Thoracic and Abdominal Aortic Aneurysms

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Aneurysms of the aorta are at times evaluated and treated by physicians from a number of specialties. Indeed, whereas cardiac surgeons operate on the ascending aorta and arch and vascular surgeons manage abdominal aortic aneurysms, at present the responsibility often falls to cardiologists to oversee the medical care of patients with aortic disease of all types. However, although formally trained in “cardiovascular medicine,” most cardiologists devote their attention to the heart and its coronary arteries, and relatively few have experience in the management of diseases of the aorta. It is therefore important that cardiologists acquire a sufficient knowledge base so that they can confidently evaluate and manage patients with aortic disease and know when it is appropriate to refer them for surgery. Toward this end, the purpose of this review is to summarize the current understanding of thoracic and abdominal aortic aneurysms.

Thoracic Aortic Aneurysms

Thoracic aneurysms may involve one or more aortic segments (aortic root, ascending aorta, arch, or descending aorta) and are classified accordingly (Figure 1). Sixty percent of thoracic aortic aneurysms involve the aortic root and/or ascending aorta, 40% involve the descending aorta, 10% involve the arch, and 10% involve the thoracoabdominal aorta (with some involving >1 segment). The etiology, natural history, and treatment of thoracic aneurysms differ for each of these segments.

Etiology and Pathogenesis

Aneurysms of the ascending thoracic aorta most often result from cystic medial degeneration, which appears histologically as smooth muscle cell dropout and elastic fiber degeneration. Medial degeneration leads to weakening of the aortic wall, which in turn results in aortic dilatation and aneurysm formation. When such aneurysms involve the aortic root, the anatomy is often referred to as annuloaortic ectasia. Cystic medial degeneration occurs normally to some extent with aging, but the process is accelerated by hypertension.1

Marfan Syndrome

The occurrence of cystic medial degeneration in young patients is classically associated with Marfan syndrome (or with other less-common connective-tissue disorders, such as Ehlers-Danlos syndrome). Marfan syndrome is a heritable autosomal-dominant disorder caused by mutations in one of the genes for fibrillin-1, which is a structural protein that is the major component of microfibrils of elastin. The mutations result in both a decrease in the amount of elastin in the aortic wall and a loss of elastin’s normally highly organized structure. As a consequence, the aorta exhibits markedly abnormal elastic properties that lead to progressive increases in stiffness and dilatation.2

Familial Thoracic Aortic Aneurysm Syndrome

Cystic medial degeneration is also seen in patients with ascending thoracic aortic aneurysms who do not have overt connective-tissue disorders. Moreover, it is now recognized that although cases of thoracic aortic aneurysms in the absence of overt connective-tissue disorders may be sporadic, they are often familial and are now referred to as the familial thoracic aortic aneurysm syndrome. In an analysis of their large database of thoracic aortic aneurysm patients, Coady and colleagues3 found that at least 19% of patients had a family history of a thoracic aortic aneurysm, and they presented at significantly younger ages than did those with sporadic aneurysms.

Most pedigrees suggest an autosomal-dominant mode of inheritance, but there is marked variability in the expression and penetrance of the disorder, such that some inherit and pass on the gene but show no manifestation of the disease. Several mutations have been identified. A mutation on 3p24.2–25 can cause both isolated and familial thoracic aortic aneurysms, with histological evidence of cystic medial degeneration.4,5 Mutations have also been mapped to 2 other chromosomal loci (5q13–14 and 11q23.2-q24).6 The extent of genetic heterogeneity is likely to become more evident as more families with thoracic aortic aneurysms are studied. It is also possible that this is actually a polygenic condition, thus explaining the variable expression and penetrance. Consequently, at present, it is not possible to perform routine genetic screening for this syndrome.

Bicuspid Aortic Valve

Many cases of ascending thoracic aortic aneurysms are associated with an underlying bicuspid aortic valve. It was once thought that such aneurysms were due to “poststenotic dilatation” of the ascending aorta, but the data suggest otherwise. Nistri et al7 used echocardiography to evaluate young people with normally functioning bicuspid aortic valves and found that 52% had aortic dilatation (44% at the...
level of the tubular portion of the ascending aorta and 20% at the level of the sinuses [ie, root]). Indeed, other studies have demonstrated that a bicuspid aortic valve is associated with a dilated aorta, regardless of the presence or absence of hemodynamically significant valve dysfunction.8

Cystic medial degeneration has been found to be the underlying cause of the aortic dilatation associated with a bicuspid aortic valve. In one study, 75% of those with a bicuspid aortic valve undergoing aortic valve replacement surgery had biopsy-proven cystic medial necrosis of the ascending aorta, compared with only 14% of those with tricuspid aortic valves undergoing similar surgery.9 Inadequate production of fibrillin-1 during embryogenesis may result in both the bicuspid aortic valve and a weakened aortic wall.10 Fedak et al11 examined ascending aortic specimens from those with bicuspid aortic valves and tricuspid aortic valves undergoing cardiac surgery. They found that patients with bicuspid aortic valves had significantly less fibrillin-1 than did patients with tricuspid aortic valves, and the reduction in fibrillin-1 was independent of patient age or aortic valve function. Interestingly, samples of the pulmonary arteries of the same subjects showed a similar reduction in fibrillin-1 content among those with bicuspid aortic valves. This might account for why some patients with a bicuspid valve having undergone the Ross procedure develop late dilatation of the pulmonary autograft (see later sections). Additionally, in a recent study of patients with ascending thoracic aortic aneurysms, Schmid et al12 found that compared with tricuspid aortic valve controls, the aortic aneurysm tissue of those with a bicuspid aortic valve demonstrated more lymphocyte infiltration and smooth muscle cell apoptosis. This suggests that the walls of aneurysms associated with bicuspid aortic valves may be weaker than more “typical” aneurysms.

