

Current Imaging Strategies in Patients with Abdominal Aortic Aneurysms

Aktuelle Bildgebungsstrategien bei Patienten mit Bauchaortenaneurysma

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ABSTRACT

Background An abdominal aortic aneurysm (AAA) is defined as a localized dilatation of the abdominal aorta of ≥ 3 cm. With a prevalence of 4–8%, AAA is one of the most common vascular diseases in Western society. Radiological imaging is an elementary component in the diagnosis, monitoring, and treatment planning of AAA patients.

Method This is a narrative review article on preoperative imaging strategies of AAA, incorporating expert opinions based on the current literature and standard-of-care practices from our own center. Examples are provided to illustrate clinical cases from our institution.

Results and Conclusion Radiological imaging plays a pivotal role in the initial diagnosis and monitoring of patients with AAA. Ultrasound is the mainstay imaging modality for AAA screening and surveillance. Contrast-enhanced CT angiography is currently considered the gold standard for preoperative imaging and image-based treatment planning in AAA repair. New non-contrast MR angiography techniques are robustly applicable and allow precise determination of aortic diameters, which is of critical importance, particularly with regard to current diameter-based surgical treatment guidelines. 3D imaging with multiplanar reformation and automatic center-line positioning enables more accurate assessment of the maximum aortic diameter. Modern imaging techniques such as 4D flow MRI have the potential to further improve individualized risk stratification in patients with AAA.

Key points:

- Ultrasound is the mainstay imaging modality for AAA screening and monitoring
- Contrast-enhanced CT angiography is the gold standard for preoperative imaging in AAA repair
- Non-contrast MR angiography allows for accurate monitoring of aortic diameters in AAA patients
- Measurement of aortic diameters is more accurate with 3D-CT/MRI compared to ultrasound
- Research seeks new quantitative imaging biomarkers for AAA risk stratification, e. g., using 4D flow MRI

ZUSAMMENFASSUNG

Hintergrund Das abdominelle Aortenaneurysma (AAA) ist definiert als eine lokale Erweiterung der abdominalen Aorta auf ≥ 3 cm. Mit einer Prävalenz von 4–8% ist das AAA eine der häufigsten Gefäßerkrankungen in der westlichen Gesellschaft. Die radiologische Bildgebung ist ein elementarer Bestandteil sowohl in der Diagnosestellung als auch der Überwachung und operativen Planung von Patienten mit Bauchaortenaneurysma.

Methode Dies ist ein narrativer Übersichtsartikel zu präoperativen Bildgebungsstrategien beim AAA, der Expertenmeinungen auf der Grundlage der aktuellen Literatur und Standardverfahren aus unserem eigenen Zentrum berücksichtigt. Anhand von Beispielen werden klinische Fälle aus unserer Einrichtung illustriert.

Ergebnisse und Schlussfolgerungen Die radiologische Bildgebung spielt eine zentrale Rolle bei der Erstdiagnose und Überwachung von Patienten mit AAA. Ultraschall ist das wichtigste bildgebende Verfahren für das Screening und die Überwachung des AAA. Die kontrastmittelverstärkte CT-Angiographie ist derzeit der Goldstandard für die präoperative Bildgebung und bildbasierte Behandlungsplanung. Neue kontrastfreie MR-Angiografiertechniken sind robust einsetzbar und ermöglichen eine präzise Bestimmung des Aortendurchmessers, der insbesondere im Hinblick auf die hierauf basierenden chirurgischen Therapierichtlinien von entscheidender Bedeutung ist. Die 3D-CT- oder MRT-Bildgebung mittels multiplanarer Reformation und automatischer Centerline-Positionierung erlaubt eine präzisere Messung des maximalen Aortendurchmessers. Moderne bildgebende Verfahren wie die 4D-Fluss-MRT haben das Potenzial, die individualisierte Risikostratifizierung bei Patienten mit AAA weiter zu verbessern.

Kernaussagen:

- Ultraschall ist das wichtigste bildgebende Verfahren für das AAA-Screening und die Überwachung
- Die kontrastverstärkte CT-Angiographie gilt derzeit als Goldstandard zur präoperativen Bildgebung bei der AAA-Reparatur
- Die kontrastmittelfreie MR-Angiographie ermöglicht eine genaue Überwachung des Aortendurchmessers bei AAA-Patienten
- 3D-CT- oder MR-Bildgebung mit multiplanarer Reformation ermöglicht im Vergleich zum Ultraschall eine genauere Bestimmung des maximalen Aortendurchmessers
- Die Forschung sucht nach neuen quantitativen Biomarkern für die AAA-Risikostratifizierung, z. B. mit Hilfe der 4D-Fluss-MRT

Zitierweise

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Introduction

An abdominal aortic aneurysm (AAA) is defined as a localized dilatation of the abdominal aorta of 3 cm or greater in sagittal or transverse orientation or, alternatively, as a maximum infrarenal aortic diameter of at least 1.5 times larger than the expected diameter of the normal adjacent infrarenal aortic segment [1]. Screening studies have reported a prevalence for AAA of approximately 4–8 % [2–5].

