Pre-procedure imaging planning for dialysis access in patients with end-stage renal disease using ultrasound and upper extremity computed tomography angiography: a narrative review

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Background and Objective: The incidence of patients with end-stage renal disease (ESRD) and subsequent need for dialysis is continuously rising. The detailed preoperative planning and careful creation of a functioning access for hemodialysis as a bridge to transplant or as a long-term solution, has a crucial role to reduce vascular access associated morbidity and mortality and improve quality of life of the ESRD patient population. In addition to a detailed medical workup including physical exam, a variety of imaging modalities exist to support further decision making with regard to the best suited vascular access for each individual patient. These modalities provide both, a comprehensive anatomical overview of the vascular tree and specific pathologic findings, which may increase the likelihood of access failure or insufficient access maturation. This manuscript aims to provide a comprehensive review of current literature and an overview of the different imaging modalities in vascular access planning. Additionally, we provide a step-by-step planning algorithm for hemodialysis access creation.

Methods: After searching in PubMed and Cochrane database of systematic review, we reviewed eligible English literatures published up to 2021, including guidelines and meta-analyses, retrospective and prospective cohort studies.

Key Content and Findings: Duplex ultrasound is widely accepted as first line imaging tool for preoperative vessel mapping. However, this modality has its inherent limitations, therefore specific questions can be assessed using digital subtraction angiography (DSA) or venography and computed tomography angiography (CTA). These modalities are more invasive, are associated with radiation exposure and require nephrotoxic contrast agents. Magnetic resonance angiography (MRA) may be an alternative in selected centers with available expertise.

Conclusions: Pre-procedure imaging recommendations are mainly based on retrospective (register-) studies and case-series. Prospective studies and randomized trials are primarily related to access outcomes in ESRD patients who underwent preoperative duplex ultrasound. Comparative prospective data related to invasive DSA and non-invasive cross-sectional imaging (CTA or MRA) are lacking.

Keywords: Preoperative planning; vascular access creation; imaging modalities; vein mapping

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Introduction

In patients suffering from end-stage renal disease (ESRD), functioning access for hemodialysis is a life sustaining requirement. The access can serve either as a bridge to renal transplant or as a long-term solution in non-transplant candidates.

Vascular access modalities for long-term hemodialysis include tunneled dialysis catheter placement and surgical access creation [arteriovenous fistula (AVF), arteriovenous graft (AVG) and percutaneous arteriovenous fistula (pAVF)]. The purely autologous AVF is considered first vascular access option of choice (1) and preferred to a polytetrafluoroethylene (PTFE)-graft (AVG). However, creation of early cannulation AVGs in patients with poor native options is gaining increasing popularity, as they show reasonable short-term patency. Long-term patency of the graft is limited by thrombotic occlusion requiring frequent endovascular interventions as well as increased risk of infection. Although central venous catheters (CVCs) are regarded as tertiary options due to their significantly higher morbidity and mortality rate (2,3), they are frequently used if hemodialysis needs to be initiated immediately and as a definitive solution in a subset of patients with poor native vessels and significant comorbidities. Furthermore, a delay in access planning and the rising occurrence of acute kidney injury on chronic kidney disease stage 5 requiring urgent dialysis initiation leads to increased reliance on CVC (1).

To create the proper vascular access for each individual patient (considering a patient-centered approach) detailed preoperative planning, including workup of the access history, transplant candidacy, vessel status and comorbidities/risk factors is mandatory.

A cornerstone of this planning procedure is the assessment of the patients' vasculature to identify those potentially suitable for the creation of a hemodialysis access. The two main elements of this evaluation are the physical exam and imaging. Traditionally, the physical exam has been the primary assessment tool for access planning and imaging was only reserved in cases of equivocal physical exam. The newer guidelines incorporate routine diagnostic imaging prior to access placement (3,4). This paradigm shift was driven by the intention to decrease the number of CVCs and AGV and to increase AVF creation. The different imaging modalities help to identify suitable autologous veins and determine pathologic findings (both arterial and venous) which may impair fistula maturation or increase the risk of access failure.

This manuscript aims to provide an overview of the different imaging modalities that can be utilized for vascular access planning and creation. Advantages and drawbacks for each modality will be discussed along with the implications for daily clinical practice. We present the following article in accordance with the Narrative Review reporting checklist (available at https://cdt.amegroups.com/article/view/10.21037/cdt-21-797/rc).

