Intravascular Ultrasound Imaging as Applied to the Aorta: A New Tool for the Cardiovascular Surgeon

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Intravascular ultrasound is a novel endovascular imaging technology that is useful as an imaging tool for diagnosis and treatment of arterial and venous pathologies. Intravascular ultrasound is particularly useful as a decision-making tool in the endovascular management of vascular pathologies. Recently the aorta has become increasingly amenable to endovascular technology, and with the advent of intravascular ultrasound detailed imaging, using intravascular ultrasound permits the diagnosis and endovascular management of various complex aortic pathologies affecting the abdominal and thoracic aorta. Various aortic pathologies including thoracic and abdominal aortic aneurysms, type B dissections, penetrating aortic ulcers, coarctation of the aorta, and many other aortic pathologies, which were once only amenable by open surgical repair are increasingly being managed with endoluminal technology. As experience develops with this technology, more complex aortic pathologies would become readily amenable to advanced endovascular interventions.

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The explosion of the endovascular revolution with particular application to the aorta has placed new demands on accurate preoperative and intraoperative imaging to obtain accurate aortic measurements for endovascular stent grafting of the aorta [1, 2]. A variety of imaging modalities have been used for preoperative graft planning, including contrast-enhanced spiral computed tomography (CT), digital subtraction angiography, magnetic resonance imaging, three-dimensional rotational angiography transesophageal echocardiography, and lately intravascular ultrasound (IVUS). In patients undergoing cardiac surgery, transesophageal echocardiography and epi-aortic ultrasound have been used to characterize the severity of atherosclerosis within the ascending aorta [3]. This information has been used to modify surgical technique, altering the location of cannula insertion, the position of aortic cross clamps, and the placement of saphenous vein grafts, and reduce the risk of dislodging atheromatous debris. Similarly, in the same fashion, IVUS imaging as applied to the endovascular management of the thoraco-abdominal aorta may provide similar anatomical and morphological information and may represent the optimal modality for preoperative assessment of endovascular stent–graft candidates. Transesophageal echocardiography has been used for many years as an invasive quick reference tool for imaging the aorta, especially in cases of aortic dissections. Transesophageal echocardiography is operator-dependent, and accurate imaging requires the anesthesiologist or cardiologist performing the procedure to be conversant with imaging of aortic pathologies and readily available to perform this steadily when the need is required. Transesophageal echocardiography has a limited role in evaluation of the arch aorta and therefore cannot provide adequate information on burden of the thrombus, presence or absence of an intimal tear in the arch in cases of type B dissections, and accurate sizing of proximal landing zones in patients who require treatment of proximal aortic pathologies. Unlike transesophageal echocardiography, which requires an anesthesiologist or a cardiologist to be present to perform the imaging, IVUS technology requires that the user be adequately versed in the process of performing the acquisition and interpretation of the images, which may also not be a skill acquired by most endovascular sur-

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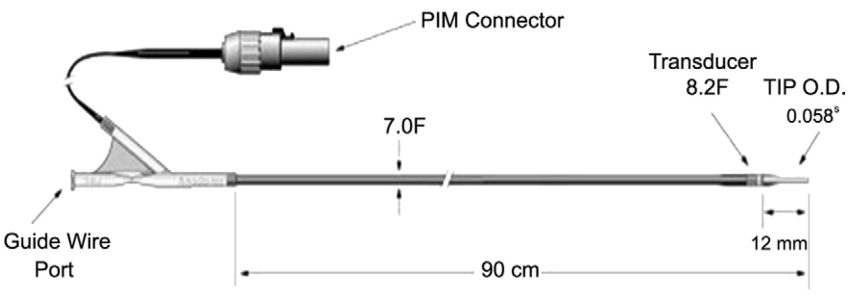

Fig 1. Intravascular ultrasound 0.035 PV catheter system. (PIM Connector = patient interface module connector; TIP O.D. = tip outer diameter of probe.)

