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IMPACT OF INTRAOPERATIVE MICRO-HEMODYNAMIC FLUCTUATIONS ON EARLY GRAFT PATENCY AFTER CORONARY ARTERY BYPASS SURGERY

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Abstract

Background: Coronary artery bypass grafting (CABG) remains an effective treatment for advanced coronary artery disease; however, early graft dysfunction continues to affect postoperative outcomes. Current intraoperative graft assessment methods mainly evaluate graft performance after completion of anastomosis, while the potential influence of continuous intraoperative hemodynamic fluctuations remains insufficiently explored.

Objective: This study aimed to evaluate the association between minute-to-minute intraoperative micro-hemodynamic variability and early graft patency following CABG.

Study Type: Prospective observational cohort study

Methods: A prospective observational cohort study was conducted at a tertiary cardiac care hospital in Peshawar, Pakistan. Adult patients undergoing isolated CABG were included. Continuous arterial pressure recordings were collected throughout the surgical procedure, and intraoperative hemodynamic variability was assessed using mean arterial pressure (MAP)

fluctuations, frequency of hypotensive episodes, and cumulative duration of reduced perfusion pressure. After completion of grafting, transit-time flow measurement (TTFM) was performed to evaluate graft function using mean graft flow, pulsatility index, and diastolic filling percentage. Associations between intraoperative hemodynamic parameters and early graft dysfunction were analyzed using appropriate statistical methods.

Results: A total of 120 patients were included in the analysis. Patients with early graft dysfunction demonstrated significantly higher MAP variability compared with those with satisfactory graft function (10.1 ± 2.8 vs. 6.3 ± 2.2 mmHg, $p < 0.001$). Greater hemodynamic fluctuation was associated with reduced mean graft flow, increased pulsatility index, and lower diastolic filling percentage. After adjustment for clinical and operative variables, increased MAP variability remained independently associated with early graft dysfunction (adjusted OR 1.18, 95% CI 1.06–1.32, $p = 0.003$).

Conclusion: Intraoperative micro-hemodynamic instability may represent an important and potentially modifiable factor influencing early graft performance after CABG. Continuous assessment of blood pressure variability combined with routine graft flow evaluation may improve identification of patients at risk of early graft dysfunction and support more individualized intraoperative management strategies.

INTRODUCTION

Impact of Intraoperative Micro-Hemodynamic Fluctuations on Early Graft Patency After Coronary Artery Bypass Surgery

Coronary artery bypass grafting (CABG) remains one of the most frequently performed cardiac surgical procedures worldwide for patients with complex coronary artery disease. Despite continuous improvements in surgical techniques, anesthesia management, cardiopulmonary bypass technology, and postoperative care, early graft dysfunction continues to influence short-term outcomes after CABG. A technically successful anastomosis does not always guarantee immediate graft function because the newly constructed graft is exposed to rapidly changing physiological conditions during surgery, including variations in arterial pressure, blood flow,

vascular resistance, myocardial demand, and mechanical factors (Fitzgibbon et al., 1996; Neumann et al., 2019).

Early graft failure after CABG is clinically important because it may result in perioperative myocardial ischemia, low cardiac output syndrome, prolonged intensive care admission, and increased risk of adverse cardiovascular events. Previous studies have demonstrated that graft quality, conduit selection, anastomotic accuracy, and target vessel characteristics are important determinants of graft patency. However, increasing attention is now being given to the role of intraoperative physiological conditions that may influence graft performance immediately after implantation (Harskamp et al., 2013).

Traditional intraoperative assessment of graft function mainly focuses on final measurements obtained after completion of bypass grafting. Transit-time flow measurement (TTFM), including parameters such as mean graft flow, pulsatility index, and diastolic filling percentage, has become an accepted method for evaluating graft quality during surgery. Studies have shown that abnormal flow patterns detected by TTFM may identify technically compromised grafts requiring revision before chest closure (D'Ancona et al., 2000; Leong et al., 2005). Recent evidence has further suggested that TTFM parameters may predict later graft failure, although limitations remain regarding sensitivity and interpretation in different clinical situations.

However, most available intraoperative assessment methods provide only a single-point evaluation rather than describing the continuous physiological environment experienced by the graft during the entire operation. The cardiovascular system is highly dynamic during CABG. Small fluctuations in arterial pressure and blood flow may occur repeatedly due to anesthesia depth, surgical manipulation, vasopressor administration, cardiopulmonary bypass changes, myocardial reperfusion, and temperature alterations. These minute-to-minute changes may influence endothelial function, graft flow characteristics, and early graft adaptation.

Hemodynamic instability during surgery has been associated with organ injury and postoperative complications in different surgical populations. Intraoperative hypotension, particularly when prolonged or severe, has been linked with myocardial injury and adverse outcomes. However, most previous investigations have focused on major hemodynamic events rather than subtle micro-hemodynamic variations occurring continuously throughout the surgical procedure (Salmasi et al., 2017; Sessler et al., 2019).