Because half of those with a bicuspid valve have aortic dilatation, cardiologists should routinely image the ascending aorta in all bicuspid aortic valve patients. In many cases, this can be accomplished with echocardiography. However, whereas the aortic root is easily visualized in most transthoracic echocardiograms, in many cases the midportion of the ascending aorta is not. Consequently, if an ascending aortic diameter is not reported on an echocardiogram, one cannot safely assume that it was visualized and found to be normal in diameter. One might review the images to specifically examine the ascending aorta, but if it was not adequately visualized, one should instead obtain a computed tomography (CT) scan or magnetic resonance imaging (MRI) study to determine aortic diameter.

**Atherosclerosis**

Atherosclerosis is an infrequent cause of ascending thoracic aortic aneurysms. Conversely, atherosclerosis is the predominant etiology of aneurysms of the descending thoracic aorta. These aneurysms typically originate just distal to the origin of the left subclavian artery. The pathogenesis of atherosclerotic aneurysms in the thoracic aorta may resemble that of abdominal aneurysms (see later sections), but this has not been extensively investigated.

**Syphilis**

Syphilis was once perhaps the most common cause of ascending thoracic aortic aneurysms, but in the era of aggressive antibiotic treatment, such luetic aneurysms are rarely seen in modern medical centers. The latent period from initial spirochetal infection to aortic complications is typically 10 to 30 years, although it may range anywhere from 5 to 40 years. During the secondary phase of the disease, spirochetes directly infect the aortic media, causing an obliterator endarteritis of the vasa vasorum, particularly the proximal ascending thoracic aorta. Destruction of collagen and elastic tissues leads to dilatation of the aorta, fibrosis, and calcification. Longitudinal wrinkling of the aortic wall produces a radiographic pattern of “tree barking.” Weakening of the aortic wall leads to progressive aortic dilatation, resulting in aneurysms that may be fusiform but are often sacular. The ascending aorta is most often affected, but aneurysms can involve the arch or root. The ascending aortic involvement often produces secondary aortic regurgitation, and inflammation within the aortic root may result in ostial coronary artery stenoses.

**Turner Syndrome**

Turner syndrome is associated with a number of cardiovascular anomalies, including a bicuspid aortic valve (present in...
one third of subjects) and coarctation of the aorta. Thoracic aortic aneurysms are also found and typically involve the ascending aorta. In a recent systematic study of adults with Turner syndrome, Elsheikh et al.\textsuperscript{13} screened 38 asymptomatic women and found that 42% had aortic root dilatation. Of these, 4 of 38 (11%) had a bicuspid aortic valve and 11 of 38 (29%) had hypertension. This population is at increased risk for aortic dissection and rupture. Indeed, those with both a bicuspid aortic valve and aortic dilatation may be at particularly high risk, given that both the bicuspid aortic valve and Turner syndrome are potent risk factors for aortic dissection. Consequently, it has been recommended that all women with Turner syndrome undergo a complete cardiac evaluation and echocardiographic or MRI examination at least every 5 years to detect potential aortic dilatation.\textsuperscript{14}

### Aortic Arteritis

Takayasu’s arteritis—the most striking of arteritides that affect the aorta—is a chronic inflammatory disease of unknown etiology. The disease affects women far more often than men, and the mean age at the time of diagnosis is 29 years.\textsuperscript{15} It typically causes obliterator luminal changes in the aorta and other involved arteries. However, in 15% of cases, aortic dilatation may occur and result in aneurysms. These may arise either in the acute inflammatory (early) stage of the disease or in the sclerotic (late) stage of the disease. Therefore, the finding of a thoracic aortic aneurysm in a young woman with symptoms of a systemic inflammatory process should raise consideration of the disease.

Giant-cell arteritis typically affects the temporal or cranial arteries but can also affect the aorta and produce aneurysms. In a longitudinal cohort of 169 patients in Olmstead County with giant-cell arteritis, 30 (18%) developed aortic aneurysms (18 thoracic and 16 abdominal).\textsuperscript{16} Overall, 9 patients suffered aortic dissection, and in 2 cases there was no evidence of aortic dilatation as a predisposing factor. Unfortunately, there were no clinically useful predictors of aortic involvement. Ankylosing spondylitis is associated with inflammation of fibrocartilage, and it is hypothesized that the inflammation is directed at tissues rich in fibrillin-1.\textsuperscript{17} Thus, this may be the cause of aneurysms of the ascending aorta.\textsuperscript{18}

### Aortic Dissection

Chronic aortic dissections tend to dilate over time. The affected aortic walls were weakened at baseline (leading to dissection), and after dissection, the outer wall of the false lumen is weakened further because its inner half (the intimal flap) has been dissected away. Consequently, those with chronic aortic dissection are at high risk for aneurysm formation and need to be followed up vigilantly with surveillance imaging studies.