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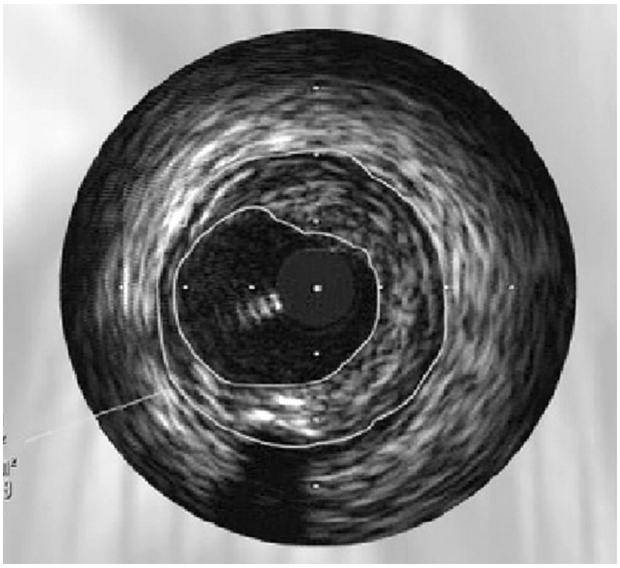

Fig 2. Intravascular ultrasound used to calculate area and percentage of stenosis flow by dividing the lumen diameter by vessel diameter.

geons. Intravascular ultrasound enables full evaluation of the ascending arch and thoracoabdominal aorta including size, tortuosity, and presence of calcification in access vessels used for endovascular management of aortic diseases. Intravascular ultrasound permits adequate sizing of the proximal and distal landing zones, selection of an appropriately sized endograft and assessment of aortic morphology, including atherosclerotic plaque burden to identify patients at highest risk for athero-embolic complications when treating patients with aortic pathologies with an endovascular stent graft.

Method

Unlike traditional cardiac ultrasound that uses an exterior probe and is limited to imaging between the patient's ribs or a transesophageal probe, intravascular ultrasound uses a miniature ultrasound transducer mounted on the tip of a catheter. Due to its intraluminal perspective, IVUS imaging provides information that supplements other imaging modalities such as angiography, CT angiography, and magnetic resonance imaging angiography.

Standard IVUS catheters use a 9-French delivery sheath and a 0.035-inch guidewire (Fig 1), but smaller catheters do exist, such as the eagle eye gold catheter, which uses a 0.014-inch guidewire. The ultrasound transducer emits and receives signals at 12.5, 20, or 30 MHz, producing an axial image (or frame) similar to the cuts from computed tomographic and magnetic resonance imaging. Sizes (in megahertz) increase results in a more detailed image (known as "near vision") with a decrease in size (in megahertz) resulting in more penetration with a larger field of view.

Two-dimensional IVUS images are obtained by passing an ultrasound catheter over a guidewire into the area of investigation. The axial view is a 360° real-time image obtained by rotating the ultrasound beam rapidly around the axis of the catheter. The radius of detection can be altered to suit the diameter of the vessel. In the normal artery, ultrasound waves are reflected differently by various vessel wall components. The reflections from collagen and elastin are stronger than smooth-muscle cells, revealing the muscular media as a hypoechoic circle, distinct from the reflective intima and adventitia.

The use of three-dimensional IVUS technology [4–7] is of particular importance in preventing suboptimal intraluminal device deployment that may not be appreciated on angiography, as well as selecting the size of the endovascular device to use. Intravascular ultrasound three-dimensional images are created by the computer using an edge-tracking formula (algorithm). Consecutive axial two-dimensional images are aligned and stacked longitudinally during a "pullback" of the ultrasound catheter through the vessel. Each picture element (pixel) of the two-dimensional image is assigned a digital position on an X and Y axis. By adding a Z axis, or a third dimension, each square pixel becomes a cubic picture element (voxel). When all the stacked frames are put together, the three-dimensional reconstruction is com-

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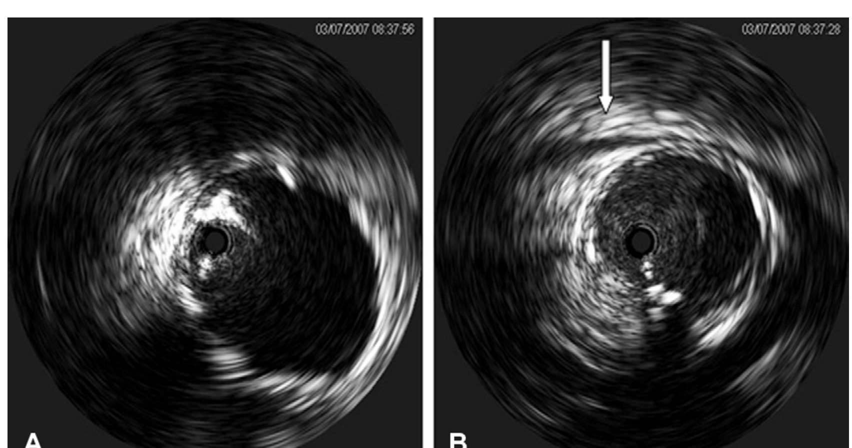

Fig 3. (A) Intravascular ultrasound image demonstrates distal aortic neck without any thrombus and (B) renal vein crossing the aorta (arrow).

