scientific reports

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Impact of hemodynamic doppler ultrasound parameters on patency and post-thrombotic syndrome in patients with iliofemoral venous stents

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Chronic venous obstruction affects thousands worldwide and may lead to severe long-term complications such as post-thrombotic syndrome (PTS), marked by pain, swelling, skin changes, and venous ulcers. Endovenous stenting has become a cornerstone in restoring venous outflow, yet surveillance strategies to detect stent dysfunction early remain unstandardized. Doppler ultrasound (DUS), widely available and non-invasive, holds potential as a monitoring tool, but lacks validated markers to guide long-term follow-up. In this retrospective study of 161 patients and over 1,100 DUS assessments, we examined the predictive value of hemodynamic parameters for stent dysfunction and PTS. Stent patency was assessed using DUS or CT venography, and PTS was defined by a Villalta score ≥ 5 at last follow up. Hemodynamic parameters were compared using univariate and multivariable logistic regression models. Significant stent stenosis or occlusion (≥ 50%) was more common in younger patients (mean age 37.7 vs. 48.2 years, $p = 0.003$), with risk increasing by 4.4% per year decrease in age (OR = 1.044, $p = 0.008$). Loss of respiratory modulation was strongly associated with stent dysfunction ($p < 0.001$). Patients who had PTS at last follow up, had lower venous flow (297 vs. 463 mL/min, $p = 0.047$), reduced peak velocity ($p = 0.003$), and impaired respiratory modulation ($p = 0.017$). These findings support using DUS-derived parameters for early, non-invasive detection of stent-related complications to improve long-term patient outcomes.

Keywords Doppler ultrasound, Venous stenting, Iliofemoral deep vein thrombosis, Post-trombotic syndrome, Stent patency

Post-thrombotic syndrome (PTS) is a chronic and potentially debilitating complication of deep vein thrombosis (DVT), affecting up to 50% of patients[1]. Characterized by pain, swelling, skin changes, and in severe cases, venous ulcers, PTS significantly impairs quality of life and contributes to long-term healthcare burden[2]. As DVT remains a prevalent vascular condition worldwide, strategies to prevent and monitor PTS have become a clinical priority[3].

Endovenous stenting represents a cornerstone intervention in the management of both acute and chronic ilio-femoral venous obstruction[4]. In acute DVT, percutaneous mechanical thrombectomy (PMT) followed by

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stenting can restore venous outflow and reduce the risk of PTS development[5]. In chronic venous obstruction (CVO) and moderate to severe PTS, endovenous recanalization and stenting alleviate symptoms such as pain, edema, and ulceration, particularly in patients who are refractory to conservative therapy[6].

Despite the growing adoption of venous stenting, there remains no consensus on optimal follow-up strategies for ensuring stent patency and detecting early complications[7]. The 2022 guidelines of the European Society for Vascular Surgery (ESVS) recommend Doppler Ultrasound (DUS) surveillance at defined intervals post-procedure[8]. However, they do not establish specific diagnostic threshold for detecting stent dysfunction. This absence of standardized parameters remains a critical gap in clinical practice hinders recognition of complications such as restenosis, recurrent thrombosis, and pulmonary embolism (PE), all of which carry significant morbidity and affect long-term outcomes[9,10].

DUS is widely available, non-invasive, and the most practical tool for post-stenting surveillance. Prior studies have proposed hemodynamic thresholds, including peak flow velocity > 10 cm/s combined with a flow pattern modulated by breathing or post/pre-stenotic velocity ratio > 2.5, as markers of venous outflow impairment. However, their clinical validity in detecting significant in-stent stenosis remains unconfirmed in peripheral veins[11,12]. Establishing standardized Doppler parameters remains a critical need to improve the consistency and effectiveness of long-term stent monitoring[13].

The present study investigates the prognostic value of DUS in predicting clinical and imaging outcomes after venous stenting, with a particular focus on hemodynamic parameters. Through a systematic, intermediate-term follow up, we aim to identify reliable, non-invasive Doppler indicators for stent surveillance. Specifically, we examine the association between Doppler-derived hemodynamic parameters, the presence of in-stent stenosis, and the development or persistence of PTS following stenting.

Methods

Study design and patient selection

This was a retrospective observational study conducted at the Vascular Medicine Department of a university hospital between 2015 and 2023. The aim was to evaluate hemodynamic changes and clinical outcomes in patients undergoing venous stenting for acute DVT or chronic post-thrombotic obstruction (PTO). Data were collected from electronic medical records and DUS examinations. The primary hemodynamic parameters investigated were peak flow velocity, flow volume, flow ratio, and respiratory modulation, with details of their measurement described in the Doppler Ultrasound Investigation subsection.

Inclusion criteria included patients aged 18 and 90 years who had undergone venous PMT with stenting for acute DVT or PTO (involving at least the iliac or common femoral vein); and at least one DUS follow-up performed 6 months after the procedure. Exclusion criteria included absence of follow-up data, acute stent thrombosis documented on post-procedural day 1, or patient refusal to participate or consent to data use.

Definitions

Acute DVT was defined as a thrombotic event managed with catheter-directed thrombolysis (CDT) or percutaneous mechanical thrombectomy (PMT), followed by balloon angioplasty and stenting, performed within two weeks of symptom onset as part of the initial treatment. In contrast, post-thrombotic obstruction (PTO) referred to patients with CVO secondary to prior DVT, treated more than 6 months after symptoms onset with endovenous recanalization and stenting.

PTS was defined as a Villalta score ≥ 5 at last follow-up. Due to the retrospective nature of the study, Villalta score were not systematically recorded for all patients. Therefore, only patients with available Villalta scores were included in the PTS analysis.

Chronic venous insufficiency was classified based on the CEAP classification, including patients from C3 to C6. This ranged from edema (C3) to active venous ulcers (C6). Intermediate stages included skin changes such as pigmentation or eczema (C4), and healed venous ulcers (C5)[14].