### Trauma

Nonpenetrating traumatic aortic injuries typically occur as the result of deceleration injuries. Most often, the trauma results in a partial or complete transection of the descending thoracic aorta at the level adjacent to the left subclavian artery. The majority of those with aortic transection die within the hour, and others undergo aortic repair during their initial hospitalization. However, in 1% to 2% of such patients, the traumatic aortic transection is not diagnosed initially, and patients may go on to develop chronic pseudoaneurysms at that site. These aneurysms are distinct in that they are typically saccular (rather than the more common fusiform shape), relatively discrete, and located immediately distal to the left subclavian artery.\textsuperscript{19} Over time they tend to calcify.

### Clinical Manifestations

Most patients with thoracic aortic aneurysms are asymptomatic at the time of diagnosis, because the aneurysms are typically discovered incidentally on imaging studies (chest x-ray, CT scan, or echocardiogram) ordered for other indications. Aneurysms of the root or ascending aorta may produce secondary aortic regurgitation, so a diastolic murmur may be detected on physical examination or, less often, patients may present with congestive heart failure. When thoracic aortic aneurysms are large, patients may suffer a local mass effect, such as compression of the trachea or mainstem bronchus (causing cough, dyspnea, wheezing, or recurrent pneumonia), compression of the esophagus (causing dysphagia), or compression of the recurrent laryngeal nerve (causing hoarseness). Rarely, chest or back pain may occur with nondissecting aneurysms as a result of direct compression of other intrathoracic structures or erosion into adjacent bone.

The feared consequence of thoracic aneurysms is aortic dissection or rupture (often referred to as an acute aortic syndrome), which is potentially lethal. Typical symptoms of acute aortic syndrome include the abrupt onset of severe pain in the chest, neck, back, and/or abdomen.

### Diagnosis and Sizing

Often, thoracic aortic aneurysms are evident on chest x-ray films and are characterized by widening of the mediastinal silhouette, enlargement of the aortic knob, or tracheal deviation. However, smaller aneurysms and even some large ones may not produce any abnormalities on chest x-ray films. One should be cautious in interpreting a radiology report that describes an abnormal aortic silhouette as an “ectatic aorta.” “Ectasia” is formally defined as dilatation of a vessel, but commonly radiologists use the term to describe a tortuosity of the thoracic aorta that often occurs with later age (see discussion). In fact, on the basis of the chest x-ray film alone, one cannot typically distinguish whether an enlarged aortic silhouette represents a tortuous aorta or the presence of an aneurysm. Consequently, if a chest x-ray film shows an enlarged aortic silhouette, one should have a low threshold for ordering a tomographic imaging study (eg, CT scan) to define the aortic anatomy.

Contrast-enhanced CT scanning and MR angiography are the preferred modalities to define aortic (and branch vessel) anatomy, and both accurately detect and size thoracic aortic aneurysms (Figure 2). However, the specific aortic anatomy may dictate which imaging study is optimal. For example, when aneurysms involve the aortic root, MR is preferable to CT scanning, because CT images the root less well and is less accurate in sizing its diameter.

When imaging a tortuous thoracic aorta, which is common among the elderly, one must use caution in measuring the aortic diameter on axial images; such images may slice
through the aorta off-axis, resulting in a falsely large diameter (Figure 3A). One option is to reconstruct the axial data into 3-dimensional images (ie, CT angiography), with which one can then measure the tortuous aorta in true cross section to obtain an accurate diameter (Figure 3B). An alternative is MR angiography (Figure 4), which images the thoracic aorta in multiple planes and therefore readily permits on-axis measurements.

Transthoracic echocardiography is effective for imaging the aortic root (Figure 5) and is thus often used to evaluate patients with Marfan syndrome. However, it does not consistently visualize the mid or distal ascending aorta well, nor does it well visualize the descending aorta. Therefore, other than for those with Marfan syndrome, transthoracic echocardiography should generally not be used for diagnosing and sizing thoracic aortic aneurysms. Although transesophageal echocardiography can visualize the entire thoracic aorta well, given its semi-invasive nature it is not favored for the routine imaging of those with stable (nondissecting) thoracic aneurysms.

Natural History
The natural history of thoracic aortic aneurysms has not been well defined. One reason for this is that both the etiology and location of an aneurysm may affect its rate of growth and propensity for dissection or rupture. A second reason is that it is rare, in the era of modern imaging and aneurysm sizing, to actually allow known aneurysms to grow until they rupture, because surgery is usually performed when aneurysms are just large enough to be considered at significant risk for rupture. Although some patients with large aneurysms do not undergo surgery, they are usually elderly or have important comorbidities, thus increasing their mortality, irrespective of the aneurysm.

On the basis of longitudinal data from the Yale group, Davies et al\textsuperscript{20} found that the mean rate of growth for all thoracic aneurysms was 0.1 cm/y. The rate of growth, however, was greater for aneurysms of the descending aorta versus ascending aorta, was greater for dissected aneurysms versus nondissected ones, and was greater for those with Marfan syndrome versus those without. Initial size is an important predictor of the rate of thoracic aneurysm growth. However, even controlling for initial aneurysm size, there is still substantial variation in individual aneurysm growth rates,\textsuperscript{21} thus making it difficult to prospectively predict growth for a given aneurysm. Therefore, all aneurysms need to be followed up with regular surveillance imaging to monitor growth. With regard to aneurysm size and the risk of
rupture or dissection, in their series Davies et al.\textsuperscript{20} found an annual rate of 2% for aneurysms $<5$ cm, 3% for aneurysms 5 to 5.9 cm, and 7% for aneurysms $\geq 6$ cm in diameter. Therefore, the risk appears to rise abruptly as thoracic aneurysms reach a size of 6 cm.

