Review Article

Imaging for surveillance and operative management for endovascular aortic aneurysm repairs

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Abstract: Endovascular aortic aneurysm repairs rely heavily on radiologic imaging modalities for preoperative surveillance, intraoperative management, and postoperative follow-up. Ultrasonography, computed tomography (CT), magnetic resonance imaging (MRI) and angiography all have utility at different stages of management. Often one imaging modality compliments another by providing supplementary information. Data from the imaging exams must be synthesized into one coherent plan for managing patients with aortic aneurysms.

Keywords: Aortic aneurysm; abdominal; aortic aneurysm; thoracic; endovascular procedures

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Introduction

Imaging plays a large role in the management of aortic aneurysms ranging from preoperative surveillance to intraoperative management, and postoperative follow-up. The majority of aneurysms are discovered incidentally or found during surveillance studies in high risk subsets of patients. Few aneurysms present with acute symptoms such as chest pain, back pain, or abdominal pain. Most aortic aneurysms that are discovered are small-moderate size and require only periodic monitoring, reserving surgery for either rapidly enlarging aneurysms or if the aneurysm reaches the threshold in size for intervention. These small to moderate sized aneurysms are monitored by periodic ultrasonography, computed tomography (CT) scans, or magnetic resonance imaging (MRI).

Descending thoracic aneurysms (DTA) and abdominal aortic aneurysms (AAA) are now routinely repaired using endovascular techniques (1,2). Operative mortality for endovascular abdominal aneurysm repair (EVAR) is less than 2% (3). Thoracic endovascular aneurysm repair (TEVAR) and EVAR require high quality preoperative imaging for proper planning of the case. High resolution images with and without contrast are often helpful in identifying adequate site for access, ensuring adequate length of landing zones, and measuring sizes of endovascular stent-grafts. Intraoperatively, fluoroscopy and often intravascular ultrasound are used to ensure proper placement and positioning of the stent-graft devices. Postoperatively, imaging is necessary to monitor for early or late endoleaks that may require further intervention.

A wide variety of imaging modalities are available in current clinical practice. Aortic surgeons must be familiar and may need to use combinations of these modalities at different stages of management. The endovascular 'revolution' would not have been as successful without the advanced imaging techniques that are available. We present some of the established and emerging concepts in imaging for aortic endovascular repair.

Preoperative surveillance imaging

The diagnosis of aortic aneurysms is largely dependent on imaging. Physical exam is an unreliable method for diagnosing thoracic aneurysms and it detects as few as 38% of AAA. The majority are found on radiologic exams (4).

Ultrasound

Ultrasonography was first used to detect and diagnose an abdominal aortic aneurysm in 1966 (5). The ultrasound probe generates a sound wave when an electrical signal is applied. The sound wave travels through the tissue and is reflected back towards the transducer, which detects the signal. Early ultrasound generated one-dimensional images (A-mode) and later generations with additional crystal arrays generated two-dimensional images (B-mode). Modern machines can now generate three- and four-dimensional images with Doppler capabilities.

Ultrasonography is excellent for detecting and monitoring small aneurysms of the ascending aorta and abdominal aorta. Echocardiography is a primary detection method for those at risk for developing ascending aortic aneurysms. The aortic arch and descending thoracic aorta are more difficult to image accurately using surface ultrasonography due to interference and shadowing from the nearby ribs and air-filled lungs. Ultrasonography is commonly used to image the infrarenal abdominal aorta, but it is still operator-dependent and it can often underestimate the maximal diameter by 2–5 mm (6,7). Nevertheless, the sensitivity and specificity of ultrasound for detecting the presence of AAA approaches 100%, making it an excellent screening tool (8). The Multicentre Aneurysm Screening Study showed that compliance with ultrasound screening for AAA resulted in a 53% risk-reduction in aneurysm-related death (9). This and other large ultrasound screening studies led to the United States Preventive Services Task Force recommendation to screen all men aged 65–75 who have ever smoked for abdominal aortic aneurysm using abdominal ultrasonography (10). The Society for Vascular Surgery (SVS) practice guidelines recommend one-time ultrasound screening for all men over age 65 and all women over age 65 who have ever smoked (11).

