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Detailed ultrasonographic assessment of calcified arteries before arterio-venous fistula construction and fistula outcomes - a prospective observational study

Jakob Gubensek[1,2*], Denis Fornazaric[1,2] and Matej Zrimsek[1,2]

Abstract

Background Arterial calcifications (mainly mediocalcinosis) are highly prevalent in patients on hemodialysis. Severe calcifications reduce the possibility of a forearm arterio-venous fistula (AVF) construction, reduce maturation rates and increase the risk of hemodialysis access-induced distal ischemia (HAIDI). We report a prospective observational study on detailed ultrasound assessment of calcified arteries and outcomes of AVFs constructed in those conditions.

Methods In patients referred for vascular mapping, distal, mid and proximal radial artery (RA) as well as brachial artery were assessed for grade of calcifications (B-mode), homogeneity of color Doppler (CD) and compressibility of the artery. Pulsed-wave Doppler parameters at rest and during reactive hyperemia were also assessed. Based on the results, a site for AVF construction was planned. Outcomes of constructed AVFs were assessed.

Results In 35 patients (mean age 68±13 years, 89% diabetics) we assessed 240 arterial sites, made 44 plans and constructed 31 AVFs/grafts. We observed several ultrasonographic phenotypes of calcified arteries. Severely calcified arteries (B-mode assessment) were heterogeneous when assessed for CD homogeneity and compressibility. Constructed AVFs/grafts had very good maturation rates (> 75%) even in a subgroup of radio-cephalic AVFs made on significantly calcified RAs (79%). There were no cases of clinically significant HAIDI.

Conclusions AVF construction with high likelihood of maturation and low likelihood of HAIDI in patients with significantly calcified arteries is possible, after proper evaluation of the artery. Homogeneity of CD and compressibility of the artery with ultrasound probe are useful additional criteria for assessing the suitability of a severely calcified artery for AVF construction.

Keywords Arterial calcifications, Maturation rate, Reactive hyperemia, Ultrasound assessment, Vascular access

*Correspondence:
Jakob Gubensek
jakob.gubensek@kclj.si
[1]Center for Acute and Complicated Dialysis and Vascular Access, Department of Nephrology, University Medical Center Ljubljana, Zaloska cesta 7, Ljubljana 1000, Slovenia
[2]Faculty of Medicine, University of Ljubljana, Ljubljana 1000, Slovenia

Introduction

Arterial calcifications (mainly in the form of mediocalcinosis) are common in patients with advanced stages of chronic kidney disease (CKD) or end-stage kidney disease. In addition to the CKD itself, advanced age, longstanding diabetes mellitus, smoking and deranged CKD mineral and bone disease are common additional risk factors [1]. Arterial calcifications increase cardiovascular morbidity and mortality in patients with CKD [2] and are usually detected and quantified by coronary artery calcium score or presence of abdominal aortic calcifications on lateral abdominal X-ray [3].

In addition to aortic and coronary calcifications, which affect prognosis of CKD patients, calcifications are also present on the arteries of the upper (and lower) limbs. In a large biopsy study of radial arteries (RA) calcifications were present in 21% of RAs with 9% classified as severe [4]. Our group reported an even higher prevalence (20%) of moderate/severe calcifications detected on ultrasound vascular mapping in elderly patients [5]. Severe calcifications reduce the possibility of a forearm arterio-venous fistula (AVF) construction and also make suturing of the anastomosis more difficult. A large study reported that radio-cephalic AVF construction was not possible due to arterial wall calcifications or stenosis in 5% of patients and in some further cases there were combined (arterial and venous) reasons for the impossibility of distal AVF creation [6]. Even when a distal AVF is constructed, primary failure is more common [7] and maturation rate is reduced. Furthermore, if an elbow AVF/graft is constructed in patients with calcified arteries, the risk of hemodialysis access-induced distal ischemia (HAIDI) is increased. Therefore, creating a distal radio-cephalic AVF whenever it is technically feasible is preferred in hemodialysis patients, as they have a much lower risk of HAIDI and development of high flow.

Ultrasound examination is routinely used for vascular mapping prior to an AVF construction [8], but it has traditionally focused primarily on the size, patency and location of the vessels. One study showed that a preoperative ultrasound examination of the arteries very often changed the surgical plan, particularly when a radio-cephalic AVF was initially planned [9]. Qualitative assessment of a calcified artery, grading of calcifications and evaluating the suitability of a calcified artery for AVF construction remain a challenging task [10], without established recommendations in the guidelines [8].

In this study, we assessed the degree of calcifications of the upper limb arteries using a combination of B-mode and Doppler ultrasound examination, with the aim of defining common ultrasonographic phenotypes of calcified arteries and aimed to identify factors predicting compressibility of the artery. Furthermore, we report outcomes of AVFs constructed under these conditions.

Methods

Study design

This was a prospective observational study in patients with advanced or end-stage CKD referred for vascular mapping prior to an AVF construction between September 2022 and December 2024. Only patients with arterial calcifications observed on vascular mapping were included in the study. The study used a convenience sample (i.e. all eligible patients within the recruitment window) with no a priori sample size calculation. For the study purposes, an additional detailed Doppler ultrasound examination of the arteries was performed. The study was performed in accordance with the Declaration of Helsinki and approved by the National Medical Ethics Committee (No. 0120 – 51/2021/6). Written informed consent was obtained from all patients prior to inclusion.

Ultrasound assessment of the arteries

A detailed ultrasound assessment of the arteries was performed in one or both upper limbs with a linear probe at four sites: the brachial artery at the elbow and proximal, mid- and distal segments of the RA. Ultrasound assessment at each site comprised: (1) grading of arterial wall calcifications in B-mode imaging (longitudinal view), (2) assessment of the homogeneity of the color Doppler signal (longitudinal view) and (3) evaluating compressibility of the artery with the ultrasound probe (transverse view), as described previously [10]. In B-mode imaging arterial calcifications were classified as none, mild (spotty or short linear wall hyperechogenicities), moderate (longer wall hyperechogenicities without or with incomplete distal shadowing) or severe (linear hyperechogenicities with complete distal shadowing, see Fig. 1). Homogeneity of color Doppler signal was classified as homogeneous or patchy, defined as coloring of >50% or < 50% of the visible length of the artery (see Fig. 2). The compressibility of the artery was assessed in a cross-sectional view by pressing the probe at an appropriate angle to compress the artery against the nearby bone (radius or humerus, see Fig. 3 and Supplementary videos S1 and S2). Pulsed-wave Doppler parameters measured at all sites included peak systolic velocity (PSV), end-diastolic velocity (EDV) and resistance index (RI = (PSV - EDV)/PSV) at rest. Additionally, systolic acceleration and acceleration time (AT) (measured from the onset to the peak of systole), as well as RI during reactive hyperemia (induced by clenching a fist for 30 s) were measured over brachial artery and distal RA.

