Advances in image acquisition and reconstruction technology have paralleled the development of endovascular devices. Of particular interest is the application of endovascular grafts to the treatment of aortic aneurysms. Prior publications have defined the feasibility of the use of customized devices to treat aneurysms abutting or involving the visceral vessels. To discuss this technology further, we will describe the use of sophisticated imaging techniques to plan procedures to treat aneurysms of the descending thoracic aorta. Although this region does not have branch vessels of large diameter, the inherent tortuosity, larger aortic diameter, and varied etiology of diseases underscores the need for comprehensive evaluation of the aortic pathology combined with careful procedure planning and device sizing. The follow-up of patients treated with thoracic endovascular grafts is also critical and requires precise image assessment using similar techniques.

Classification of Thoracic Aortic Diseases

The descending thoracic aorta (DTA) extends from the left subclavian artery to the level of the aortic hiatus in the diaphragm, although many consider the portion of the abdominal aorta proximal to the celiac artery origin also to be part of the descending thoracic aorta. Aneurysms are defined as an aortic transverse diameter exceeding twice the normal surrounding aortic diameter. Although aneurysms are defined on the basis of diameter measurements, there is considerable lengthening of the diseased segment as well. Most aneurysms are considered non-specific in nature, implying that we do not fully understand the pathogenesis of this disease. Several theories exist, and experts cite many causative factors including genetic predisposition, atherosclerosis, hypertension, remote infections, and smoking. However, not all aneurysms are non-specific in nature. Aneurysms can be saccular (Figure 1) or fusiform (Figure 2) in nature, the latter being more diffuse, frequently affecting the entire DTA.
Dissections are the second most common cause of thoracic aortic dilation (Figure 3). These occur when there is a tear in the intima of the aorta extending into the media (typically just distal to the left subclavian artery). This split in the aortic wall tends to propagate distally, frequently involving the abdominal aorta, the visceral and iliac vessels. The observed flap within an aortic lumen is characteristic of a dissection, which is managed differently than a non-specific aneurysm (Figure 3).

Other less common conditions exist that are frequently confused with aortic dissections. These include intramural hematomas and ruptured aortic plaques, but are pathologically distinct entities. Additional pathologies that afflict the thoracic aorta must also be considered, including inflammatory diseases, autoimmune diseases, sarcoma and trauma. Therefore, it is important to define the etiology of the aortic disease prior to treatment. This is best accomplished using a variety of image reconstruction techniques that are common to the Aquarius Workstation. For the purpose of this article, we will limit most of the discussion to non-specific aneurysms.
Anatomy
The descending thoracic aorta is bounded on one side by the brachiocephalic vessels (innominate, left carotid and left subclavian arteries) (Figure 4), and the abdominal visceral segment distally. Most aneurysms of the DTA involve the proximal segment, near the brachiocephalic vessels. This region is tortuous and has a diameter typically between 18 and 30 mm. Anatomic anomalies exist, such as aberrant right subclavian arteries, vertebral arteries arising directly from the aorta, and more complex situations such as nutcracker aortas (where the aorta is split and traverses anterior and posterior to the esophagus) that are beyond the scope of this summary, but must be defined prior to the endovascular treatment of aneurysmal disease.

Endovascular devices should be fixated and sealed within healthy aorta. Thus, the importance of assessing the regions immediately proximal and distal to the aneurysmal segment (the neck) is critical. Healthy aorta is typically cylindrical, free of debris along the wall, and not dilated. Endovascular devices typically require 2-3 cm of non-aneurysmal proximal and distal aortic neck. The diameter of the native aorta is measured such that the implant device diameter can be calculated by oversizing the aorta by 15-20%. Determining the length of the aorta to be covered using the center line of flow is necessary to select the length and number of components to be implanted. Most devices are have a maximum length of about 20 centimeters; thus if the aneurysm proper is longer than 15 centimeters, consideration must be given to using multiple devices. Of particular interest is the morphology of the sealing and fixation zones. This has implications as to how the proximal and distal stents will reside along the wall. The overall tortuosity of the aorta will determine whether a delivery system can be readily advanced (extreme tortuosity will preclude most device deliveries), and the morphology of the iliac access vessels will predict where devices may be introduced into the arterial system (femoral versus iliac approach).

CAVEAT: Preoperative CT data acquisition must include comprehensive imaging of the thoracic aorta, brachiocephalic vessels, and abdominopelvic vasculature. Precontrast images should be obtained to highlight regions of calcification. High-resolution studies are optimal with properly timed contrast boluses allowing opacification of the aorta and the proximal portion of all branches. Data should be reconstructed with a smoothing algorithm.
Considerations to Planning and Sizing

The complexity of defining limits of healthy tissue in the thoracic aorta is similar to challenges in the abdominal aortic neck with additional considerations. In a population where prior aortic aneurysm repair is not uncommon, concerns of postoperative neuro-muscular deficit are very real. Aortic tortuosity precludes the use of thin slice axial CT images for the assessment of the region to be treated. Cross sectional images obtained from high-resolution spiral CT scans and reconstructed on a 3D workstation allow clinicians to evaluate these images using MPRs or thin MIPs. “Slicing through” data in axial, coronal and sagittal planes demonstrates the relationship between vascular and other structures, improving the evaluation of a patient’s disease process compared to evaluating axial images alone (Figure 5).