Methods

A literature search was performed in PubMed and Cochrane database of systematic review covering publications up to 2021. We used the following combination of keywords: (I) imaging modalities and vascular access; (II) preoperative planning and vascular access; (III) vein mapping; (IV) duplex ultrasound for vascular access planning; (V) DSA and vascular access planning; (VI) MRA and vascular access planning; (VII) CTA and vascular access planning; (VIII) clinical practice guidelines vascular access. Current guidelines, meta-analyses and prospective studies were included, however, most of provided data/references are derived from observational studies. The search was restricted to guidelines, original research and papers published in English language.

Key inclusion criterion was the description of one of the following imaging modalities, examined/analyzed for feasibility with respect to vascular access creation for hemodialysis: (I) duplex ultrasound; (II) CTA; (III) DSA; (IV) MRI. Papers, that dealt with imaging modalities, used for maintenance and revision of vascular access, were not included. The initial literature search was performed by SR, MA and DS. They independently assessed the methodological quality of the studies prior to their final inclusion (*Table 1*).

Duplex ultrasound

According to current guidelines, pre-operative ultrasound of bilateral upper extremity arteries and veins is recommended in all patients in the workup of vascular access creation (Class I, Level A) (3).

After a dedicated clinical examination to exclude overt pathologies and assess for venous chest wall collaterals, the arterial vasculature of the upper extremity is scanned from the subclavian artery to the radial and ulnar arteries at the level of the wrist to evaluate inflow criteria (*Table 2*).

The vessel diameters of the radial and brachial arteries

Table 1 The search strategy summary

Items	Specification
Date of search	July and August 2021
Databases and other sources searched	PubMed, Cochrane database
Search terms used	(I) Imaging modalities and vascular access; (II) preoperative planning and vascular access; (III) vein mapping; (IV) duplex ultrasound for vascular access planning; (V) DSA and vascular access planning; (VI) MRA and vascular access planning; (VII) CTA and vascular access planning; (VIII) clinical practice guidelines vascular access
Timeframe	1.1.1990 to 31.08.2021
Inclusion and exclusion criteria	The search was restricted to guidelines, original research and papers published in English language
	Key inclusion criterion was the description of one of the following imaging modalities, examined/analyzed for feasibility with respect to vascular access creation for hemodialysis: (I) duplex ultrasound; (II) CTA; (III) DSA; (IV) MRI. Papers, that dealt with imaging modalities, used for maintenance and revision of vascular access, were not included
Selection process	The initial literature search was performed by SR, MA and DS. They independently assessed the methodological quality of the studies prior to their final inclusion

DSA, digital subtraction angiography; MRA, magnetic resonance angiography; CTA, computed tomography angiography; NA, not applicable.

are measured in the longitudinal and/or cross-sectional view on B-mode ultrasound and assessment for atherosclerotic involvement of these arteries is pursued (*Figure 1*). Concerning surgical planning, the most crucial part of the exam is the color and pw-Doppler evaluation to exclude stenotic disease or occlusion within the subclavian, axillary, brachial and radial as well as ulnar arteries. Anatomical variants, such as high brachial bifurcation need to be reported, due to their potential to alter the surgical approach.

For pAVF creation, specific information on the cubital (Ellipsys® vascular access system) and wrist (WavelinQ®) vessel anatomy is of relevance, particularly related to the arterio-venous proximity and presence of perforators (5).

Using color- and pw-Doppler the central veins (subclavian, jugular internal and brachiocephalic vein) are examined to detect any occlusion, post-thrombotic alterations or anatomic abnormalities that might impede adequate venous outflow of the arm (*Figure 2*).

In case of a free central outflow, the superficial veins are scanned from the distal cephalic vein at the wrist to the subclavian vein (with and without tourniquet) (outflow criteria, *Table 2*). In case of a patent central venous system and absence of postphlebitic alterations or acute phlebitis (*Figure 3*), the measurement of the vein diameter in the cross-section view on B-mode ultrasound is performed (*Figure 4*). Additionally, the anatomic course of the vein (straight, <6 mm from the skin surface, side branches) is documented.