AVF construction and outcomes

Peripheral veins were assessed for continuity and diameter according to standard practice. The site of AVF construction was planned based on arterial and venous examination. The minimal criteria for AVF construction

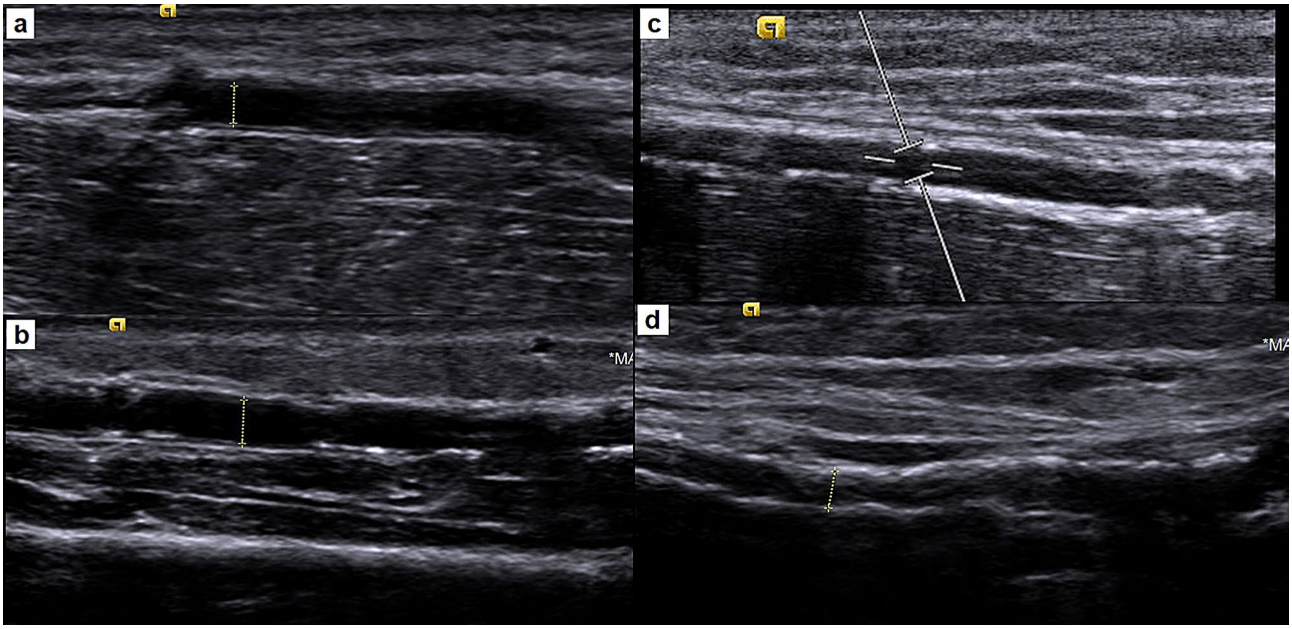

Fig. 1 B-mode assessment of arterial calcifications: panel **a** – none, panel **b** – spotty calcifications, panel **c** – linear calcifications without complete distal shadowing, panel **d** – linear calcifications with complete distal shadowing

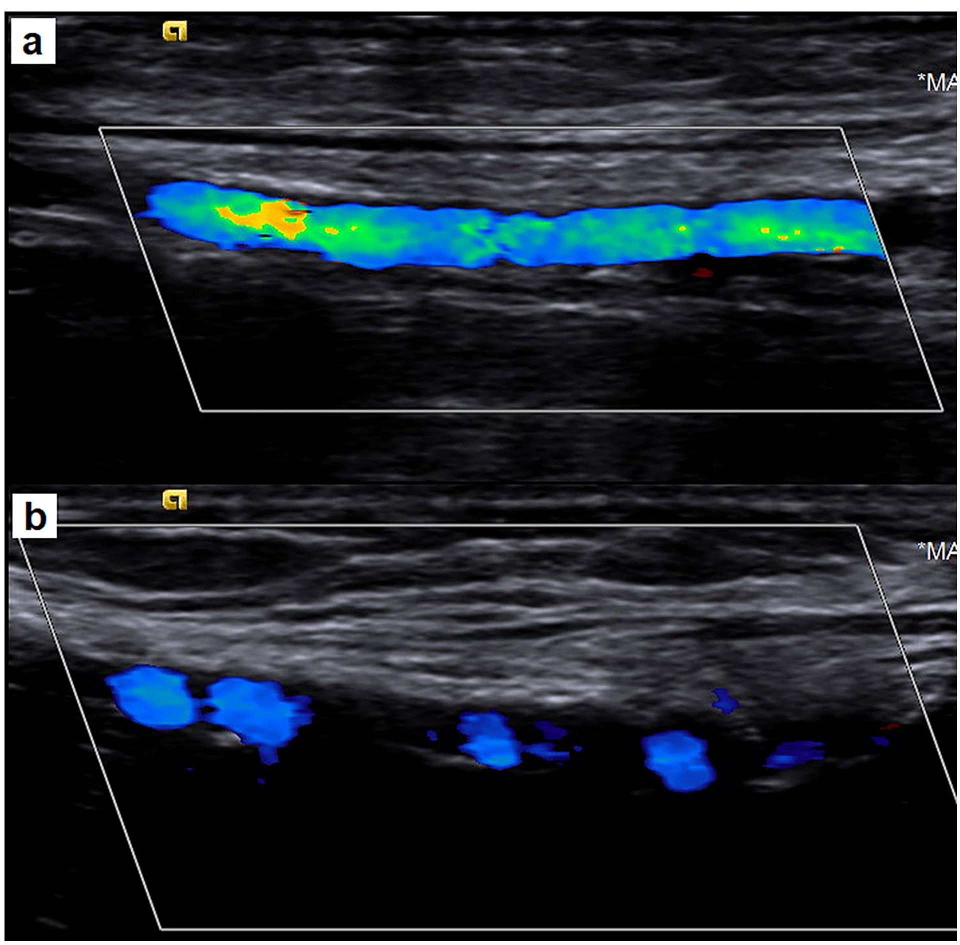

Fig. 2 Color Doppler assessment of arterial calcifications: panel **a** - homogeneous color Doppler (> 50% of visible length of the artery colored), panel **b** - patchy color Doppler (< 50% colored)

