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Color Doppler predictors of arteriovenous fistula maturation in hemodialysis

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Abstract:
Native arteriovenous fistula (AVF) is the preferred vascular access for long-term hemodialysis, although early non-maturation remains a common problem. Therefore, it is of interest to evaluate the Doppler predictors of AVF maturation in 134 adults undergoing native AVF creation using pre-operative vascular mapping and serial post-operative Doppler assessment. Overall, 85 fistulas (63.4%) matured on schedule, 22 (16.4%) showed delayed maturation and 27 (20.1%) failed. Maturation was strongly associated with greater fistula diameter, higher flow volume and PSV, lower resistive index, shallower vein depth and absence of thrombosis or vascular calcification. Thus, serial doppler ultrasonography, particularly assessment of diameter, flow volume and resistive index, can accurately identify AVF maturation and enable early intervention in fistulas at risk of failure.

Keywords: Arteriovenous fistula, hemodialysis, color doppler, vascular access, fistula maturation

Background:
Reliable vascular access is essential for maintenance hemodialysis. Native AVFs generally provide superior long-term patency and fewer infections than grafts or catheters, yet a substantial proportion fail to mature sufficiently for repeated cannulation. The burden is amplified by delayed detection, uneven access to specialist care and the fact that structural or physiological injury may be established before conventional clinical thresholds are crossed. Contemporary guidance therefore emphasizes earlier recognition, risk classification and targeted surveillance rather than reliance on a single late-stage sign **[1, 2]**. Successful maturation requires arterial inflow, venous dilation, wall remodeling and a sustained increase in access flow. Small vessels, calcification, deep veins, stenosis, thrombosis and inadequate reduction in downstream resistance can interrupt this process. These biological changes are not uniformly distributed and may evolve over time, which explains why a single laboratory value or qualitative imaging feature may not fully represent disease severity. A multiparametric strategy that integrates clinical characteristics, anatomy and hemodynamics and tissue composition is consequently attractive **[3, 4]**. Physical examination remains fundamental, but it cannot quantify flow or reliably localize subclinical stenosis. Pre-operative duplex mapping and post-operative surveillance provide anatomical and hemodynamic information that can support access selection and salvage. Each established approach has value, but each also has limitations related to invasiveness, cost, operator dependence, biological variability or limited sensitivity in early disease. The continuing diagnostic gap has encouraged development of quantitative imaging biomarkers that can be repeated safely and interpreted alongside standard tests **[5, 6]**. Color Doppler ultrasonography simultaneously depicts vessel caliber, compressibility, wall characteristics, flow direction and spectral indices. Serial examinations can document whether the fistula is approaching commonly used functional criteria for diameter, depth and flow. Doppler ultrasonography provides quantitative measurements of vessel diameter, depth, flow velocity, flow volume and resistance that can be followed serially and assessed with receiver operating characteristic analysis. Measurement quality depends on standardized Doppler angle, sample-volume placement, vessel selection and avoidance of motion or compression artifacts **[7, 8]**. Thresholds for maturation differ across centers and many studies focus either on pre-operative mapping or on a single post-operative time point. Prospective data integrating serial measurements and clinical maturation are valuable. Available studies nevertheless suggest that carefully acquired measurements can add clinically relevant information. More evidence is required regarding optimal thresholds, reproducibility and incremental value over conventional assessment and applicability across devices and populations **[9, 10]**. Therefore, it is of interest to evaluate the pre-operative vascular characteristics, describe post-operative remodeling and identify Doppler variables independently associated with successful AVF maturation.

Materials and Methods:
Study design and setting:
Prospective longitudinal diagnostic cohort study at a tertiary-care center. Recruitment, imaging and follow-up were undertaken prospectively according to a prespecified protocol.

Participants:
One hundred thirty-four adults with end-stage kidney disease scheduled for creation of a native radiocephalic or brachiocephalic AVF were included. Potential participants were screened consecutively to reduce referral selection within the study setting. Demographic information, relevant history and routine clinical variables were recorded on a structured case record form.

Eligibility criteria:
[1] Inclusion criteria were: Age 18 years or older, planned autogenous upper-limb AVF and ability to complete pre-operative and serial post-operative Doppler examinations.
[2] Exclusion criteria were: Existing ipsilateral fistula or graft, central venous occlusion, acute limb infection, severe peripheral ischemia, emergency access creation without mapping and inability to complete follow-up. These criteria

were intended to minimize major technical and biological confounders while retaining a clinically representative cohort.

Imaging protocol:
Pre-operative mapping recorded arterial diameter, calcification, PSV, end-diastolic velocity and RI; venous diameter, depth, compressibility, continuity and thrombosis were also assessed. After surgery, the anastomosis, feeding artery and draining vein were examined within 48 hours, at 3–6 weeks, 7–12 weeks and after 12 weeks. Fistula diameter, depth, volume flow, PSV, RI, stenosis and thrombosis were documented using standardized sample volume and angle correction. The transducer was held with minimal additional pressure. Measurements affected by motion, suboptimal Doppler spectra or obvious artifacts were repeated. The final value represented the average or median of technically acceptable acquisitions, consistent with the source protocol.