For small aneurysms that are unlikely to need intervention in the near future, ultrasound is an excellent non-invasive method of monitoring for growth. SVS guidelines recommend that aneurysms 3 to 3.4 cm be monitored by ultrasound every three years and those measuring 3.5 to 4.4 cm should undergo yearly ultrasound monitoring. Aneurysms measuring 4.5 cm or greater, which are closer to requiring interventions, should be images every 6 months (11). Larger aneurysms may benefit from more accurate imaging modalities such as CT or MRI, as ultrasound may underestimate the size of aneurysms by up to 5 mm.

CT

CT and CT angiography (CTA) is the gold standard of aortic imaging for endovascular interventions due, in large part, to the wealth of accurate information that is provided by a properly protocoled scan. It is a non-invasive method of providing high resolution data that can be post-processed for a variety of purposes such as complex measurements and analyses. All modern CT scanners use multiple detectors mounted in a gantry opposite an X-ray emitter and images are acquired in a helical manner. Acquisition of data is rapid and there is minimal discomfort for patients. High-resolution thin slices of <1 mm provide extremely detailed images that allow for accurate depiction of aortic anatomy and measurements of sizes. The level of detail and accuracy of measurements is increased compared to ultrasound (7).

CTA scans are performed in multiple phases and require intravenous iodinated contrast to enhance the images. Pre-contrast images allow for evaluation of vessel walls for calcification. The arterial contrast phase highlights the lumen of the vessels, depicting its course within the body as well as intraluminal irregularities such as dissection flaps, ulcerations, or mural thrombus. Branch vessels are easily seen and end organs are opacified. Features associated with a higher risk for rupture, such as inflammation, a crescent sign, or saccular shape, may be revealed. Delayed phase images are useful in follow up to evaluate for type II endoleaks and may provide additional imaging detail for end organs. Renal insufficiency may contradict the use of intravenous contrast but non-contrast images still have utility for monitoring absolute aortic aneurysm diameter.

After data are acquired in the axial plain, post-processing allows for reconstruction of the images in two or three dimensions. Sagittal and coronal reconstructions help in visualizing aneurysm anatomy and the course of the aorta through the body. Major branch vessels including their takeoff angles from the aorta, relationship to and distance from each other can be easily measured in reconstructed views. This aids in pre-operative planning. Advanced processing allows for measurements using the center line of flow. Angulation of the aorta and off-axis or oblique measurements of the aorta can result in inaccurate sizing, particularly in elderly patients with kyphosis or scoliosis. The normal tortuous course of the aorta often leads to oblique measurements that can overestimate maximal aortic diameter. Reconstructions with the center line of flow provide a more accurate method of measuring aortic diameter. A measurement made perpendicular to the center line of flow prevents off-axis measurements and most accurately provides the maximal aortic diameter (12).

MRI

MRI can provide imaging of the entire aorta and its branch vessels in multiple different planes. MRI allows for comprehensive detailed imaging without the use of ionizing radiation or iodinated contrast dye. This makes MRI an excellent option to monitor aneurysms in younger patients and those with renal insufficiency or severe contrast allergies (13). However, some gadolinium agents are contraindicated in patients with very low glomerular filtration rate less than 30 mL/min due to the increased incidence of nephrogenic systemic fibrosis. The main disadvantages of using MRI are the longer acquisition times and the inability to use MRI in patients with metallic implants or significant claustrophobia. Additionally, physicians are often less accustomed to operative planning for endovascular grafts using MRI images and without the appropriate processing capabilities it is more difficult to obtain all of the information that would be available with a high resolution CTA.

MRI images are captured most often by using a strong magnetic field to align hydrogen atoms in the body. Radiofrequency pulses cause the atoms to emit signals which are collected. Briefly, image processing depends on time constants. T1-weighted images show fat to be bright and T2-weighted images show water-filled structures to be bright. Fast pulse sequences and gradient echo sequences allow for imaging of blood and this is enhanced by the use of gadolinium contrast.

In our practice, we may monitor younger patients with thoracic aneurysms that are not yet in need of repair using MRI. If they approach a size where endovascular intervention will be necessary soon, then we switch to CTA to aid in operative planning.