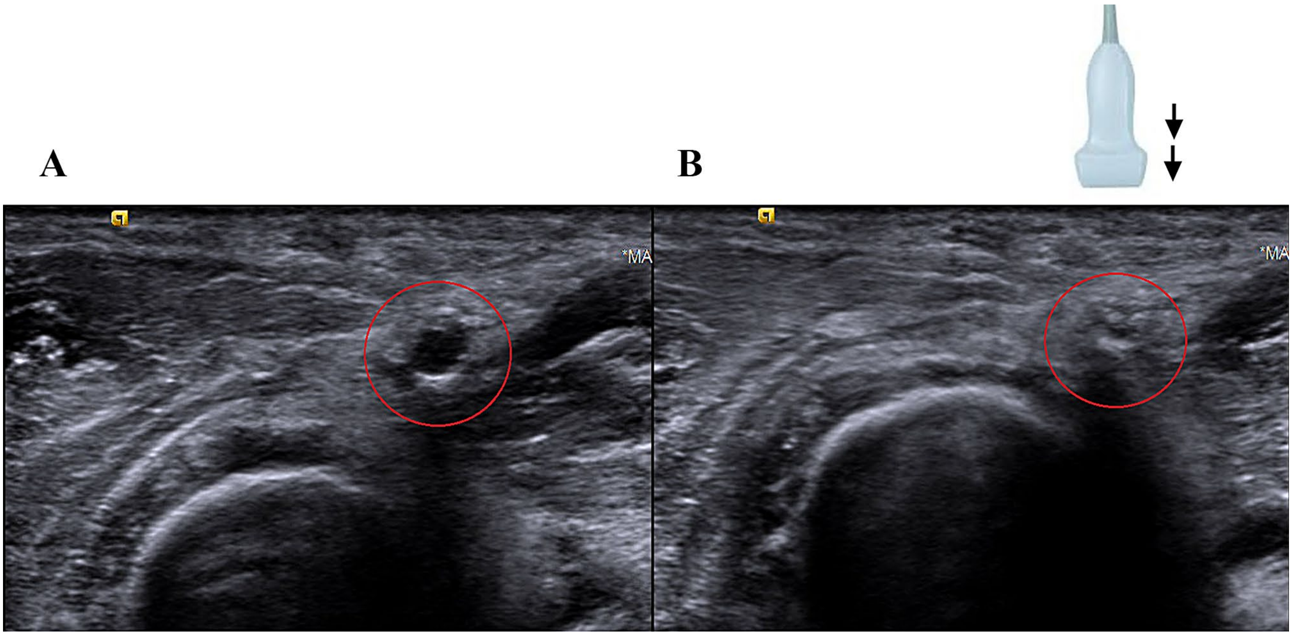

Fig. 3 Assessing compressibility of the artery: a calcified artery (panel **a**) is compressible, when pressed against the bone by the ultrasound probe (panel **b**). See also Supplementary Videos S1 and S2

were: an appropriately long (about 3–4 cm, enough for clamping and suturing of the anastomosis) compressible segment of the artery of suitable diameter (≥2 mm) and an optimal vein diameter (≥2.5 mm in the forearm, ≥3.0 mm at the elbow and ≥4.0 mm for a graft) at the site of anastomosis, without stenosis of the target vein. In patients with severe distal calcifications and low PSV at the wrist a decision not to create an elbow AVF was made to avoid steal syndrome. Patients with poor vasculature were maintained on a catheter.

The outcome of created AVFs was established. A matured AVF was defined as an AVF, successfully used for hemodialysis in the majority of hemodialysis sessions or (in a few patients not yet starting hemodialysis) assessed as appropriate for dialysis by ultrasound examination (blood flow of at least 500 ml/min and fistula vein diameter of 5 mm). For matured AVFs, 1-year primary and secondary (assisted) patency was also determined.

Statistical methods

Continuous data are presented as means and standard deviations and categorical as frequencies (percentages). Concordance of different categorical parameters was visualized with fluvial diagrams. Continuous data were compared between two groups with Student's T test and between multiple groups by ANOVA. Ordinal data (calcification grade) were compared by Mann-Whitney U test. Measures of diagnostic accuracy (sensitivity, specificity, positive (PPV) and negative predictive value (NPV) and accuracy were calculated to assess diagnostic performance of some clinical and ultrasound parameters. Area under the receiver-operator curve (ROC) was calculated for variables that were found to be significantly different between groups. Statistical analysis was performed with Statistica 12.0 (StatSoft inc., USA), fluvial diagrams were constructed using Jamovi (version 2.5.2.0) [11]. P-value < 0.05 was considered statistically significant.

Results

During the study period there were 174 patients referred for vascular mapping. We included 35 patients with calcified arteries in the study in whom we assessed 240 arterial sites. Mean age of patients was 68±13 years, 28 (80%) were male, 31 (89%) had diabetes, 18 (51%) were current or former smokers; 17 (49%) had advanced CKD, while 18 (51%) were already on hemodialysis.

The distribution of the grade of arterial wall calcification on B-mode image according to the location of the assessment site is shown in Fig. 4 and confirms a peripheral distribution of calcifications, which are more frequent and also more severe on mid- and distal RA.