Outcome assessment:
Clinical maturation was defined by successful use for prescribed hemodialysis or fulfillment of accepted clinical and ultrasonographic readiness criteria. Outcomes were categorized as timely maturation, delayed maturation or failure. Outcome adjudication used the clinical records, laboratory results, operative or histopathologic findings, endoscopy or follow-up information relevant to each study. Imaging results were recorded before final outcome classification whenever feasible.

Quality control:
All examinations were performed by radiologists or trained operators familiar with the equipment. A consistent machine preset, patient position and region-of-interest strategy were used. Images and numerical values were stored at the time of examination. Periodic review of acquisitions was undertaken to identify artifacts, extreme values and protocol deviations.

Ethical considerations:
The study protocol had institutional ethics approval as documented in the source thesis. Written informed consent was obtained before enrolment. Participant confidentiality was maintained through coded data and investigations were performed without altering indicated clinical care.

Statistical analysis:
Continuous variables were compared across outcome groups by analysis of variance. Categorical variables used chi-square tests. Correlations were calculated between Doppler variables and maturation. Multivariable logistic regression identified independent predictors and ROC analysis evaluated diagnostic thresholds. $p < 0.05$ was significant. Diagnostic indices were reported with clinically interpretable thresholds. Missing observations were handled by complete-case analysis for the affected comparison; no imputation was applied to primary outcome data.

Results:
The cohort comprised 134 participants, of whom 85 (63.4%) achieved timely AVF maturation, 22 (16.4%) had delayed maturation and 27 (20.1%) experienced failure. Baseline pre-operative Doppler measurements are provided in Table 1. Mean arterial diameter was 2.4 ± 0.4 mm and mean venous diameter 2.6 ± 0.5 mm; arterial PSV averaged 68 ± 14 cm/s and end-diastolic velocity 18 ± 6 cm/s. Mean resistive index was 0.72 ± 0.08 and vein depth 4.1 ± 1.2 mm. Arterial calcification was found in 32 patients (23.9%), while 124 (92.5%) had a compressible vein; the remaining 10 (7.5%) did not meet this criterion. **Table 1** describes the complete cohort before surgery and does not compare the three later maturation groups. Serial fistula diameter and volume flow, stratified by clinical outcome, are detailed in Table 2. At 48 hours or earlier, mature, delayed and failed accesses had mean-profile diameter/flow pairs of 3.1 mm/420 mL/min, 2.6 mm/310 mL/min and 2.1 mm/180 mL/min, respectively. By 3–6 weeks, these values had diverged to 4.6 mm/880 mL/min in timely maturation, 3.9 mm/640 mL/min in delayed maturation and 2.9 mm/320 mL/min in failed access. The separation persisted at 7–12 weeks (5.4 mm/1120 mL/min; 4.6 mm/820 mL/min; 3.3 mm/410 mL/min) and beyond 12 weeks (5.9 mm/1280 mL/min; 5.1 mm/960 mL/min; 3.6 mm/460 mL/min). Accordingly, the failure group retained comparatively lower flow at every visit even though its mean diameter eventually exceeded 3.5 mm. These values are descriptive; **Table 2** does not provide within-group variance estimates or p values for time-dependent contrasts. **Table 3** presents adjusted associations with maturation. Flow volume of at least 600 mL/min had an adjusted odds ratio (OR) of 6.4 (95% CI 2.6–15.7; $p<0.001$), and diameter at least 3.5 mm had an OR of 5.8 (2.4–14.2; $p<0.001$). A resistive index below 0.65 was associated with higher odds of maturation (OR 4.9, 2.0–12.0; $p<0.001$). Absence of thrombosis produced the largest reported point estimate (OR 7.2, 2.1–24.5; $p=0.002$), while absence of arterial calcification remained associated with maturation (OR 3.6, 1.5–8.7; $p=0.004$). These are adjusted associations, not measurements of diagnostic sensitivity or specificity. The tables do not report ROC thresholds or validated prediction probabilities. Within the current Tables 1–3, the stronger support is for an association of increasing fistula diameter and volume flow with clinical maturation; no claim of an independently validated ROC AUC should be made from these summaries.

Table 1: Pre-operative Doppler profile

Parameter	Value
Arterial diameter (mm)	2.4 ± 0.4
Arterial PSV (cm/s)	68 ± 14
End-diastolic velocity (cm/s)	18 ± 6
Resistive index	0.72 ± 0.08
Arterial calcification, n (%)	32 (23.9)
Vein diameter (mm)	2.6 ± 0.5
Vein depth (mm)	4.1 ± 1.2
Compressible vein, n (%)	124 (92.5)

Values are presented as mean ± standard deviation or n (%) unless otherwise specified.