Conventional angiography

Conventional angiography has been mostly supplanted by ultrasound, CT and MRI for initial evaluation of aortic aneurysms. During endovascular surgical procedures, the use of angiography is imperative, but it is not necessary for surveillance imaging or preoperative planning. It is an invasive test requiring arterial puncture and it is limited in the information it can provide. Angiography cannot be used to accurately measure the aneurysm size. Exact measurements are difficult to obtain due to differences in magnification. Additionally, angiography shows only the flow/lumen channel of the aorta and it can underestimate total aortic diameter if there is significant mural thrombus present on the aneurysm wall.

The remaining utility of preoperative catheterization and angiography is in hemodynamic evaluation of stenoses and in patients with renal insufficiency. Branch arteries that have stenosis may benefit from hemodynamic measurements and calculation of pressure gradients. Significant lesions may require preoperative intervention or concomitant angioplasty/stenting at the time of endovascular aneurysm repair. In patients with significant renal insufficiency, angiography can be helpful in preoperative imaging by combining its techniques with CT imaging. A pigtail catheter can be placed in the aorta and the patient is taken for a CT scan. Contrast dye is injected and the scan is obtained immediately. This allows a much lower dose of 20–40 mL of contrast to be used rather than the larger 200–300 mL dose needed for CTA (14,15).

Operative planning

The most critical portion of an EVAR or TEVAR procedure is the preoperative planning. CTA is the ideal imaging modality for this purpose. High resolution pre-contrast and contrast images allow for planning from the beginning to the end of the procedure. The aorta and its major branches are assessed for size, angulation, calcification, and length so that a proper endovascular graft is chosen to minimize future risk of endoleak or migration.

The proximal and distal ends of the endovascular graft should ideally land in normal aorta. The landing zones should be assessed on pre-contrast images for calcification. Protruding calcific plaques may prevent the stent-graft from having a proper seal. Calcific plaques also prevent the use of endovascular anchors, if they are necessary, since the coil cannot be driven into hard plaque tissue. Contrast images should be used to evaluate the landing zones for diameter, length, shape, and luminal irregularities. In general, 10–20% oversizing is recommended to ensure good seal and prevent late endoleaks. Less oversizing or excessive oversizing can increase risk of endoleak or neck dilatation (16,17).

For TEVAR, the analysis of the proximal landing zone is critically important. Most commonly, thoracic stent-grafts will have to land proximally in zone 3 (distal to the left subclavian artery) or zone 2 (covering the left subclavian artery and distal to the left carotid artery). There should be at least a 2 cm neck proximally. The shape of the aortic arch must be taken into account. Landing in an angulated portion of the arch can lead to a type I endoleak, most commonly due to "bird-beaking" at the lesser curvature of the aortic arch. If one suspects a risk of "bird-beaking", a more proximal landing zone is likely necessary. Landing in zone 2 and covering the left subclavian artery may help provide an adequate length landing zone in a straight segment of aorta. Preoperative carotid-subclavian bypass helps prevent left upper extremity claudication, posterior circulation stroke, spinal cord injury, and sometimes myocardial ischemia. Many patients will tolerate coverage of the left subclavian artery without sequela, but up to 10–20% may develop left arm claudication and 5% posterior circulation stroke (18).

The distal landing zone for TEVAR depends on the extent of aneurysmal disease. For isolated DTA, there should be at least a 2 cm neck zone above the celiac artery. Landing higher above the celiac artery helps to preserve any patent intercostal arteries and maximize spinal cord perfusion. In some surgical series, preservation of intercostal arteries has shown a significant reduction in rate of spinal cord injury (19). We generally aim to have enough coverage of aorta to prevent type I endoleaks, but leave as much normal aorta as possible uncovered to keep the intercostal arteries patent. Thoracoabdominal aneurysms that extend into the visceral segment require more complex planning if they are to be repaired using endovascular techniques with mortality and spinal cord injury rate that is comparable to open surgery (20). Fenestrated and branched grafts can be custom-made to fit the anatomy of the individual patient. These grafts require 3–4 weeks for fabrication. Careful planning is necessary to position each fenestration and branch in the proper orientation in order to make intraoperative placement easier and to prevent late obstruction due to kinking of branches or leaks due to inadequate seal.