Ultrasonographic arterial phenotypes

Concordance of different ultrasound parameters on all assessed arterial sites is presented on a fluvial chart (see Fig. 5). Several typical ultrasonographic phenotypes can be observed: almost all the arterial sites with no, mild or moderate calcifications had a homogeneous color Doppler signal and were compressible with the probe. In contrast, arteries with severe calcifications with distal shadowing were more heterogeneous with three phenotypes (i.e. “flows” on the diagram) emerging: 34/84 (40%)

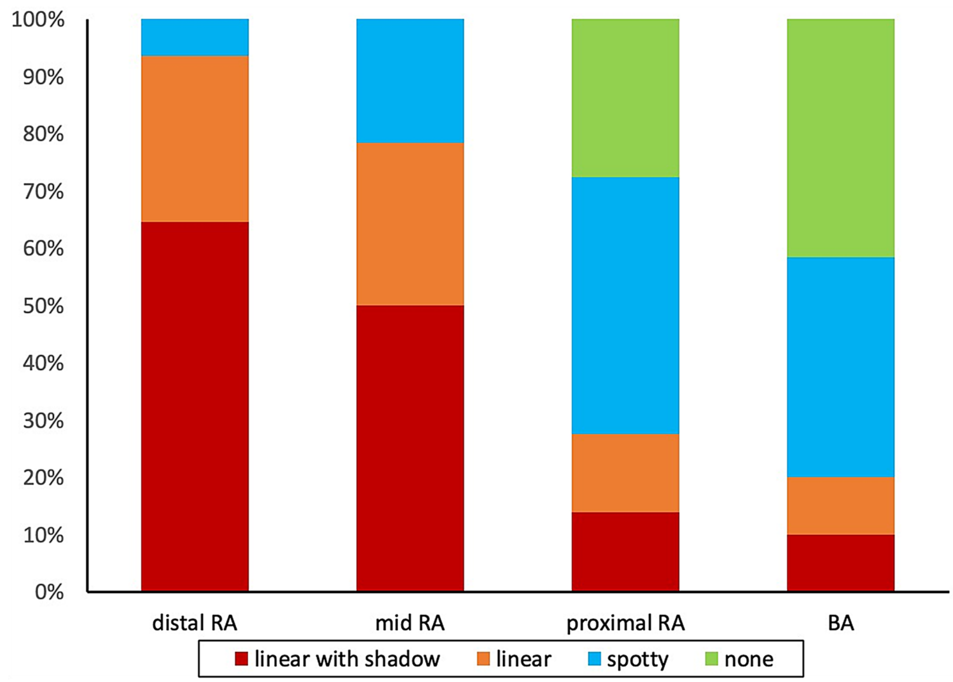

Fig. 4 B-mode assessment of the grade of calcifications according to the location of the assessment site. RA- radial artery, BA - brachial artery

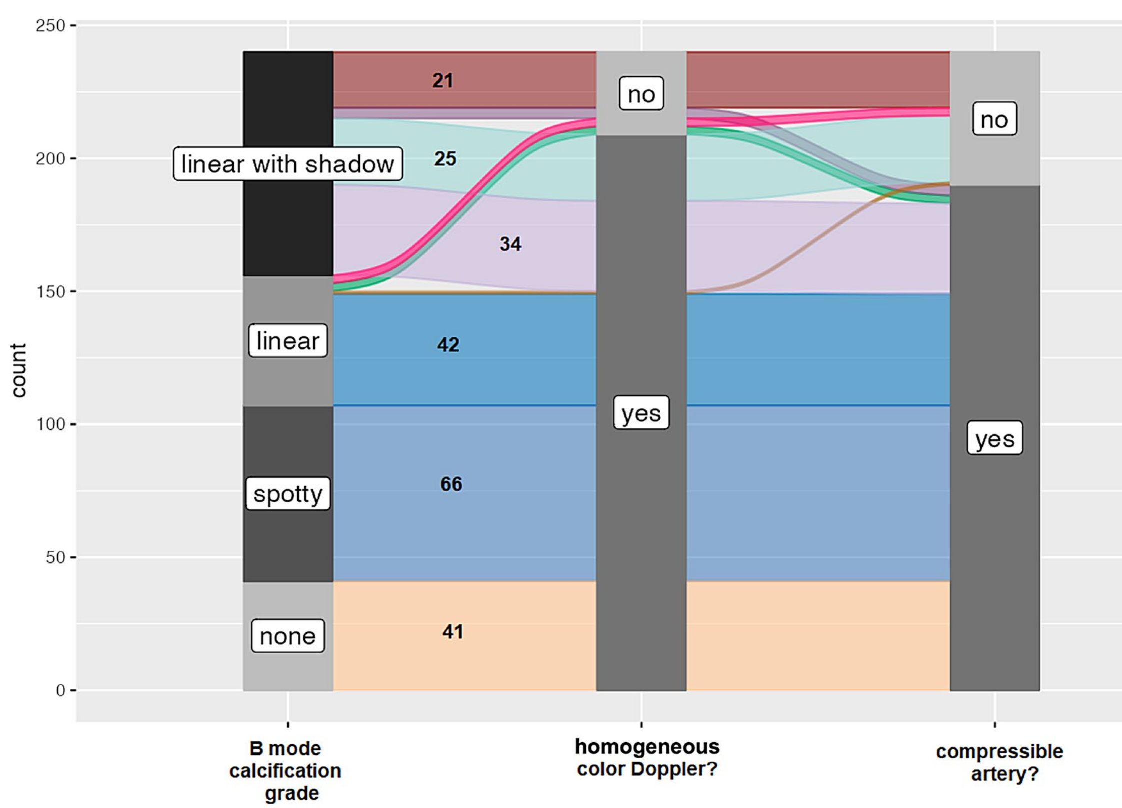

Fig. 5 Fluvial diagram showing typical combinations ("ultrasonographic phenotypes") of different ultrasound parameters (flows) used for assessment of the arteries, as assessed at all sites. Number of arterial sites in each flow is given

had a homogeneous color Doppler and were compressible, therefore likely suitable for anastomosis creation, 25 (30%) had a homogeneous color Doppler but were not compressible, while 21 (25%) had the worst combination, a patchy color Doppler and non-compressibility. Only a few sites had other combinations of parameters.