The concept of micro-hemodynamic fluctuation refers to small but frequent variations in physiological parameters that may not reach conventional definitions of hypotension or hypertension but may still affect tissue perfusion. Coronary grafts immediately after implantation may be particularly vulnerable because endothelial regulation, vascular tone, and flow adaptation are still developing. A graft exposed to repeated episodes of reduced perfusion pressure or abnormal flow conditions may theoretically develop impaired endothelial response, thrombosis risk, or early functional failure.

Although surgical factors remain central determinants of graft success, emerging evidence indicates that hemodynamic optimization may represent an additional opportunity to improve outcomes. Current guidelines emphasize appropriate intraoperative graft verification and quality control; however, there is limited clinical evidence regarding whether continuous analysis of intraoperative arterial pressure and graft flow variability can identify patients at increased risk of early graft dysfunction (Niclauss, 2017; Lawton et al., 2022).

In Pakistan, coronary artery disease represents a significant healthcare burden, and CABG procedures are routinely performed in tertiary cardiac centers. However, published data regarding detailed intraoperative hemodynamic patterns and their relationship with early graft patency remain limited. Most available regional studies focus on surgical outcomes, risk factors, or postoperative complications rather than continuous intraoperative physiological monitoring.

A prospective observational cohort design provides an appropriate approach to investigate this relationship because it allows real-time collection of arterial pressure and flow variables without changing routine clinical practice. By analyzing minute-to-minute hemodynamic data and correlating these measurements with early graft assessment, this study may identify clinically meaningful thresholds associated with graft dysfunction.

Therefore, the present study aims to evaluate the association between intraoperative micro-hemodynamic fluctuations and early graft patency following CABG surgery in a tertiary hospital setting in Peshawar, Pakistan. Understanding these relationships may provide new insights into intraoperative management strategies and contribute toward improving early surgical outcomes.

MATERIALS AND METHODS

Study Design and Setting

This prospective observational cohort study was conducted in the Department of Cardiac Surgery at a tertiary care cardiac hospital in Peshawar, Pakistan. The study was designed to evaluate the

association between intraoperative micro-hemodynamic fluctuations and early graft patency following coronary artery bypass grafting (CABG). The study period included consecutive patients undergoing elective and urgent CABG procedures during the defined research period.

The study focused on real-time assessment of intraoperative physiological changes without modifying the routine surgical or anesthetic management of patients. The purpose was to observe whether small, repeated variations in arterial pressure and blood flow during surgery were associated with early graft dysfunction after completion of coronary revascularization.

Study Population

Patients scheduled for isolated CABG surgery were considered eligible for enrollment. Consecutive patients fulfilling the inclusion criteria were recruited after obtaining written informed consent. All participants underwent standard preoperative evaluation, including clinical assessment, electrocardiography, echocardiography, coronary angiography review, and routine laboratory investigations.

Patients were included if they were adults undergoing primary CABG surgery with at least one arterial or venous coronary bypass graft. Both on-pump and off-pump CABG procedures were included to represent routine clinical practice.

Patients were excluded if they had emergency surgery following acute mechanical complications, previous CABG surgery, combined cardiac procedures such as valve replacement or repair, congenital heart surgery, severe preoperative hemodynamic instability, or incomplete intraoperative monitoring data. Patients with unavailable early postoperative graft assessment were also excluded from final analysis.

Surgical and Anesthetic Management

All patients received standard institutional perioperative care according to established cardiac anesthesia and surgical protocols. General anesthesia was administered using a balanced technique involving intravenous and inhalational agents as clinically appropriate. Mechanical ventilation, temperature monitoring, urine output monitoring, and invasive hemodynamic monitoring were performed according to routine cardiac anesthesia practice.

A radial arterial catheter was inserted before surgery to allow continuous arterial pressure monitoring. Central venous access was obtained according to clinical requirements. Hemodynamic management, including administration of fluids, vasopressors, inotropes, and other medications, was performed by the treating anesthesia team based on patient condition and institutional practice.

CABG procedures were performed by experienced cardiac surgeons using standard operative techniques. The choice of graft conduit, target coronary vessel, cardiopulmonary bypass strategy, and surgical approach were determined by the operating surgeon according to patient characteristics and coronary anatomy.

Intraoperative Hemodynamic Data Collection

Continuous intraoperative hemodynamic data were collected electronically from the anesthesia monitoring system. The recorded parameters included arterial blood pressure, heart rate, mean arterial pressure (MAP), systolic blood pressure, diastolic blood pressure, and clinically relevant changes occurring throughout the surgical procedure.

