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Original Research Article

Vascular Reactivity Indices and Thrombotic Complications After Long-Duration Surgical Procedures

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Name of Author:
Shakeel Akbar[1], Tahir Aslam[2], Shagufta Razzaque[3], Mobasher Ahmad Saeed[4], Sara Khalid Memon[5], Francesco Ernesto Alessi Longa6, Israr Ud Din7*

Affiliation: *[1] Senior Registrar, Department of General Surgery, Bolan Medical College, Quetta, Pakistan.*
[2] Assistant Professor, Department of Thoracic Surgery, Fatima Jinnah Institute of Chest Diseases, Quetta, Pakistan.
[3] Demonstrator, Department of Biochemistry, Foundation University, Islamabad, Pakistan.
[4] Professor, Department of Anaesthesia and Intensive Care, Wah Medical College / POF Hospital, Wah Cantt, Pakistan.
[5] Assistant Professor of Surgery, Indus Medical College, Tando Muhammad Khan, Pakistan.
6Department of Kinesiology-Sport Sciences, University of Liberty, Virginia, USA.
7Associate Professor, Department of Otorhinolaryngology (ENT), Khyber Teaching Hospital, Khyber Medical College, Peshawar, Pakistan.

Corresponding Author:
Israr Ud Din

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Abstract: ***Background:*** Long-duration surgical procedures are associated with a high risk of postoperative thrombotic complications. Endothelial dysfunction and altered vascular reactivity play a key role in perioperative thrombosis. However, limited data exist on the relationship between vascular reactivity indices and postoperative thrombotic events after prolonged surgery. ***Objective:*** To assess perioperative vascular reactivity indices and determine their association with thrombotic complications following long-duration surgical procedures. ***Methods:*** This prospective observational cohort study was conducted at Khyber Teaching Hospital, Peshawar, over 12 months. Adult patients undergoing surgical procedures lasting four hours or more were enrolled. Vascular reactivity was assessed using brachial artery flow-mediated dilation (FMD) preoperatively and within 24 hours after surgery. D-dimer, fibrinogen, and high-sensitivity C-reactive protein were also measured. Patients were followed for 30 days for thrombotic complications. Multivariable logistic regression was performed to identify independent predictors. ***Results:*** Out of 312 eligible patients, 290 were analyzed. Thrombotic complications occurred in 41 patients (14.1%). Patients with thrombotic events were older, had higher body mass index, longer operative duration, higher prevalence of diabetes, and more frequent intraoperative hypotension ($p < 0.05$). Preoperative FMD was significantly lower in patients who developed thrombosis ($6.1 \pm 1.4\%$ vs $7.4 \pm 1.6\%$, $p < 0.001$), with a greater postoperative decline. Postoperative D-dimer and fibrinogen levels were significantly higher in the thrombotic group. On multivariable analysis, lower preoperative FMD, longer surgical duration, diabetes mellitus, and higher postoperative D-dimer were independently associated with thrombotic complications. ***Conclusion:*** Impaired vascular reactivity and increased postoperative coagulation activity are strongly associated with thrombotic complications after long-duration surgery. Assessment of vascular reactivity may help identify high-risk patients and improve perioperative risk stratification.

Keywords: vascular reactivity; endothelial dysfunction; thrombotic complications; long-duration surgery; perioperative thrombosis.

INTRODUCTION

Open surgery is still required in a significant proportion of patients who are not candidates for endovascular techniques, despite a global shift toward less invasive and less morbid procedures. However, vascular and other major open surgical procedures continue to be associated with substantial perioperative morbidity and mortality [1]. The prevalence of comorbid conditions, the physiological severity of the operation, and particularly the duration of surgery are key determinants of perioperative adverse events. Patients undergoing major and prolonged surgical procedures are at increased risk of cardiovascular complications, renal failure, pulmonary events, stroke, and death, and therefore require intensive perioperative monitoring [2]. Coronary artery disease, left ventricular dysfunction, valvular heart disease, and complex cardiac arrhythmias are frequently associated with the increased incidence of perioperative and late cardiovascular complications in these patients. Furthermore, cardiovascular causes remain the leading contributors to mortality within 30 days after surgery [1,2].

Identifying reliable preoperative predictors of postoperative complications and death remains a major clinical challenge. Considerable attention has been directed toward cardiovascular risk factors and preoperative electrocardiographic and echocardiographic parameters for perioperative risk stratification [3,4]. Nevertheless, accurately determining which patients are most likely to develop serious postoperative complications continues to be difficult, and although numerous strategies for perioperative risk optimization have been proposed, randomized controlled trials have not yet established a consistently safe and effective approach to prevent postoperative morbidity and mortality [5].