Major Thrombophilia included antithrombin deficiency[15], antiphospholipid syndrome[16], and selected cases of protein C or protein S deficiency[17].

Recent major surgery was defined as any major surgical intervention performed within 3 months prior to the thrombotic event.

Doppler ultrasound investigation

A standardized follow-up surveillance program was implemented with DUS performed at 1, 3, 6, and 12 months post-stenting, and annually thereafter. All evaluations were conducted by vascular medicine specialists within a single department to ensure consistency and accuracy.

Ultrasound protocols were standardized to minimize measurement variability. Patients were examined in the supine position with a 30° backrest elevation and arms resting comfortably at their sides. To reduce venous flow fluctuations, patients remained at rest, refrained from speaking, and maintained regular, shallow breathing without deep inspiration.

DUS evaluations focused on key hemodynamic parameters. Peak flow velocity (in cm/s) in common femoral vein and within the stented segment. Flow volume (in mL/min) was automatically calculated by the ultrasound system using the vessel diameter and time-averaged velocity measurements, assuming a circular cross-sectional area.

Venous flow was also assessed in the external iliac vein. A flow ratio was calculated, comparing the flow in the stented external iliac vein or common femoral vein (depending on the distal end of the stent), to the flow in the contralateral native vein, providing a relative index of venous flow symmetry and quantifying the hemodynamic impact of stenting on venous return.

Additionally, respiratory modulation of venous flow was evaluated. Under normal conditions, peripheral veins such as the external iliac and femoral veins exhibit respirophasic flow, characterized by decreased velocity during inspiration (due to increased intra-abdominal pressure) and increased velocity during expiration. This pattern reflects unobstructed venous return. Flow was considered normal when consistent variation was observed during spontaneous breathing. Abnormal modulation was defined as either a lack of variation or variation occurring only with deep or forced inspiration, suggestive of proximal obstruction or impaired stent outflow[18]. Representative waveforms are provided in Fig. 1.

CT venography assessment

Pre-procedural imaging was tailored according to clinical presentation. In patients with PTO, we performed direct CT venography with contrast injected into a distal vein of the affected limb to accurately delineate venous anatomy and collateral pathways. This method enabled precise assessment of lesion length, inflow/outflow quality, and facilitated accurate stent sizing and planning. The extent of CVO was classified according to Jalaie et al.[19].

In cases of acute iliofemoral DVT, patients underwent a thoraco-abdominopelvic CT scan, extending from the chest to the proximal third of the thigh, to evaluate thrombus burden, screen for embolic sources, and guide initial management. While less detailed distally, this imaging provided adequate coverage of the target segment for stent planning in acute interventions.

For follow-up at 1, 3, and 5 years, indirect CT venography via antecubital vein injection was used to assess stent patency and detect possible stent fracture (Fig. 1). Imaging was initiated 2–3 min post-injection, with scan coverage from the mid-calf to the diaphragm, ensuring visualization of both inflow and outflow zones.

Post-procedural treatment

All patients received on a standardized post-stenting regimen: combined therapeutic anticoagulation and antiplatelet therapy for the first month. Antiplatelet therapy was discontinued after 1 month, while anticoagulation was continued and reassessed at 6 months based on risk profile.

Patients with persistent risk factors, such as unprovoked or recurrent DVT, active cancer, chronic inflammatory disease, major thrombophilia or low venous inflow, continued long-term anticoagulation. This was administered either at therapeutic doses (Rivaroxaban 20 mg once daily or Apixaban 5 mg twice daily) or reduced doses (Rivaroxaban 10 mg once daily or Apixaban 2.5 mg twice daily), based on individual risk assessment.

In contrast, patients with transient risk factors, such as recent surgery (< 3 months), hormonal exposure, or prolonged immobility, who demonstrated confirmed stent patency and adequate inflow were eligible for anticoagulation discontinuation after 6 months.