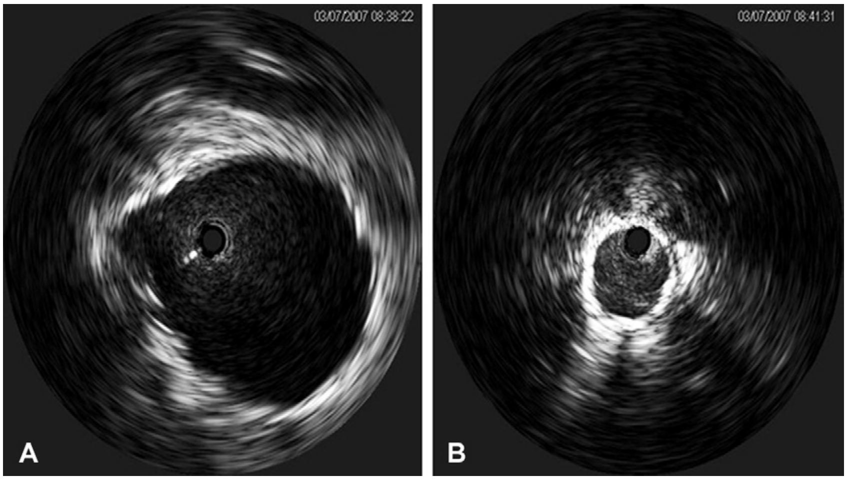

Fig 4. (A) Intravascular ultrasound demonstrates an abdominal aortic aneurysm with thrombus in wall. (B) Intravascular ultrasound image used to assess of size common iliac artery to determine eligibility for endoluminal graft.

plete and can then be examined by the computer software to view the vessel from any angle, slice, or rotation. Three-dimensional reconstruction can assemble the stack of serial two-dimensional axial frames into both a “longitudinal” image and a “volume” image. For acquisition of high-quality longitudinal and volume views, a smooth pullback of the catheter at a steady rate is required. This may be done manually or using a motorized device. In general, 1 mm/s with a 30 frames/s rate are recommended for shorter lesions. For longer areas of interrogation (>7 cm), the frame rate needs to be lowered to 10 frames/s, because the computer can only handle 2,048 frames in one pullback.

Currently in clinical practice there are three types of IVUS catheters that are currently in use for coronary and aortic interventions, the 0.035 PV 8.2-French (Volcano Therapeutics, Rancho Cordova, CA) IVUS catheter system, the 0.014 Eagle Eye Gold (Volcano Therapeutics) IVUS catheter system and the 0.018 PV (Volcano Therapeutics) IVUS catheter system. The 0.035 PV IVUS catheter is an over the wire catheter based ultrasound with an 8.2-French crossing profile at the transducer and a 7.0-French shaft diameter. The minimum sheath internal diameter is a 9-French. The working catheter length is 90 cm, and the imaging diameter is 60 mm, and it is an over the wire device. The 0.014 Eagle Eye Gold IVUS catheter system is a monorail based system with a 2.9-French crossing profile at transducer and a 2.7-French shaft diameter. The minimum guide catheter internal diameter is 5-French. The working length is 150 cm and the imaging diameter of 16 mm. The transducer, however, cannot be flushed, and the catheter is compatible with Volcano Trak Back II and R-100 Pullback devices (Volcano Therapeutics). The 0.018 PV IVUS catheter system is a monorail based system with a 3.5-French crossing profile at transducer, an imaging diameter up to 24 mm, and a working length of 135 cm. The minimum guiding catheter inner diameter is 6-French, and the transducer cannot be flushed.