A descriptive report is generated for surgical planning purposes. *Figure 5* provides a template of such report, showing the upper extremity arterial and venous tree, including documentation of vessel diameter and stenotic degree as well as venous outflow segments.

Digital subtraction angiography (DSA) and venography

DSA and venography (DSV) is considered the gold standard for visualization of the arterial and venous vasculature, especially for assessment of the central venous system. It enables identification of clinically occult central venous stenotic disease and occlusion (6,7).

In case of preoperative vascular access planning, the standard approach for visualization of the arterial vasculature includes a retrograde puncture of the brachial artery leading to visualization of the entire arterial inflow from the subclavian artery to the digital arterial supply. The technique enables detection of inflow stenosis and provides information on vessel diameter and anatomical abnormalities (*Figure 6*).

In order to visualize the venous outflow tree, a superficial forearm or hand vein is punctured in an antegrade approach.

Table 2 Imaging requirement for VA-creations

VA modalities	(Arterial) inflow	(Venous) outflow
AVF		
Snuffbox/radio-cephalic	≥2–2.5 mm	No central venous stenosis/occlusion
	No significant stenosis	Inner diameter: 2–2.5 mm
	No circumferential calcification at intended anastomotic site	No phlebitis/postphlebitic alterations
		Course of cephalic vein
		Distance vein to skin surface (preferably <6 mm)
Brachio-cephalic	≥3 mm	No central venous stenosis/occlusion
	No significant stenosis	Inner diameter: 3 mm
	No circumferential calcification at intended anastomotic site	No phlebitis/postphlebitic alterations
	Anatomic variant (high bifurcation of brachial artery)	Course of cephalic vein
		Distance vein to skin surface (preferably <6 mm)
Brachio-basilic	≥3 mm	No central venous stenosis/occlusion
	No significant stenosis	3 mm
	No circumferential calcification at intended anastomotic site	No phlebitis/postphlebitic alterations
	Anatomic variant (high bifurcation of brachial artery)	Course of basilic vein
		Level of junction with brachial vein-transposition possible?
AVG		
Forearm straight graft	≥2–2.5 mm	Adequate deep cubital outflow
	No significant stenosis	No central venous stenosis/occlusion
	No circumferential calcification	
Forearm loop graft	≥3 mm	Adequate deep cubital outflow
	No significant stenosis	No central venous stenosis/occlusion
	No circumferential calcification	
	Anatomic variant (high bifurcation of brachial artery)	
Upper arm straight graft	≥3 mm	Adequate outflow (basilic/brachial vein)
	No significant stenosis	No central venous stenosis/occlusion
	No circumferential calcification	
	Anatomic variant (high bifurcation of brachial artery)	
pAVF		
WavelinQ	≥2 mm (ulnar or radial artery)	2 mm (ulnar or radial vein)
		Distance between ulnar/radial artery and ulnar/radial vein <2 mm
Ellipsys	≥3 mm	Distance between proximal radial artery and perforating vein of the elbow <1.5 mm

VA, vascular access; AVF, arteriovenous fistula; AVG, arteriovenous graft; pAVF, percutaneous arteriovenous fistula.

Venous punctures above the elbow should be avoided to preserve these veins for fistula and/or graft creation in the future.

Computed tomography angiography (CTA)

CTA is typically used for detection of pathology after creation of the vascular access. Alternatively, it may be used for mapping the arterial anatomy. However, similar to DSA this modality requires the use of iodinated contrast agents which should be avoided in pre-dialysis patients to prevent further decline/deterioration of their already markedly impaired renal function. Although, modern multidetector CT scanners have extremely short acquisition times with consecutive reduction of radiation dose, the use of ionizing radiation needs to be considered. CTA provides 3D reconstructions and maximum intensity projection (MIP) images, which can be helpful in vascular access planning. CTA can also detect extrinsic compression as an underlying cause of central venous stenosis (8) and as a possible cause of stenosis of the central arterial vasculature including the supra-aortic vessels (*Figure 7*).

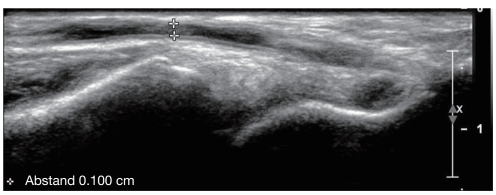

Figure 1 B-mode ultrasound of the distal radial artery with assessment showing not suitable diameter of 1 mm.