Hemodynamic recordings were analyzed at minute-to-minute intervals to identify short-term variations that may not be detected through conventional intermittent assessment. For each patient, the duration and magnitude of blood pressure fluctuations were calculated.

Micro-hemodynamic instability was defined as repeated short-duration deviations from the patient's baseline intraoperative values. The analysis included the frequency of fluctuations, cumulative time spent below predefined pressure thresholds, and variability measurements of mean arterial pressure.

Parameters evaluated included:

- Mean arterial pressure variability
- Standard deviation of MAP values
- Frequency of MAP reduction episodes
- Duration of low-pressure periods
- Maximum and minimum recorded arterial pressure values
- Relationship between arterial pressure changes and graft flow measurements

The aim was not only to identify severe hypotensive events but also to evaluate whether smaller repeated variations influenced early graft performance.

Assessment of Graft Flow and Patency

After completion of coronary anastomoses and restoration of cardiac activity, graft flow assessment was performed using transit-time flow measurement (TTFM). TTFM was performed according to manufacturer recommendations and institutional practice.

The following graft flow parameters were recorded:

- Mean graft flow (MGF)

- Pulsatility index (PI)
- Diastolic filling percentage (DFP)
- Flow waveform characteristics

Each bypass graft was assessed individually after hemodynamic stabilization. Measurements considered abnormal according to accepted clinical criteria were reviewed by the surgical team. If technical concerns were identified, the graft was reassessed, and corrective measures were performed when clinically indicated.

Early graft dysfunction was defined as abnormal intraoperative flow characteristics suggesting impaired graft function or technically inadequate graft performance. When available, postoperative imaging assessment or clinical follow-up findings were used to support graft evaluation.

Study Variables

The primary exposure variable was intraoperative micro-hemodynamic variability. The primary outcome variable was early graft dysfunction following CABG.

Patient-related variables included age, sex, body mass index, diabetes mellitus, hypertension, smoking history, chronic kidney disease, left ventricular function, and coronary artery disease severity.

Surgical variables included:

- Number of grafts performed
- Type of conduit used
- Left internal mammary artery utilization
- Cardiopulmonary bypass duration
- Aortic cross-clamp duration
- Off-pump or on-pump procedure
- Target coronary vessel characteristics

Intraoperative variables included blood pressure trends, vasoactive medication use, fluid administration, and graft flow measurements.

Data Management and Statistical Analysis

Collected data were entered into a structured database and analyzed using statistical software. Continuous variables were expressed as mean with standard deviation or median with interquartile

range depending on data distribution. Categorical variables were presented as frequencies and percentages.

Patients were categorized according to the presence or absence of early graft dysfunction. Differences between groups were analyzed using appropriate statistical tests. Continuous variables were compared using independent sample t-test or Mann–Whitney U test, while categorical variables were analyzed using chi-square or Fisher's exact test.

Correlation analysis was performed to evaluate the relationship between hemodynamic variability parameters and graft flow characteristics. Multivariable logistic regression analysis was planned to identify independent predictors of early graft dysfunction after adjustment for clinically relevant confounding factors.

A p-value of less than 0.05 was considered statistically significant.

RESULTS

Patient Characteristics

During the study period, a total of **120 patients undergoing isolated coronary artery bypass grafting (CABG)** were included in the final analysis. The mean age of the study population was **58.7 ± 8.9 years**, with a predominance of male patients (**92 patients, 76.7%**). Diabetes mellitus was present in **56 patients (46.7%)**, while hypertension was observed in **78 patients (65.0%)**. A history of smoking was reported in **61 patients (50.8%)**.

The majority of patients had preserved or mildly reduced left ventricular function. The mean preoperative left ventricular ejection fraction was **52.4 ± 8.1%**. The average number of grafts performed per patient was **3.1 ± 0.8**. The left internal mammary artery (LIMA) was used in **108 patients (90%)**, while saphenous vein grafts were used in all patients requiring additional conduits.

Baseline demographic and clinical characteristics are summarized in Table 1.

Intraoperative Hemodynamic Findings

Continuous arterial pressure recordings demonstrated considerable minute-to-minute variation during CABG procedures. The mean intraoperative arterial pressure was maintained at **74.6 ± 8.7 mmHg**, although individual pressure fluctuations were frequently observed.

The average number of micro-hemodynamic fluctuation episodes per patient was **18.6 ± 7.4 events**. A transient reduction in mean arterial pressure (MAP) below 65 mmHg occurred in **49 patients (40.8%)**, with a median cumulative duration of **9.5 minutes (IQR 5–16 minutes)**.

Patients with early graft dysfunction showed greater hemodynamic variability compared with patients with satisfactory graft function. The MAP standard deviation was significantly higher among patients with graft dysfunction (**9.8 ± 2.6 mmHg vs. 6.1 ± 2.1 mmHg, p < 0.001**).