Association of pulsed-wave doppler parameters with the calcification grade on RA

Comparison of pulsed-wave Doppler parameters between different grades of calcifications in the distal RA is given in Table 1. It showed significantly lower PSV at rest and during reactive hyperemia as well as lower systolic acceleration with increasing level of calcifications, which implies decreased perfusion. Acceleration time was comparable across groups, implying the absence of severe proximal (focal or cumulative) stenosis. RI during reactive hyperemia was also comparable and with relatively good values (mean RI 0.81±0.11) even in the most calcified arteries, indicating that this parameter is inappropriate for assessing the severity of calcifications. It was also not associated with PSV at rest ($p = 0.85$). The increase in PSV during reactive hyperemia was only insignificantly smaller with increasing degree of calcification.

Association of clinical and doppler parameters with compressibility of the RA

Clinical parameters (presence of pulse, palpable calcifications of the arterial wall) can only be assessed on distal RA. Their concordance with grade of calcifications on B-mode image and compressibility of the distal RA is presented on a fluvial diagram (Fig. 6) and an explanation is provided in the legend.

Association of Doppler parameters with the compressibility of RA is shown in Table 2. Non-compressible RAs had significantly smaller diameter (even when only distal RAs were analyzed), lower PSV at rest and during reactive hyperemia (similarly to the increasing grade of calcification) and lower acceleration at rest (which was not associated with the grade of calcification). Despite this, in the majority of non-compressible RAs PSV at rest was >50 cm/s (a cut-off which is sometimes used for assessing appropriateness for AVF construction [12] and was found to be associated with outcome [7]). Area under the ROC curve was low for acceleration (0.54) and PSV at rest (0.63), while it was better for PSV during reactive hyperemia (0.78) with the optimal cut-off value of 62 cm/s for PSV at rest and 73 cm/s for PSV during reactive hyperemia.

Diagnostic accuracy of clinical and ultrasound parameters

We evaluated the diagnostic performance of clinical (presence of pulse and absence of palpable calcifications of the arterial wall) and ultrasound parameters (homogeneous color Doppler and absence of severe calcifications (i.e. with complete distal shadowing) on B-mode) to detect a compressible artery (with an ultrasound probe, taken as the gold standard clinical criterion) and calculated measures of diagnostic accuracy. Since homogeneity of color Doppler signal has additional diagnostic value only in the presence of severe calcifications with distal shadowing, we further calculated measures of accuracy within this subgroup. The results are presented in Table 3 and an algorithm for arterial evaluation, based on these results, is proposed in Fig. 7.

Clinical outcomes

In our group of 35 patients 44 access plans for a location of an AVF construction or a permanent use of a catheter were made (a few patients had a second AVF constructed after failure of the initial one). The planned accesses, the actual accesses constructed and their maturation rates are given in Table 4. The difference between planned and actually constructed AVFs was due to some patients who did not decide for or did not yet need an AVF. Altogether, 31 AVFs/grafts were constructed; in all surgical procedures, an AVF was constructed as planned. All AVFs/grafts had very good maturation rates (> 75%), confirming the appropriateness of the decision process.

Table 1 Comparison of pulsed-wave doppler parameters on distal radial artery, stratified by degree of calcification on B-mode

	None	Spotty	Linear	Linear with shadow	*p* value*
N	0	4	18	40	/
PSV [cm/s]	/	109±17**	78±29	72±26**	**0.03**
EDV [cm/s]	/	4±10	4±6	4±9	0.97
RI	/	0.96±0.10	0.95±0.07	0.95±0.13	0.97
AT [ms]	/	66±22	52±12	57±12	0.09
Acceleration [m/s^2]	/	21.2±8.8**	14.6±7.3	12.1±4.7**	**0.01**
PSV during RH [cm/s]	/	125±13**	91±37	78±35**	**0.03**
EDV during RH [cm/s]	/	15±6	17±10	15±13	0.91
RI during RH	/	0.88±0.06	0.82±0.07	0.81±0.11	0.41
increase in PSV during RH	/	16±6	17±16	5±22	0.13

* one-way ANOVA, ** significant difference between the groups by Bonferroni post-hoc test