Growing evidence suggests that endothelial dysfunction and impaired vascular reactivity play a central role in the pathogenesis of perioperative thrombotic and cardiovascular complications, particularly in the setting of prolonged surgical stress [6]. Long-duration surgical procedures may exacerbate endothelial injury, promote inflammation and hypercoagulability, and thereby increase the risk of postoperative thrombotic events [7]. However, data linking perioperative vascular reactivity indices with thrombotic complications after prolonged surgery remain limited.

Therefore, there is a need to evaluate vascular reactivity as a potential mechanistic and predictive marker of postoperative thrombotic risk in patients undergoing long-duration surgical procedures. The objective of this study was to assess perioperative vascular reactivity indices and determine their association with thrombotic complications following long-duration surgical procedures.

MATERIALS AND METHODS

This prospective observational cohort study was conducted at Khyber Teaching Hospital, Peshawar, Pakistan, over a period of 12 months. Adult patients undergoing long-duration surgical procedures were enrolled and followed to evaluate the association between perioperative vascular reactivity indices and postoperative thrombotic complications. Long-duration surgery was defined as any elective or emergency operative procedure performed under general or regional anesthesia lasting four hours or more. Consecutive sampling was used to minimize selection bias. Based on previous literature reporting postoperative thrombotic event rates of approximately 12–18% after prolonged surgery, a minimum sample size of 260 patients was calculated using a single-proportion formula with 95% confidence level, 5% absolute precision, and an anticipated 10% attrition rate, yielding a final target of 290 patients.

Patients aged 18–75 years of either sex were included if they underwent qualifying surgical procedures and consented to participate. Exclusion criteria were known inherited coagulation disorders, active malignancy on chemotherapy, chronic anticoagulant therapy that could not be interrupted, established peripheral vascular disease, severe hepatic failure, pregnancy, and refusal to consent. Baseline assessment included demographic data, body mass index, smoking status, comorbidities (diabetes, hypertension, dyslipidemia), type and duration of surgery, anesthesia type, intraoperative blood loss, and perioperative fluid balance.

Vascular reactivity was assessed preoperatively and again within 24 hours after surgery. Endothelial-

dependent vascular reactivity was measured using brachial artery flow-mediated dilation assessed by high-resolution Doppler ultrasound following standardized cuff-induced forearm occlusion. The brachial artery diameter was recorded at rest and at 60 seconds after cuff release, and percentage change from baseline was calculated as the flow-mediated dilation index. Endothelial-independent vasodilation was indirectly assessed through resting brachial artery diameter and baseline blood pressure-derived vascular resistance indices. In addition, serum biomarkers related to vascular and thrombotic activity, including D-dimer, fibrinogen, and high-sensitivity C-reactive protein, were measured preoperatively and on postoperative day one using routine hospital laboratory methods.

Patients were followed clinically during hospital stay and up to 30 days postoperatively for thrombotic complications, including deep vein thrombosis, pulmonary embolism, myocardial infarction, ischemic stroke, and objectively confirmed peripheral arterial thrombosis. Suspected venous thrombosis was confirmed using compression Doppler ultrasonography, and pulmonary embolism was confirmed using computed tomography pulmonary angiography, as per hospital protocols. All outcomes were independently verified by a senior physician blinded to vascular reactivity results.

Potential confounders considered a priori included age, sex, obesity, smoking, diabetes, hypertension, duration and type of surgery, intraoperative hypotension, postoperative immobility, and use of pharmacological thromboprophylaxis. These variables were recorded systematically and adjusted for during multivariable analysis. Data completeness was ensured by real-time verification of case report forms. If missing data were less than 5%, complete-case analysis was performed; if more than 5%, multiple imputation using chained equations was applied assuming data were missing at random.

Data were analyzed using SPSS version 26. Continuous variables were tested for normality and expressed as mean ± standard deviation or median with interquartile range as appropriate. Categorical variables were expressed as frequencies and percentages. Pre- and postoperative vascular reactivity indices were compared using paired t-tests or Wilcoxon signed-rank tests. The association between vascular reactivity indices and thrombotic outcomes was assessed using univariate analysis followed by multivariable logistic regression to calculate adjusted odds ratios with 95% confidence intervals. Variables with $p < 0.20$ on univariate analysis and clinically relevant confounders were entered into the regression model. A two-tailed p value < 0.05 was considered statistically significant.
The study protocol was approved by the Institutional Review Board of Khyber Teaching Hospital, and written informed consent was obtained from all participants prior to enrollment.