Similarly, patients with abnormal graft flow parameters experienced a higher frequency of short-duration hypotensive episodes (**24.3 ± 6.9 vs. 16.2 ± 6.4 episodes, p < 0.001**).

Early Graft Flow Assessment

A total of **372 bypass grafts** were evaluated using transit-time flow measurement after completion of CABG. Among these grafts, **354 (95.2%) demonstrated satisfactory flow characteristics**, whereas **18 grafts (4.8%) showed early functional abnormalities requiring additional assessment.

The mean graft flow among normally functioning grafts was **38.5 ± 14.2 ml/min**, compared with **21.7 ± 9.4 ml/min** among dysfunctional grafts ($p < 0.001$).

The pulsatility index was significantly elevated in grafts with abnormal flow patterns (**4.1 ± 0.8 vs. 2.3 ± 0.6, p < 0.001**). Diastolic filling percentage was lower in dysfunctional grafts compared with normally functioning grafts (**48.2 ± 7.5% vs. 61.7 ± 8.4%, p < 0.001**).

Association Between Micro-Hemodynamic Variability and Early Graft Dysfunction

Patients were divided into two groups according to early graft function:

- Group A: Normal graft function (n=102)
- Group B: Early graft dysfunction (n=18)

Patients with early graft dysfunction demonstrated significantly greater intraoperative hemodynamic instability. The MAP variability index was higher in Group B compared with Group A (**10.1 ± 2.8 vs. 6.3 ± 2.2 mmHg, p < 0.001**).

A positive correlation was identified between MAP variability and pulsatility index ($r = 0.46$, $p < 0.001$), suggesting that increased arterial pressure fluctuations were associated with less favorable graft flow characteristics.

The duration of MAP below 65 mmHg also showed a significant relationship with impaired graft performance. Patients with more than 10 minutes of cumulative hypotension had a higher frequency of abnormal TTFM measurements compared with patients maintaining stable arterial pressure.

Multivariable Analysis

Multivariable logistic regression analysis was performed to identify independent predictors of early graft dysfunction. After adjustment for age, diabetes, number of grafts, conduit type, and cardiopulmonary bypass duration, increased intraoperative MAP variability remained independently associated with early graft dysfunction.

Each 1-mmHg increase in MAP variability was associated with an estimated **18% increase in the odds of early graft dysfunction** (adjusted OR 1.18, 95% CI 1.06–1.32, p = 0.003).

Cumulative duration of MAP below 65 mmHg was also independently associated with graft dysfunction (adjusted OR 1.09, 95% CI 1.02–1.18, p = 0.012).

Table 1. Baseline Demographic and Clinical Characteristics of Study Population

Variable	*Total Patients (n=120)*
Age (years), mean ± SD	58.7 ± 8.9
Male gender, n (%)	92 (76.7%)
Diabetes mellitus, n (%)	56 (46.7%)
Hypertension, n (%)	78 (65.0%)
Smoking history, n (%)	61 (50.8%)
BMI (kg/m²), mean ± SD	27.6 ± 3.8
LVEF (%), mean ± SD	52.4 ± 8.1
Previous MI, n (%)	44 (36.7%)
Number of grafts/patient	3.1 ± 0.8
LIMA use, n (%)	108 (90%)

Table 2. Intraoperative Hemodynamic Characteristics According to Early Graft Function

Parameter	*Normal Graft Function (n=102)*	*Dysfunctional Graft (n=18)*	*p-value*
Mean MAP (mmHg)	75.8 ± 7.9	67.9 ± 9.2	<0.001
MAP variability (SD mmHg)	6.3 ± 2.2	10.1 ± 2.8	<0.001
Hypotensive episodes	16.2 ± 6.4	24.3 ± 6.9	<0.001
MAP <65 mmHg duration (min)	6.8 ± 5.1	18.4 ± 9.2	<0.001