Men are four to six times more frequently affected than women [5–7]. Further risk factors for developing AAA include age > 60 years, tobacco use, hyperlipidemia, hypertension, chronic obstructive pulmonary disease (COPD), coronary, cerebrovascular, or peripheral arterial disease, and family history of AAA [8, 9]. Moreover, people of Caucasian race are at higher risk of developing an AAA [10].

The pathophysiology of the atherosclerotic AAA is multifactorial and not yet fully understood. In short, preexisting atherosclerotic wall changes lead to the migration of inflammatory cells. These initial changes promote the degradation of elastic collagen fibers and apoptosis of vascular smooth muscle cells by expression of matrix metalloproteases and secretion of proinflammatory cytokines [11, 12]. Weakening of the arterial wall results in localized dilatation of the aorta. The dilatation leads to blood flow stasis with formation of turbulent blood flow profiles, favoring formation of an intraluminal thrombus (ILT) [13]. Thick ILT may cause local hypoxia of the vessel wall, promoting local inflammatory processes and resulting in further weakening of the arterial vessel wall [14]. However, from a biomechanical perspective, the formation of a mural thrombus is thought to reduce the risk of rupture by reducing aortic wall shear stress of blood flow [15].

AAA is associated with the risk of dissection and consecutive aortic rupture as a life-threatening complication. According to Laplace's law, aortic wall stress is proportional to the vessel radius. Rupture

occurs when the aortic wall stress exceeds the tensile strength of the aortic wall. Clinical data showed an exponential association between aortic diameter and rupture risk [16]. For example, the risk of rupture was estimated at 10 % per year for AAA from 5.5 to 6.9 cm in diameter but > 33 % per year for AAA ≥ 7 cm in diameter [17].

According to their morphology, AAAs can be further classified as saccular or fusiform aneurysms. Other image-based classifications consider the presence of an intraluminal thrombus (ILT) or possible involvement of the renal arteries (infrarenal AAA vs. juxtarenal or pararenal). The latter is particularly relevant for planning of an interventional procedure, as treatment of juxta- and pararenal AAA is performed using branched or fenestrated endoprostheses [18].

Urgent repair is recommended in symptomatic patients. Indications for elective aortic aneurysm repair in asymptomatic patients with AAA are aneurysm growth of more than 5 mm in 6 months, or a maximum aortic diameter of at least 5.5 cm in men or 5.0 cm in women, respectively [19].

Therefore, monitoring of the maximum aortic diameter by imaging techniques (ultrasound, contrast-enhanced computed tomography (CT), or magnetic resonance angiography (MRA)) are an integral part of the clinical management of patients with AAA.

Technical and practical considerations of different aortic imaging techniques

Ultrasound

Abdominal ultrasound is the mainstay imaging modality for AAA screening and surveillance due to its noninvasiveness, low cost, wide availability, high sensitivity, and high specificity [20, 21]. Ultrasound allows accurate assessment of abdominal aortic morphology such as aortic diameter, kinking, and involvement of the renal as well as iliac artery branches. In addition, it enables assess-

ment of the presence of an ILT, which has been associated with rapid aneurysm growth and early AAA rupture [22, 23]. An ILT is present in more than 75 % of all large aneurysms requiring surgical intervention and in about half of smaller AAAs [22].

Ultrasound screening programs

One-time ultrasound screening for AAAs in men or women 65 to 75 years of age with a history of tobacco use is recommended in current practice guidelines [19]. In Germany, men over the age of 65 with statutory health insurance have been entitled to one-time ultrasound screening of the abdominal aorta since 2018. Similar programs were established earlier in other countries. In the United States, Medicare has covered one-time AAA ultrasound screening at age 65 for men who have smoked at least 100 cigarettes and for women with a family history of AAA disease since 2007 [24]. Since then, AAA screening programs have been introduced in the United Kingdom, Scotland, and Sweden [25, 26].

According to the current practice guidelines of the Society for Vascular Surgery, surveillance ultrasound imaging is recommended at 3-year intervals for patients with an AAA between 3.0 and 3.9 cm in diameter, at 12-month intervals for patients with an AAA with a diameter of 4.0 to 4.9 cm, and at 6-month intervals for patients with an AAA with a diameter of 5.0 to 5.4 cm [19].