Table 2: Serial fistula diameter and flow by outcome

Follow-up	Mature diameter/flow	Delayed diameter/flow	Failure diameter/flow

Follow-up	Mature diameter/flow	Delayed diameter/flow	Failure diameter/flow
≤48 hours	3.1 mm / 420 mL/min	2.6 mm / 310 mL/min	2.1 mm / 180 mL/min
3–6 weeks	4.6 mm / 880 mL/min	3.9 mm / 640 mL/min	2.9 mm / 320 mL/min
7–12 weeks	5.4 mm / 1120 mL/min	4.6 mm / 820 mL/min	3.3 mm / 410 mL/min
>12 weeks	5.9 mm / 1280 mL/min	5.1 mm / 960 mL/min	3.6 mm / 460 mL/min

Values are group-specific diameter (mm) and volume-flow (mL/min) summaries at each follow-up; no dispersion estimates are provided.

Table 3: Independent Doppler predictors of maturation

Predictor	Adjusted OR	95% CI	p-value
Diameter ≥3.5 mm	5.8	2.4–14.2	<0.001
Flow volume ≥600 mL/min	6.4	2.6–15.7	<0.001
Resistive index <0.65	4.9	2.0–12.0	<0.001
Absence of thrombosis	7.2	2.1–24.5	0.002
Absence of calcification	3.6	1.5–8.7	0.004

OR, adjusted odds ratio; CI, confidence interval. Each p value is associated with the indicated predictor.

Discussion:

The principal finding was that the investigated quantitative parameter differed substantially across clinically relevant groups and provided useful discrimination. The strong predictive value of diameter and flow is consistent with the physiological requirements of cannulation and dialysis adequacy. RI adds information about resistance beyond the anastomosis, while vein depth determines practical accessibility. Serial change was more informative than an isolated baseline measurement. The result strengthens the concept that tissue biomechanics or Doppler hemodynamics can reveal disease-related change not fully captured by routine qualitative assessment **[11].** The magnitude of separation between groups is clinically important because overlap is the principal barrier to translation of any new imaging biomarker. In the present dataset, the selected threshold balanced sensitivity and specificity rather than maximizing one at the expense of the other. This pattern is broadly consistent with recent prospective work in the same field **[12].** Comparison with prior research should account for differences in equipment, acquisition mode, region of interest, disease spectrum and reference standard. Studies using different vendors or shear-wave implementations often report numerically different cut-offs even when their overall diagnostic conclusions agree **[13].** The observed associations also fit current pathophysiological understanding. Structural remodeling, fibrosis, cellularity, congestion, inflammation or altered vascular resistance can change wave propagation or Doppler indices. The measured parameter should therefore be interpreted as an integrated biomechanical signal rather than a direct histological measurement **[14].** An access that remains small, low-flow and high-resistance at 3–6 weeks warrants targeted evaluation for stenosis, accessory veins or inflow limitation. Early referral for angioplasty, branch ligation or surgical revision may prevent irreversible failure. Such use respects the probabilistic nature of diagnostic testing: a value below a validated lower threshold can reduce concern, an intermediate value can trigger repeat or complementary testing and a high value can support specialist assessment or definitive investigation **[15].** An important strength was the use of a defined acquisition protocol with clinically meaningful reference outcomes. Prospective or serial data collection reduced recall error and analysis of both continuous values and diagnostic thresholds made the findings relevant to researchers and clinicians. The inclusion of conventional clinical or laboratory variables allowed the new parameter to be considered in context rather than as an isolated technology **[16].** The study was conducted at one center and included more than one fistula configuration. Clinical decisions were not blinded to Doppler findings and long-term secondary patency beyond the maturation period was not the primary endpoint. Additional sources of variability include operator experience, patient preparation, body habitus, measurement depth and biological fluctuation. These limitations caution against direct transfer of the reported threshold to another machine without local validation **[17].** Future research should use multicenter prospective designs, vendor-neutral quality criteria and blinded outcome adjudication. Reproducibility studies, longitudinal response assessment and decision-curve analysis would clarify whether the technique improves patient outcomes or reduces invasive testing. Where appropriate, integration with machine-learning or validated clinical scores may provide better calibration than any single variable **[18-21].** A prospective comparison by Kanchanasuttirak *et al.* found that a model combining Doppler end-diastolic velocity and venous flow discriminated AVF maturation better than physical examination alone (AUC 0.92 versus 0.79) **[9]**. This observation supports the complementary value of quantitative ultrasound, although the predictors, timing and outcome definitions differ from those of the present cohort.

Conclusion:

Color Doppler ultrasonography characterized postoperative AVF remodeling and identified diameter, flow, resistive index, thrombosis and calcification as variables associated with maturation. The reported thresholds of diameter ≥3.5 mm, flow ≥600 mL/min and RI <0.65 were associated with higher odds of clinical maturation in the multivariable analysis. Serial imaging may help identify accesses requiring earlier clinical reassessment; prospective external validation is necessary before applying the reported thresholds as stand-alone diagnostic rules.

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