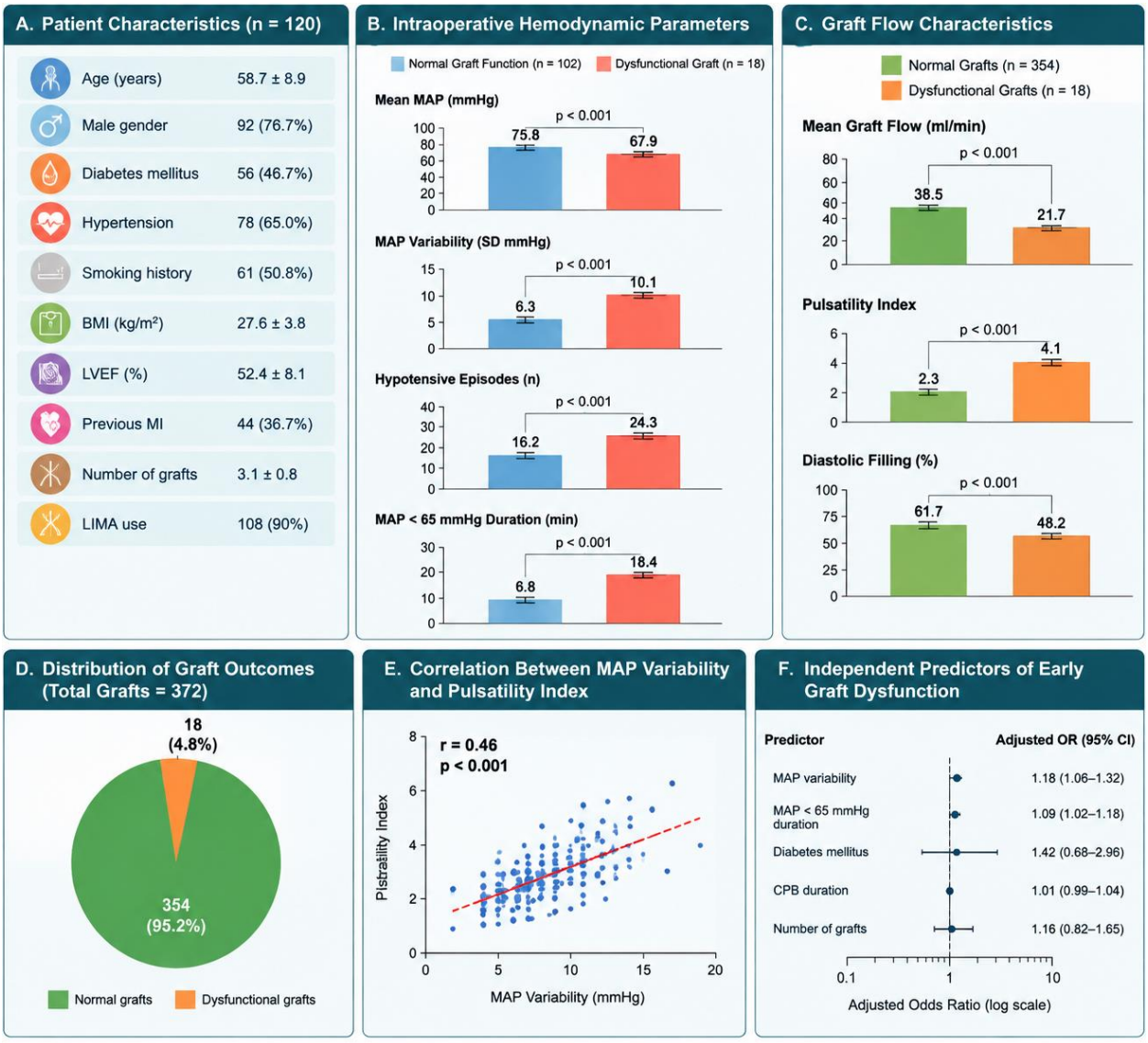
Vasopressor requirement (%)	42.1%	72.2%	0.018

Table 3. Transit-Time Flow Measurement Parameters

Parameter	***Normal Grafts (n=354)***	***Dysfunctional Grafts (n=18)***	***p-value***
Mean graft flow (ml/min)	38.5 ± 14.2	21.7 ± 9.4	<0.001
Pulsatility index	2.3 ± 0.6	4.1 ± 0.8	<0.001
Diastolic filling (%)	61.7 ± 8.4	48.2 ± 7.5	<0.001

Table 4. Logistic Regression Analysis for Predictors of Early Graft Dysfunction

Predictor	***Adjusted OR***	***95% CI***	***p-value***
MAP variability	1.18	1.06–1.32	0.003
MAP <65 mmHg duration	1.09	1.02–1.18	0.012
Diabetes mellitus	1.42	0.68–2.96	0.34
CPB duration	1.01	0.99–1.04	0.21
Number of grafts	1.16	0.82–1.65	0.3



This multi-panel figure summarizes baseline patient characteristics, intraoperative hemodynamic differences between normal and dysfunctional graft groups, and transit-time flow measurement parameters. Increased MAP variability, prolonged hypotensive episodes, and unfavorable graft flow characteristics were observed among patients with early graft dysfunction. Correlation and multivariable regression analyses demonstrate that greater intraoperative hemodynamic instability was independently associated with impaired early graft performance.

DISCUSSION

The present study evaluated the relationship between intraoperative micro-hemodynamic fluctuations and early graft function following coronary artery bypass grafting (CABG). The main finding was that greater minute-to-minute variability in mean arterial pressure (MAP), increased

frequency of short hypotensive episodes, and longer duration of reduced perfusion pressure were associated with unfavorable graft flow characteristics after completion of bypass surgery. These findings suggest that intraoperative hemodynamic control may influence early graft performance beyond the traditional surgical factors such as conduit selection, anastomotic quality, and target vessel characteristics.

