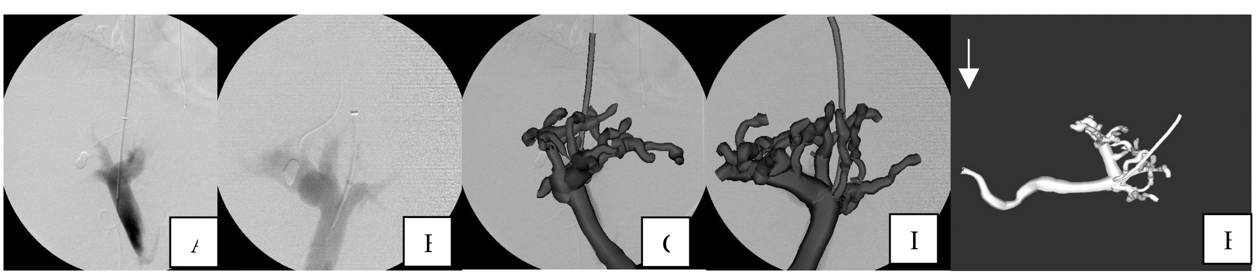

Figure 3. Catheter reconstruction from a pair of projection views. A-B: AP and lateral x-ray angiograms. C-D: 3D vessels segmented from preoperative CTA and registered with and projected upon each angiogram. The catheter is reconstructed into 3D and is projected upon each angiogram. E: The 3D vessels and the interventionalist's catheter (arrow) can now be shown from an arbitrary angle.

We are currently experimenting with 3D, stereo, head-tracked visualizations of the segmented vessels and catheter (Figure 4). The system employs a polarized screen, a lightweight pair of passive, polarized glasses, and an infrared tracker that tracks a marker placed between the eyes of the polarized glasses[14]. The system is wireless, so the physician is not "tethered" by wiring which might hamper movement around the operative field. Another important feature is that the glasses are lightweight and comfortable. Because of the low optical density of the lenses, the physician's vision of the operating field and fluoroscopic images is relatively unaffected. The system is also relatively inexpensive, costing approximately $5,500.

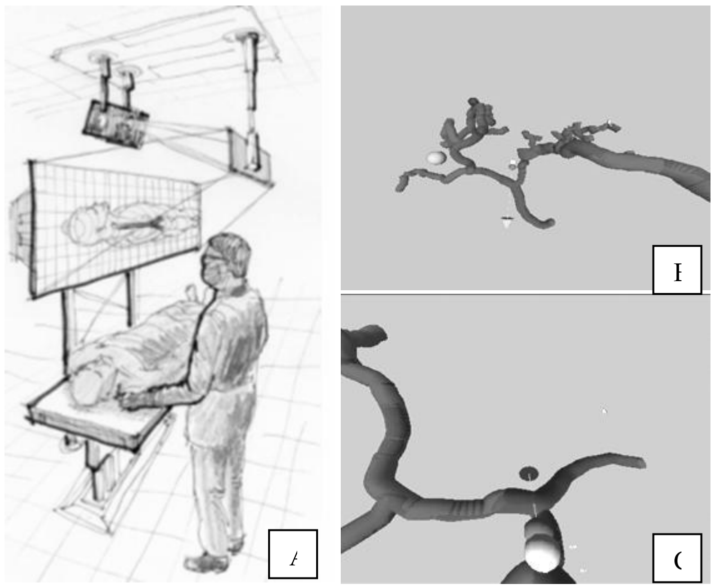

Figure 4. Stereo, head-tracked display. A: Artist's drawing of a potential visualization system for use during transjugular, intrahepatic, portosystemic shunt formation. In this operation, a needle is driven through the liver to connect one venous circulation with another. B: 3D vessels shown from the point of view of one of the original x-ray angiograms. Colored balls indicate two points along the needle and a "target" location that can be interactively selected by the clinician. C: "Needle's eye" view.

One application in which this kind of system may be particularly useful is transjugular, intrahepatic, portosystemic shunt formation (TIPS). In this operation, a needle is driven through the liver to connect one venous circulation with another. The target point is visualized at one point in time during the procedure but cannot be seen thereafter, and, most importantly, cannot be seen during needle passage.

Figures 4B and 4C illustrate two possible visualizations in which two points along the needle are depicted as differently colored balls, and an interactively selected target point is shown as a ball in a third color. In 4B, the vessels are depicted from the point of view of one of the original x-ray angiograms. In 4C, the vessels are shown in a "needle's eye" view, which automatically changes as the angle of needle insertion changes. What the most effective means of visualization will prove to be is unknown. It is also unknown whether the additional information provided by head tracking will prove useful, or even if the use of a 3D stereo display will prove superior to more traditional computer displays. Determination of the most effective method to provide 3D image guidance to a procedure traditionally guided by single projection views is a topic of research.