Magnetic resonance angiography (MRA)

MRA is a non-invasive modality offering complete overview of the arterial (MR arteriography) and venous (MR venography) anatomy of the upper extremity in a one-exam session. For vascular access planning it is usually performed as contrast-enhanced MRA (CE-MRA), using a gadolinium-based agent. The application of gadolinium does not bear the risk of an acute deterioration of the renal function, which is an important aspect in (pre-dialysis) patients with marginal renal function. Nevertheless, the risk of developing a nephrogenic systemic fibrosis (NSF) secondary to gadolinium needs to be considered but is exceedingly low and can be almost neglected with newer macrocyclic ionic contrast media gadolinium based MR contrast agents (9-11). In chronic renal failure the half-life of gadolinium is prolonged to 12–30 hours and the combination of metabolic acidosis and inadequate clearance triggers the development of dermopathy with older MR contrast agents (11).

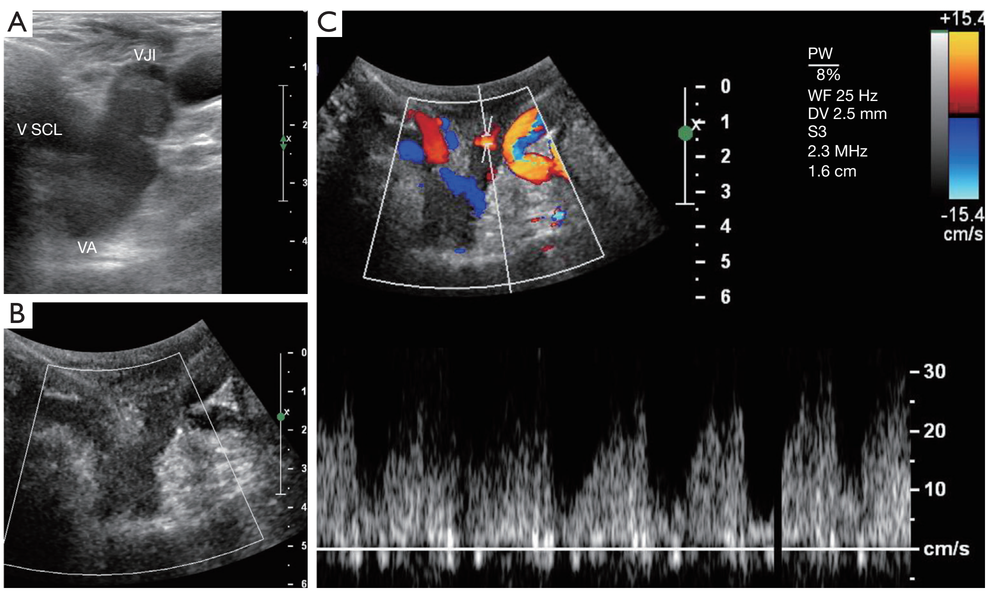

Figure 2 Color and pw-Doppler assessment of the central venous system. Central vein obstruction with completely occluded brachiocephalic vein on B-mode ultrasound (A) and Color-Doppler ultrasound (B). Partial occlusion of the most proximal part of the internal jugular vein with retrograde flow on pw-Doppler (C). VJI, internal jugular vein; V SCL, subclavian vein; VA, anonyma vein; PW, pulsed wave Doppler; WF, wall filter.

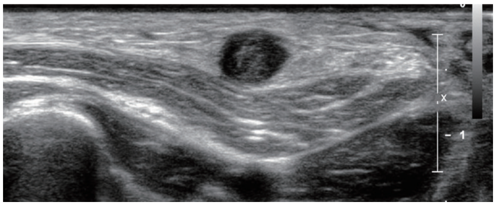

Figure 3 B-mode ultrasound with cross-sectional view demonstrating acute to subacute thrombosis of the cephalic vein.

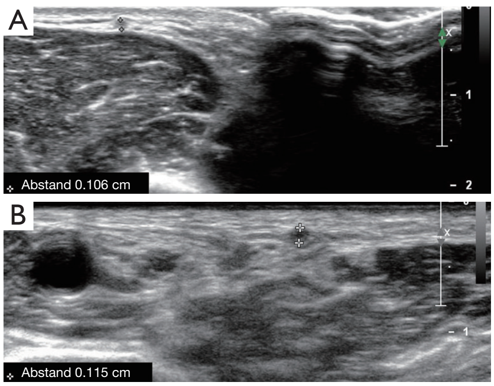

Figure 4 B-mode ultrasound of the superficial arm vein. Not suitable cephalic vein located in the upper arm (A) and basilic vein (B).