Previous research on CABG graft assessment has mainly focused on technical evaluation of the completed graft. Transit-time flow measurement (TTFM) has become an important intraoperative tool because it provides immediate information regarding graft flow, pulsatility, and waveform characteristics. Studies by Leong et al. and other investigators demonstrated that abnormal intraoperative flow patterns can identify technically inadequate grafts and allow correction before completion of surgery (Leong et al., 2005; Kieser et al., 2005). However, most previous studies have evaluated graft function at a single time point. The current study extends this concept by examining the continuous physiological environment experienced by the graft during the operation.

In this study, patients who developed early graft dysfunction demonstrated significantly higher MAP variability compared with patients with satisfactory graft function. This observation highlights the potential importance of small but repeated hemodynamic disturbances that may not fulfil conventional definitions of severe hypotension. During CABG, newly implanted grafts are exposed to changing pressure gradients, altered vascular resistance, and fluctuations in myocardial demand. Although these changes are usually tolerated, repeated disturbances may influence endothelial function and early graft adaptation.

The association between intraoperative blood pressure instability and postoperative organ injury has been increasingly recognized in cardiac and non-cardiac surgery. Previous studies have shown that prolonged intraoperative hypotension is associated with myocardial injury, renal dysfunction, and adverse postoperative outcomes (Salmasi et al., 2017; Sessler et al., 2019). However, these studies mainly examined absolute blood pressure thresholds rather than dynamic variability. The present findings suggest that variability itself may represent an additional physiological stress marker. A patient may maintain an acceptable average MAP while still experiencing multiple episodes of reduced perfusion pressure, which could potentially affect newly constructed coronary grafts.

The observed relationship between MAP variability and pulsatility index provides further support for the influence of intraoperative hemodynamics on graft performance. Pulsatility index reflects resistance to flow within the graft system and is commonly used during TTFM interpretation. Previous studies have shown that elevated pulsatility index and reduced mean graft flow are associated with a higher likelihood of graft abnormalities and potential early failure (Jokinen et al., 2011; Niclauss, 2017). In the present analysis, patients with greater hemodynamic instability showed higher pulsatility index values and lower mean graft flow, suggesting that unstable perfusion conditions may contribute to impaired early graft function.

The mechanisms behind this association are likely multifactorial. Immediately after CABG, the graft endothelium undergoes adaptation to a new flow environment. Arterial grafts and venous grafts experience changes in pressure, shear stress, and vascular tone after implantation. Sudden reductions in perfusion pressure may decrease graft flow, promote transient endothelial dysfunction, and increase susceptibility to low-flow states. In addition, repeated administration of vasoactive medications to correct pressure fluctuations may produce rapid changes in vascular resistance, further influencing graft flow patterns.

The study findings also support the growing importance of continuous physiological monitoring in cardiac surgery. Conventional intraoperative decision-making often depends on intermittent measurements and clinical judgment. However, modern monitoring systems allow high-frequency data collection, making it possible to identify patterns that may previously have remained unnoticed. Recent investigations have emphasized the clinical value of TTFM and advanced intraoperative monitoring approaches for improving graft quality assessment and reducing preventable technical complications. Combining continuous hemodynamic analysis with graft flow evaluation may provide a more comprehensive assessment of graft performance.

The regression analysis in this study showed that MAP variability remained independently associated with early graft dysfunction after adjustment for common clinical and operative variables. Traditional risk factors such as diabetes, number of grafts, and cardiopulmonary bypass duration have previously been associated with postoperative complications and graft outcomes. However, the independent contribution of intraoperative physiological instability suggests that potentially modifiable intraoperative factors may also influence early graft success.

These findings may have practical implications for cardiac anesthesia and surgical management. Maintaining stable perfusion pressure throughout the operation, avoiding unnecessary

fluctuations, and identifying patients with significant hemodynamic variability may represent additional strategies to improve early graft outcomes. Rather than focusing only on episodes of severe hypotension, attention toward cumulative pressure variability may provide a more sensitive approach for identifying patients at risk.

The study should also be interpreted considering several limitations. First, as an observational cohort study, it demonstrates association rather than direct causation between hemodynamic variability and graft dysfunction. Second, although continuous arterial pressure data provide detailed physiological information, other factors such as graft quality, coronary target characteristics, competitive flow, and surgical technique may influence graft measurements. Third, early graft function was assessed using intraoperative flow parameters, and longer-term angiographic follow-up would be required to determine whether these findings translate into improved long-term graft patency.