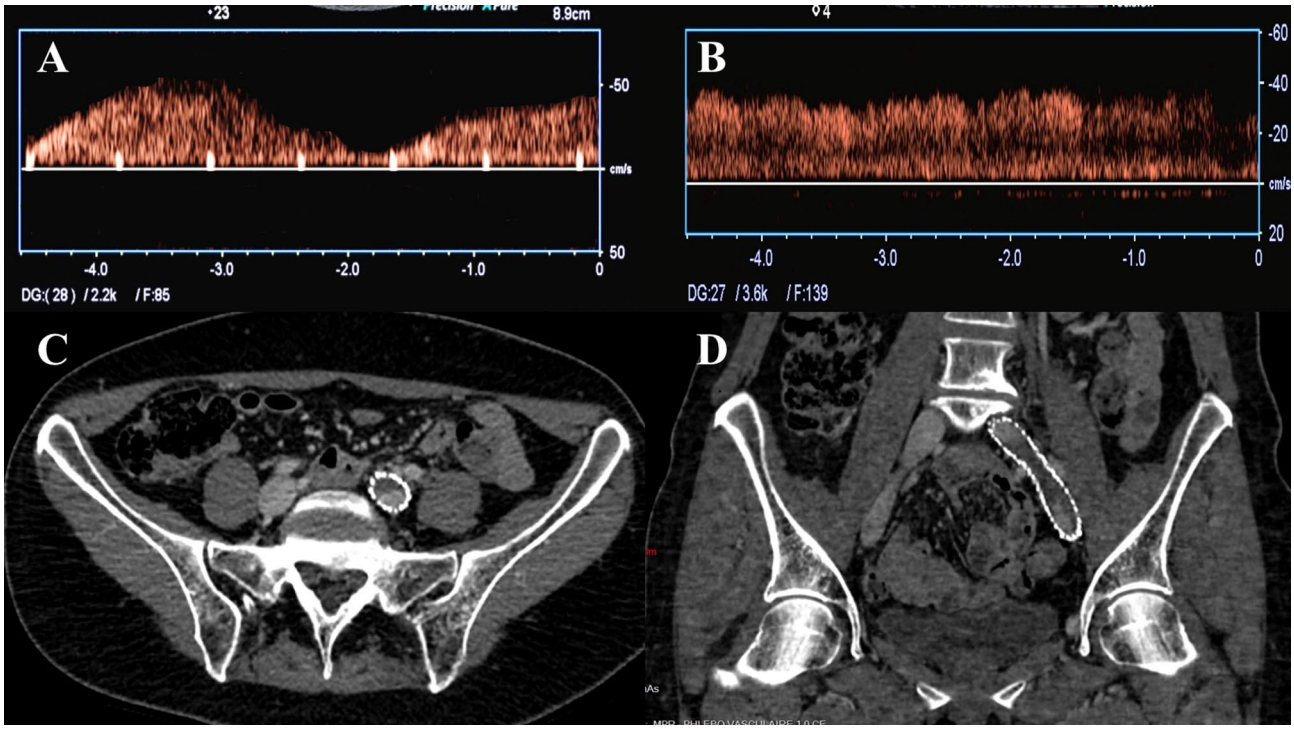

Fig. 1. Doppler ultrasound flow and CT venography assessments of stent patency. Doppler Ultrasound imaging displaying normal flow synchronized with respiration. Doppler Ultrasound imaging displaying non-modulated flow. Cross-sectional CT Venography assessing stent patency and highlighting thrombus-related stenosis. Longitudinal CT Venography assessing stent patency and highlighting thrombus-related stenosis.

Data collection
Clinical data included demographics, comorbidities, VTE risk factors, post-procedural treatment, and adherence. Hemodynamic parameters (venous peak velocity, flow, flow ratio, and respiratory modulation) were collected from DUS reports at baseline (post-procedural day 1), 6 months, 12 months, and final follow-up.

Study outcomes
The primary outcomes included stent restenosis, categorized as ≥ 50% or < 50% in-stent stenosis, the presence of PTS, and hemodynamic parameters. Stent patency was assessed using DUS or CT venography, and patients were classified according to the degree of in-stent stenosis (≥ 50% vs. <50%) at the last follow up. PTS was defined by Villalta score ≥ 5 at last follow up. Its evaluation was standardized at that time point to account for its appearance after stenting in acute DVT and its evolution in patients stented for PTO.

Hemodynamic parameters, included peak velocity (cm/s), external iliac or common femoral venous flow, external iliac or common femoral venous flow ratio, and respiratory modulation, were measured at baseline (post-procedural day1) and at follow-up intervals 6 months, 12 months, and final assessment.

Secondary outcomes included venous thromboembolic complications, treatment adherence, and the need for re-intervention. PE and in-stent occlusive thrombosis were recorded as complications in the PTS analysis, while only PE was considered in the analysis of stent patency.

Statistical analysis
All analyses were performed using IBM SPSS Statistics version 26.0. Variables were analyzed with respect to two main outcomes: in-stent stenosis and PTS. Continuous variables were compared using the Mann-Whitney U test and reported as means, median [Q1 - Q3]. Categorical variables were compared using chi-square or Fisher's exact, as appropriate.

To identify predictors of PTS and in-stent stenosis or occlusion, binary logistic regression models were conducted. Variables with a p-values < 0.10 in the bivariate analysis were included in the multivariable models. Odds ratios (ORs) with 95% confidence intervals were reported. A p-value < 0.05 was considered statistically significant.

Ethical considerations
This study was conducted in compliance with the Declaration of Helsinki principles and received ethics approval by GNEDS (Groupe Nantais d'Ethique et de Soins), the local ethics committee of the University Hospital of Nantes (20190606). Each patient included in this study received written information and no patient objected to the use of their data. The need for written informed consent was waived by the institutional review board due to the retrospective nature of the study in accordance with French public health code article: L 1121-1.

Results
A total of 161 patients were included in the study, 32 (19.9%) treated during acute phase of DVT and 129 (80.1%) treated for PTO, contributing over 1100 DUS assessments and enabling a comprehensive longitudinal evaluation of hemodynamic changes. Patients were categorized according to stent patency status and the presence of PTS at final follow-up.

Table 1 presents the baseline characteristics according to acute or chronic presentation. Patients treated during the acute phase were significantly younger (median age 35.5 years [27.5–49.3]) compared to those with PTO (49.0 years [34.0–60.0]; $p = 0.028$). The PTO group exhibited a higher proportion of female patients (62.0% vs. 40.6%; $p = 0.046$) and had a markedly greater prevalence of chronic venous insufficiency (32.8% vs. 6.9%; $p = 0.005$). Lesion extent differed significantly between groups: patients with PTO more frequently demonstrated involvement of the femoral and popliteal veins (both $p < 0.001$). Additionally, they required a greater number of stents (median 3.0 [2.0–4.0] vs. 2.0 [2.0–3.0]; $p = 0.0002$), and stent extension across the inguinal ligament was more common in the chronic group (82.0% vs. 54.2%; $p = 0.043$).

Stent patency and hemodynamics
At the last follow-up, 30 of 161 patients (18.6%) had ≥ 50% in-stent stenosis or complete occlusion. Table 2 summarizes baseline patient characteristics according to stent patency. Patients with ≥ 50% in-stent stenosis or complete occlusion were significantly younger (median age 37.7 years [24.5–53.0]) compared to those with < 50% stenosis (48.0 years [34.0–62.0]; $p = 0.003$). Pulmonary embolism was more prevalent in the ≥ 50% stenosis group (22.2%) versus 1.8% in the < 50% group ($p < 0.001$).

In patients with ≥ 50% stenosis or occlusion, a progressive decline in normal respiratory flow modulation was observed: from 63.2% at 6 months ($p = 0.034$) to 57.1% at 12 months ($p < 0.001$), and 62.5% at final follow-up ($p < 0.001$). However, no significant changes in peak velocity or venous flow were observed over time (Table 3).