Intravascular ultrasound (IVUS)

Although this imaging modality does not play any role in pre- or postoperative vascular access imaging yet, its use in assessing central venous pathologies (thrombus, stenosis, occlusion, dissection) is gaining increased attention. Data suggest that IVUS is superior to DSA in detecting post angioplasty recoil and persistent intraluminal webs (12).

The use of this relatively new modality is limited to the post interventional setting and its use is not incorporated yet into the most recent guidelines.

Discussion

This manuscript provides an overview of the different imaging modalities, which can be applied for planning to create a vascular access for hemodialysis focusing on the advantages and limitations of the different modalities and the specific requirements for each type of access (AV fistula, AV graft, CVC).

DSA/DSV is considered the gold standard to assess the central venous system, but is also a valuable tool for the arterial vasculature due to the possibility of immediate percutaneous intervention (e.g., angioplasty/stenting). However, in clinical practice, its application is usually

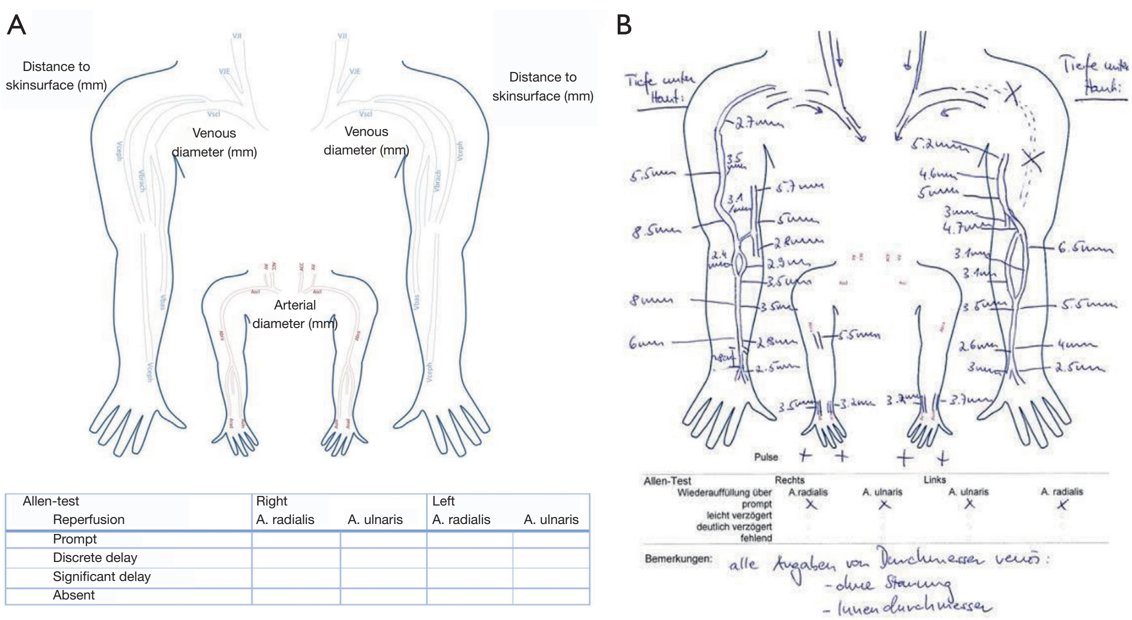

Figure 5 Template (A) and clinical example (B) of a report of upper extremity arterial and venous ultrasound assessment for pre-procedure planning purposes.