**Management**

**Surgical Treatment**

The optimal timing of surgical repair of thoracic aortic aneurysms remains somewhat uncertain, given the limited data on their natural history. For most ascending thoracic aortic aneurysms, surgery is indicated at a diameter of $\geq 5.5$ cm. Among those with an increased operative risk (eg, the elderly or those with comorbidities), we will typically raise the threshold to 6 cm or more before recommending surgery. Conversely, among patients who are at increased risk of aortic dissection or rupture (eg, Marfan syndrome or bicuspid aortic valve), we often recommend ascending aortic repair when aneurysms reach only 5 cm and in selected cases (those at especially high risk), at even smaller diameters.\textsuperscript{22} Moreover, when patients with a bicuspid valve require aortic valve replacement surgery, we recommend prophylactic replacement of the ascending aorta if its diameter is 4 cm or greater, given that we now recognize that such patients would otherwise remain at high risk for subsequent aortic dissection. For most descending thoracic aortic aneurysms, we recommend surgery at an aortic diameter of 6 cm or greater.

**Ascending Thoracic Aortic Aneurysms**

The mortality of elective surgical repair of ascending aortic aneurysms in large centers is 3% to 5%. Thoracic aortic repair requires cardiopulmonary bypass (there is no “off-the-pump” option), and the aneurysm is generally resected and replaced with a prosthetic Dacron graft of appropriate size. When the aneurysm involves the aortic root and is associated with significant aortic regurgitation, one usually performs a composite aortic repair (Bentall procedure) by using a tube graft with a prosthetic aortic valve sewn into one end. The valve and graft are then reimplanted into the Dacron aortic graft (Figure 6).
Alternatively, when the aortic valve leaflets are structurally normal and the aortic regurgitation is secondary to dilatation of the root, a valve-sparing root replacement may be performed (Figure 7). This technique, advanced by Dr Tirone David, involves excising the sinuses of Valsalva while sparing the aortic leaflets, sewing a Dacron graft to the base of the aortic annulus, and reimplanting the aortic valve leaflets within the graft to restore their normal anatomic configuration. When successful, this procedure avoids the need for prosthetic valve replacement and the associated long-term risks and reduces the risk for repeated valve surgery. In a series of 151 patients with aortic root aneurysms who underwent valve-sparing surgery, David et al found that at 8 years of follow-up, 67% had mild or no aortic regurgitation, whereas only 2% developed severe aortic regurgitation.

Some younger patients have a dilated aortic root, but because of intrinsic valve dysfunction, the aortic valve cannot be spared. For those wishing to avoid the prosthetic valve required with the composite aortic graft, one option has been a pulmonary autograft, also known as the Ross procedure. In this procedure, the patient’s own pulmonary root is then excised and transplanted into the aortic position. The pulmonary root is, in turn, replaced with a cryopreserved pulmonary (or aortic) homograft. Though conceptually attractive, the procedure has not been free of complications. One of its major limitations is the development of late autograft root dilatation, which is particularly problematic among those who had aortic root dilatation preoperatively. In one series of 91 patients, the incidence of pulmonary autograft root dilatation was 61% at 5 years among those with a prior aortic aneurysm, compared with 27% among those with no prior aortic aneurysm (ie, those who had surgery for aortic valve disease only).24

When full aortic root/valve replacement is necessary, another alternative to a composite graft is the use of cryopre-
periods of surgery. In fact, the use of the multilimbed, prosthetic aortic graft has made such selective antegrade cerebral perfusion easier and more effective. The data available thus far suggest that selective antegrade cerebral perfusion significantly reduces the incidence of temporary neurological dysfunction, although its impact on stroke risk remains unclear.27

Descending Thoracic Aortic Aneurysms
The most feared nonfatal complication of resection of descending thoracic and thoracoabdominal aneurysms is postoperative paraplegia secondary to interruption of the blood supply to the spinal cord (Figure 9). Fortunately, a number of methods have been introduced to reduce the likelihood of paraplegia; these include regional hypothermic protection of the spinal cord by epidural cooling during surgery, cerebrospinal fluid drainage, reimplantation of patent critical intercostal arteries, the use of intraoperative somatosensory evoked-potential monitoring, and maintenance of distal aortic perfusion during surgery with the use of antegrade bypass to the distal aorta. With the use of these adjuncts, the incidence of paraplegia has fallen from a historical rate of 13% to 17% to a rate of 5% to 6% in most modern series. Elective surgical repair of descending thoracic aortic aneurysms is also associated with a mortality rate ranging from 5% to 14%. Importantly, a recent study of surgical repair of thoracoabdominal aortic aneurysms found that surgical mortality was substantially higher in low-volume hospitals and for low-volume surgeons compared with high-volume hospitals and high-volume surgeons.28

An alternative approach for the repair of descending thoracic aneurysms is the use of a transluminally placed endovascular stent-graft (Figure 10). This technique has the advantage of being far less invasive than surgery, with potentially fewer postoperative complications and lower morbidity. Ellozy et al29 recently reported a series of 84 patients receiving endovascular stent-grafts to treat descending thoracic aortic aneurysms. Primary technical success was achieved in 90%, and successful exclusion of the aneurysm was achieved in 82%. However, major procedure-related or device-related complications occurred in 38%, including proximal attachment failure (8%), distal attachment failure (6%), mechanical device failure (3%), perioperative death (6%), and late aneurysm rupture (6%). More encouraging was the fact that only 3% suffered persistent neurological complications. Compared with open surgical repair, endovascular stent-grafting does appear to have an acceptable perioperative morbidity and mortality, but clearly, technical refinements need to be made before it can become a routine treatment for such aneurysms. At present, it is best reserved for those with ideal aortic anatomy or those who are otherwise poor surgical candidates.