In addition to providing precise measurements, IVUS also provides important qualitative information on luminal morphology, including the presence of atherosclerotic plaque, calcification, fibrous lesions, and intralumi-

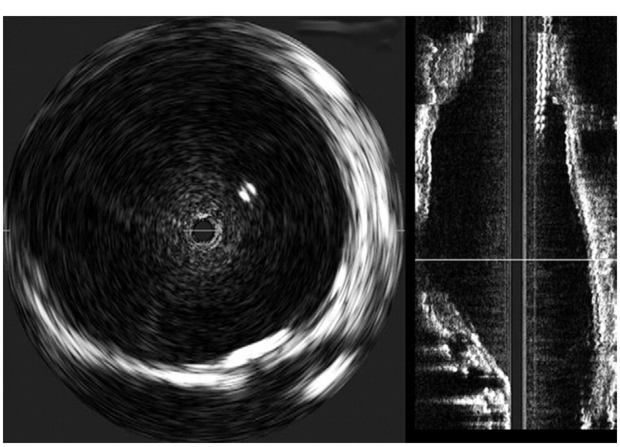

Fig 5. Intravascular ultrasound demonstrates a thoracic aortic aneurysm in an axial view and a longitudinal view demonstrates a conical proximal neck, aneurysm and a distal aortic neck minimal thrombus is seen on the axial and longitudinal views.

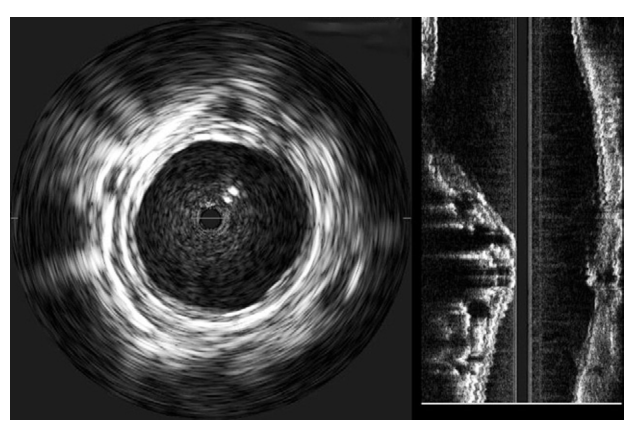

Fig 6. Intravascular ultrasound image demonstrates distal neck of thoracic aortic aneurysm with no demonstrable thrombus adequate site for distal fixation of endograft.

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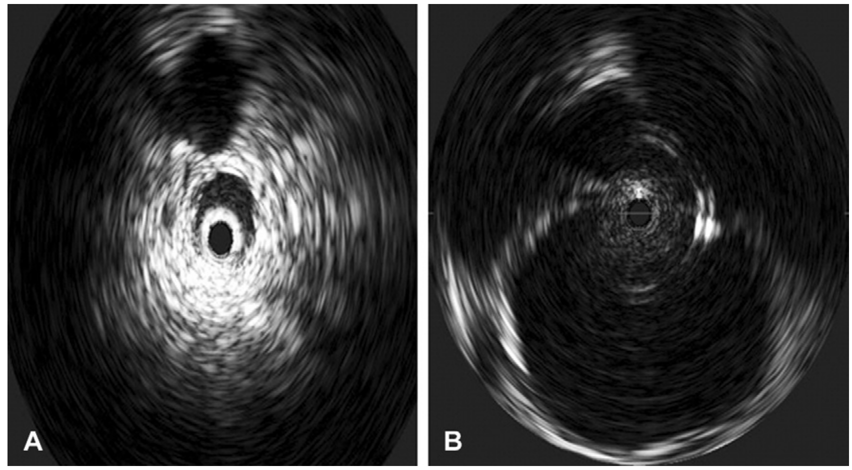

Fig 7. (A) Intravascular ultrasound demonstrating a common iliac artery measuring 8.5 mm with no thrombus and mild calcification amenable to deployment of a stent graft. (B) Intravascular ultrasound used to determine diameter of the proximal neck of a thoracic aortic aneurysm to determine proximal landing zone for endovascular management of thoracic aneurysms.

nal thrombus. A strong correlation has been identified between arterial lumen diameter measurements performed on histologic specimens and IVUS.