EVAR procedures require an adequate neck zone below the lowest renal artery for the proximal landing zone. Ideally there should be a straight neck of at least 1.5 cm length, with no calcification or mural thrombus. Higher risk features of the infrarenal neck include short length, conical shape, angulation greater than 45 degrees, calcification, and mural thrombus. Patients with these features are at higher risk for developing early and late endoleak after EVAR. For those with two or more high risk features, adjunctive or alternative measures should be considered. More proximal extension with a fenestrated graft or a snorkel/chimney technique can help land in less hostile aorta, but these techniques remain higher risk than standard infrarenal EVAR (21). Devices with novel proximal fixation mechanisms are now available but there are limited long-term data on these devices (22). Endovascular fixation devices are available which use transmural helical or curved screws to fixate the graft to the aortic wall (23). These have shown satisfactory short-term results but again long-term data are unavailable.

The majority of modern EVAR stent-graft systems are modular bifurcated systems with iliac limbs that are sized to land in the common iliac arteries. Up to 20% of patients will have large or aneurysmal common iliac arteries requiring extension of the stent-graft into the external iliac artery. Coverage of the internal iliac artery requires planning for a vascular plug or other embolization device to be placed prior to placement of the stent-graft. Embolization of an internal iliac artery is generally well tolerated but can lead to temporary buttock claudication in 28%, erectile dysfunction in 17%, and rarely pelvic ischemia (24). Branched iliac artery grafts are commercially available to maintain perfusion the internal iliac system and results are promising (25).

Access vessels should be evaluated on both pre-contrast and contrast images. Femoral arteries are evaluated for calcification and access in calcified areas should be avoided if possible. Noting the relation of the bifurcation of the common femoral artery to the bony structures may be helpful when puncturing the common femoral artery if a percutaneous technique is used to implant the stent-grafts. The iliofemoral system is evaluated for tortuosity and calcification. Severe tortuosity can make advancing the delivery system of the stent-graft into the aorta difficult. Extensive calcification can also make maneuvering the device difficult and may prevent the vessel from expanding to fit the device. Patients with heavily calcified iliac and femoral arteries are at higher risk for vascular injury from manipulation. The size of the iliofemoral arteries must be large enough to accommodate the delivery system. Modern stent-grafts are mostly low profile and many can accommodate access vessels as small as 6–8 mm. If access vessels are prohibitively small or otherwise unusable, an 8–10 mm graft sewn onto the iliac artery directly may be used as a means to access the vascular system.

Intraoperative imaging

Ultrasound

Intraoperative ultrasonography allows us to evaluate the vasculature in real time without ionizing radiation or contrast and it gives views that are not obtainable by other methods. Both surface ultrasonography and intravascular ultrasonography (IVUS) are valuable tools for endovascular procedures. Surface ultrasonography is helpful for accessing the common femoral artery in the appropriate location, especially if a percutaneous technique is planned. The operator must ensure that the common femoral artery rather than the superficial femoral artery is accessed. The vessel should be compressible without any anterior calcification at the access site. The vessel should be punctured anteriorly and not laterally. This allows for successfully percutaneous closure of the arterial puncture site. If a femoral cutdown is planned, ultrasound can help to properly position the incision, although it is not often necessary.

In many cases, IVUS is an invaluable tool to ensure proper placement of the stent-graft. In dissection cases, it is critical to deploy the stent-graft in the true lumen of the aorta in order to avoid malperfusion. IVUS helps ensure that the wire is traveling in the true lumen throughout its course and not weaving in and out of fenestrations. IVUS may be used concomitantly with fluoroscopic imaging to check the positions of major branches. This is important when landing zones are short or in cases of hostile neck anatomy. In EVAR cases, IVUS can be placed over the contralateral limb wire after the contralateral gate is accessed to ensure that the wire is in fact within the stent-graft rather than behind it. After the graft is fully deployed, IVUS can be utilized in each limb to ensure proper expansion of the limbs. Any incompletely expanded areas can be balloon dilated with properly sized equipment.

In patients with renal insufficiency, many steps normally performed using contrast angiography can be replaced with IVUS-assisted placement (26). Once the proximal and distal landing zones are identified on IVUS, a pre-deployment angiogram is performed to confirm placement and anatomy. The graft is deployed and balloon-dilated if necessary. Then a completion angiogram is performed to ensure there is no endoleak. This technique minimizes the amount of contrast necessary for endovascular repair.