3. Tumor Surgery

Meningiomas, arteriovenous malformations, and other hypervascular tumors both induce growth of new vessels that feed the tumor and may encase healthy vessels that pass through the tumor to supply normal tissue. When operating upon such tumors one must interrupt the blood supply to the tumor in order to remove it, but one must also spare the vessels that are encased by the tumor and that feed normal tissue. Figures 5 and 6 illustrate. It can sometimes be difficult, when operating upon large, bloody, hypervascular tumors, to determine which vessels can be interrupted with impunity and which must be dissected free of the tumor in what is often a painful, slow, tedious procedure.

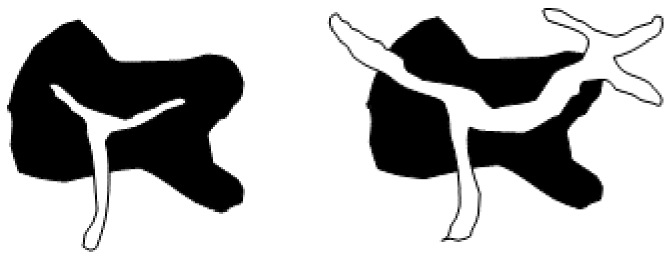

Figure 5. Tumor (black) and associated blood vessels (white). A: The vessels depicted feed only the tumor and can be interrupted with impunity. B: The vessels depicted are encased by tumor and proceed through it to supply normal brain. One therefore should not interrupt these vessels but rather resect the tumor around them, leaving the vessels intact.

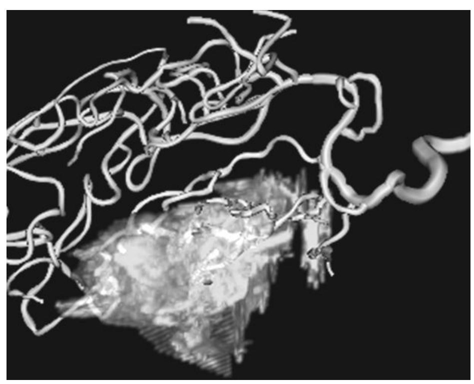

Figure 6. Tumor shown in relationship to a single carotid circulation. The anterior cerebral subtrees have been turned off. Note that the tumor is supplied by several major arterial branches, some of which are partially encased by tumor and exit its surface.

Our group is therefore developing methods of automated tumor segmentation[16,17]. Given a segmented tumor margin and a set of segmented vessels registered with the tumor, one can classify vessels relative to the tumor surface as entirely outside, entirely inside, or traversing. Only those vessels that are entirely inside the tumor, or that only have child branches entirely inside the tumor, can be resected with impunity.

There are at least two display issues critical to the development of an effective, 3D image-guidance system aimed at expressing the relationship between tumors and vessels:

1. Providing meaningful correspondence between the 3D image display and what the surgeon sees intraoperatively,
2. Depiction of uncertainty in regard to possible segmentation errors.

3.1 Providing meaningful correspondence

One obvious means of helping to provide correspondence between what the surgeon sees intraoperatively and a 3D display is to register the 3D images with the patient and to show them from the surgeon's perspective. A variety of methods exist for rigid registration of a 3D image with the patient. A major problem posed by open surgery, however, is that retraction and tissue resection, as well as brain swelling or relaxation, alter the anatomy in deformable fashion, often making meaningful registration impossible. This issue is discussed in more detail in section 4.

Even if one assumes a good registration between the images and the patient, however, a number of significant display issues exist. When looking at the operative field, the surgeon sees only an irregular, curved surface in which potentially important anatomical objects may be obscured. By constrast, the 3D segmentations may contain a plethora of objects, and it may be unclear which object in the 3D display corresponds to which object (or to which portion of which object) the physician is looking at intraoperatively.