Despite these limitations, this study provides a clinically relevant perspective by linking continuous intraoperative physiology with early graft performance. The findings suggest that micro-hemodynamic fluctuations may represent an underrecognized factor affecting early CABG outcomes. Future prospective multicenter studies incorporating continuous hemodynamic monitoring, advanced graft imaging, and long-term follow-up are required to validate these observations.

In conclusion, this study highlights that small, repeated intraoperative hemodynamic variations may have measurable effects on early graft function after CABG. Integration of continuous hemodynamic analysis with established graft assessment techniques may improve intraoperative decision-making and contribute toward better surgical outcomes.

CONCLUSION

This prospective observational study highlights the possible role of intraoperative micro-hemodynamic fluctuations in influencing early graft performance after coronary artery bypass grafting. The findings suggest that not only major episodes of hypotension, but also frequent small variations in arterial pressure during surgery may affect immediate graft flow characteristics.

Patients showing greater variability in mean arterial pressure, increased frequency of short-duration pressure reductions, and longer exposure to reduced perfusion periods demonstrated less favorable graft flow parameters on intraoperative assessment. These observations indicate that

maintaining a stable hemodynamic environment during CABG may be an important factor in supporting early graft function.

Although surgical technique, conduit selection, and target vessel quality remain major determinants of graft success, continuous monitoring of intraoperative physiological changes may provide additional information regarding patients at increased risk of early graft dysfunction. Integration of high-resolution hemodynamic analysis with established graft verification methods such as transit-time flow measurement may improve intraoperative decision-making and allow earlier identification of potentially compromised grafts.

The findings of this study provide a basis for further investigation into individualized hemodynamic management during CABG. Future multicenter studies with larger patient populations and long-term angiographic follow-up are required to confirm whether controlling micro-hemodynamic variability can translate into improved graft durability and better clinical outcomes.

In conclusion, careful attention to continuous intraoperative blood pressure patterns may represent an important component of modern CABG quality improvement strategies. Understanding the interaction between surgical factors and real-time physiological changes may help optimize graft performance and enhance early outcomes following coronary revascularization.

REFERENCES

D'Ancona, G., Karamanoukian, H. L., Ricci, M., Bergsland, J., & Salerno, T. A. (2000). Graft patency verification in coronary artery bypass grafting: Principles and clinical applications of transit time flow measurement. *Angiology, 51*(9), 725–731. https://doi.org/10.1177/000331970005100904

Leong, D. K. H., Ashok, V., Arulkumaran, N., Shan, Y. H., & Sim, E. K. W. (2005). Transit-time flow measurement is essential in coronary artery bypass grafting. *The Annals of Thoracic Surgery, 79*(3), 854–857. https://doi.org/10.1016/j.athoracsur.2004.06.010

Kieser, T. M., Rose, S., Kowalewski, R., & Belenkie, I. (2005). Transit-time flow measurement in coronary artery bypass grafting: Graft patency and clinical outcomes. *The Journal of Thoracic and Cardiovascular Surgery, 130*(2), 315–320. https://doi.org/10.1016/j.jtcvs.2004.11.033

Walker, P. F., Daniel, W. T., Moss, E., Thourani, V. H., Kilgo, P., Guyton, R. A., Puskas, J. D., & Halkos, M. E. (2013). The accuracy of transit time flow measurement in predicting graft patency after coronary artery bypass grafting. *Innovations: Technology and Techniques in Cardiothoracic and Vascular Surgery, 8*(6), 386–390. https://doi.org/10.1097/IMI.0000000000000021

Niclauss, L. (2017). Techniques and standards in intraoperative graft verification by transit time flow measurement after coronary artery bypass graft surgery: A critical review. *European Journal of Cardio-Thoracic Surgery, 51*(1), 26–33. https://doi.org/10.1093/ejcts/ezw203

Quin, J. A., Noubani, M., Rove, J. Y., Almassi, G. H., & Shroyer, A. L. W. (2021). Coronary artery bypass grafting transit time flow measurement: Graft patency and clinical outcomes. *The Annals of Thoracic Surgery, 112*(5), 1615–1623. https://doi.org/10.1016/j.athoracsur.2020.12.011

Zeng, C., Li, X., Dai, Y., Zhou, Y., Li, C., Liu, N., & Wang, J. (2021). Transit time flow measurement predicts graft patency in off-pump coronary artery bypass grafting upon 5-year angiographic follow-up. *Journal of Cardiothoracic Surgery, 16*, 334. https://doi.org/10.1186/s13019-021-01716-3

Takami, Y., Ina, H., & Shimizu, T. (2007). Relation of waveform of transit-time flow measurement and graft patency in coronary artery bypass grafting. *The Journal of Thoracic and Cardiovascular Surgery, 134*(3), 789–791. https://doi.org/10.1016/j.jtcvs.2007.04.054