Universal IVUS Imaging Applications and Indications

Intravascular ultrasound permits imaging of the vessel wall with identification of branch vessel landmarks. Using the pullback techniques, lumen diameters and cross-sectional area, wall thickness, lesion length, shape, and volume, lesion position within the lumen (concentric vs eccentric), lesion type (fibrous [soft] vs calcific [hard]), presence and extent of flap, dissection, or ulceration, presence and volume of thrombus, length measurements, and diameters of vessels or vessel pathology (or both) can be determined. Tracing of the circumference of a vessel can also be performed to calculate vessel area, size, flow lumen area and size, as well as percentage stenosis (Fig 2). Settings on IVUS include grayscale, which determines level of blackness and whiteness (contrast). The gain enhances the details of the image and the pixel determines increase and decrease matrix. Intravascular ultrasound has multiple advantages, such as imaging of calcification or stenosis, which may affect stent-graft placement. Intravascular ultrasound is critical during the treatment of aortic dissections to confirm guidewire location in the true or false lumens. Intravascular ultrasound catheters also have the advantage of measuring lengths, which are often underestimated by computed tomographic scans. Intravascular ultrasound is also helpful in the identification of the exact location of an aneurysm when intraluminal thrombus may create a normal angiographic arterial lumen at either landing zone. Intravascular ultrasound may be critical in the identification of saccular aneurysm or arterial ulcerations filled by thrombus, and atheromatous sources of arterial emboli may at times be identified only by IVUS. Despite the numerous advantages of IVUS, there are two distinct concerns with the use of IVUS measurements. The first is off-center measurements that distort the image and may mislead the observer. The second is tangential measurements on a curve, which would not reflect a true centerline diameter. Instead, the two-dimensional representation may be an oblique slice through the aorta.

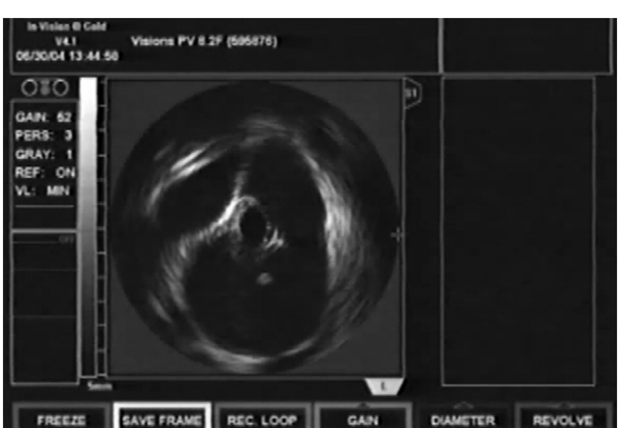

Fig 8. Intravascular ultrasound demonstrates a type B dissection with a dissecting flap separating a compressed true lumen.

Selective IVUS Imaging as Applied to the Abdominal Aorta

Intravascular ultrasound is an important tool that can be applied for endovascular management of infrarenal abdominal aneurysms. Intravascular ultrasound can be used to confirm measurements of the aneurysm size as measured on a routine computed tomographic scan of the abdomen [7]. Using IVUS technology allows one to identify the renal vein as our landmark, and subsequently identification of the diameter and length of the neck to determine suitability for endovascular technology as well as choice of graft. Presence of thrombus at the neck of the aneurysm (Fig 3A) may be a relative contraindication for deployment of an endograft, and this can easily be detected with the help of an IVUS. The distal aortic neck (Fig 3A) and renal vessels can be identified and flow can be assessed (Fig 3B). The diameter of the aneurysm and the characteristics of the neck looking for

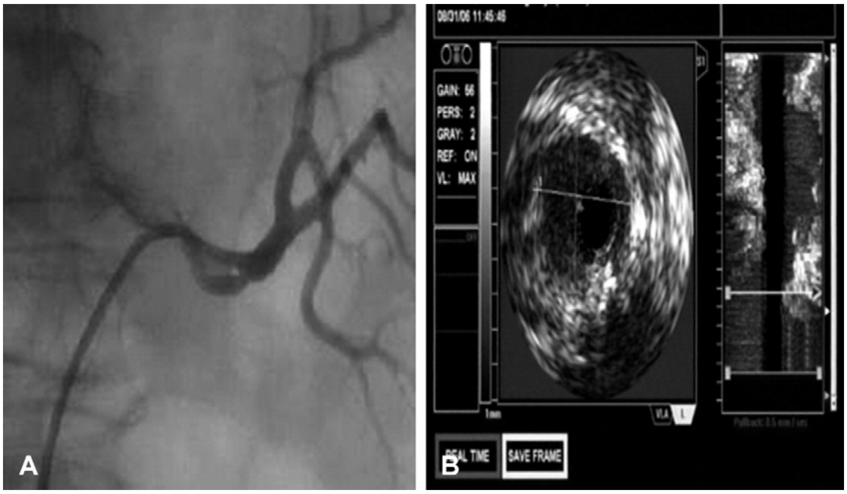

Fig 9. (A) Angiogram in a patient with a type B dissection with renal malperfusion as a result of branch vessel dissection (B) confirmed with intravascular ultrasound.