Fluoroscopy/angiography

Fluoroscopy is a necessity during any endovascular procedure to ensure proper wire and catheter placement. Fixed-systems are preferred to provide improved quality imaging. Digital subtraction angiography provides high quality images of the vasculature to allow for precise stent-graft deployment. During the procedure, angiography identifies branch vessel origins. Accuracy is critical since it is necessary to maximize the length of landing zones without covering the branch vessel origins. It is important to combine information gained from the CTA with the angiographic images, which only provide a two-dimensional image of the aorta. For example, renal arteries may not branch off of the aorta directly laterally and a simple AP projection may not show the true level of the ostium of the branch vessel. The CTA should be used to determine whether an oblique projection is necessary to identify the exactly level of the origin of branch vessels.

After deployment of the stent-graft, a completion angiogram must be performed to evaluate for endoleaks. The aortogram will determine whether additional balloon-dilation is necessary or if proximal or distal extension is necessary. It will also ensure that branch vessels remain patent and are not covered inadvertently.

Post-operative monitoring

Radiologic monitoring after TEVAR or EVAR is critical to prevent late complications. Although operative mortality is lower, the rate of re-intervention is significantly higher than with open surgery due to continued risk for developing late endoleaks (2,27).

Ultrasound

Ultrasonography is an attractive option for long-term follow-up imaging since it is cost-effective, readily available, and requires no ionizing radiation or iodinated contrast. Ultrasound does not adequately image the thoracic aorta but it does provide a reasonable amount of information with AAA. The maximal diameter of the aneurysm is measured in AP and transverse dimensions to evaluate for aneurysmal sac expansion or shrinkage. Patency of the stent-graft and its limbs is confirmed with color Doppler ultrasound. The proximal, distal, and graft-to-graft attachment sites are examined for perigraft flow indicating an endoleak. The aneurysmal sac itself is examined for flow to rule out type II endoleak. Renal and visceral branch vessel patency should also be confirmed and significant graft migration should be ruled out.

The accuracy of ultrasound imaging for finding endoleaks remains operator-dependent. In experienced hands it can approach the accuracy of CTA but in general, diagnostic accuracy is too low to recommend its routine use for follow up after EVAR. In systematic reviews, sensitivity of ultrasound in detecting endoleaks was only 69.1% (95% CI, 51.7–86.6%) and specificity was 90.6% (95% CI, 86.7–94.6%) (28). Contrast-enhanced ultrasonography is emerging as a viable alternative for postoperative imaging. It significantly improves the diagnostic accuracy for endoleaks with sensitivity of 97–100% and specificity of 82–100% (29). Contrast-enhances ultrasound is nearly as accurate as CTA and may help detect more type II endoleaks (30). However, availability and adequate operator skill is not widely available.

In patients who have had 1 year of CTA follow-up imaging with no evidence of endoleak or migration and shrinkage of sac diameter, ultrasound may be used as an alternative to CTA for long-term follow-up. In patients with renal insufficiency who cannot receive intravenous contrast, color Doppler ultrasound is a good alternative imaging technique as well.

CT

CTA is the gold standard for follow-up imaging after EVAR and TEVAR procedures. CTA is widely available and it acquires consistently high quality images that can then be post-processed, if necessary, by 3D software, which is becoming more commonplace. Pre-contrast images allow for examination of the integrity of the metallic components of the stent-graft. Calcification patterns are noted so that they can be differentiated from endoleaks on contrast images. Contrast-phase images allow for measurement of maximal aneurysm diameter and center line reconstructions for optimal accuracy. The aneurysm sac should remain stable or shrink after endovascular repair. The position of the stent-grafts is evaluated and aortic branch vessel patency is examined. The ends of the graft are examined for type I endoleaks and the stent-graft is examined for type III endoleaks. Slower filling type II endoleaks are often best evaluated on delayed images.

CTA is a powerful method of evaluating the aorta after endovascular repairs. However, it does require radiation exposure and intravenous iodinated contrast agents. Additionally, there is significant cost associated with long-term CT follow-up imaging. After CTA has demonstrated an absence of endoleak and shrinkage of sac size after one or more years of follow-up, many centers will switch to an alternative method of imaging and then return to CTA if the alternative imaging modality reveals suspicion of a problem.