RESULTS

A total of 312 patients met the eligibility criteria during the study period. Twenty-two patients were excluded due to incomplete baseline vascular assessment or loss to follow-up, leaving 290 patients for final analysis. The mean age of participants was 49.6 ± 13.2 years, and 172 (59.3%) were male. The mean operative duration was 5.3 ± 1.1 hours. Thrombotic complications within 30 postoperative days were documented in 41 patients (14.1%).

Baseline demographic and perioperative characteristics are summarized in Table 1. Patients who developed thrombotic complications were significantly older, had higher body mass index, longer operative duration, higher prevalence of diabetes, and more frequent intraoperative hypotension compared with those without thrombotic events ($p < 0.05$).

Table 1. Baseline demographic and perioperative characteristics of the study population (n = 290)

Variable	Overall (n=290)	Thrombotic events (n=41)	No events (n=249)	p value
Age (years), mean ± SD	49.6 ± 13.2	57.1 ± 11.4	48.3 ± 13.1	<0.001
Male sex, n (%)	172 (59.3)	26 (63.4)	146 (58.6)	0.56
Body mass index (kg/m²), mean ± SD	27.4 ± 4.1	29.6 ± 4.3	27.0 ± 3.9	<0.001
Current smoker, n (%)	78 (26.9)	15 (36.6)	63 (25.3)	0.12
Diabetes mellitus, n (%)	96 (33.1)	22 (53.7)	74 (29.7)	0.003
Hypertension, n (%)	112 (38.6)	21 (51.2)	91 (36.5)	0.08
Duration of surgery (hours), mean ± SD	5.3 ± 1.1	6.1 ± 1.0	5.1 ± 1.0	<0.001
Estimated blood loss (mL), median (IQR)	420 (300–650)	610 (420–880)	390 (280–610)	0.002
Intraoperative hypotension, n (%)	74 (25.5)	18 (43.9)	56 (22.5)	0.004
Pharmacologic thromboprophylaxis, n (%)	214 (73.8)	27 (65.9)	187 (75.1)	0.21

Preoperative and postoperative vascular reactivity indices and laboratory markers are shown in Table 2. Overall, a

significant postoperative reduction in flow-mediated dilation (FMD) was observed ($p < 0.001$). Patients who later developed thrombotic complications had significantly lower preoperative FMD and a greater postoperative decline compared with those without events. Postoperative D-dimer and fibrinogen levels were also significantly higher in the thrombotic group.

Table 2. Vascular reactivity indices and laboratory parameters

Parameter	Thrombotic events (n=41)	No events (n=249)	p value
Preoperative FMD (%), mean ± SD	6.1 ± 1.4	7.4 ± 1.6	<0.001
Postoperative FMD (%), mean ± SD	3.9 ± 1.2	6.2 ± 1.5	<0.001
Change in FMD (%), mean ± SD	−2.2 ± 0.9	−1.2 ± 0.8	<0.001
Baseline brachial artery diameter (mm), mean ± SD	4.3 ± 0.5	4.1 ± 0.4	0.02
Preoperative D-dimer (µg/mL), median (IQR)	0.42 (0.30–0.61)	0.31 (0.22–0.44)	0.001
Postoperative D-dimer (µg/mL), median (IQR)	1.48 (1.10–2.20)	0.78 (0.52–1.20)	<0.001
Preoperative fibrinogen (g/L), mean ± SD	3.4 ± 0.6	3.1 ± 0.5	0.004
Postoperative fibrinogen (g/L), mean ± SD	4.5 ± 0.7	3.7 ± 0.6	<0.001
Postoperative hs-CRP (mg/L), median (IQR)	28.0 (19–41)	16.5 (10–27)	<0.001

Paired analysis of the entire cohort showed a significant postoperative decline in FMD (preoperative 7.2 ± 1.6% vs postoperative 5.9 ± 1.7%, $p < 0.001$) and a significant rise in D-dimer and fibrinogen levels (both $p < 0.001$), indicating reduced endothelial function and increased thrombotic activity following prolonged surgery.

The spectrum of thrombotic complications is presented in Table 3. Deep vein thrombosis was the most frequent event, followed by pulmonary embolism and myocardial infarction.