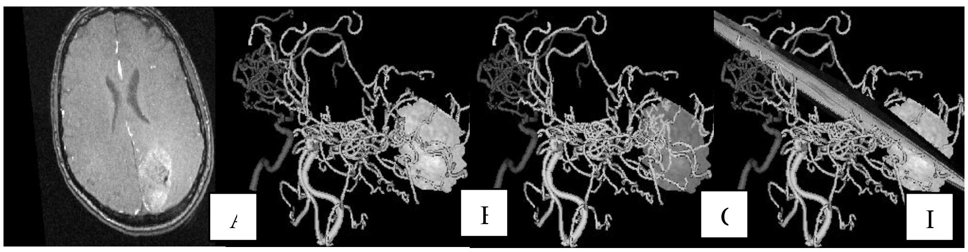

Figure 7. Occipital tumor that encases vessels supplying healthy brain. A: Gadolinium-enhanced T1 slice showing the tumor. B: 3D visualization of vessels and tumor, with the tumor at full opacity. C: 3D visualization of vessels and tumor with tumor at partial opacity. D: The slice shown in A is added to the 3D display to aid with orientation and object identification.

One means of helping to provide meaningful correspondence is to insert an interactively selected slice of the image data into the 3D display (Figure 7). Indeed, several groups are developing methods of registering preoperative images with the intraoperative microscope, allowing automated change of the slice position and orientation as the operator adjusts the microscope's angle and field of view. Other useful display methods include the use of color and of variable opacity.

The issue of how best to present the surgeon with a complex set of 3D objects is far from solved, however. The operator must be capable of perceiving individual structures and the relationship between important structures, of viewing these objects from the most useful point of view (which may not always correspond to the surgeon's view of the operative field), and of associating individual structures in the 3D display with the appropriate structures visualized intraoperatively. How to do this effectively while preserving an intuitive, easy-to-use interface remains an important area of research.

3.2 Depiction of uncertainty

If a 3D display is to be employed for surgical guidance, it is important that the surgeon understand how fully he can trust the images shown. Unfortunately, no method of segmentation or registration is yet perfect. As a result, the clinician may appropriately mistrust any display that provides only hard-edged surfaces with apparent absolute certainty. It would be highly valuable to develop display methods that allow the depiction of varying degrees of uncertainty in at least the segmentations provided. Such uncertainty can often be quantitatively estimated at varying points over a segmented object's surface by the segmentation method itself or by such means as calculation of the image intensity gradient at each surface point.

One potential model of uncertainty is provided by radiation oncologists, who employ concentric isodose curves on slice data to depict varying radiation doses at progressive distance from the target lesion's center. Presentation of such surfaces can be confusing in 3D, however. Indeed, the development of display methods that indicate the uncertainty in the definition of a surface is itself a useful area of research.

We have experimented with selective ray-casting through segmented image objects, allowing progressive dilation of the object's surface[13]. Although the approach is indeed effective in displaying some kinds of segmentation errors, the image must be rotated into an appropriate point of view in order to perceive these errors, and this point of view cannot be determined in advance. Another approach is to coat the object's surface with glyphs whose lengths are proportional to the uncertainty with which that region of the object's surface was defined. This approach also suffers from the disadvantage that that it is difficult or impossible to perceive information for regions other than the margins of the displayed surface from any particular point of view.

The combination of texture mapping with use of partial opacities may be a more effective in displaying two surfaces simultaneously. One of our collaborative groups is currently experimenting with a number of different display methods, two of which are shown in Figure 8, with plans to perform formal psychometric tests to determine which of the methods under evaluation is the most effective.

In general, the display of uncertainty in the segmentation of image objects is an important area of research that has received relatively little attention. The ability to display such uncertainty both clearly and accurately would be of high value in encouraging physician acceptance of new image-guided surgical methods.

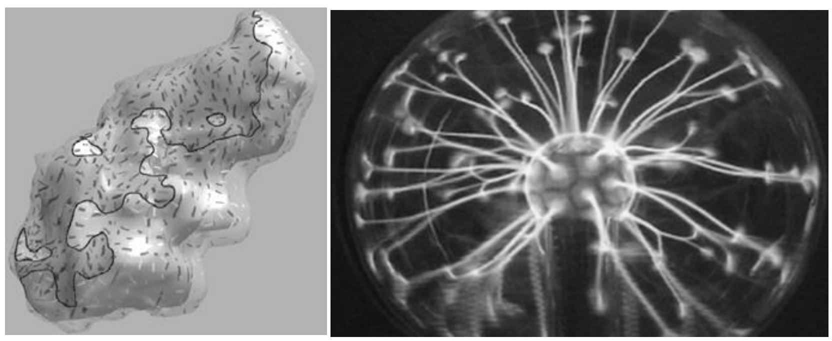

Figure 8. Two experimental visualizations aimed at displaying uncertainty in the segmentation of an object.