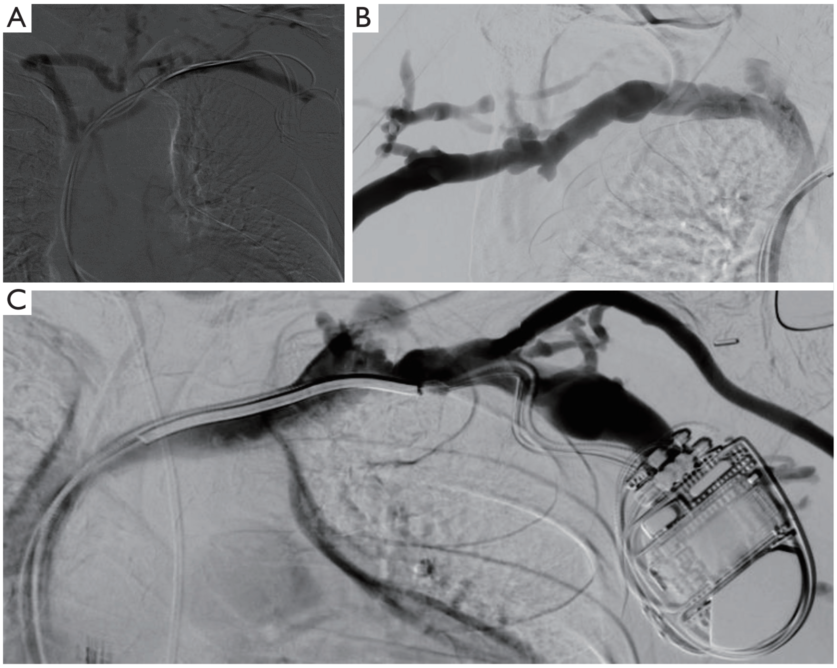

Figure 6 Digital substraction venography. (A) Left upper extremity CO_2 venogram with left chest wall pacemaker device in place. The venogram depicts patent left axillary and subclavian veins. There is stenosis of the left innominate vein with large venous collateral visualized between the left and (patent) right innominate vein. (B) Right upper extremity venogram with iodine based contrast showing widely patent right axillary, subclavian and innominate veins. (C) Left upper extremity venogram demonstrating patent left cephalic venous arch and patent left subclavian vein. There is mild stenosis at the junction of the left innominate vein-superior vena cava.

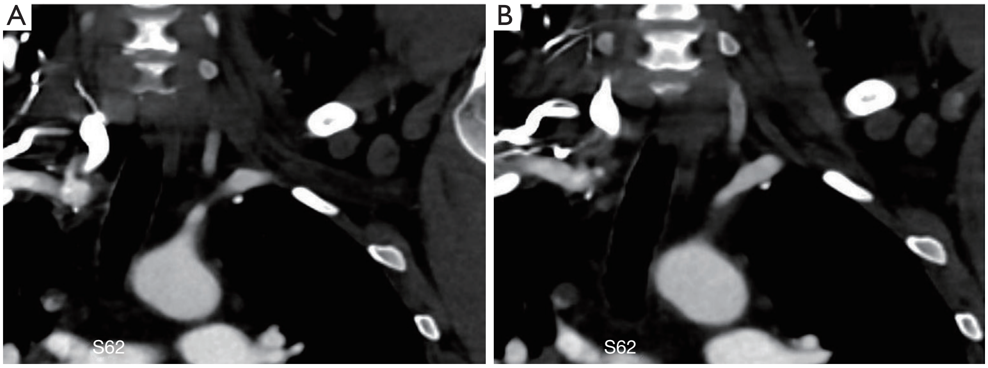

Figure 7 Two axial CTA images (A,B) of the left upper extremity with injection of iodine based contrast via a right peripheral intravenous access showing mild stenosis at the proximal portion of the left subclavian artery. CTA, computed tomography angiography.

reserved for postoperative assessment and treatment of non-maturing or failing fistulas. The downside of this modality is the required iodinated contrast agent administration and the radiation exposure (13). In patients in whom iodinated contrast should be avoided, CO_2 as contrast agent can be used and has a similar performance compared to conventional venography with iodine-based contrast agents (14).