Staged Repair
Some patients requiring surgical repair have aneurysms that involve multiple aortic segments (the ascending, arch, and/or descending thoracic aorta). Trying to repair both the ascend-
ing and descending segments in one operation is both challenging and risky. Therefore, most centers will address these complicated situations by performing staged procedures, with repair of one aortic segment (ascending or descending) first, to be followed at a later date by a second surgery. The order of surgical repair is dictated by the individual’s specific aortic anatomy—for example, depending on which aortic segment is at greatest risk of rupture and where the surgeon can expect to place the aortic cross-clamp.

However, in some cases, the lack of an adequate neck (a relatively nondilated segment of the proximal descending aorta) makes it difficult to perform such a staged procedure. In such cases, an alternative staged surgical approach known as the “elephant trunk” technique is used. The first part of the surgery is, for the most part, similar to the standard ascending aneurysm and total arch repair. However, the distal end of the arch aortic graft is several centimeters longer than the native arch, so that after the anastomosis is made to the proximal descending aorta (just distal to the left subclavian artery), the excess length of the graft is left protruding distally within the lumen of the descending thoracic aortic aneurysm. In the second stage of this procedure, the descending or thoracoabdominal aortic aneurysm is repaired via a standard left thoracotomy. However, the surgeon cross-clamps the distal end of the existing elephant trunk (rather than clamping the dilated native aorta), and the proximal end of the new descending aortic graft is now anastomosed to the free distal end of the elephant trunk.

**Medical Management**

The medical therapies available to slow the growth of thoracic aortic aneurysms and reduce their risk of dissection or rupture are quite limited. In a randomized study of adults with Marfan syndrome, Shores et al found that treatment with propranolol (versus no β-blocker therapy) over 10 years resulted in a significantly slower rate of aortic dilatation, fewer aortic events, and lower mortality. Unfortunately, whether these benefits can truly be extrapolated to the non-Marfan population with thoracic aneurysms remains unknown. Nevertheless, it is mechanistically logical that medical therapy to reduce dP/dt and to control blood pressure would be beneficial for the treatment of all patients with thoracic aortic aneurysms. Moreover, given the safety of β-blockers, there is no downside to presumptive therapy, provided it is well tolerated. There is some early experimental evidence to suggest that oxidative stress may play a role in the pathogenesis of atherosclerotic thoracic aortic aneurysms and that perhaps statin therapy and angiotensin II receptor blocker therapy may potentially have a protective effect. However, much further research is needed before any therapeutic implications can be drawn.

Once β-blocker therapy is maximized (or in the event that β-blockers are contraindicated or not tolerated), any persistent hypertension should be treated with other antihypertensive agents to bring the blood pressure down to a low-normal range, eg, a systolic pressure of 105 to 120 mm Hg. “White-coat hypertension” is not uncommon among patients undergoing evaluation for aneurysms, and it may therefore be challenging for a physician to determine whether or not the in-office blood pressure is truly representative. Consequently, it is often helpful to have a patient use an automatic arm blood pressure cuff to regularly monitor his or her response to therapy and thereby confirm that the blood pressure is within the prescribed range.

Although the majority of aortic dissections appear to occur spontaneously, a minority are known to occur in the setting of strenuous isometric exertion. Patients should therefore be counseled to avoid heavy lifting or straining, because these activities may abruptly increase intrathoracic pressure and blood pressure. Aerobic exercise is generally safe, provided the patient does not have a hypertensive response to exercise. Consequently, should a patient wish to engage in vigorous aerobic exercise (eg, running or biking), it is prudent to obtain an exercise treadmill test—on β-blockers and/or other baseline antihypertensive medications—to assess the physiological response to exercise and ensure that the systolic blood pressure does not rise above 180 mm Hg.

Patients should be informed of the typical symptoms of acute aortic dissection. Moreover, patients should be instructed that should they ever experience the abrupt onset of significant chest, neck, back, or abdominal pain, they should present immediately to an emergency department for evaluation. They should be warned of the risks, should they choose to wait hours or days to see whether the symptoms resolve spontaneously. In addition, patients should be instructed to inform the emergency physician of the existence of a thoracic aortic aneurysm and explain explicitly that their physician recommends an urgent CT scan of the chest (or transesophageal echocardiography or MRI if a CT is contraindicated) to rule out acute aortic dissection or rupture. This may prompt an emergency department physician who might not otherwise consider aortic dissection in the differential diagnosis to image the aorta promptly.

As detailed earlier, several etiologies of thoracic aortic aneurysms, including a bicuspid aortic valve, may be familial. Because thoracic aneurysms are typically asymptomatic, the only way to detect their presence among other potentially affected family members is with formal screening. For relatives of those with Marfan syndrome or a bicuspid aortic valve, a screening echocardiogram may be appropriate. For all other etiologies (including idiopathic aneurysms), a CT scan or MRI is preferred, because imaging of the ascending aorta is crucial.