MRI

MRI is an alternative to CTA which is especially helpful in younger patients in order to reduce their cumulative lifetime radiation dose. It may also be helpful in patients with endoleaks that are difficult to characterize by CTA or other imaging methods (31,32). However, MRI is typically more expensive, takes longer to acquire images and may not be applicable for patients who are claustrophobic or have metallic implants. The quality of images also varies considerably depending on the acquisition techniques that are used.

Conventional angiography

Angiography is not used for routine postoperative surveillance. It may be helpful if CTA, MRA, and/or duplex ultrasound are unable to demonstrate the source of an endoleak. It is an invasive procedure reserved for selective use when other alternatives have provided insufficient data.

Conclusions

Endovascular aortic aneurysm repairs rely heavily on a variety of different imaging modalities at all stages of treatment, whether it is preoperative surveillance, operative planning, intraoperative techniques, or postoperative surveillance. There is no perfect imaging technique and each imaging modality has advantages and disadvantages. Often one imaging modality compliments another by providing supplementary information. Data from the imaging exams must be synthesized into one coherent plan for managing patients with aortic aneurysms.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

References

1. Gopaldas RR, Huh J, Dao TK, et al. Superior nationwide outcomes of endovascular versus open repair for isolated descending thoracic aortic aneurysm in 11,669 patients. J Thorac Cardiovasc Surg 2010;140:1001-10.
2. De Bruin JL, Baas AF, Buth J, et al. Long-term outcome of open or endovascular repair of abdominal aortic aneurysm. N Engl J Med 2010;362:1881-9.
3. Greenhalgh RM, Brown LC, Kwong GP, et al. Comparison of endovascular aneurysm repair with open repair in patients with abdominal aortic aneurysm (EVAR trial 1), 30-day operative mortality results: Randomised controlled trial. Lancet 2004;364:843-8.
4. Chervu A, Clagett GP, Valentine RJ, et al. Role of physical examination in detection of abdominal aortic aneurysms. Surgery 1995;117:454-7.
5. Segal BL, Likoff W, Asperger Z, et al. Ultrasound diagnosis of an abdominal aortic aneurysm. Am J Cardiol 1966;17:101-3.
6. Chiu KW, Ling L, Tripathi V, et al. Ultrasound measurement for abdominal aortic aneurysm screening: a direct comparison of the three leading methods. Eur J Vasc Endovasc Surg 2014;47:367-73.
7. Manning BJ, Kristmundsson T, Sonesson B, et al. Abdominal aortic aneurysm diameter: a comparison of ultrasound measurements with those from standard and three-dimensional computed tomography reconstruction. J Vasc Surg 2009;50:263-8.
8. Lederle FA. Ultrasonographic screening for abdominal aortic aneurysms. Ann Intern Med 2003;139:516-22.
9. Ashton HA, Buxton MJ, Day NE, et al. The Multicentre Aneurysm Screening Study (MASS) into the effect of abdominal aortic aneurysm screening on mortality in men: a randomised controlled trial. Lancet 2002;360:1531-9.
10. Guirguis-Blake JM, Beil TL, Senger CA, et al. Ultrasonography screening for abdominal aortic aneurysms: a systematic evidence review for the U.S. Preventive Services Task Force. Ann Intern Med 2014;160:321-9.
11. Chaikof EL, Brewster DC, Dalman RL, et al. SVS practice guidelines for the care of patients with an abdominal aortic aneurysm: Executive summary. J Vasc Surg 2009;50:880-96.
12. Dillavou ED, Buck DG, Muluk SC, et al. Two-dimensional versus three-dimensional CT scan for aortic measurement. J Endovasc Ther 2003;10:531-8.
13. Bush RL, Lin PH, Bianco CC, et al. Endovascular aortic aneurysm repair in patients with renal dysfunction or severe contrast allergy: utility of imaging modalities without iodinated contrast. Ann Vasc Surg 2002;16:537-44.
14. Joshi SB, Mendoza DD, Steinberg DH, et al. Ultra-low-dose intra-arterial contrast injection for iliofemoral computed tomographic angiography. JACC Cardiovasc Imaging 2009;2:1404-11.
15. Zemedkun M, LaBounty TM, Bergman G, et al. Effectiveness of a low contrast load CT angiography protocol in octogenarians and nonagenarians being evaluated for transcatheter aortic valve replacement. Clin Imaging 2015;39:815-9.
16. Sternbergh WC 3rd, Money SR, Greenberg RK, et al. Influence of endograft oversizing on device migration, endoleak, aneurysm shrinkage, and aortic neck dilation: results from the Zenith Multicenter Trial. J Vasc Surg 2004;39:20-6.
17. Tolenaar JL, Jonker FH, Moll FL, et al. Influence of oversizing on outcome in thoracic endovascular aortic repair. J Endovasc Ther 2013;20:738-45.
18. Feezor RJ, Lee WA. Management of the left subclavian artery during TEVAR. Semin Vasc Surg 2009;22:159-64.
19. Safi HJ, Miller CC 3rd, Carr C, et al. Importance of intercostal artery reattachment during thoracoabdominal aortic aneurysm repair. J Vasc Surg 1998;27:58-66; discussion 66-8.
20. Roselli EE, Greenberg RK, Pfaff K, et al. Endovascular treatment of thoracoabdominal aortic aneurysms. J Thorac Cardiovasc Surg 2007;133:1474-82.
21. Lee JT, Lee GK, Chandra V, et al. Comparison of fenestrated endografts and the snorkel/chimney technique. J Vasc Surg 2014;60:849-56; discussion 856-7.
22. Perdikides T, Georgiadis GS, Avgerinos ED, et al. The Aorfix stent-graft to treat infrarenal abdominal aortic aneurysms with angulated necks and/or tortuous iliac arteries: midterm results. J Endovasc Ther 2009;16:567-76.
23. Deaton DH, Mehta M, Kasirajan K, et al. The phase I multicenter trial (STAPLE-1) of the Aptus endovascular repair system: results at 6 months and 1 year. J Vasc Surg 2009;49:851-7.
24. Rayt HS, Bown MJ, Lambert KV, et al. Buttock claudication and erectile dysfunction after internal iliac artery embolization in patients prior to endovascular aortic aneurysm repair. Cardiovasc Intervent Radiol