The clinical practice guidelines for vascular access for hemodialysis recommend DSA/DSV in a preoperative assessment only in patients with a certain likelihood of central venous stenosis secondary to previous catheter placements (7). It needs to be noted that European

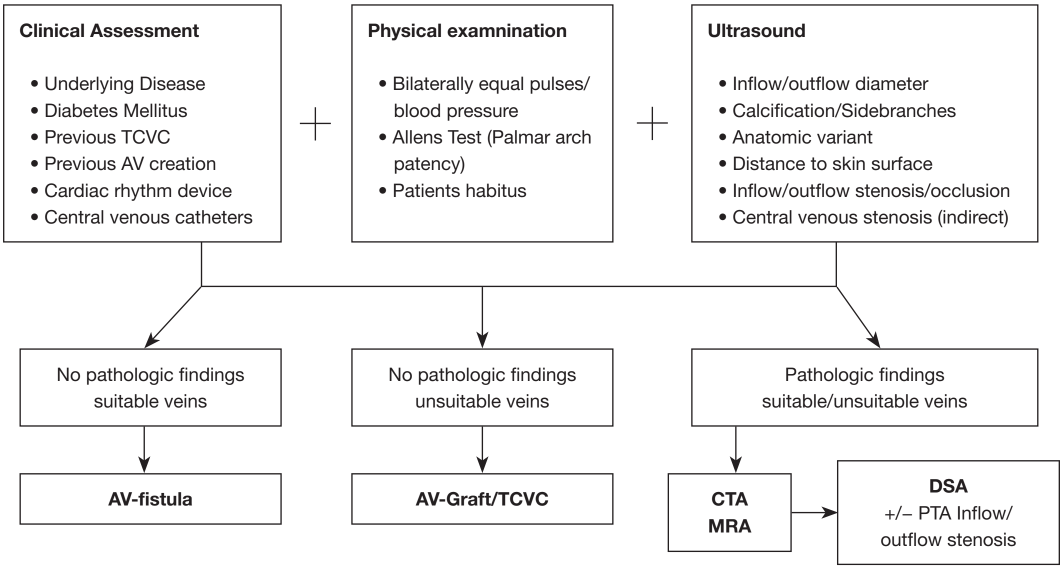

Figure 8 Pre-procedure planning algorithm of vascular access. TCVC, tunneled central venous catheter; AV-fistula, arteriovenous fistula; AV-graft, arteriovenous graft; CTA, computed tomography angiography; MRA, magnetic resonance angiography; DSA, digital subtraction angiography; PTA, percutaneous transluminal angioplasty.

guidelines are even more restrictive when recommending DSA/DSV solely in patients in whom a subsequent intervention is anticipated (Class I, Level C) (3).

CTA and MRA play an inferior role as imaging modalities in pre-procedural planning and are more often used to detect pathologies in patients with already established vascular accesses.

CTA imaging provides an overview of the arterial vasculature of the upper extremity and potential anatomic abnormalities. It reveals highly calcified arterial segments and detects inflow limiting stenoses (>50%) or occlusions (3,15). Depending on the examination protocol related to timing of image acquisition it can also visualize central venous pathologies.

The current literature does not provide any comparative data between duplex ultrasound and CTA for preoperative vascular access planning, and the 2018 Clinical Practice guidelines recommend to consider CTA only in patients with inconclusive ultrasonographic or angiographic/venographic results related to the degree of stenotic disease (Class IIb, Level C) (3).

MRA provides excellent information on central venous pathologies, e.g., in patients with a history of recurrent CVC placements, but its use is limited by accessibility, costs and local expertise. Furthermore, the MRA exam is time consuming.

Another important drawback in the antecedent was the risk of the development of a gadolinium associated NSF. This severe complication can be avoided by performing non-contrast enhanced MRA (NCE-MRA).

Published data (9,16) demonstrated this technique to be inferior compared to conventional gadolinium based MRA in terms of total numbers of visible arterial segments and image quality. NCE-MRA can be useful in the depiction of venous structures (9).

Compared to duplex ultrasound, MRA has a superior performance with regard to detection of arterial and venous stenoses (17) and provides a comprehensive overview of the vascular anatomy.

Despite these advantages, the ESVS Guidelines do not recommend CE-MRA in patients with end-stage renal disease (Class III, Level C) (3) for pre-access evaluation, although actual recommendations of radiologic societies state that the risk for development of NSF is minimal at best.

The preferred imaging modality for performing vascular access planning is duplex ultrasound (4). This recommendation is mainly based on its advantage of wide accessibility, non-invasiveness and the absence of ionizing radiation without requiring contrast agent administration. However, clear evidence is lacking with regard to the usefulness of preoperative ultrasound translating into superior results in long-term access patency.

A meta-analysis by Georgiadis *et al.* (18), comparing preoperative physical examination versus duplex ultrasound, did not show significant differences in postoperatively fistula maturation/usability for hemodialysis after one and six months (19-22).