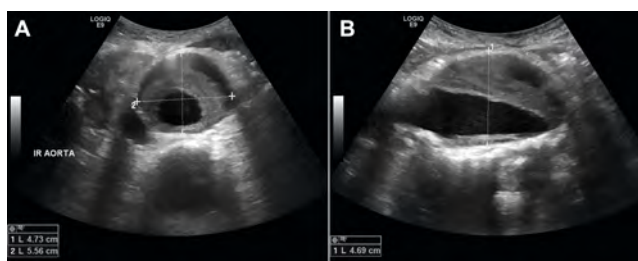
Ultrasound – technical considerations

B-mode ultrasound is the method of choice for anatomical visualization. Typically, low-frequency curved transducers (2–5 MHz) are used. An expansion of the frequency range to 1 MHz can be helpful in obese patients. Slight inspiration assists in the visualization of the proximal portion of the abdominal aorta. Color duplex ultrasound provides additional information on aortic flow characteristics and may occasionally be helpful to differentiate between perfused lumen and mural thrombus.

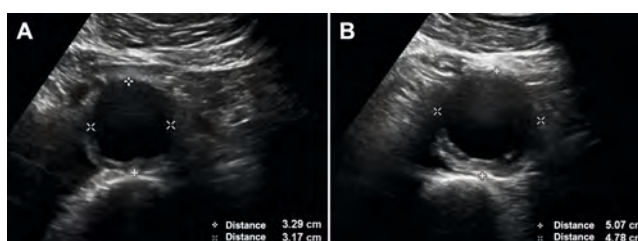
The maximum AAA diameter is measured orthogonally in the anteroposterior (AP) and transverse plane (► Fig. 1). When compared with diameter measurements derived from computed tomography angiography (CTA), systematic underestimation has been reported for ultrasound [27, 28]. In addition to modality-associated influences, examiner-dependent influences, such as the angulation of the transducer and patient-dependent (physiological) pulsation-related deviations of up to 4 mm between systole and diastole add to variations in the assessment of the aortic diameter [29].

Although there are no generally accepted guidelines whether to use an outer-to-outer or inner-to-inner diameter measurement, previous studies have demonstrated a consistent and significant underestimation of inner-to-inner-measurements by 4–5 mm on average [30, 31]. ► Fig. 2 shows ultrasound-guided determination of the maximum infrarenal diameter in an exemplary patient with size-progressive AAA by measuring the outer-to-outer diameter.

AAA imaging using three-dimensional (3D) ultrasound is largely independent of the angulation of the transducer and may thus improve comparability of diameter assessment [32, 33]. In addition, 3D ultrasound makes it possible to quantify the aortic volume, which has been proposed as a more sensitive indicator of AAA progression compared to using only the diameter [34, 35].



► **Fig. 1** Abdominal ultrasound in an abdominal aortic aneurysm (AAA) patient with indication for operation. Transverse (A) and sagittal (B) cross-section of a 69-year-old male patient with a circumferentially thrombosed infrarenal AAA. The intraluminal thrombus presents as a layered circular structure with mixed echogenicity. Ultrasound demonstrated a maximal aneurysm diameter of 5.6 cm. In the sagittal cross-section, the cranial end of the aorta should always be displayed on the left side of the monitor, the caudal end on the right.



► **Fig. 2** Ultrasound-based follow-up of an AAA. A Transverse ultrasound in a 78-year-old male AAA patient with a semicircular posterior intraluminal thrombus. Note that the posterior wall caliper must be positioned on the outside of the dorsal intraluminal thrombus, rather than the inside, to correctly determine aortic size. B Long-term follow-up in the same patient after 3.5 years reveals progression of the aortic aneurysm diameter from 3.3 cm to 5.1 cm.

Contrast-enhanced ultrasound is a complementary tool for AAA characterization. Recent studies have demonstrated its potential as a sensitive tool for endoleak surveillance following endovascular aneurysm repair (EVAR), which was comparable to that of CTA [36].

Another drawback of ultrasound is its decreased reproducibility of AAA diameter measurements, which is often compromised by examiner dependence. Furthermore, the limited field of view can result in missed contained ruptures. If clinically suspected, clarification by CT or MRI should always be performed. An example of a symptom-free female patient with known AAA under ultrasound monitoring who presented to our institution is shown in ► Fig. 3. The chronic contained rupture shown on MR and CT imaging had not been detected until then despite repeated previous ultrasound examinations.

Computed tomography angiography

CTA provides thin-sliced, three-dimensional, high-resolution anatomical images, which are of particular importance for surgical planning. CTA makes it possible to determine AAA diameter, thrombus burden, and aneurysm morphology, i.e., assessment of the aortic neck angle, landing zone, diameter and length, and involvement of aortic side branches as well as pelvic arteries. Moreover, CT can be

useful to determine calcium burden of the aortic wall [27]. High calcium burden has been proposed as a risk marker for a worse overall cardiovascular outcome, i. e., risk factor for AAA rupture [37] and both higher overall and cardiovascular mortality [37] in AAA patients. Moreover, CTA enables an exact determination of the position of existing implants containing metal.