the presence or absence of thrombus (Fig 4A) is confirmed, and size of the iliac vessels (Fig 4B) is determined for suitability of femoral deployment of an endoluminal graft [8, 9]. Intravascular ultrasound catheter is useful for measurement of length of the distal main body to internal iliac to confirm limb selection and also to visualize the guidewire in "the gate" after the main body is deployed and before iliac extension limbs are deployed. Confirmation of the true diameter of proximal neck and common iliac arteries are determined with the help of IVUS in choosing the appropriate sized balloon(s) for percutaneous balloon angioplasty. Intravascular ultrasound is also helpful for determination of apposition of the stent graft to the aortic wall. A significant advantage of IVUS in comparison with the angiogram is that it may be used instead of the angiogram to save contrast on a patient that has renal insufficiency [10]. The endoluminal graft diameter and length can be determined and deployed using only IVUS technology.

IVUS Imaging Application to Thoracic Aortic Aneurysms

Intravascular ultrasound is useful for the treatment of thoracic aortic aneurysms [11, 12]. Intravascular ultrasound confirms measurements from computed tomographic scans and maps different diameters in the proximal aortic and distal aortic neck, as well as determining actual neck length. Pullback measures centerline lengths, which enable accurate measurement of length and size of aneurysm, proximal and distal neck diameter and lengths. The anatomy can be well-demarcated with demonstration of the branched arch vessels without the need for an angiogram. The absence of thrombus can also be detected in the aneurysm sac and the proximal and distal landing zones are well characterized (Figs 5, 6). Prior to deployment of an endograft, the following information, which includes luminal area and length of proximal and distal necks (Fig 7A), length of aneurysm, or arteriovenous fistula, wall morphology (ie, calcifications, thrombus, and access vessels [Fig 7B]) chosen for endoluminal graft fixation are determined to help select the appropriate sized and length of endoluminal graft. Position of collateral vessels that could produce distal ischemia if they were excluded from the lumen by the endograft can be accurately determined at deployment.

Appropriate endoluminal graft position, appropriate expansion of fixation devices, and proper alignment of graft can be determined. After deployment device fixation is determined to prevent migration as well as con-

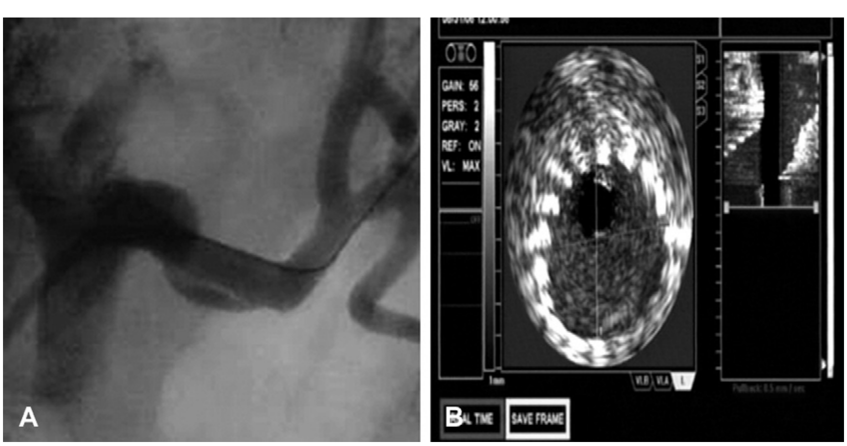

Fig 10. (A) Angiogram post stent deployment with lumen expansion with improvement in renal flow confirmed with (B) Intravascular ultrasound that demonstrates an increased renal lumen diameter with demonstration of a well apposed renal stent.

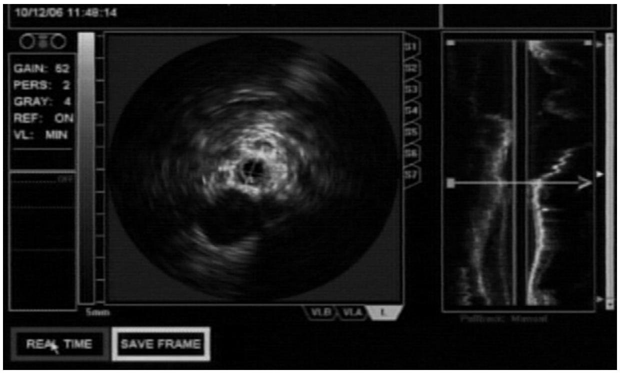

Fig 11. Intravascular ultrasound demonstrating a coarctation of the thoracic aorta with a post-stenotic dilatation.

firmation of exclusion of the aneurysm from blood flow as well as identify the presence or absence of graft kinking, folding, or abnormal motion that might predispose to luminal narrowing, embolization, or graft thrombosis.