Age was found to be a significant predictor of stent occlusion or stenosis. For each one-year decrease in age, the odds of developing stent occlusion or stenosis increased by 4.4% (OR = 1.044; 95% CI: 1.012–1.081; $p = 0.008$). This suggests that younger patients were at a higher risk of experiencing stent-related complications compared to older individuals. Other variables, including female sex, chronic venous insufficiency, femoro-popliteal vein involvement, and cessation of anticoagulation, were not found to be statistically significant predictors of stent occlusion or stenosis (Table 4).

Post-thrombotic syndrome and hemodynamics
At last follow up, 29 of 103 patients (28.2%) had PTS. Among these, 5 of 29 patients (17.2%) were from the acute DVT group (newely developed PTS), while 24 of 29 patients (82.8%) were from the PTO group (persistent PTS). Patients who developed PTS tended to be older (median age 51.5 years [37.5–69.0]; $p = 0.065$) and more

Patient demographics, *n*/total (%)	Acute deep vein thrombosis *n* = 32	Post thrombotic obstruction *n* = 129	*P*-Value
Age (years) median [Q1– Q3]	35.5 [27.5–49.3]	49.0 [34.0–60.0]	**0.028**
Female Sex	13/32 (40.6%)	80/129 (62.0%)	**0.046**
BMI (kg/m^2) median [Q1– Q3]	25.0 [23.0–29.5]	25.2 [22.7–28.7]	0.76
Past medical history			
May-Thurner syndrome	10/32 (31.3%)	31/129 (24.0%)	0.54
Chronic venous insufficiency	2/29 (6.9%)	42/128 (32.8%)	**0.005**
History of thromboembolic event	6/32 (18.8%)	10/30 (33.3%)	0.30
VTE risk factors			
Major thrombophilia	10/30 (33.3%)	42/116 (36.2%)	0.94
Surgery	1/28 (3.6%)	30/119 (25.2%)	> 0.99
Cancer	2/32 (6.3%)	7/129 (5.4%)	> 0.99
Hormonal and reproductive risk factors	7/32 (21.9%)	41/129 (31.8%)	0.63
Travel (> 6 h)	1/28 (3.6%)	8/120 (6.7%)	> 0.99
Immobilization (> 3 days)	8/29 (27.6%)	36/115 (31.3%)	0.87
Idiopathic	14/32 (43.8%)	56/128 (43.8%)	> 0.99
Lesion laterality			
Left	25/32 (78.1%)	21/129 (16.3%)	0.71
Right	3/32 (9.4%)	3/129 (2.3%)	
Bilateral	4/32 (12.5%)	6/129 (4.7%)	
Venous lesion extension at time of DVT diagnosis			
Iliac- common femoral veins	32/32 (100.0%)	129/129 (100.0%)	> 0.99
Femoro-popliteal veins	30/32 (93.8%)	72/129 (55.8%)	**< 0.001**
Popliteal-infra-popliteal veins	15/32 (46.9%)	17/129 (13.2%)	**< 0.001**
Stenting characteristics			
Total stents implanted mean; median [Q1– Q3]	2.7; 2.0 [2.0–3.0]	3.1; 3.0 [2.0–4.0]	**0.0002**
Stents crossing the inguinal ligament	13/24 (54.2%)	73/89 (82.0%)	**0.043**
Treatment post stenting			
Antiplatelet at discharge	30/32 (93.8%)	121/129 (93.8%)	> 0.99
Antiplatelet at last update	1/28 (3.6%)	5/100 (5.0%)	> 0.99
Anticoagulation at discharge	32/32 (100.0%)	126/126 (100.0%)	> 0.99
Anticoagulation at last update			
Full dose	17/28 (60.7%)	64/100 (64.0%)	0.82
Half dose	7/28 (25.0%)	20/100 (20.0%)	
Stopped	4/28 (14.3%)	16/100 (16.0%)	
Complications post stenting			
Pulmonary embolism	3/26 (11.5%)	5/113 (4.4%)	0.17
Time from stenting to post- stenting thrombosis onset (months) mean; median [Q1– Q3]	30.7; 27.0 [11.8–46.0]	39.4; 34.0 [19.0–57.0]	0.07
Villalta score at last update mean; median [Q1– Q3]	2.5; 2.0 [0.0–4.0]	3.6; 2.0 [1.0–5.0]	0.37

Table 1. Baseline demographic and clinical characteristics according to acute or chronic venous presentation (BMI: body mass index, VTE: venous thromboembolism; DVT: deep vein thrombosis, in bold p value < 0.05).

frequently had underlying chronic venous insufficiency (30.8% vs. 14.7%; $p = 0.077$), although these differences did not reach statistical significance (Table 5).

Hemodynamics differences became more pronounced over time. At 6-months, peak velocity did not differ between PTS and non-PTS groups (median 29.5 cm/s [22.5–40.0] vs. 31.0 cm/s [20.0–40.0]; $p = 0.39$). Venous flow tended to be lower in the PTS group (median 523.0 mL/min [410.0–627.0]) versus non-PTS (median 627.0 mL/min [460.0–710.0]; $p = 0.13$), with similar rates of normal respiratory modulation (~ 81%). By 12 months, normal respiratory modulation persisted in 100% of non-PTS patients but significantly declined in the PTS group (82.4%; $p = 0.014$). At final follow-up, patients with PTS showed significantly lower peak velocity (median 29.7 cm/s [26.1–35.0] vs. 33.0 cm/s [30.0–40.0]; $p = 0.003$), reduced iliac venous flow (median 370.0 mL/min [261.5–580.0] vs. 462.0 mL/min [375.0–580.0]; $p = 0.047$), and impaired respiratory modulation (80.0% vs. 97.8%, $p = 0.017$) (Table 6). These differences were driven by progressive hemodynamic deterioration in the PTS group, whereas non-PTS patients maintained relatively stable parameters across follow-up.