It should be recognized that the presence of an aortic aneurysm may be a marker of more diffuse aortic disease, as up to one quarter of those with thoracic aortic aneurysms have concomitant abdominal aortic aneurysms. Therefore, to exclude the presence of other aneurysms, it is essential that all patients diagnosed with a thoracic aneurysm undergo at least one baseline imaging study that includes the abdominal aorta. This can be accomplished easily by CT scanning or MRI.

**Serial Imaging**

Patients should be followed up with serial imaging studies for surveillance. When a thoracic aortic aneurysm is first detected, it is typically not possible to determine the rate of growth. It is therefore appropriate to obtain a repeated imaging study 6 months after the initial study. If the aneu-
Aneurysm is unchanged in size, it is then reasonable to obtain an imaging study on an annual basis in most cases. In those without Marfan syndrome or acute aortitis, thoracic aortic aneurysms tend to grow quite slowly, so annual imaging is sufficient for surveillance. However, should there be a significant increase in aortic size from one study to the next, the interval between studies should be decreased to 3 or 6 months (according to the aortic diameter).

To be useful for surveillance, imaging reports must include the diameters of affected aortic segments; general descriptions, such as “there is an ascending aortic aneurysm” or “the descending thoracic aorta is dilated,” are inadequate. To quantify aneurysm growth over time, maximal aortic diameters must be compared. In addition, one must be cautious in relying entirely on the conclusions reported by the reader. Some readers may state, “There is a 5-cm ascending thoracic aortic aneurysm, which is unchanged compared with the prior examination.” However, if, for example, the previous aortic diameter was 4.8 cm and before that it was only 4.6 cm, the conclusion that the aneurysm is “unchanged” is misleading, because it fails to illuminate the true pattern of progressive aneurysm growth. Moreover, it is ideal to have serial imaging studies performed in the same center with the same technique, so that direct comparisons can be made between comparable images.

Finally, individual readers may measure aortic diameters differently, so even when the report states that the aortic diameter has changed, it does not necessarily mean that the aorta has truly grown in size from one study to the next. In fact, in a recent systematic evaluation of interobserver variability, 8 experienced readers interpreted CT scans of aortic aneurysms, and among them, there was a mean difference of 4 mm in the measurement of maximal aortic diameter. Consequently, the only way to be absolutely certain as to whether or not the aortic diameter has changed is for a given reader to compare similar images from sequential studies and then to make each set of measurements personally.

Abdominal Aortic Aneurysms
Abdominal aortic aneurysms are much more common than thoracic aortic aneurysms. Age is an important risk factor, and the incidence of abdominal aortic aneurysm rises rapidly after the age of 55 years in men and 70 in women. The prevalence of abdominal aortic aneurysms is ~5% among men ≥65 years of age screened by ultrasound.

Etiology and Pathogenesis
Smoking is the risk factor most strongly associated with abdominal aortic aneurysms, followed by age, hypertension, hyperlipidemia, and atherosclerosis. Sex and genetics also influence aneurysm formation. Men are 10 times more likely than women to have an abdominal aortic aneurysm of 4 cm or greater. Those with a family history of abdominal aortic aneurysm have an increased risk of 30%, and their aneurysms tend to occur at a younger age and carry a greater risk of rupture than do sporadic aneurysms. Unfortunately, no gene defects have yet been identified.

The strength of the aortic wall lies in the elastin and collagen of its extracellular matrix. Consequently, degrada-

tion of these structural proteins weakens the aortic wall and allows aneurysms to develop. Classically, atherosclerosis has been considered the underlying cause of abdominal aortic aneurysms: The infrarenal abdominal aorta is most affected by the atherosclerotic process and is similarly the most common site of abdominal aneurysm formation. However, current research suggests that genetic, environmental, hemodynamic, and immunologic factors all contribute to the development of aneurysms.

There is histological evidence of inflammatory infiltrates within the wall of aortic aneurysms, and such inflammation has been implicated in the degradation of the extracellular matrix. Matrix metalloproteinases are enzymes that are produced by smooth muscle and inflammatory cells, and several of these proteinases may participate in abdominal aortic aneurysm formation. Indeed, certain of the matrix metalloproteinases can degrade elastin and collagen. The levels of some matrix metalloproteinases are significantly elevated in the walls of aneurysms compared with controls. In addition, several other proteinases, including plasminogen activators, serine elastases, and cathepsins, may also contribute to the formation of aneurysms.

Clinical Manifestations
Most abdominal aortic aneurysms are asymptomatic and are discovered incidentally on routine physical examination or on imaging studies ordered for other indications. When symptoms do arise, pain is the typical complaint. The pain is usually located in the hypogastrium or lower back and is typically steady and gnawing, lasting hours to days. Actual rupture is associated with an abrupt onset of back pain along with abdominal pain and tenderness. Most patients have a palpable, pulsatile abdominal mass, and many are hypotensive and appear critically ill.

Physical Examination
Many aneurysms can be detected on physical examination as a pulsatile mass extending from the xiphoid to the umbilicus. However, the sensitivity of the physical examination is limited, and even large aneurysms may be difficult or impossible to detect in overweight or obese individuals. The size of an aneurysm tends to be overestimated on physical examination, so even normal aortas may sometimes feel enlarged.