Scan volume should cover supraaortic vessels, the entire aorta as well as the pelvic axis to visualize concomitant aneurysms and relevant stenoses of the commonly applied transfemoral access pathway for endovascular aortic repair (EVAR). CTA should be acquired with a slice thickness of ≤ 1 mm to allow for exact multiplanar reconstruction and thus planning of endovascular procedures.

Owing to its high spatial resolution and large scan volume, CTA detects incidental findings of varying clinical relevance in the thorax or abdomen more frequently. It was reported that 2/3 of AAA patients had findings of immediate or potential clinical relevance. Of these, the most common were colorectal and lung tumors, bladder wall thickening, and pneumonia. The incidence of malignant findings at the time of the initial CTA scan was 6.5 % [38].

However, disadvantages of CTA include its increased cost compared to ultrasound, ionizing radiation exposure, and requirement of intravenous contrast for adequate evaluation of aortic morphology. The use of iodinated contrast agents can cause adverse reactions including hyperthyroidism, acute renal failure, and allergic reactions.

CTA – technical considerations

The current diagnostic reference level set by the German Federal Office for Radiation Protection (BfS) for CTA of the entire aorta is 10 CTDI_{vol} [mGy] [39]. Patient doses for CTA can vary significantly depending on the CT system, scanning parameters, and protocol used. Advanced iterative reconstruction algorithms make it possible to obtain high-quality images with <5 mGy of radiation exposure by reducing the tube voltage [40, 41].

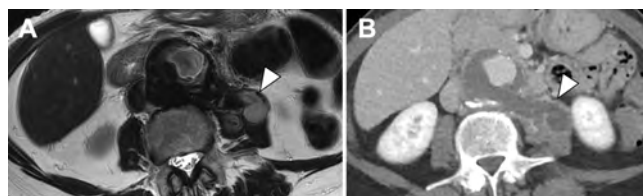
Most CTA protocols of the aorta include multiphase imaging [42]. However, for preoperative imaging purposes (without clinical suspicion of a contained rupture), performing thin-sliced single arterial phase imaging (slice thickness ≤ 1 mm) is sufficient for EVAR planning [25].

CTA-based assessment of the maximum aortic diameter

Precise assessment of the maximum aneurysm diameter is pivotal since the AAA represents one of the surgical conditions in which size is such a critical factor in the timing of surgery.

Diameter measurements performed on axial images become unreliable when aortic angulations are $>25^\circ$ because tortuous vessels result in correspondingly elliptical cross-sections on axial images, resulting in overestimation of AAA size [43]. Therefore, determination of the maximum aneurysm diameter derived from CT imaging based on an outer-to-outer wall measurement perpendicular to the centerline of the aorta is considered the gold standard by current practice guidelines of the Society for Vascular Surgery [19]. 3D imaging using multiplanar reformation may allow correction for vessel angulation.

Many vascular centers use dedicated vessel imaging software with automatic centerline positioning for semiautomatic diameter



► **Fig. 3** MRI and CT of a chronic contained AAA rupture in a symptom-free 63-year-old female that was missed during repeated previous ultrasound monitoring examinations. A chronic contained rupture with hematoma in the left major psoas muscle (arrowheads) is shown on **A** axial T2-weighted MRI as well as on **B** axial portal-venous CT. The chronic covered AAA had not been known until then despite repeated previous ultrasound monitoring examinations. Upon request, the patient reported a sudden abdominal pain event about 10 years prior.

measurement. However, it should be noted that most algorithms for diameter assessment operate on a threshold basis. Especially in larger aneurysms, where an ILT is usually present, the hypodense/hypointense ILT is excluded from the initial evaluation. In such a case, manual correction of the outer vessel wall may be required to determine a correct outer-to-outer diameter. However, in the absence of intraluminal thrombus, a semi-automatic centerline is a powerful tool for determining aortic diameters in order to plan oversizing of the stent grafts at the level of the landing zones and for determining the distance between the involved aortic branches, even in tortuous vessels. ► **Fig. 4** presents an AAA after 3D reconstruction, using IntelliSpace Portal software (Philips Healthcare) to semiautomatically determine the maximum infrarenal diameter along the centerline.