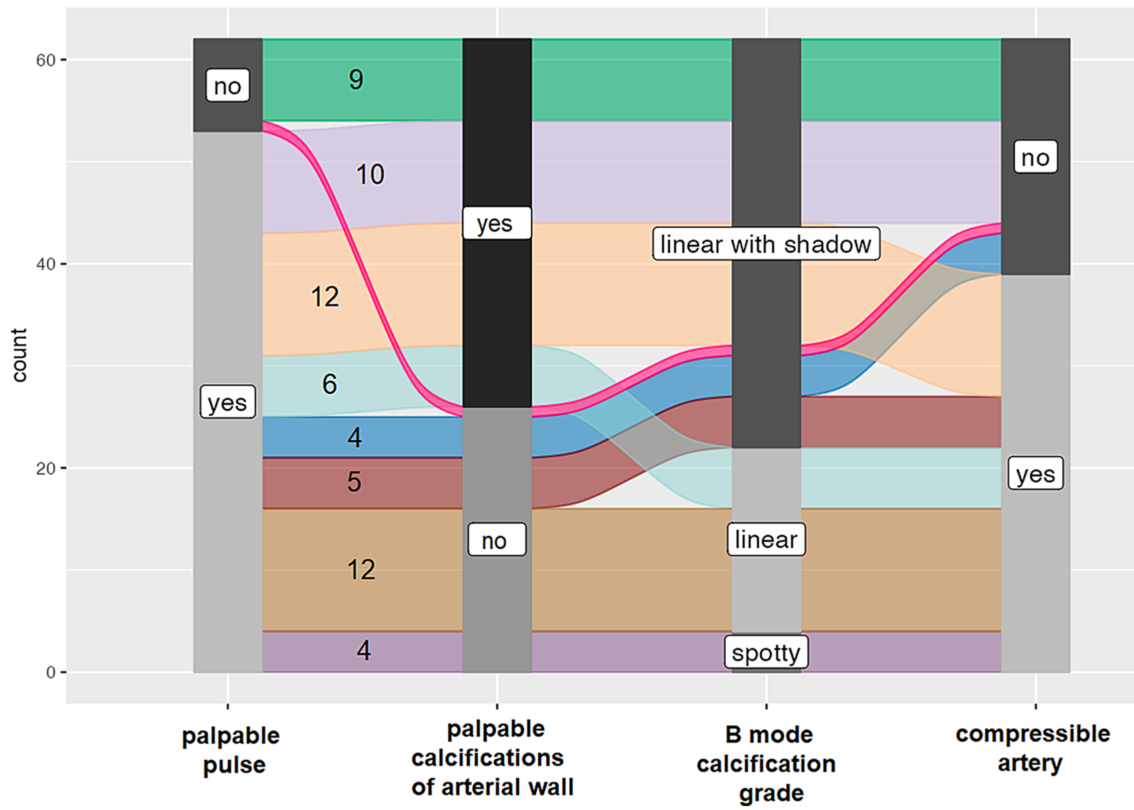

Fig. 6 Fluvial diagram showing concordance of clinical parameters (presence of pulse and palpable calcifications of the arterial wall) with ultrasound parameters on distal radial artery. Absent pulse predicts non-compressible artery with great precision (green flow). Clinically palpable calcifications of arterial wall correspond very well with presence or absence of severe calcifications with distal shadowing on B-mode ultrasound image (green, light purple, orange, light brown and dark purple flows), but not so well with compressibility of the artery. While no palpable calcifications predict compressible artery with great precision (dark purple, dark and light brown flows), palpable calcifications do not uniformly predict an uncompressible artery (green and light purple flows), as there is a significant proportion of compressible arteries (orange flow) among them, which can only be detected by ultrasound exam and not clinically

Table 2 Association of doppler ultrasound parameters with the compressibility of radial artery (RA) (proximal, mid or distal)

Parameter	Compressible RA	Non-compressible RA	*p* value
Proximal, mid or distal RA			
N	128	48	/
arterial diameter [mm]	2.5±0.4	2.1±0.3	**< 0.001**
PSV [cm/s]	75±27	63±21	**0.004**
EDV [cm/s]	2±6	4±8	0.23
Distal RA			
N	39	21	/
AT [ms]	58±14	53±12	0.19
Acceleration [m/s^2]	14.8±13.7	11.2±3.4	**0.04**
PSV during RH [cm/s]	95±38	63±19	**0.001**
EDV during RH [cm/s]	18±12	12±8	0.08
RI during RH	0.82±0.09	0.82±0.10	0.91

The acceleration time (AT), acceleration and resistive index (RI) during reactive hyperemia (RH) were only measured in the distal RA. Comparison by Student's T test

Outcomes of a subgroup of distal RC AVFs (constructed on distal or mid-RA), made on RAs with significant calcifications (linear with or without distal shadowing) at the site of anastomosis were also very good, with 79% (11/14) maturation rate. 1-year primary and secondary patency rates were also favorable (73% for distal RCAVFs and 100% secondary patency for proximal RCAVF and BA-based accesses).

Possible predictors of maturation success in RA based AVFs are analyzed in Table 5. Only the diameter of the target vein was significantly larger in the matured group, however, the vein dimeter exceeded the guideline-recommended cut-off value in both groups. None of the arterial parameters, including grade of calcifications and RI during reactive hyperemia, were different between the groups.

There were no cases of clinically significant HAIDI during the observation period, therefore, we could not analyze any predictors of HAIDI.

Table 3 Measures of diagnostic accuracy (sensitivity, specificity, positive (PPV) and negative predictive value (NPV) and accuracy) for the ability of some clinical and ultrasound parameters to predict an artery, compressible with the ultrasound probe (i.e. appropriate for surgery, taken as a "gold standard")

Clinical or ultrasonographic parameter	*N*	Sensitivity	Specificity	PPV	NPV	Accuracy
Palpable pulse	122	100%	39%	88%	100%	89%
Absence of palpable calcifications of the arterial wall	122	77%	78%	94%	44%	77%
Absence of linear calcifications with complete distal shadowing	240	80%	92%	97%	55%	83%
Homogeneous color Doppler signal	240	96%	48%	88%	77%	86%
• In a subgroup of arteries with linear calcifications with complete distal shadowing	84	90%	46%	58%	84%	66%

Normal result of a test was considered as a positive test result. The pulse and wall of the artery can only be palpated at the wrist and at the elbow, which reduces the number of observations for these two parameters

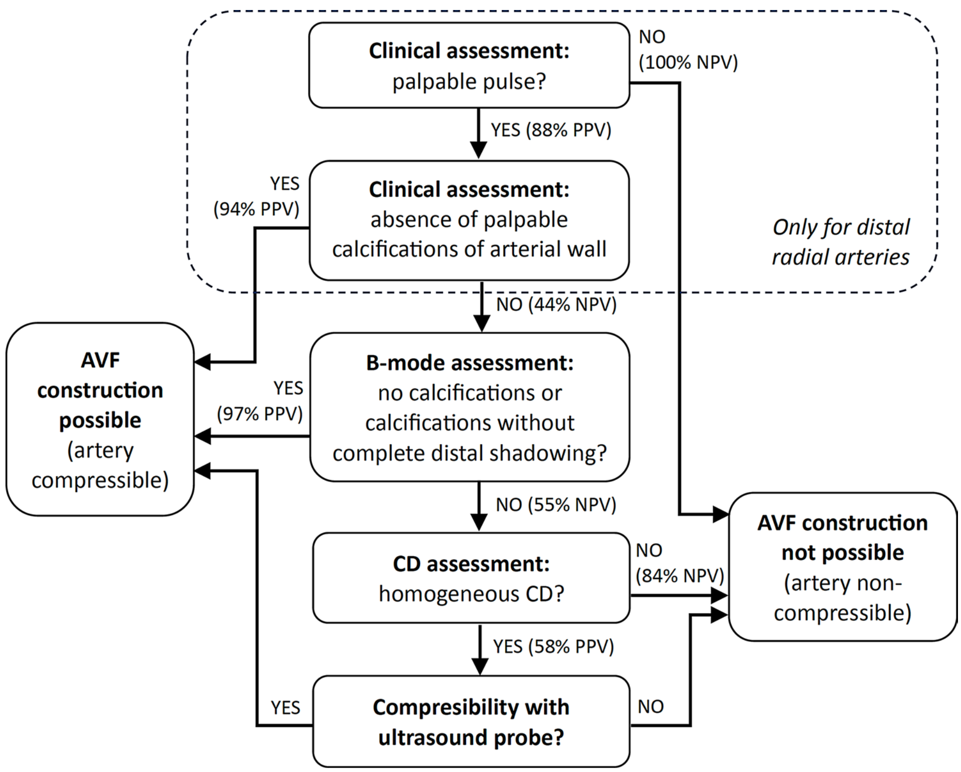

Fig. 7 A proposed algorithm for step-by-step clinical and ultrasound assessment of a calcified artery