IVUS Imaging Application to Thoracic Aortic Dissections

Intravascular ultrasound is an important tool in identifying and confirming the presence of a type A or B dissection [13]. The applicability of managing type B dissections with an endovascular graft depends on the location of the intimal tear, which determines whether one needs to cover the left subclavian artery or not. The dynamics of true lumen flow depends on the state of visceral and renal vessels with respect to if a dissecting flap is present as depicted in Figure 8 where the dissecting flap involves the renal arteries or if the branched vessels are spared. Intravascular ultrasound is able to give us all this information, as well as confirm the true lumen index flow and diameter of the thoracic aorta for device selection. Intravascular ultrasound can be used to confirm angiographic images of branch vessel dissection (Fig 9) and also to confirm accurate apposition of stents used to increase true lumen flow and restore perfusion to the branch vessel organ after stent placement (Fig 10).

IVUS Imaging Application to Coarctation of the Thoracic Aorta

Intravascular ultrasound technology can also be applied to diagnose and treat using an endovascular approach primary coarctation, recurrent coarctation, and post-coarctation pseudoaneurysms [14]. Intravascular ultrasound can be used to measure the diameter of the area of coarctation, the proximal aorta diameter, and the post-stenotic aorta diameter, as well as the length of the area of coarctation (Fig 11). The choice of stent or stent graft can then be chosen and deployed, accurately based on the IVUS measurements. Intravascular ultrasound also can determine proper stent apposition to the aortic wall after balloon angioplasty and provide post-stent measurements to determine success of the procedure, post stent luminal gain (Fig 12), as well as for future follow-up evaluations.

IVUS Imaging Application to Penetrating Aortic Ulcers

Penetrating ulcers (PAU) of the thoracic aorta arise when atherosclerotic lesions rupture through the internal elastic lamina of the aortic wall with subsequent hematoma formation between the media and the adventitia. The ulcers are most often found in the distal descending thoracic aorta, and may be associated with thoracic aortic rupture (Fig 13A). Occasionally it is difficult to differentiate from penetrating ulcers and intramural hematomas of the thoracic aorta clinically. Intravascular ultrasound may be helpful in making this differentiation [15]. Penetrating aortic ulcers may represent one pathology in the spectrum of acute aortic diseases, but it may be associated with aortic dissection and aneurysm formation, although it is distinct from those conditions. Intravascular ultrasound is accurately able to diagnose aortic penetrating ulcers by demonstrating the break in the internal elastic lamina (Fig 13B). Intravascular ultrasound can further demonstrate the extent of ulcers, presence of any hematoma or dissection, and is also important in the selection of device size and length needed to treat penetrating ulcers. Once the endoluminal graft is deployed, accurate deployment and good apposition of the stent graft to the aortic wall can be determined with IVUS.

IVUS Imaging Application for Traumatic Aortic Lesions

Blunt thoracic injury from trauma and thoracic aortic transections result in life-threatening injuries. Oftentimes patients are young and have a small thoracic aorta and suffer from multiple other injuries involving other organ systems. Use of contrast material in this population of patients may accelerate renal insufficiency. Use of IVUS can result in accurate sizing of the thoracic aorta, identification of area of aortic disruption, and is a useful tool in choice and deployment of endoluminal graft [16].

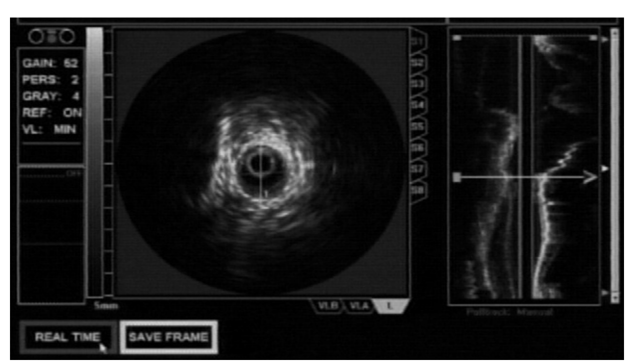

Fig 12. Intravascular ultrasound post stent deployment to treat a primary coarctation of the thoracic aorta demonstrating an increase in luminal gain.