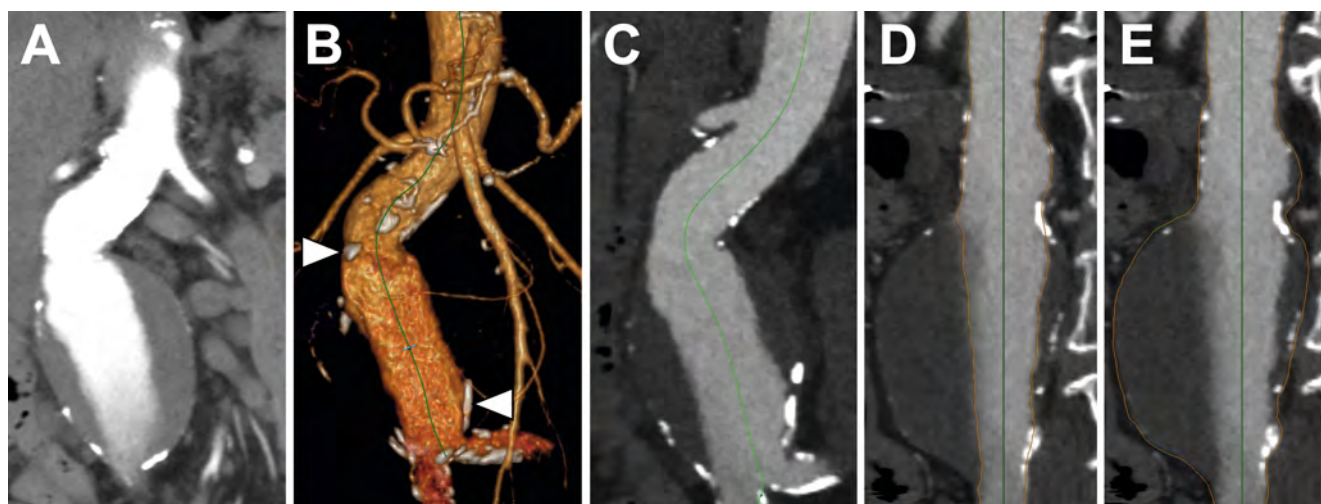
Magnetic resonance angiography

Magnetic resonance angiography (MRA) is an ionizing radiation-free imaging technique with excellent soft-tissue contrast. MRA remains the procedure of choice for patients in whom the use of an iodinated contrast agent or ionizing radiation should be avoided [44]. Move content to the end of the MRI section. According to the other imaging modalities, the “disadvantage section” was moved to the end. To avoid redundancy, this paragraph and the last paragraph on page 7 were merged.

MRA – technical considerations

Contrast-enhanced MRA is still considered the first-line technique due to its high signal-to-noise ratio, which is largely independent from flow-related artifacts [45–47]. ECG gating helps to minimize motion artifacts when performing MRA of the thoracic aorta but is not required for the abdominal aorta because of its location in the retroperitoneal space. Non-contrast MRA has become increasingly important in clinical practice in recent years due to its significant artifact reduction and is therefore established in routine clinical practice for certain patient groups.

Non-contrast MRA using both two-dimensional (2D) and three-dimensional (3D) techniques has been available for several decades. 2D techniques often provide a more robust image quality but preclude multiplanar reconstructions. Flow-independent techniques have the advantage of being less dependent on rapid



► **Fig. 4** CTA-based semiautomatic assessment of the maximum infrarenal diameter of an AAA. **A** Coronal CT angiography of a 69-year-old male patient with AAA and circumferential intraluminal thrombus. **B** 3D rendering of the abdominal aorta shows atherosclerotic calcifications (arrowheads) of the infrarenal aorta. Note that the 3D rendering image visualizes only the contrast-enhanced perfused lumen of the circumferentially thrombosed AAA. **C** Curved planar reconstruction of the infrarenal aorta with automatically generated centerline (green line). **D** Straight reconstruction with semiautomatic determination of aortic diameters fails to assess the maximal aortic diameter due to the threshold-based algorithm, which aligns along the contrast-enhanced perfused lumen of the circumferentially thrombosed AAA. **E** Straight reconstruction with manual segmentation of the AAA and thus correct estimation of the maximal aortic diameter of 5.4 cm.

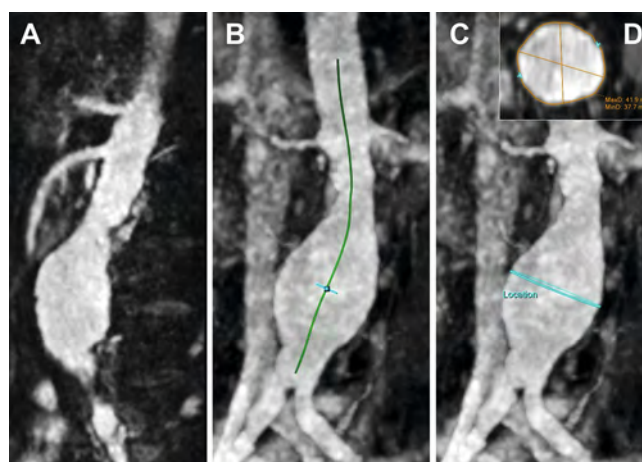
inflow of unsaturated spins into the imaging volume, which may be of relevance in slow flow conditions, e. g., in the aneurysm sac. Current non-contrast MRA of the aorta is typically based on flow-independent 2D or 3D steady-state free precession pulse (bSSFP) imaging [48, 49]. However, a major drawback of bSSFP imaging is off-resonance artifacts caused by B0 inhomogeneities, which occur particularly at higher field strengths ≥ 3 T [50].