4. INTRAOPERATIVE, VESSEL-BASED REGISTRATION

As noted in the preceding section, one of the greatest difficulties in providing useful visualizations of preoperative images during surgical procedures is that surgery itself can alter the underlying anatomy. Resection produces tissue loss, retraction both deforms and displaces anatomical structures, and both tissue swelling and tissue relaxation induce further anatomical alterations. A rigid registration between the patient and that patient's preoperative image data therefore can become useless as the operation proceeds. In those hospitals fortunate enough to possess an intraoperative MR, a tissue-based, deformable registration can realign intraoperative and preoperative images. Tissue-based, deformable registration is often very slow, however, lasting many minutes and sometimes hours, and thus may be impractical for routine use.

An alternative approach is to employ vessel-based registration between preoperative and intraoperatively acquired images[6,18]. There are several advantages to this method. First, since vessels are visualized well by ultrasound, the approach is applicable not only to intraoperative MR or CT, but also to intraoperative ultrasound, which offers a cheap and widely available imaging modality. Second, since vessels are relatively sparse, the method is extremely fast, requiring less than 3 seconds for full image registration. Third, the method can be highly accurate, with phantom studies indicating a maximum point error of 2.3 mm. Figure 9 illustrates the process in a human patient, using preoperative MR and intraoperative 3D ultrasound images.

As also outlined in the previous section, it is highly desirable to provide the clinician with a measure of the accuracy of the segmentation and registration methods employed. An advantage of the vessel-based registration approach is that it can provide an automatic, immediate, visual assessment of the registration accuracy achieved by looking at the degree of overlap of the vessels imaged. Figure 10 provides an example.

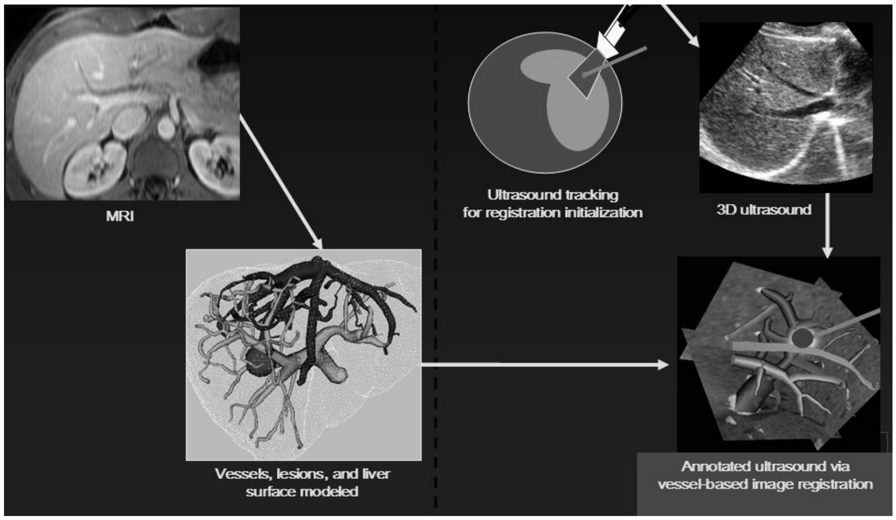

Figure 9. Illustration of vessel-based registration between a preoperatively acquired MR and an intraoperatively acquired ultrasound.

Figure 10. Evaluation of registration accuracy based upon extent of overlap of the vessels imaged by both imaging modalities. The initial picture showed ultrasound in a red channel and MR in a green channel, but the approach can still be perceived in a greyscale image. The arrow points to a vessel visualized by both imaging modalities.

5. DISEASE STAGING BASED UPON VESSEL ATTRIBUTES

Blood vessels surround and permeate almost every organ of the human body. It is therefore difficult to think of any disease process that does not alter vessel attributes (vessel morphology, vessel connectivity, and/or vessel density) in one way or another. Indeed, even the common cold produces vasodilation! Traditional methods of perfusion imaging have proven valuable although the information provided has been largely limited to an assessment of vessel density. The ability to define vessels mathematically allows one to calculate multiple additional measures of vessel shape. We believe that a quantitative, statistical measure of vessel attributes offers a new and highly exciting method of quantitatively assessing multiple diseases.