Figure 5: Evaluating vasculature by slicing volumetric data through different planes on the Aquarius Workstation
Given that the aorta should fundamentally decrease in diameter as blood travels distally from the left ventricle, unhealthy aorta can be simply defined as any region of increased diameter. Regions that appear conical on a straightened view are prototypical of aortic pathology that is frequently missed when two-dimensional studies are used in isolation to assess the disease (Figures 6 and 7).

Figure 6: 3D reconstruction demonstrates conical neck distal to curvature in aorta; therefore, the entire proximal fixation (2 – 3cm) must be planned to lie proximal to green arrow.

Figure 7A: Grayscale volume-rendered image showing distal conical neck. The distal fixation in this patient should be planned to lie distal to the green arrow, thereby involving the visceral arteries in the repair.

Figure 7B: MIP post stentgraft. Red arrow shows distal leak. Yellow arrow identifies component of stentgraft abutting the celiac artery.

Figure 7C: MIP after placement of a distal extension with a scallop to maintain distal patency of the celiac artery (yellow arrow).
Thus, the limits of coverage must be defined using CLF (center line of flow) techniques, during which accurate diameter measurements of the regions can be obtained. Using the vessel analysis tools on the 3D Aquarius Workstation, a center line of flow is created by placing “seed points” at the proximal and distal areas of interest (Figure 8). The information then generates a straightened image of the aorta (Figures 9 and 10). This vessel analysis tool additionally enables the physician the option of manipulating the center line of flow in order to simulate the path to which the stentgraft may conform. Orthogonal slices through the center line of flow provide measurements that are then used for endograft sizing (Figure 11).
Tapered Aortas
Under normal circumstances, the diameters of the proximal and distal DTA are not markedly different. However, it is not uncommon to have marked differences in the setting of aortic pathologies. In this situation, when the proximal and distal DTA diameters differ by more than 5 mm, using a tapered device should be considered. Such a device is designed to be 15-20% oversized at the region of the proximal seal and distal seal, rather than compromising the design on one or the other seals. This occurs frequently when a patient has had prior surgery that involves the placement of a graft within the proximal (such as an elephant trunk graft) or distal DTA. Currently, there are no commercially available tapered devices to treat thoracic aortic pathology in the United States; however, both the Zenith (Cook, Inc.) and Talent (Medtronic) are accumulating data on such designs.

The Proximal Landing Zone
It is critical that thoracic devices remain fixed in position and continue to exclude the aneurysm for the duration of the patient’s life. Thus, the proximal sealing zone within the aorta must be carefully chosen. This decision is based primarily on aortic diameter, angulation, tortuosity, calcification, and branches. Aneurysms involving the proximal DTA can be particularly challenging with respect to the proximal landing zone. The intended location of the sealing is most frequently near the left subclavian artery, which is more properly considered the distal aortic arch. This region has inherent tortuosity, forcing the stent to lie upon a lesser (inferior) arch curvature, and appose the greater curvature (superior aspect) of the arch along which the origins of the brachiocephalic vessels arise. This is a treacherous region for a stent with any rigidity. In fact, almost all of the devices when deployed will tend to project along the lesser curvature into the aortic lumen. Although there are potential device designs that will prevent this, the most readily available solution for the interventionalist is to deploy the device in a non-tortuous region. That means deploying distal to the curvature if the proximal DTA is healthy. However, if the proximal DTA is diseased, then a deployment that will cover the origin of the subclavian artery must be considered. This decision should be made during the design and planning phase of the procedure. Regardless of

the landing zone location, the aortic diameter (outer wall to outer wall) should be assessed orthogonal to the center line of flow, and the device oversized by 15-20%. The tortuosity of the arch and status of the proximal DTA should be accurately assessed from the preoperative images to establish an operative plan. Failure to do so will relegate the interventionalist to undesirable outcomes including more complicated procedures, the frequent use of proximal extensions, excessive manipulation or ballooning in the arch, and longer procedure times.

The Distal Landing Zone
In most circumstances, the distal landing zone is simpler to deal with than the proximal landing zone. However, it is important not to underestimate the potential for tortuosity within the distal aorta, particularly as the aorta traverses the left chest to reside upon the anterior aspect of the spine in the region of the diaphragmatic hiatus. Many of the same concerns exist for this region. The operator must delineate the distal margin of the aneurysmal disease, and measure the length and diameter of the distal fixation and sealing zone. The distal device diameter is oversized by 15-20% in a manner similar to the proximal device diameter calculation.