Currently used 2D MRA techniques include, for example, cardiac-gated inflow-dependent quiescent-interval slice-selective (QISS) MRA (Siemens Healthineers) [51, 52]. This technique is a notably useful option for patients with additional peripheral arterial disease (pAVD), which is of particular interest in light of the more than 3-fold increased incidence of pAVD in AAA patients compared with non-AAA patients [53]. QISS MRA has been shown to be less susceptible to severe artifacts compared with the quite similar time-of-flight (TOF) MRA.

Regarding 3D imaging, a flow-independent non-gated relaxation-enhanced 3D angiography without contrast (REACT) technique with magnetization-prepared, non-balanced, dual-echo acquisition and generalized Dixon (Philips Healthcare) has been introduced [54, 55]. Experience in routine clinical use of this sequence at our site indicates robust applicability for the thoracic [56] as well as the abdominal aorta (unpublished data). In ► **Fig. 5**, non-contrast 3D REACT MRA is illustrated in an in-house AAA patient.

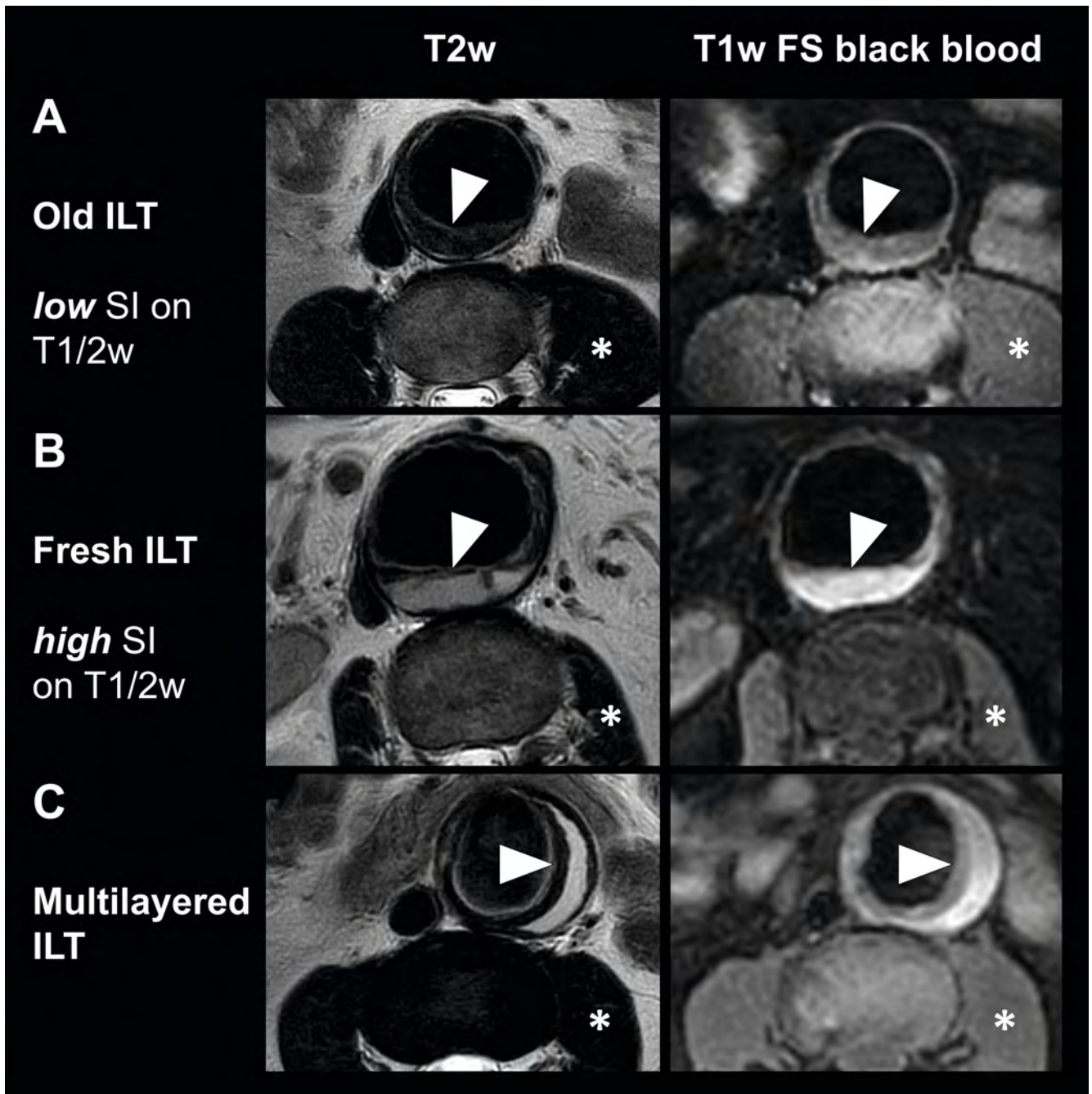
Intraluminal thrombus characterization

ILT is recognized as a biologically active component of AAA acting as a factor in AAA progression and rupture [22, 23]. However, its exact role in AAA pathogenesis remains unclear and continues to be controversial. Suppression of the blood signal using black blood imaging can be helpful in assessing thrombus burden and age by providing a sharp delineation of the surrounding vessel wall [57, 58].



► **Fig. 5** MRA-based semiautomatic assessment of the maximum diameter of an AAA. **A** Sagittal reconstruction of a non-contrast 3D REACT MRA sequence of a 71-year-old male with AAA. **B** Maximum intensity projection (MIP) of the 3D REACT MRA with automatic centerline positioning of the aorta (green line). **C** MIP visualizing automatic determination of the vessel contours (turquoise circle) perpendicular to the centerline. **D** Vessel cross-section for determination of the maximum diameter based on automatic segmentation of the vessel wall (orange line). The largest aneurysm diameter (MaxD, 41.9 mm) and smallest diameter (MinD, 37.7 mm) at this level are determined automatically. MRA = magnetic resonance angiography, REACT = relaxation-enhanced 3D angiography without contrast.

ILT is a heterogeneous structure consisting of various components, such as fibrous matrix, lipid-rich necrotic core, calcifications, or hemorrhage. MRI using T1- and T2-weighted imaging allows detailed characterization of ILT components [59]. Based on



► **Fig. 6** Thrombus characterization using T2- and T1-weighted MR imaging. Axial T2-weighted and T1-weighted fat-saturated (FS) black blood MR imaging of three different intraluminal thrombi (ILT). **A** Old fibrotic ILTs (arrowheads) are characterized by a predominantly iso- to hypointense signal intensity on both T1- and T2-weighted imaging relative to the major psoas muscle (asterisk). **B** Fresh disintegrated ILTs are predominantly hyperintense on both T1- and T2-weighted imaging (arrowheads). **C** Partially organized ILTs have a multilayered appearance with both hyper- and hypointense components (arrowheads). T2w = T2-weighted MRI, T1w FS black blood = T1-weighted fat-saturated black blood MRI, SI = signal intensity.