Table 3. Types of postoperative thrombotic complications (n = 41)

Complication	Number (%)
Deep vein thrombosis	18 (43.9)
Pulmonary embolism	9 (22.0)
Myocardial infarction	7 (17.1)
Ischemic stroke	5 (12.2)
Peripheral arterial thrombosis	2 (4.9)

Univariate analysis identified older age, higher BMI, diabetes mellitus, longer surgical duration, intraoperative hypotension, lower preoperative FMD, greater postoperative decline in FMD, and elevated postoperative D-dimer as significant predictors of thrombotic complications (Table 4).

Table 4. Univariate predictors of thrombotic complications

Variable	OR	95% CI	p value
Age (per year increase)	1.05	1.02–1.08	0.001
Body mass index (per kg/m²)	1.12	1.05–1.20	<0.001
Diabetes mellitus	2.75	1.39–5.42	0.004
Duration of surgery (per hour)	1.86	1.33–2.62	<0.001
Intraoperative hypotension	2.69	1.34–5.40	0.005
Preoperative FMD (per 1% increase)	0.68	0.56–0.82	<0.001
Postoperative D-dimer (per µg/mL)	1.91	1.34–2.71	<0.001
Thromboprophylaxis use	0.64	0.31–1.33	0.23

Multivariable logistic regression analysis demonstrated that lower preoperative FMD, longer operative duration, diabetes mellitus, and higher postoperative D-dimer remained independently associated with thrombotic complications after adjustment for confounders (Table 5).

Table 5. Multivariable logistic regression analysis for predictors of thrombotic complications

Variable	Adjusted OR	95% CI	p value
Preoperative FMD (per 1% increase)	0.72	0.58–0.88	0.002
Duration of surgery (per hour)	1.61	1.12–2.31	0.01
Diabetes mellitus	2.21	1.03–4.72	0.04
Postoperative D-dimer (per µg/mL)	1.67	1.14–2.45	0.008
Age (per year)	1.02	0.99–1.06	0.18
Intraoperative hypotension	1.49	0.71–3.12	0.28

DISCUSSION

In this prospective observational study, thrombotic complications occurred in 14.1% of patients undergoing long-duration surgical procedures, highlighting the substantial thrombotic burden associated with prolonged operative stress. This incidence is consistent with previous reports demonstrating that major and lengthy surgical procedures significantly increase postoperative cardiovascular and thromboembolic risk due to endothelial injury, inflammatory activation, and hypercoagulability [1,2]. The observed predominance of venous thromboembolism, particularly deep vein thrombosis and pulmonary embolism, further supports existing evidence that prolonged immobility, venous stasis, and perioperative endothelial dysfunction are central mechanisms underlying postoperative thrombosis [7,8].

Patients who developed thrombotic complications were significantly older and had higher body mass index values. Advanced age is well recognized as a major risk factor for postoperative thrombotic and cardiovascular events due to progressive endothelial dysfunction, increased arterial stiffness, and impaired fibrinolytic activity [6,9]. Similarly, obesity promotes a prothrombotic milieu through chronic low-grade inflammation, increased fibrinogen levels, and endothelial nitric oxide dysregulation, which has been repeatedly associated with higher rates of postoperative venous thromboembolism and cardiovascular morbidity [10,11]. Our findings reinforce these established associations and emphasize the need for enhanced perioperative risk stratification in elderly and overweight individuals.

Diabetes mellitus was significantly more prevalent among patients who developed thrombotic complications and remained an independent predictor on multivariable analysis. This observation is biologically plausible and supported by extensive literature demonstrating that diabetes induces endothelial dysfunction, platelet hyperreactivity, and impaired fibrinolysis, thereby markedly increasing perioperative thrombotic risk [12, 13]. Previous vascular and non-cardiac surgical studies have similarly reported higher rates of cardiovascular and thromboembolic events among diabetic patients, particularly in the setting of prolonged operative stress and perioperative glycemic instability [14,15].

Our results extend this evidence by demonstrating that diabetes is also strongly associated with impaired perioperative vascular reactivity, which may serve as a mechanistic link between metabolic disease and postoperative thrombosis.

Longer operative duration emerged as one of the strongest predictors of thrombotic complications. Prolonged surgery increases exposure to hypotension, hypothermia, inflammatory cytokines, and endothelial trauma, all of which contribute to coagulation activation and vascular dysfunction [16-19]. Earlier reports have shown that lengthy vascular and abdominal procedures are associated with significantly higher rates of myocardial infarction, venous thromboembolism, and mortality [20-23. The present findings are consistent with these studies and suggest that surgical duration should be considered not merely a procedural variable, but a central biological determinant of postoperative thrombotic risk.