Length of Aortic Coverage
The distance between the proximal and distal landing zones delineates the required length of aortic coverage. Although it may be appealing to simply cover the entire DTA, one must be cautious of the risk of paraplegia, which has been linked to the extent of aortic tissue lined with the endovascular graft. In general, if the amount of coverage is 12 cm or less, a single piece design can be considered. The actual length is a simple calculation based upon the CLF, and most devices have prefabricated devices with lengths in increments of 2-5 cm that will suffice. However, most commonly the diseased segment of aorta is in excess of 12 cm and will require two or more pieces to achieve an optimal result. In these circumstances, there will be an overlap region. The importance of a proper design for this region cannot be overstated. Morphologic changes of the DTA and the endograft over time will result in component separation and sac repressurization if an adequate overlap between components is not planned.
The overlap region between the devices should be planned such that it resides in a relatively straight segment if possible and within the aneurysm proper. A simple way to design devices requiring two components is to plan the first (proximal) piece so that it extends from the origin of the proximal landing zone to just above the distal margin of the aneurysm. The second (distal) component extends from the origin of the aneurysm through the distal landing zone. Thus, the entire aneurysm will then represent the region of overlap. Yet, given the sometimes excessive length of the DTA, a third piece may be required. This piece should be used to supplement the overlap zone rather than constitute the proximal or distal landing zone (Figure 12).

Figure 12: Three-piece stentgraft design (red arrows show areas of overlap)

Figure 13: 3D reconstruction of coarctation patient. White arrow is area of aortic stricture. The red arrow shows significant collateral flow.

Miscellaneous Pathologies
Aneurysms represent the most common manifestation of DTA disease; however, proper assessment of imaging data will allow for the recognition of other pathology. Aortic coarctation (Figures 13 and 14) and dissection are treated using similar techniques with respect to image manipulation, planning and sizing.

Figure 14: 3D reconstruction of same patient post-angioplasty and endovascular stentgraft placement distal to the subclavian artery.
Follow-up Studies
The methods for analyzing migration in a patient with an abdominal aortic device are insufficient when applied to a thoracic aortic device. A 3D scan is needed to make an accurate observation of device stability and device migration within the thoracic aorta since a significant portion of the aorta is oriented parallel to axial images as indicated by the red arrow (Figure 15).

Figure 15: Volumetric image of the thoracic aorta. Red arrow indicates portion oriented parallel to axial images.

The aorta will frequently remodel during the life of the patient following the placement of an endovascular graft within the DTA. Consequently, the assessment of device stability is complicated following endovascular repair. Historically, axial image table positions were used to determine migration of stentgrafts within the aorta. However, a detailed analysis recently published by O’Neill et al. illustrates the complexity of the problem of follow-up and clearly mandates careful image manipulation using 3D tools. In his study, the CLF distance measurement between the left common carotid and the celiac artery was used to assess aortic lengthening. In the absence of aortic lengthening, the distance between a reference vessel (such as the left common carotid origin) and the proximal aspect of the graft is established shortly after implantation and during each follow-up visit. Similarly, the distance between another reference vessel (the celiac artery) and the distal aspect of the stentgraft is determined at various time points. Movement of the device in relation to these reference vessels warrants further investigation. In this case, and in cases of aortic lengthening, attention to the three-dimensional reconstructed image is required. Calcification patterns within the aortic wall that exist in close proximity to the implanted device are used as reference points. If the device position has changed relative to nearby aortic wall patterns, migration must have occurred. However, all of this must be considered in the context of the image resolution at each stage. Not infrequently, careful image assessment of the aortic wall will yield concrete evidence that migration has occurred, as there exists an imprint of the initial device position in addition to a traceable path of slippage.
Device Integrity

In addition to the relationship between the device and the aortic wall, the integrity of the device, and device intercomponent relationships can be readily established using specific reconstruction techniques. Data reconstruction using an edge detection algorithm, rather than a smoothing algorithm, illustrates the ability to detect fractures of the metallic device components (Figure 16 A, B).

**Figure 16A:** The blue line indicates area of overlap in a stentgraft with suspected barb fracture in two locations. Closer inspection using this technology with stent specific template clearly identifies a fracture of both a “z” stent (red arrow) and a longitudinal nitinol wire (red circle).

**Figure 16B:** Enlarging aneurysm of patient with stentgraft fracture.
The degree of overlap between components can be accurately measured, and the relationship between the device and fixed surgical landmarks can also help to assess device movement during follow-up (Figure 17).

Endoleak is also assessed during follow-up using the vascular side-by-side module of the Aquarius Workstation. A non-contrast and contrast CT scan are compared to determine if a true endoleak is present, and its source (Figure 18).

Figure 17: Fixed surgical landmarks are surgical clips (red arrows) and pacing wire (denoted by white arrows) sutured to the distal end of previously placed elephant trunk. Figure on left is at time zero. Comparisons are made at follow-up with respect to migration. This example is evidence that the same amount of overlap of stentgraft is in the elephant trunk at one year.

Figure 18: Endoleak confirmed comparing non-contrast scan on left with contrast scan on right at same table position.
Conclusion
Endovascular technology is expected to benefit the treatment of aneurysmal disease in the chest more than in the abdomen because of the higher morbidity of open thoracic aortic procedures. However, the assessment of long-term durability of the endovascular descending thoracic aorta repair will require compliancy in patient follow-up and sophisticated imaging techniques.

References