ILT compositional variations, it is possible to differentiate between i) old solid/fibrotic organized thrombi, ii) fresh disintegrated/hemorrhagic thrombi, and iii) partially organized multilayered thrombi with mixed old as well as fresh components.

An old fibrotic ILT is characterized by a predominantly iso- to hypointense signal intensity on T1- and T2-weighted imaging relative to the major psoas muscle, whereas a fresh disintegrated thrombus is predominantly hyperintense. A partially organized

ILT has a multilayered appearance with both hyper- and hypointense components. Fresh thrombi were shown to be associated with more rapid aortic growth than old thrombi [60, 61]. MR images of exemplary thrombi (fresh, old, partially organized) from in-house patients are shown in ► **Fig. 6**.

In addition to the examiner-dependent visual ILT classification, there is also a semi-automatic approach to determine the age of the thrombus. The so-called ILT signal ratio (ILT_r) is calculated by

dividing the T1-weighted signal intensity of the ILT by the signal of the major psoas muscle ($\text{signal}_{\text{ILT}} / \text{signal}_{\text{major psoas muscle}}$). AAAs with a high relative signal ratio on T1-weighted MRI (> 1.2) have been shown to be associated with a higher AAA growth rate [62].

However, in addition to being more expensive and less available, disadvantages of MRI include incompatibility with certain medical devices (e. g., pacemakers) and claustrophobic patients. Especially in patients who have undergone previous implantation of metallic implants, image quality may be reduced due to corresponding magnetic susceptibility artifacts, preventing diagnostic evaluation of the aorta at this level and adjacent structures. Further drawbacks are a significantly longer acquisition time, precluding examination of individuals with suspected acute AAA rupture, and the potential requirement of intravenous contrast. The latter is often omitted in patients with renal failure due to controversies regarding potential retention in tissues and nephrogenic systemic fibrosis [63, 64].

¹⁸F-FDG PET-CT

¹⁸F-fluoro-deoxy-glucose positron emission tomography (PET/CT) is currently not implemented in the routine pre-procedural diagnosis and treatment of atherosclerotic AAA. However, it may provide valuable information regarding the presence of chronic aortic wall inflammation [65, 66]. The potential clinical application of positron emission tomography (PET) in predicting aneurysm growth may be further optimized by the development and use of more specific radiotracer agents targeting, for instance, angiogenesis [67].