Table 4 Plans for the type of vascular access made based on ultrasound exam, the actual vascular accesses constructed and their maturation rates

Vascular access type	Planed access	AVF/graft construction	Maturation rate	1-year primary patency	1-year secondary patency
Catheter	7	/	/	/	/
Distal RCAVF	22	20	15 / 19* (79%)	8 / 11** (73%)	8 / 11** (73%)
• Distal RCAVF on RA with significant calcifications***	/	14	11 / 14 (79%)	8 / 11 (73%)	8 / 11 (73%)
Proximal RCAVF	7	6	4 / 5* (80%)	3 / 3** (100%)	3 / 3** (100%)
BCAVF	3	1	1 / 1 (100%)	1 / 1 (100%)	1 / 1 (100%)
Graft	5	4	3 / 4 (75%)	1 / 2** (50%)	2 / 2** (100%)

*for one distal and one proximal radio-cephalic (RC) AVFs the outcome could not be assessed, as patients died within 6 weeks of access surgery, **for other patients the outcome after 1 year could not be assessed (AVFs < 1 year old or patient died), ***linear calcifications with or without distal shadow, BCAVF - brachio-cephalic AVF

Table 5 Possible predictors of maturation of radio-cephalic arterio-venous fistulas (RCAVFs)

Parameter	Matured RCAVFs	Non-matured RCAVFs	*p* value
N	19	5	/
calcification grade:			0.76*
• none	1	0	/
• spotty	7	2	/
• linear	9	2	/
• linear with shadow	2	1	/
arterial diameter [mm]	2.4±0.3	2.4±0.5	0.89
venous diameter [mm]	3.6±0.8	2.8±0.3	**0.05**
PSV [cm/s]	82±20	94±47	0.36
EDV [cm/s]	4±6	1±3	0.25
AT [ms]	57±15	62±23	0.56
acceleration [m/s^2]	15.1±7.3	19.9±9.7	0.24
PSV during RH [cm/s]	105±41	119±68	0.56
EDV during RH [cm/s]	19±14	19±23	0.96
RI during RH	0.83±0.08	0.84±0.11	0.77

Calcifications grade, diameters and velocities refer to the site of anastomosis (PSV - peak systolic velocity, EDV - end-diastolic velocity). Acceleration time (AT), acceleration and resistance index (RI) during reactive hyperemia (RH) refer to the distal radial artery, regardless of the site of anastomosis. *Mann-Whitney U test, other comparisons by Student's T test

Discussion

Our study on detailed ultrasound assessment of calcified arteries describes several ultrasonographic phenotypes and shows that severely calcified arteries on B-mode imaging are actually a heterogeneous group, when additional ultrasound parameters are used for a more comprehensive assessment. As we have shown, many of them are in fact suitable for AVF construction which makes this finding clinically relevant. We have chosen compressibility of the artery by an ultrasound probe as the gold standard criterion for an attempt of AVF construction from a practical (surgical) perspective and predictive ability of other parameters for compressibility was calculated. Furthermore, we assessed the utility of simple clinical parameters (pulse, palpable calcifications) for predicting compressibility of RA, which can be useful in low-resource settings. Lastly, we demonstrated good clinical outcomes of AVFs constructed on calcified arteries using the described decision-making.

Mediocalcinosis is the typical form of arterial wall degeneration, which occurs in patients with CKD, diabetes and elderly and is therefore highly prevalent in end-stage kidney disease patients. Our study confirms a peripheral distribution of mediocalcinosis, which typically appears first and is also more severe in distal parts of upper (and lower) limbs. Severe calcifications can prevent successful AVF construction and increase the risk for HAIDI [8]. There are several different classifications of the severity of calcifications in the literature. Georgiadis et al. proposed a classification based on the length of calcifications (on forearm radiograph), which was shown to be associated with AVF outcome [13]. We have previously proposed an ultrasound-based classification, which assesses the degree of calcifications at each specific arterial segment considered for anastomosis [10]. Both classifications are likely partly correlated, as a greater length of calcified RA also implies greater degree of calcification (of the distal RA). From a functional point of view, the length of the calcified, non-compliant part of RA is likely associated with the degree of resistance to the increased flow after AVF construction. On the other hand, assessing the degree of calcifications at a specific site enables planning the site of anastomosis, allows for testing the compressibility of the artery and, therefore, the ability to clamp it during surgery, and also predicts the ease of suturing of the anastomosis.

Although severe calcifications are often considered a contraindication for AVF construction [14, 15], we have found that a significant proportion of these arteries are compressible and allow construction of an AVF with good outcomes. The severity of calcifications can be further assessed by the ability of Doppler signal to penetrate the calcified arterial wall, which can be visually assessed by the homogeneity of the color Doppler signal in a longitudinal view of the artery. Complete circumferential calcifications can be excluded by testing the compressibility of the artery by compressing it with the ultrasound probe to the bone (radius) in a cross-sectional view, which is possible along the entire length of the RA using an appropriate angle. Compressibility of the artery was selected as a minimal criterion for AVF construction, as this simple test non-invasively simulates the clamping of the artery during surgery. This resulted in successful construction of an anastomosis in all surgical procedures, contrary to our previous cohort, where anastomosis formation was not possible in significant number of cases due to completely calcified and non-compressible RA [16]. Nevertheless, as we have excluded non-compressible arteries from surgical attempts in this study, we cannot claim that they are indeed inappropriate for experienced surgeons and that their use cannot result in a clinically useful AVF. We have declared non-compressible arteries as unsuitable in advance, based on perceived and not observed high failure rate.