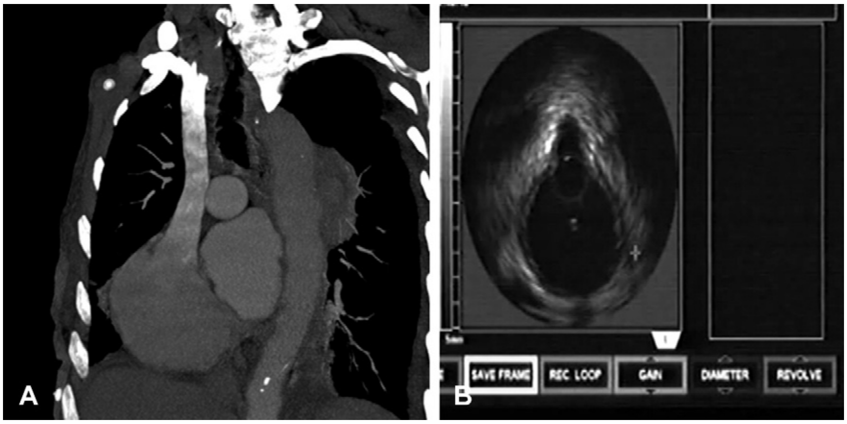

Fig 13. (A) Computed tomographic scan demonstrates a penetrating aortic ulcer of the descending thoracic aorta with contained rupture. (B) Intravascular ultrasound image demonstrates a break in the intima of the descending thoracic aorta compatible with a penetrating aortic ulcer.

Due to the high incidence of the bird beak phenomenon in such patients, especially when the use of an oversized endoluminal graft is used, it is of utmost importance that confirmation of good apposition of the endoluminal graft to the aortic wall is achieved. Intravascular ultrasound can accurately rule out the bird beak phenomenon even when aortograms seem normal.

IVUS Imaging Application in Aortobronchial Fistulas

Aortobronchial and aortoesophageal fistulas are devastating problems associated with patients with previous aortic surgery. Commonly, there is a disruption in the anastomosis resulting in a pseudoaneurysm, which with time may fistulize and result in an aortobronchial fistula with hemoptysis when the airway is involved or hematemesis when the aero digestive system is involved. Intravascular ultrasound can accurately demonstrate the fistulous tract as well as the disruption in the aorta or the formation of a pseudoaneurysm. Accurate sizing of the aorta, as well as length of aorta to be excluded, is accurately determined with two-dimensional or three-dimensional IVUS.

Other applications of IVUS to complex aortic pathologies include diagnosis and therapeutic interventions for pseudoaneurysms, aortic transections, blunt thoracic injuries of shaggy aorta, aortobronchial fistulas, and aortoesophageal fistulas. Virtual histology is a recent modality added to IVUS that is very useful in carotid stenting. Virtual histology is able to differentiate from calcification, fibrous cap, and thin cap. The data from virtual histology enables to determine vulnerability of plaques, including those plaques most likely to embolize when subject to stenting.

Personal Experience

We routinely use IVUS for every single case of endovascular repair of abdominal and thoracic aortic pathologies. We have realized during the years that IVUS was more accurate than computed tomographic angiography measurements, especially for determining the size of the proximal and distal landing zones for aneurysm exclusion in tortuous aortas. Intravascular ultrasound allows us to accurately determine the length of the aorta to be covered, as well as allowing us to determine accurate deployment of the device and ensure that the graft is well apposed to the aortic wall in patients with extensive thrombus in the neck, and also ensure that branched vessels are not excluded with the device in patients with very angulated aortic necks and tortuous access vessels. The use of IVUS to treat complex aortic pathologies, such as penetrating aortic ulcers and dissections, is that the most accurate diagnosis can be made and the most appropriate graft length, size, and device type can be chosen for the specific disease. As we continue to expand the indications for endovascular management of the aorta to involve more proximal arch pathologies, including hybrid debranching procedures and complex aortic pathologies, advanced imaging techniques would be required and need to be mastered by highly advanced endovascular surgeons. Newer endovascular applications for the treatment of structural heart diseases, such as percutaneous and apical heart valve therapies would also require the use of IVUS for adequate sizing, deployment, and troubleshooting, as the management of cardiovascular diseases becomes less invasive in nature.

In conclusion, IVUS technology has opened a new frontier in how we diagnose and treat pathologies of the aorta. As the technology of IVUS improves more advanced thoraco- abdominal pathologies would be treated with advanced endograft technology, which includes fenestrated and branched endograft technology. An interest in adequate training in performing and interpretation of IVUS technology should be encouraged to expand the applications of endograft technology to treat various thoracic aortic pathologies in a safe and minimal invasive manner.

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