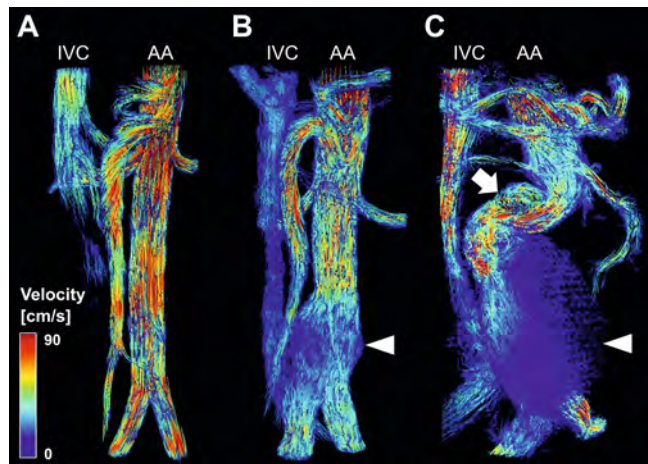
Emerging imaging techniques and technical applications

Aneurysmal dilatation of the aorta favors not only a reduction of flow velocity but also the occurrence of turbulent blood flow. In recent years, it has been proposed that local hemodynamics contribute significantly to ILT formation and growth [22, 23].

Four-dimensional (4D) flow MRI is a noninvasive functional imaging technique that makes it possible to obtain time-resolved information on human blood flow dynamics [68–72]. This technique is based on phase contrast imaging, an MRI technique that allows simultaneous co-registration of morphological images and velocity data. It has been shown that flow stasis in AAA can be visualized and quantified using 4D flow MRI [73].

Wall shear stress and relative residence time derived from 4D MRI have been suggested as potential risk factors for AAA development [74]. However, prospective longitudinal 4D flow MRI studies are lacking, which would allow the identification of flow-based biomarkers for better risk stratification of AAA growth. Exemplary 4D flow MRI-based blood flow profiles of i) a patient without an AAA, ii) a patient with a small AAA, and iii) with a large AAA are displayed in ► Fig. 7.

Mathematical models utilizing finite element analysis (FEA) and computational fluid dynamics (CFD) can estimate aortic stress distribution based on various geometries (e. g., CTA scans) and material properties. These techniques aim at predicting local hemodynamics contributing to ILT deposition and AAA rupture [75, 76]. For example, an association between the hemodynamics



► **Fig. 7** 4D flow MRI-based characterization of abdominal aortic blood flow profiles. **A** 4D flow MRI demonstrates a laminar flow profile in the abdominal aorta (AA) of a 27-year-old male control subject without AAA. **B** 52-year-old male with a small AAA with a diameter of 4.6 cm. Reduced flow velocity in the aneurysm sac is illustrated by blue streamlines. **C** 87-year-old woman with a large AAA with a diameter of 6.7 cm. In addition to the slowed flow in the aneurysm sac, there is significant kinking in the cranial portion of the abdominal aorta causing turbulent flow (arrow) and flow acceleration as illustrated by red streamlines. IVC = inferior vena cava, AA = abdominal aorta.

of near-wall particles and the onset of ILT formation in AAA has been demonstrated, suggesting a critical role of regional shear stress in the pathogenesis of AAA [77].

Speckle tracking ultrasound is another innovative technique that has primarily been applied to quantify cardiac function, specifically to assess strain. This technique tracks tissue movement by analyzing speckle patterns on the B-mode ultrasound image. Interestingly, speckle tracking ultrasound has also been evaluated to assess displacement of aortic wall motion throughout the cardiac cycle in AAA patients [78].

Nevertheless, it should be noted that all techniques discussed in this chapter are currently considered experimental and are not yet established in the clinical routine. Further studies are needed to demonstrate the utility of these techniques in the diagnosis and treatment of AAA.

Conclusion

Radiological imaging plays a pivotal role in the initial diagnosis, monitoring, and treatment planning of AAA patients. Ultrasound is the mainstay imaging modality for AAA screening and monitoring. Contrast-enhanced CT angiography is currently considered the gold standard for preoperative imaging in AAA repair. Non-contrast MR angiography allows for accurate monitoring of aortic diameters in AAA patients. Accurate measurement of aorta diameters is crucial, particularly in terms of current diameter-based surgical treatment guidelines. 3D CT or MR imaging with multiplanar reformation and automatic centerline positioning enables more accurate assessment of the maximum aortic diameter. Current research seeks new quantitative imaging biomarkers for AAA

risk stratification. Modern imaging techniques such as 4D flow MRI have the potential to further improve individualized risk stratification in patients with AAA.

Conflict of Interest

The authors declare that they have no conflict of interest.

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