We have proposed an algorithm for the assessment of the artery based on diagnostic performance of clinical and ultrasound parameters (see Fig. 7). Clinical assessment, which can be useful in low-resource settings, can only be performed in the distal RA, where the artery is palpable. Our result showed that the presence of a palpable pulse and absence of palpable calcifications in the arterial wall are highly associated with compressibility of the artery with an ultrasound probe. Absence of a pulse is useful for fast elimination of a small proportion of severely calcified and non-compressible arteries (10/62, 16%, Fig. 6) and should be considered an absolute contraindication for distal AVF construction, unless further evaluation is made [17]. Palpation of a normal arterial wall will identify a large proportion of mildly calcified and compressible arteries (21/62, 34%; Fig. 6), which are appropriate for AVF construction. For further assessment of arteries with a palpable wall and mid- or proximal segments of RA, an ultrasound assessment is necessary. A study from India found that a palpable arterial wall was an independent predictor of primary AVF failure [7], confirming the need for further ultrasound evaluation in such cases to improve outcomes. Assessment of calcifications in B-mode imaging is the first step, where only severe calcifications with distal shadowing should be considered problematic. Assessing the homogeneity of color Doppler signal is a useful screening tool for identifying high-risk segments. It is easily performed, as longitudinal imaging of the artery is already necessary for B-mode assessment. A non-homogeneous color Doppler signal eliminates the need for testing the compressibility of the artery, which can sometimes be a bit cumbersome to perform, as it is almost universally associated with a non-compressible artery. Furthermore, since compressibility (in a cross-sectional view) is a very focal phenomenon, it is advisable to check for it in an appropriately long segment, to ensure enough length for clamping and suturing of the anastomosis. As calcifications and their severity are peripherally distributed, a point where the radial artery slowly becomes incompressible can often be determined, and anastomosis should be planned proximal to this site.

In our study, power Doppler measurements were not very useful for the assessment of arterial calcifications. PSV at rest and during reactive hyperemia and acceleration were significantly higher only in very mildly calcified arteries, which is not clinically useful. These parameters differed also between non-compressible and compressible arteries, but with low ROC AUC, except for PSV during reactive hyperemia, furthermore, this result is based on relatively low number of distal RAs. Similar results were reported in a study on 104 patients from India, where PSV at rest was also significantly associated with RCAVF maturation, with a cut-off of 30 cm/s and a very poor ROC AUC of 0.57 [18]. Furthermore, there is a great variety of cut-off values for PSV at rest reported in the literature, ranging from 30 [18] to 45 cm/s [7] and 62 in our study, often rounded-up in the literature to 50 cm/s [12]. It should be acknowledged, that stiffness of a calcified artery should increase PSV, inducing a bias to this parameter. Therefore, none of the power Doppler parameters was found to be useful for clinical decision making. Additionally, from a surgical perspective it is more important to test the compressibility of the artery than to perform a relatively time-consuming reactive hyperemia test, which seemed promising initially [19], but was later not confirmed useful in other studies [16, 20] including the present one.

Our results show good maturation rates and 1-year patency using these criteria for arterial assessment and decision-making for the location of anastomosis. The maturation rates were good (≈80%) even in AVFs, constructed on moderately to severely calcified RAs. These results are comparable to our previously reported cohort, where we reported 67% maturation rate, but the calculation included 22% of cases where no anastomosis was created during surgery due to a completely calcified artery; therefore, an 86% maturation rate was achieved in cases, where an AVF was actually created [16]. Other reports in the literature for moderately to severely calcified RAs are very variable, ranging from 22% to 89% maturation rate [7, 13, 21]. Our data compare very favorably to results of a recent meta-analysis of studies in over-all (non-calcified) population, which reported a meta-analytical maturation rate of 73% for RCAVF based on studies after year 2000, although with great heterogeneity of studies [22]. Looking at possible predictors of maturation, although PSV at rest and during reactive hyperemia, as well as systolic acceleration, were associated with the degree of calcifications only venous diameter was significantly associated with AVF maturation, but none of the arterial parameters. Therefore, we were not able to find any further predictors of successful maturation.

Due to the absence of HAIDI in our study population and the low number of elbow-based AVFs/grafts, we are not able to provide any parameters predicting HAIDI. In theory, possible predictors could include PSV at rest (as a marker of perfusion pressure), acceleration (as a marker of stenosis) and possibly EDV at rest (as a marker of already present peripheral vasodilatation, resulting from subclinical HAIDI). Further studies on larger cohorts of patients with severely calcified arteries are necessary to test these parameters and provide guidance.

Our study has several strengths. It was prospectively designed and evaluated several clinical, ultrasound and Doppler parameters on a moderately sized sample of arterial sites. It also has some limitations. Although the number of assessed arterial sites was relatively high, the number of constructed AVFs with clinical outcomes was relatively low, which reduces the power of statistical analysis and may compromise the reliability and generalizability of our findings. Furthermore, our findings are derived from a single-center cohort where the majority of patients were already on dialysis, with diabetes and high age, so the proposed protocol may primarily apply to similar populations. Further observational studies on larger cohorts are necessary to confirm these observations.

To conclude, our detailed ultrasound and Doppler analysis of calcified arteries has shown that even the most calcified arteries are a heterogeneous group, where homogeneity of the color Doppler signal and compressibility of the artery with an ultrasound probe can be useful additional criteria for the assessment of suitability for an AVF construction. If compressibility at the site of planned anastomosis is considered as the minimal criterion for an AVF construction attempt, then only arteries with linear calcifications with complete distal shadowing are problematic. Even among them approximately 40% are compressible and therefore likely appropriate for AVF construction. Using these criteria, even in patients with significantly calcified arteries, an AVF construction with high likelihood (approximately 80%) of maturation and low risk of HAIDI is possible, after proper ultrasound evaluation. Further studies are necessary to establish doppler parameters that predict HAIDI.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12882-025-04660-9.

Supplementary Material 1: Video S1: A calcified radial artery, which is compressible with the ultrasound probe

Supplementary Material 2: Video S2: A calcified radial artery, which is not compressible, when pressed with the ultrasound probe to the radius

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Author contributions
JG performed ultrasound exams, statistical analysis and wrote the manuscript draft. DF and MZ revised the manuscript. All authors were involved in designing of the study, treatment of patients, collection and interpretation of data and reviewed and approved the final version of the article.

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Data availability
The raw data supporting the conclusions of this article will be made available by the authors upon request.

Declarations

Ethics approval and consent to participate
The study was performed in accordance with the Declaration of Helsinki and approved by the National Medical Ethics Committee (No. 0120 – 51/2021/6). Written informed consent was obtained from all patients prior to inclusion.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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