2008;31:728-34.
25. Karthikesalingam A, Hinchliffe RJ, Holt PJ, et al. Endovascular aneurysm repair with preservation of the internal iliac artery using the iliac branch graft device. Eur J Vasc Endovasc Surg 2010;39:285-94.
26. Hoshina K, Kato M, Miyahara T, et al. A retrospective study of intravascular ultrasound use in patients undergoing endovascular aneurysm repair: its usefulness and a description of the procedure. Eur J Vasc Endovasc Surg 2010;40:559-63.
27. United Kingdom EVAR Trial Investigators, Greenhalgh RM, Brown LC, et al. Endovascular versus open repair of abdominal aortic aneurysm. N Engl J Med 2010;362:1863-71.
28. Sun Z. Diagnostic value of color duplex ultrasonography in the follow-up of endovascular repair of abdominal aortic aneurysm. J Vasc Interv Radiol 2006;17:759-64.
29. Gürtler VM, Sommer WH, Meimarakis G, et al. A comparison between contrast-enhanced ultrasound imaging and multislice computed tomography in detecting and classifying endoleaks in the follow-up after endovascular aneurysm repair. J Vasc Surg 2013;58:340-5.
30. Ten Bosch JA, Rouwet EV, Peters CT, et al. Contrast-enhanced ultrasound versus computed tomographic angiography for surveillance of endovascular abdominal aortic aneurysm repair. J Vasc Interv Radiol 2010;21:638-43.
31. Ayuso JR, de Caralt TM, Pages M, et al. MRA is useful as a follow-up technique after endovascular repair of aortic aneurysms with nitinol endoprostheses. J Magn Reson Imaging 2004;20:803-10.
32. van der Laan MJ, Bakker CJ, Blankensteijn JD, et al. Dynamic CE-MRA for endoleak classification after endovascular aneurysm repair. Eur J Vasc Endovasc Surg 2006;31:130-5.

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