Multivariable analysis confirmed that older age increased the odds of PTS by 12% per additional year (OR = 1.12; 95% CI: 1.02–1.23; $p = 0.020$), while higher venous flow was protective. For every unit increase in venous flow, the odds of developing PTS decreased by 1.1% (OR = 0.989; 95% CI: 0.980–0.998; $p = 0.019$) (Table 7).

Patient demographics, *n*/total (%)	Total patients *n* = 161	Stent-free or stenosis < 50% *n* = 131	Stent occlusion or stenosis ≥ 50% *n* = 30	*P*-Value
Age (years), median [Q1– Q3]	47.0 [33.0–60.0]	48.0 [34.0–62.0]	34.5 [24.5–53.0]	**0.003**
Female sex	93/161 (57.8%)	79/131 (60.3%)	14/30 (46.7%)	0.17
BMI (kg/m^2), mean; median [Q1– Q3]	25.1 [22.7–29.0]	25.1 [22.7–28.3]	26.0 [22.8–30.0]	0.53
Past medical history				
May-Thurner syndrome	41/161 (25.5%)	36/131 (27.5%)	5/30 (16.7%)	0.22
Chronic venous insufficiency	31/161 (19.3%)	28/117 (23.9%)	3/30 (10.0%)	0.13
Thromboembolic event	48/160 (30.0%)	38/130 (29.2%)	10/30 (33.3%)	0.66
VTE risk factors				
Major thrombophilia	28/138 (20.3%)	23/112 (20.5%)	5/26 (19.2%)	0.88
Surgery	31/147 (21.1%)	24/119 (20.2%)	7/28 (25.0%)	0.57
Cancer	9/161 (5.6%)	6/131 (4.6%)	3/30 (10.0%)	0.37
Hormonal and reproductive risk factors	48/161 (29.8%)	38/131 (29.0%)	10/30 (33.3%)	0.64
Travel (> 6 h)	9/148 (6.1%)	8/121 (6.6%)	1/27 (3.7%)	> 0.99
Immobilization (> 3 days)	44/144 (30.6%)	35/117 (29.9%)	9/27 (33.3%)	0.73
Idiopathic	70/160 (43.8%)	59/130 (45.4%)	11/30 (36.7%)	0.39
Lesion laterality				> 0.99
Left	115/161 (71.4%)	94/131 (71.8%)	21/30 (70.0%)	
Right	15/161 (9.3%)	12/131 (9.2%)	3/30 (10.0%)	
Bilateral	31/161 (19.3%)	25/131 (19.1%)	6/30 (20.0%)	
Venous lesion extension at time of DVT diagnosis				
Iliac-common femoral veins	161/161 (100.0%)	131/131 (100.0%)	30/30 (100.0%)	> 0.99
Femoro-popliteal veins	102/161 (63.4%)	79/131 (60.3%)	23/30 (76.7%)	0.09
Popliteal-infra-popliteal veins	32/161 (19.9%)	27/131 (20.6%)	5/30 (16.7%)	0.63
Treatment post stenting				
Antiplatelet at discharge	151/161 (93.8%)	123/131 (93.9%)	28/30 (93.3%)	> 0.99
Antiplatelet at last update	6/128 (4.7%)	5/107 (4.7%)	1/21 (4.8%)	> 0.99
Anticoagulation at discharge	161/161 (100.0%)	131/131 (100.0%)	30/30 (100.0%)	> 0.99
Anticoagulation at last update				
Full dose	101/128 (78.9%)	83/107 (77.6%)	18/21 (85.7%)	0.56
Half dose	27/128 (21.1%)	24/107 (22.4%)	3/21 (14.3%)	
Stopped	47/128 (36.7%)	64/107 (59.8%)	17/21 (81.0%)	
Complications post stenting				
Pulmonary embolism	8/139 (5.8%)	2/112 (1.8%)	6/27 (22.2%)	**< 0.001**
Time from stenting to post-stenting thrombosis onset (months), mean; median [Q1– Q3]	15.5; 10.6 [0.3–20.3]	15.7; 11.9 [0.4–18.3]	15.2; 8.1 [0.2–22.7]	0.92
CT venography at last update	*n* = 159	*n* = 130	*n* = 29	
Time between stenting and last CT (years), mean; median [Q1– Q3]	2.6; 2.0 [1.0–4.0]	2.6; 2.0 [1.0–4.0]	2.5; 2.0 [1.0–4.0]	0.79

Table 2. Demographic profile of patients according to stent patency at last update (BMI: Body Mass Index, VTE: venous thromboembolism; DVT: deep vein thrombosis, in bold p value < 0.05).

Discussion

In this retrospective cohort of 161 patients undergoing iliofemoral venous stenting, 18.6% developed in-stent restenosis ≥ 50% and 28.2% had PTS at last follow-up. These findings indicate that, even after technically successful stenting, patients remain at risk for long-term anatomical and clinical complications. Hemodynamically, our analyses showed that early alterations in DUS parameters, particularly loss of respiratory modulation and reductions in venous flow, were associated with subsequent stent dysfunction and PTS. Together, these results underscore the importance of systematic DUS surveillance not only to monitor stent patency but also to identify patients at higher risk for progressive venous disease.

As shown in Table 1, patients treated for PTO had more extensive disease than those with acute DVT, including higher rates of femoro-popliteal involvement, greater number of stents, and more frequent crossing of the inguinal ligament. These anatomical and clinical differences reflect the distinct pathophysiology between acute and chronic disease. The increased number of stents in the PTO group is therefore consistent with the greater anatomical extent of disease; however, whether stent number itself has an independent impact on long-term outcomes could not be addressed in this study and warrants further investigation.