Our group has been particularly interested in quantitative measurements of vessel tortuosity as applied to the assessment of malignancy. Malignancy induces characteristic vessel shape changes, described as "…a profound sort of tortuosity, with many smaller bends upon each larger bend"[21]. This abnormality is found in a wide variety of malignant tumors including those of the breast, brain, colon, and lung. Important to those interested in *in vivo* MRA and CTA images which do not usually delineate the tiny vessels of the capillary bed, these vessel shape changes are not confined to new, tiny vessel sprouts induced by angiogenesis, nor are they directly related to tissue perfusion[20]. Instead, these shape changes appear to be related to the production of specific growth factors[22]. Vessel tortuosity abnormalities appear within 24 hours of implantation of only a few 10s of cancer cells, affect the initially healthy vessels coursing in the vicinity of the cancer, and spread far beyond the confines of the tumor margins[23]. Moreover, successful tumor treatment results in rapid normalization of vessel shape[23,24]. Indeed, a recent blinded study successfully discriminated all benign from malignant tumors on the basis of vessel shape as determined from preoperative MR images[19], and preliminary work with glioblastoma patients suggests that measures of vessel shape may indeed be helpful in assessing therapeutic response[11].

Figure 11 provides an example of the characteristic vessel shape abnormality associated with malignancy. Note the "many smaller bends upon each larger bend" present in the affected vessels.

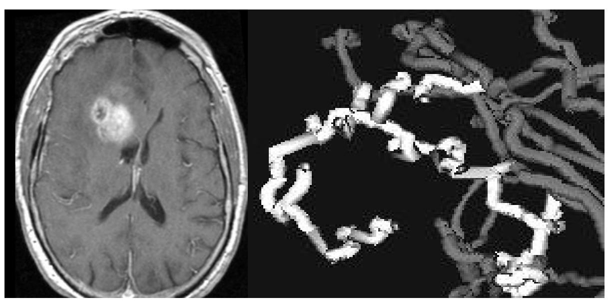

Figure 11. Abnormally tortuous vessels associated with a malignant brain tumor. A gadolinium-enhanced MR slice is shown at left. The right panel provides a magnified view of 3D, tumor-associated vessels (white). The smoother vessels shown in grey lie well outside of the tumor and have more normal shapes.

We are currently displaying tumor vessels only by color-coded classification relative to a segmented tumor surface. Vessels entirely inside the tumor are shown in one color, vessels entirely outside the tumor are shown in another color, and vessels entering, exiting, and traversing the tumor are shown in three additional colors. However, far richer displays are feasible. One could, for example, color-code those vessels whose tortuosity values fall above a threshold and then seek for clusters of such vessels. This approach could allow a potential search for foci of malignancy rather than simply analyzing vessel shapes within a predefined region of interest.

Tortuosity is only one of a great many vessel attributes, any one of which or a selected combination of which could be of value in assessing multiple disease states. In addition to tortuosity, we are also analyzing vessel radius, branching frequency, and vessel density. Additional vessel attribute measures are likely to be of value in the analysis of some diseases. Examples include fluctuations in radius along a vessel, likely to be useful in evaluating vasculitis, or change in expected branching angle, possibly useful in quantifying a tumor's mass effect.

The amount of information available is close to overwhelming. To date, our approach has been predominantly focused upon numerical analysis, with output of files containing numerical results and statistical analyses. However, the development of effective visualizations will also be important, since such visualizations can flag errors, allow intuitive perception of new connections between vessel attribute measures, and enable communication about what quantitative vessel shape measures really mean. How best to display the dizzying combinatorial measures of vessel shape is a wonderful challenge which has not yet been fully met.

6. Discussion and conclusion

This paper discusses means of displaying complex vascular information employing vessel trees segmented from MR, CT, 3D ultrasound, and 3D-rotational angiography. The clinical opportunities are enormous. Some visualization problems seem to have been effectively solved whereas many others are open to future development.

Two general points should be made about the future development of visualization methods for surgical planning purposes. These points are generic, and are relevant to applications that may or may not include the visualization of vessel trees as outlined in the current paper.

First, clinicians tend to be conservative. A mistake may injure a patient. Deviation from an accepted protocol may therefore be viewed with suspicion, and it may take a long time to accept a new approach. A new method is likely to be viewed as more acceptable for trial if the limitations of the approach can be delineated in advance. New methods of segmentation, registration, and visualization will thus be perceived as of higher value if the approach contains an inherent evaluation of its own uncertainty and can be checked by the clinician intraoperatively.

Second, new methods of segmentation, registration, and image analysis are rapidly becoming available. A plethora of clinically useful information can be provided in a fashion that was not available even a few years ago. The development of theoretical methods seems to have generally outpaced the development of display approaches. This situation provides enormous opportunities for those interested in the development of new methods of medical image display.

Acknowledgments

This work was supported by R01 EB000219 NIH-NIBIB and HL69808 NIH-HLB. We are grateful to Andrei State for his drawing in Figure 4 and to Chris Weigle for the visualizations depicted in Figure 8.

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