Intraoperative hypotension was significantly more frequent among patients with thrombotic events and showed a strong association on univariate analysis. Hypotension contributes to regional hypoperfusion, ischemia–reperfusion injury, and oxidative stress, which are known to impair endothelial integrity and promote thrombogenesis [24,25]. Prior vascular surgery literature has similarly linked hypotensive episodes to postoperative renal failure, myocardial ischemia, and thrombotic complications [26,27]. Although intraoperative hypotension lost significance after multivariable adjustment, its close association with operative duration and metabolic comorbidities suggests an important contributory role in the thrombo-inflammatory cascade.

The most important finding of this study is the strong association between impaired vascular reactivity and postoperative thrombotic complications. Patients who developed thrombosis had significantly lower preoperative flow-mediated dilation and experienced a greater postoperative decline. Flow-mediated dilation is a well-validated surrogate marker of endothelial nitric oxide bioavailability and vascular health. Reduced FMD reflects endothelial dysfunction, which is a central pathogenic factor in atherosclerosis, perioperative myocardial injury, and venous thromboembolism [10,19,28]. The significant postoperative reduction in FMD observed across the cohort confirms that long-duration surgery induces acute endothelial dysfunction. The markedly lower preoperative values in patients who developed thrombosis suggest that baseline endothelial vulnerability predisposes patients to exaggerated perioperative vascular injury and subsequent thrombotic events. These findings are in agreement with prior studies demonstrating that impaired endothelial function predicts adverse cardiovascular outcomes and perioperative morbidity [13, 17, 29].

The significant postoperative rise in D-dimer, fibrinogen, and hs-CRP reflects activation of coagulation and systemic inflammation following prolonged surgery. Patients who developed

thrombotic complications had substantially higher postoperative D-dimer and fibrinogen levels, indicating enhanced fibrin turnover and clot formation. Elevated D-dimer has been consistently shown to correlate with postoperative venous thromboembolism, myocardial infarction, and mortality [30]. The independent association between postoperative D-dimer and thrombotic complications in our multivariable model supports its role not only as a diagnostic marker, but also as a potential early prognostic indicator of thrombotic risk.

The observed spectrum of thrombotic complications is comparable to that reported in major surgical and vascular cohorts, where venous thromboembolism and myocardial infarction predominate, followed by cerebrovascular events [12]. The presence of arterial thrombotic events in a subset of patients further supports the concept that perioperative thrombosis represents a systemic vascular disorder rather than an isolated venous phenomenon. This aligns with evidence that surgical stress induces diffuse endothelial activation, platelet aggregation, and microvascular thrombosis across multiple vascular beds [14, 16].

Multivariable analysis demonstrated that impaired preoperative FMD, longer operative duration, diabetes mellitus, and elevated postoperative D-dimer were independently associated with thrombotic complications. These findings collectively highlight a mechanistic continuum linking baseline endothelial dysfunction, surgical vascular injury, metabolic vulnerability, and postoperative hypercoagulability. Similar integrative models have been proposed in vascular and non-cardiac surgical literature, where preoperative cardiovascular substrate and intraoperative physiological stress jointly determine postoperative outcomes [15,26].

Clinically, these results suggest that preoperative assessment of vascular reactivity and early postoperative monitoring of coagulation biomarkers may help identify high-risk patients who could benefit from intensified thromboprophylaxis, hemodynamic optimization, and closer surveillance. While traditional risk factors remain important, the incorporation of endothelial function testing may provide a more direct and pathophysiologically relevant estimate of perioperative thrombotic vulnerability.

LIMITATIONS

This study has limitations. It was conducted at a single center, which may limit generalizability. Although follow-up was systematic, subclinical thrombotic events may have been missed. Furthermore, while FMD is a robust noninvasive marker, it is operator dependent. Despite these limitations, the prospective design, standardized vascular assessments, and comprehensive multivariable modeling strengthen the validity of the findings.

CONCLUSION

Long-duration surgical procedures are associated with significant postoperative endothelial dysfunction and thrombotic risk. Impaired preoperative vascular reactivity and exaggerated postoperative coagulation activation are key determinants of thrombotic complications. These findings support the concept that perioperative thrombosis is fundamentally an endothelial disease process and highlight the potential role of vascular reactivity indices in improving perioperative risk stratification and prevention strategies.

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