Venous stent patency is influenced by numerous factors[9,20], including inflow quality, technical success of recanalization[19,221,22], underlying thrombophilia, provoking risk factors, and adherence to anticoagulation therapy[23]. Despite this multifactorial context, younger age emerged as a significant predictor of stent stenosis or

Assessment	All patients	Stent free or stenosis < 50%	Stent occlusion or stenosis ≥ 50%	*P*-value
At 6 months, mean; median [Q1– Q3]	*n* = 132	*n* = 110	*n* = 22	
Peak velocity (cm/s)	1.2; 1.1 [0.6–1.9]	32.3; 30.0 [20.0–40.0]	32.4; 35.0 [14.3–44.5]	0.90
Venous flow (mL/min)	1.2; 1.1 [0.6–1.9]	531.6; 478.5 [328.8–630.0]	620.7; 355.0 [330.5–757.0]	0.77
Venous flow ratio	1.3; 1.0 [0.9–1.6]	1.4; 1.0 [0.9–1.8]	620.7; 355.0 [330.5–757.0]	0.21
Normal venous flow respiratory modulation, n/total (%)	92/114 (80.7%)	80/95 (84.2%)	12/19 (63.2%)	**0.034**
At 12 months, mean; median [Q1– Q3]	*n* = 114	*n* = 94	*n* = 20	
Peak velocity (cm/s)	36.4; 32.0 [21.0–38.0]	37.4; 29.5 [21.0–39.5]	29.6; 35.0 [20.0–35.0]	0.83
Venous flow (mL/min)	463.3; 367.0 [265.5–645.0]	458.1; 400.0 [265.5–633.5]	495.4; 358.5 [270.3–784.3]	0.59
Venous flow ratio	1.3; 1.2 [0.9–1.6]	1.3; 1.3 [0.9–1.7]	1.0; 1.0 [0.8–1.1]	0.24
Normal venous flow respiratory modulation, n/total (%)	79/85 (92.9%)	71/71 (100.0%)	8/14 (57.1%)	**< 0.001**
At last update, mean; median [Q1– Q3]	*n* = 124	*n* = 104	*n* = 20	
Time between stenting and last DUS (years)	2.6; 2.0 [1.0–4.0]	2.5; 2.0 [1.0–4.0]	3.2; 3.0 [2.0–4.5]	0.13
Peak velocity (cm/s)	35.0; 30.0 [18.5–40.0]	36.8; 30.0 [19.5–43.5]	24.0; 28.0 [16.5–32.3]	0.30
Venous flow (mL/min)	435.4; 400.0 [260.0–580.0]	437.4; 380.0 [255.0–591.5]	425.5; 400.5 [312.8–542.3]	0.92
Venous flow ratio	1.2; 1.1 [0.9–1.6]	1.3; 1.1 [0.9–1.4]	1.2; 1.1 [0.6–1.9]	0.77
Normal venous flow respiratory modulation, n/total (%)	94/100 (94.0%)	84/84 (100.0%)	10/16 (62.5%)	**< 0.001**

Table 3. Hemodynamic parameters based on thrombosis level in patients at 6, 12 months, and last update (CT: computed tomography, in bold p value < 0.05).

Outcome	Variable	Univariate OR (95% CI)	*P*-value	Multivariate OR* (95% CI)	*P*-value
Stent occlusion or stenosis ≥ 50%	Age (years)	0.97 [0.93; 1.00]	0.040	0.96 [0.93; 1.00]	**0.008**
	Female sex	1.13 [0.40; 3.25]	0.815	–	–
	Chronic venous insufficiency	0.54 [0.11; 2.78]	0.464	–	–
	Femoro-popliteal veins	2.23 [0.65; 7.58]	0.201	–	–
	Anticoagulation stopped at last update	2.27 [0.66; 7.80]	0.191	–	–

Table 4. Odds ratio of stent occlusion or stenosis ≥ 50% according to binary logistic analysis for the factors predicting stent stenosis (Age, female sex, chronic venous insufficiency, Femoro-politeal veins and anticoagulation stopped at last Update). *Multivariable ORs represent adjusted odds ratios from a binary logistic regression model including variables with $p < 0.10$ in the bivariate analysis. Values in bold indicate statistical significance ($p < 0.05$).

occlusion in our study. The mean age of patients was 37.7 years, and each one-year decrease in age was associated with a 4.4% increase in the odds of developing ≥ 50% stenosis or complete occlusion (OR = 1.044). This findings aligns with previous research identifying age < 40 years as a risk factor for decreased primary patency[24,25]. Younger patients also required re-intervention more frequently (mean age 32 vs. 46 years; $p < 0.01$), consistent with prior studies on venous stenting in acute iliofemoral DVT[26]. Although the underlying mechanisms are not fully understood, potential contributors include a more active inflammatory response leading to neointimal hyperplasia, a higher prevalence of thrombophilic conditions, and increased mechanical stress due to physical activity.

Hemodynamically, patients with ≥ 50% stent stenosis demonstrated a progressive decline in respiratory modulation between 6 and 12 months, even when other parameters such as peak velocity and venous flow remain stable. This suggests that loss of respiratory modulation may precede detectable changes in velocity or flow volume, positioning as a sensitive marker of stent dysfunction. These findings support incorporating waveform analysis into routine stent surveillance, especially in younger, higher-risk populations.

In contrast, older age was a significant predictor of PTS, with each additional year of age increasing the odds of PTS by 12% (OR = 1.12). This finding is consistent with results from the GARFIELD-VTE registry and the European Society of Vascular Medicine position paper, which reported up to a threefold increased risk of PTS in older populations[27,28]. This association may reflect the cumulative impact of chronic venous stasis and age-related vascular remodeling, with together contribute to valve dysfunction, venous hypertension and progressive outflow impairment[29]. In contrast, higher venous flow was associated with a protective against PTS, with a 1.1% decrease in the odds of developing PTS per unit increase in flow (OR = 0.989), likely reflecting better preservation of venous hemodynamics and reduced progression toward outflow compromise[30].