Diagnosis and Sizing
Several diagnostic imaging modalities are available for detecting and serially monitoring abdominal aortic aneurysms. Abdominal ultrasonography is perhaps the most practical way to screen for aneurysms. Its major advantages are that it is relatively inexpensive and noninvasive and does not require the use of a contrast agent.

Compared with ultrasonography, CT scanning has the advantage that it can better define the shape and extent of the aneurysm, as well as the local anatomic relationships of the visceral and renal vessels. It is also superior to ultrasonography in imaging suprarenal aortic aneurysms. Disadvantages include its cost and its use of ionizing radiation and intravenous contrast media. Nevertheless, although CT is less practical than ultrasonography as a
screening tool, its high accuracy in sizing aneurysms makes it an excellent modality for serially monitoring changes in aneurysm size. It is important to note that CT measurements of aneurysm size tend to be larger than ultrasound measurements by a mean of 3 to 9 mm, according to the aneurysm size.41,42 CT angiography (3-dimensional display of the aorta and its branches) is particularly useful, in that it provides more comprehensive evaluation of the anatomy of both the abdominal aortic aneurysm and the renal, mesenteric, and iliac arteries (Figure 11).

In those in whom contrast-enhanced CT scanning is contraindicated (eg, renal insufficiency or allergy), MR angiography is an alternative for the comprehensive evaluation of aortic aneurysms. Given the image quality that both CT and MR angiography provide, traditional catheter-based contrast aortography is now infrequently used in the evaluation of abdominal aneurysms.

Screening
In the past decade, much attention has been paid to the potential utility of routine screening of asymptomatic adults for the presence of abdominal aneurysms. The largest and the most definitive controlled trial to date is from the Multicenter Aneurysm Screening Study Group,36 in which a population-based sample of 67 800 men (aged 65 to 74 years) were randomized to an invitation to ultrasound screening or to a control group not offered screening. Those with aneurysms were followed up with serial ultrasound scans for a mean of 4 years, and surgery was considered when the diameter reached ≥5.5 cm. There were 65 aneurysm-related deaths in the screening group versus 113 in the control group, yielding an estimated risk reduction of 42%.

Calculating the cost per life-year gained requires factoring in numerous financial variables, and differences in assumptions about costs (eg, screening, surgery, and hospitalizations) and cost savings (eg, avoiding emergency surgery for aortic rupture) significantly impact conclusions about cost efficacy. Consequently, estimates of cost per life-year gained vary from as low as $110743 to as high as $57 000,36 with screening of 700 to 1000 subjects required to prevent 1 death. Although the exact cost for life-year gained remains uncertain, it nevertheless does appear that screening is grossly cost-effective. Indeed, in a recent “consensus statement,” a number of US vascular specialists have recommended screening of all men 60 to 85 years of age, all women 60 to 85 years of age with cardiovascular risk factors, and both men and women >50 years of age with a family history of abdominal aortic aneurysm.44

Natural History
The major risk posed by an abdominal aortic aneurysm is rupture and its high associated mortality. In one large trial of those with ruptured aneurysms, 25% died before reaching a hospital, another 51% percent died at the hospital without undergoing surgery, and of the those who had surgery, the operative mortality was 46%, yielding an overall 30-day survival of just 11%.45 The goal then is to have patients undergo elective aortic repair—with a mortality of only 4% to 6%—when aneurysms are considered to be at significant risk of rupture.

The risk of rupture increases with aneurysm size. The UK Small Aneurysm Trial found that for aneurysms <4 cm, 4 to 4.9 cm, and 5 to 5.9 cm, the annual risk of rupture was 0.3%, 1.5%, and 6.5%, respectively.45 For aneurysms 6 cm or greater, the risk of rupture rises sharply, although an exact risk cannot be estimated. Although abdominal aneurysms are less prevalent among women than men, when present they rupture 3 times more frequently and at a smaller aortic diameter (mean of 5 versus 6 cm). Rupture is also more
common among current smokers and those with hypertension. A rapid rate of expansion predicts aneurysm rupture. Although the mean rate of abdominal aortic aneurysm expansion is thought to approximate 0.4 cm/y, the rates of expansion within a population are extremely variable. Baseline aneurysm size is the best predictor of aneurysm growth rate, with larger aneurysms expanding more rapidly than small ones. Figure 12 summarizes graphically the aneurysm growth rates as determined in a number of longitudinal series. A promising new technique for predicting the fate of abdominal aortic aneurysms is the analysis of wall stress. A 3-dimensional reconstruction of the aortic aneurysm is performed with the use of CT angiography, and wall stress is then determined by finite-element analysis and blood pressure. In a recent analysis of 103 patients, Fillinger et al found that the sensitivity and specificity of peak wall stress were superior to maximum aortic diameter for predicting risk of aortic rupture. Although this technique still needs to be refined and better studied, it holds promise to become an important tool in determining the timing of aortic repair.