A Cochrane Database review from 2015 (23), analyzed four randomized controlled trials (RCTs), including over 400 participants, dealing with preoperative vascular access evaluation by ultrasound compared with standard preoperative care with clinical assessment alone. Results did not show a significant difference in both, the number of successfully created [RR 1.06 (95% CI: 0.95–1.18)] and successfully usable fistulas [RR 1.12 (95% CI: 0.99–1.28)]. Furthermore, the number of patients initiating dialysis with a catheter was equally in both groups based on one study [RR 0.66 (95% CI: 0.42–1.04].

Slightly more encouraging results were published by McGill *et al.* (24). They performed a retrospective analysis of more than 30,000 patients, initiating hemodialysis on a CVC with subsequent planning for AVF or AVG creation. They compared patients undergoing any preoperative imaging (Doppler imaging or venography) versus clinical evaluation before or after starting hemodialysis. Only 7.4% of the entire cohort underwent preprocedural imaging. Patients, who had imaging underwent more frequently fistula or graft creation (70.9% *vs.* 45.9%, P=0.002) and had lower rates of ongoing CVC use (41.5% *vs.* 71.0%) and death (39.4% *vs.* 50.6%, P<0.001). Those, who received preoperative imaging, were more likely to achieve a functioning AVF/AVG (71.3% *vs.* 69.7%, P=0.02). The numbers of surgical procedures post access creation were significantly higher in patients who received pre-access imaging (P=0.001) and pre-procedure imaging was not found to be an independent predictor for achieving a working AVF/AVG (OR 1.09, 95% CI: 1.02–1.16).

Finally, a recent retrospective cohort study by Fedorova *et al.*, compared access configuration (AVF *vs.* AVG), location (forearm *vs.* upper arm), successful initiation of hemodialysis and secondary patency in 46,000 patients stratified by preoperative vein mapping or not. Data were derived from the Hemodialysis Access dataset of the Society for Vascular Surgery Vascular Quality Initiative. Results showed a significant higher creation of forearm access and better secondary patency rates (P<0.001) in those patients who underwent preoperative vein mapping (25).

Differences in society guidelines are understandable when considering these controversies. While the European Guidelines recommend a pre-access imaging exam for all patients undergoing vascular access creation (3), the 2019 KDOQI guidelines recommend preoperative vein mapping only in selected patients (26).

Based on our experience pre-access imaging might contribute to decision-making processes related to the type and localization of hemodialysis accesses in individual patients.

Based on our own experiences a preoperative planning algorithm is proposed in *Figure 8*. In the ESRD population with multiple comorbidities (diabetes, cardiovascular diseases, obesity) a comprehensive pre-access evaluation including physical examination and sonographic imaging of the bilateral upper extremities is considered institutional standard of care. A schematic drawing (*Figure 5*) based on the ultrasound examination serves as a fundamental prerequisite for interdisciplinary discussions in order to determine the most reasonable vascular access procedure for each individual patient. Additional preoperative imaging studies including CTA or MRA are pursued in selected cases. DSA/DSV can be performed if concomitant endovascular intervention is anticipated.

Summary

A single imaging modality cannot provide all necessary information prior to vascular access creation. The combination of patients' medical history, physical examination and vascular ultrasound is widely accepted as the standard of care in access planning, whereas further modalities are preserved for selected patients and circumstances. An interdisciplinary institutional access team should develop a standard pre-access algorithm based on current evidence and guidelines as well as local expertise and abilities.

The following three considerations should be at the center of the planning and creation of a vascular access in each ESRD patient:

(I) The patient's current condition (e.g., young, healthy, acute renal failure, no history of CVCs, palpable and easily identifiable veins *vs.* older, diabetic, chronic kidney disease, long-standing history of recurrent CVCs), before planning the diagnostic pathway.

(II) Adequate imaging modality for the required vascular access (e.g., ultrasound mapping prior to AV fistula creation in pre-dialysis patients with uneventful history *vs.* venography in patients with exhausted veins and long-standing history of CVCs in the setting of chronic kidney disease).

(III) Patient centered choice of the specific access (shared decision making, information of the patient on the pros and cons of all potential access options, considering the patients social and medical background; considering the impact of the vascular access on the patient's quality of life).

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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