PTS is a dynamic condition, and its hemodynamic impact becomes more evident with serial evaluations. In our study, patients with PTS showed significantly reduced peak velocity (18.9 cm/s vs. 33.6 cm/s, $p = 0.003$) and iliac venous flow (297.0 mL/min vs. 462.7 mL/min, $p = 0.047$), along with impaired respiratory modulation (82.3% vs. 98.0%, $p = 0.04$), indicating progressive venous dysfunction. The decline in respiratory modulation at 12 months further reinforces its potential as an early indicator of disease onset[31,32]. Similarly, repeated Villalta

Patient demographics, *n*/total (%)	No post-thrombotic syndrome *n* = 74	Post-thrombotic syndrome *n* = 29	*P*-Value
Age (years), mean; median [Q1– Q3]	43.4; 42.0 [29.5–55.8]	51.5; 50.0 [37.5–69.0]	0.07
Female Sex	39/74 (52.7%)	18/29 (62.1%)	0.39
BMI (kg/m^2), mean; median [Q1– Q3]	26.0; 24.8 [22.5–28.6]	26.4; 26.3 [23.2–30.1]	0.40
Past medical history			
May-Thurner syndrome	18/74 (24.3%)	8/29 (27.6%)	0.73
Chronic venous insufficiency	10/68 (14.7%)	8/26 (30.8%)	0.08
Thromboembolic event	21/74 (28.4%)	9/29 (31.0%)	0.79
VTE risk factors			
Major thrombophilia	13/66 (19.7%)	8/25 (32.0%)	0.21
Surgery	17/68 (25.0%)	6/27 (22.2%)	0.78
Cancer	2/74 (2.7%)	2/29 (6.9%)	0.32
Hormonal and reproductive risk factors	21/74 (28.4%)	9/29 (31.0%)	0.79
Travel (> 6 h)	4/67 (6.0%)	0/27 (0.0%)	0.32
Immobilization (> 3 days)	29/65 (29.2%)	9/26 (34.6%)	0.62
Idiopathic	36/74 (48.6%)	12/29 (41.4%)	0.51
Lesion laterality			0.82
Left	53/74 (71.6%)	21/29 (72.4%)	
Right	8/74 (10.8%)	2/29 (6.9%)	
Bilateral	13/74 (17.6%)	6/29 (20.7%)	
Venous lesion extension at time of DVT diagnosis			
Iliac- common femoral veins	74/74 (100.0%)	29/29 (100.0%)	> 0.99
Femoro-popliteal veins	45/74 (60.8%)	21/29 (72.4%)	0.27
Infra-popliteal veins	19/74 (25.7%)	7/29 (24.1%)	0.87
Treatment post stenting			
Antiplatelet at discharge	70/74 (94.6%)	28/29 (96.6%)	0.68
Antiplatelet at last update	2/58 (3.4%)	1/25 (4.0%)	> 0.99
Anticoagulation at discharge	74/74 (100.0%)	29/29 (100.0%)	> 0.99
Anticoagulation at last update			
Full dose	44/58 (74.9%)	17/25 (68.0%)	0.48
Half dose	14/58 (24.1%)	8/25 (32.0%)	
Stopped	24/58 (41.4%)	10/25 (40.0%)	> 0.99
Complications post stenting			
Pulmonary embolism	4/65 (6.2%)	0/26 (0.0%)	0.58
Stent occlusion or stenosis ≥ 50%			
Post- stenting	20/72 (27.8%)	10/28 (35.7%)	0.44
Time from Initial stenting to post-stenting thrombosis onset (months), mean; median [Q1– Q3]	15.8; 11.9 [0.3–21.2]	14.5; 10.6 [0.2–23.6]	0.89
Re-stenting post initial stenting	13/24 (54.2%)	4/9 (44.4%)	0.71
CT venography at last update	*n* = 73	*n* = 29	
Time between stenting and last CT (years), mean; median [Q1– Q3]	2.9; 2.5 [2.0–4.0]	2.7; 2.0 [1.0–4.8]	0.46

Table 5. Demographic profile of patient with and without post-thrombotic syndrome (BMI: body mass index, VTE: venous thromboembolism; DVT: deep vein thrombosis). *Multivariable ORs represent adjusted odds ratios from a binary logistic regression model including variables with $p < 0.10$ in the bivariate analysis. Values in bold indicate statistical significance ($p < 0.05$).

assessments may improve PTS detection, as scores fluctuate over time and a single measurement may not fully capture disease progression[33]. In our study, repeated evaluations may have allowed us to identify more PTS cases, emphasizing the need for serial assessments to improve diagnostic accuracy and track disease evolution.

Strengths and limitations

This study is among the first to systematically analyze hemodynamic parameters for assessing venous stent patency and PTS progression, utilizing DUS to monitor key markers such as respiratory modulation, venous flow, and peak velocity. The large dataset and longitudinal design provide valuable real-world insights, and the identification of respiratory modulation as an early indicator of stent dysfunction offers practical utility for clinical follow-up. However, the retrospective design introduces potential biases, and the lack of invasive validation methods limits confirmation of findings. Operator variability, non-standardized criteria, and inconsistent patient follow-up may affect the reproducibility. Our cohort included both acute and chronic DVT patients, reflecting real-world practice but introducing biological heterogeneity. While acute lesions are typically