Management

Surgical Treatment

Aneurysm size is the primary indicator for repair of asymptomatic aneurysms, and in the wake of 2 recent large-scale trials, there is now a reasonable consensus as to the appropriate aneurysm diameter that necessitates surgery. The UK Small Aneurysm Trial and the Aneurysm Detection and Management (ADAM) Veterans Affairs Cooperative Study randomized patients with small aortic aneurysms (diameter of 4 to 5.5 cm) to either early elective surgery or regular surveillance imaging, and both found no difference in survival between the 2 groups. The outcomes of the trials suggest that surgery is not indicated, in most instances, for asymptomatic aneurysms <5.5 cm. However, one important limitation is that these 2 study populations consisted almost entirely of men, and because the risk of aneurysm rupture is greater and occurs at smaller diameters in women than in men, it is believed that these results are not generalizable to women. Indeed, in a recently published set of guidelines, the Joint Council of the American Association for Vascular Surgery and Society for Vascular Surgery concurred with the recommendation that women should undergo elective repair at a smaller aortic diameter of 4.5 to 5 cm. Elective repair carries an average operative mortality of 4% to 6% and of only 2% in low-risk patients. A number of studies have shown that mortality is inversely related to a surgeon’s volume. In fact, in a recent analysis, both a high surgeon volume and a high hospital volume were both associated with lower mortality than low-volume providers and that surgeons specializing in vascular surgery had a lower mortality than did nonspecialized surgeons with the same aortic repair volume.

A less-invasive alternative to open surgery for repair of abdominal aortic aneurysms is the use of percutaneously implanted, expanding endovascular stent-grafts. Once deployed, the stent-graft serves to bridge the region of the aneurysm, thereby excluding it from the circulation while allowing aortic blood flow to continue distally through the prosthetic stent-graft lumen. To begin with, only 30% to 60% of abdominal aortic aneurysms are anatomically suitable for endovascular repair. When undertaken, the rate of successful stent-graft implantation has ranged from 78% to 94%. One of the major technical difficulties associated with the stent-graft technique that has yet to be overcome is the frequent occurrence of endoleaks, which occur in 10% to 20% of cases and are seen angiographically as persistent contrast flow into the aneurysm sac because of failure to completely exclude the aneurysm from the aortic circulation. If left untreated, these endoleaks may potentially leave the patient at continued risk for aneurysm expansion or rupture. Indeed, in a follow-up study of outcomes at 12 months or longer among >1000 stent-graft recipients, the EUROSTAR investigators reported that almost 10% of patients per year required secondary interventions, suggesting that there should be caution in the broad application of endovascular aneurysm repair. Moreover, at present, the long-term outcome of endovascular repair versus conventional surgical repair remains unknown. Therefore, the use of stent-grafts for endovascular repair of abdominal aortic aneurysms has generally been limited to older patients and those at high operative risk.

Medical Management

As with thoracic aortic aneurysms, β-blocker therapy is considered important for reducing the risk of abdominal aortic aneurysm expansion and rupture. Risk factor modification is fundamental: Hypercholesterolemia and hypertension should be controlled and cigarette smoking discontinued. Aneurysms too small to merit surgery should be followed up with periodic surveillance imaging to monitor their size. On the basis of an aneurysm’s current size and its anticipated rate of growth (as in Figure 12), one can estimate how quickly an aneurysm might grow to a size large enough to merit repair and thus recommend appropriate intervals for reimaging. A sample schedule of surveillance imaging is summarized in the Table. In a recent analysis of aneurysm growth, Brady et al have estimated that following such a rescreening algorithm would limit the possibility of an aneurysm reaching >5.5 cm between screenings to <1%. When monitoring growth of aneurysms with a diameter ≥4 cm, CT scanning

<table>
<thead>
<tr>
<th>Present Aneurysm Diameter, cm</th>
<th>Reimage Aorta in</th>
</tr>
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<tbody>
<tr>
<td>2.5–2.9</td>
<td>5 y</td>
</tr>
<tr>
<td>3.0–3.4</td>
<td>3 y</td>
</tr>
<tr>
<td>3.5–3.9</td>
<td>2 y</td>
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<tr>
<td>4.0–4.4</td>
<td>1 y</td>
</tr>
<tr>
<td>4.5–4.9</td>
<td>6 mo</td>
</tr>
<tr>
<td>5.0–5.5</td>
<td>3–6 mo</td>
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</tbody>
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*In addition to planning repeated surveillance imaging, one should also consider referral to a vascular surgeon. Note that for abdominal aortic diameters of <2.5 cm, rescreening is generally thought to be unnecessary. Data derived from References 53–56.
may be preferable to ultrasound because CT sizing is more accurate.

Conclusions
Whereas aortic aneurysms are less common than many other cardiovascular conditions, the fact that they can be life threatening and that even large aneurysms may not produce symptoms makes it all the more important for clinicians to be vigilant in their evaluation of patients at risk. Because aneurysms are often first detected on an imaging study ordered for other indications, any suggestion of an enlarged aorta should prompt follow-up with an appropriate dedicated imaging study. Fortunately, modern imaging techniques—especially CT and MRI—have now made the sizing and surveillance of aneurysms relatively easy. In the future, genetic screening may also play a role in the screening of those with a family history of thoracic aortic aneurysms.

Ideally, a broadening clinical awareness of aortic aneurysms and the methods of diagnosis will help reduce the morbidity and mortality associated with this condition. Indeed, clinicians who understand the principles of medical and surgical management of aortic aneurysms can comfortably determine when they should manage patients with medication and serial imaging studies (to follow aneurysm size and rate of growth) and when to refer to a cardiothoracic or vascular surgeon. Finally, whereas open surgical repair remains the standard approach to treating most large aortic aneurysms, it is likely that endovascular stent-grafting will assume an increasing role as the technique is further refined.

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Thoracic and Abdominal Aortic Aneurysms
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Circulation. 2005;111:816-828
doi: 10.1161/01.CIR.0000154569.08857.7A
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2005 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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