Assessment	All patients	No post thrombotic syndrome (*n* = 74)	Post-thrombotic syndrome (*n* = 29)	*P*-Value
At 6 months, mean; median [Q1– Q3]	*n* = 89	*n* = 65	*n* = 24	
Peak Velocity (cm/s)	31.0; 30.0 [20.0–40.0]	31.6; 30.0 [22.5–39.0]	29.5; 25.0 [16.0–45.0]	0.39
Venous flow (mL/min)	528.0; 450.0 [330.0–627.0]	31.6; 30.0 [22.5–39.0]	454.8; 354.0 [315.0–497.0]	0.13
Venous flow ratio	1.3; 1.0 [0.9–1.6]	31.6; 30.0 [22.5–39.0]	1.5; 1.4 [0.9–2.2]	0.36
Normal venous flow respiratory modulation, n/total (%)	66/81 (81.5%)	48/59 (81.4%)	18/22 (81.8%)	> 0.99
At 12 months, mean; median [Q1– Q3]	*n* = 80	*n* = 59	*n* = 21	
Peak Velocity (cm/s)	37.8; 32.0 [21.0–38.0]	40.1; 25.5 [21.0–37.0]	28.5; 27.0 [18.7–36.0]	0.61
Venous flow (mL/min)	427.2; 367.0 [265.5–645.0]	420.5; 325.0 [245.0–633.5]	416.2; 350.0 [256.0–586.0]	0.98
Venous flow ratio	1.25; 1.2 [0.9–1.6]	1.3; 1.1 [0.9–1.7]	1.2; 1.3 [1.0–1.6]	0.73
Normal venous flow respiratory modulation, n/total (%)	59/62 (95.2%)	45/45 (100.0%)	14/17 (82.4%)	**0.014**
At last update, mean; median [Q1– Q3]	*n* = 88	*n* = 60	*n* = 22	
Time between stenting and last DUS (years)	2.6; 2.0 [1.0–4.0]	2.7; 2.0 [1.0–4.5]	2.4; 2.0 [1.0–4.0]	0.54
Peak Velocity (cm/s)	29.3; 30.0 [18.5–40.0]	33.6; 31.5 [21.3–45.0]	18.9; 19.5 [12.1–22.5]	**0.003**
Venous flow (mL/min)	411.0; 400.0 [260.0–580.0]	462.7; 405.0 [285.8–598.5]	297.0; 261.5 [150.8–477.8]	**0.047**
Venous flow ratio	1.2; 1.1 [0.9–1.5]	1.2; 1.1 [0.9–1.4]	1.2; 1.1 [0.7–1.5]	0.85
Normal venous flow respiratory modulation, n/total (%)	57/60 (95.0%)	44/45 (97.8%)	12/15 (80.0%)	**0.017**

Table 6. Hemodynamic parameters in patients with and without Post-Thrombotic syndrome at 6, 12 months, and last update (CT: computed tomography, in bold p value < 0.05).

Outcome	Variable	Univariate OR (95% CI)	*P*-value	Multivariate OR* (95% CI)	*P*-value
Post thrombotic syndrome	Age (years)	1.14 [1.01; 1.30]	0.034	1.12 [1.02; 1.23]	**0.020**
	Chronic venous insufficiency	2.85 [0.12; 66.31]	0.515	-	-
	Peak velocity (cm/s)	0.89 [0.77; 1.03]	0.114	-	-
	Venous flow (mL/min)	0.99 [0.98; 1.00]	0.085	0.99 [0.98; 0.99]	**0.019**

Table 7. Odds ratio of post-thrombotic syndrome according to binary logistic analysis for the factors predicting post-thrombotic syndrome (Age, chronic venous insufficiency, peak velocity and venous flow). *Multivariable ORs represent adjusted odds ratios from a binary logistic regression model including variables with $p < 0.10$ in the bivariate analysis. Values in bold indicate statistical significance ($p < 0.05$).

inflamed and chronic ones fibrotic, this variable was recorded, analyzed, and not significantly associated with outcomes in our data. Nonetheless, differences in vein wall characteristics may impact long-term stent performance. Additionally, assessing venous flow remains challenging due to its lower velocity and variability, which are influenced by patient positioning and respiration. Most patients were enrolled before the publication of the ESVS 2022 guidelines[8], which may explain deviations from current surveillance protocols and grading-based therapeutic decisions.

Currently, defining a standard for the DUS evaluation of patients with venous stents remains challenging. Patency assessment in color mode, using slow-flow modes such as Superb Microvascular Imaging (SMI), may help to evaluate the proximal positioning of the iliovertebral pinch on the left, and the respiratory modulation of flows. Distally, assessing the number of veins confluent at the common femoral level is essential for evaluating inflow quality, along with patency and the presence of fibrous strands or venous retractions. Flow rates and venous velocity peaks should be interpreted with caution, as they vary significantly depending on patient positioning and breathing patterns. Unlike arterial stenosis assessment, peak velocities in venous flow are harder to evaluate due to the weaker venous circulation, which limits acceleration at stenotic sites, especially in cases with post-thrombotic sequelae. Moving forward, improving imaging techniques and establishing clear evaluation criteria will be essential for better diagnosis, follow-up, and long-term management of venous stents.

Conclusion

This study identifies significant associations between Doppler ultrasound–derived hemodynamic parameters and the presence of venous stent dysfunction and post-thrombotic syndrome. In particular, impaired respiratory modulation, reduced peak velocity, and lower venous flow were linked to ≥ 50% stent stenosis or occlusion, suggesting their potential as non-invasive indicators for early detection.

These findings support the need for standardized Doppler criteria to improve consistency in post-stenting surveillance. Future prospective, multicenter studies are essential to validate these associations and to assess the clinical utility of incorporating hemodynamic parameters into routine follow-up protocols.

Data availability

The datasets generated and analyzed during the current study are not publicly available due to patient confidentiality and institutional data protection policies but are available from the corresponding author on reasonable request.

Received: 13 June 2025; Accepted: 1 September 2025
Published online: 26 September 2025

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Acknowledgements

We would like to thank Bachir Atallah for his valuable technical support in data analysis, which contributed to this study.

Author contributions

YS, MM, LC, BE, CK, LD, ER data acquisition, YS, OE manuscript writing YS, OE, FD, BM study conception and data interpretation. All authors were involved in manuscript revision and approved the final version.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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