Mohr, F. W., Morice, M. C., Kappetein, A. P., Feldman, T. E., Ståhle, E., Colombo, A., et al. (2013). Coronary artery bypass graft surgery compared with percutaneous coronary intervention in patients with three-vessel disease and left main coronary disease: 5-year follow-up of the SYNTAX trial. *The Lancet, 381*(9867), 629–638. https://doi.org/10.1016/S0140-6736(13)60141-5

Farkouh, M. E., Domanski, M., Sleeper, L. A., Siami, F. S., Dangas, G., Mack, M., et al. (2012). Strategies for multivessel revascularization in patients with diabetes. *New England Journal of Medicine, 367*, 2375–2384. https://doi.org/10.1056/NEJMoa1211582

Gaudino, M., Benedetto, U., Fremes, S., Biondi-Zoccai, G., Sedrakyan, A., Puskas, J. D., et al. (2018). Radial-artery or saphenous-vein grafts in coronary-artery bypass surgery. *New England Journal of Medicine, 378*, 2069–2077. https://doi.org/10.1056/NEJMoa1716026

Head, S. J., Milojevic, M., Daemen, J., Ahn, J. M., Boersma, E., Christiansen, E. H., et al. (2018). Mortality after coronary artery bypass grafting versus percutaneous coronary intervention with stenting for coronary artery disease: A pooled analysis. *The Lancet, 391*(10124), 939–948. https://doi.org/10.1016/S0140-6736(18)30423-9

Lawton, J. S., Tamis-Holland, J. E., Bangalore, S., Bates, E. R., Beckie, T. M., Bischoff, J. M., et al. (2022). 2021 ACC/AHA/SCAI guideline for coronary artery revascularization. *Circulation, 145*(3), e18–e114. https://doi.org/10.1161/CIR.0000000000001038

Neumann, F. J., Sousa-Uva, M., Ahlsson, A., Alfonso, F., Banning, A. P., Benedetto, U., et al. (2019). 2018 ESC/EACTS guidelines on myocardial revascularization. *European Heart Journal, 40*(2), 87–165. https://doi.org/10.1093/eurheartj/ehy394

Puskas, J. D., Williams, W. H., Duke, P. G., Staples, J. R., Glas, K. E., Marshall, J. J., et al. (2003). Off-pump coronary artery bypass grafting provides complete revascularization with reduced myocardial injury. *The Journal of Thoracic and Cardiovascular Surgery, 125*(4), 797–808. https://doi.org/10.1067/mtc.2003.274

Diegeler, A., Börgermann, J., Kappert, U., Breuer, M., Böning, A., Ursulescu, A., et al. (2013). Off-pump versus on-pump coronary-artery bypass grafting in elderly patients. *New England Journal of Medicine, 368*, 1189–1198. https://doi.org/10.1056/NEJMoa1211666

Ranucci, M., Johnson, I., Willcox, T., Mignosa, C., Bouchard, D., & Nigro, J. J. (2012). Goal-directed perfusion to reduce acute kidney injury: A randomized trial. *The Journal of Thoracic and Cardiovascular Surgery, 143*(3), 654–662. https://doi.org/10.1016/j.jtcvs.2011.09.045

Salmasi, V., Maheshwari, K., Yang, D., Mascha, E. J., Singh, A., Sessler, D. I., & Kurz, A. (2017). Relationship between intraoperative hypotension and hypertension with postoperative myocardial injury. *Anesthesiology, 126*(1), 47–65. https://doi.org/10.1097/ALN.0000000000001430

Walsh, M., Devereaux, P. J., Garg, A. X., Kurz, A., Turan, A., Rodseth, R. N., et al. (2013). Relationship between intraoperative mean arterial pressure and clinical outcomes after noncardiac surgery. *Anesthesiology, 119*(3), 507–515. https://doi.org/10.1097/ALN.0b013e31829aaf3a

Sessler, D. I., Meyhoff, C. S., Zimmerman, N. M., Mao, G., Leslie, K., Vasquez, M. P., et al. (2019). Period-dependent associations between hypotension during and for four days after noncardiac surgery and a composite of myocardial infarction and death. *Anesthesiology, 130*(5), 731–744. https://doi.org/10.1097/ALN.0000000000002622

Chen, X., Li, X., Zhang, Y., & Wang, J. (2020). Intraoperative hemodynamic instability and postoperative outcomes after cardiac surgery: Current perspectives. *Journal of Cardiothoracic and Vascular Anesthesia, 34*(8), 2146–2155. https://doi.org/10.1053/j.jvca.2020.02.034

Sabik, J. F., Blackstone, E. H., Gillinov, A. M., Houghtaling, P. L., Smedira, N. G., & Lytle, B. W. (2005). Occurrence and risk factors for reintervention after coronary artery bypass grafting. *Circulation, 112*(9 Suppl), I454–I460. https://doi.org/10.1161/CIRCULATIONAHA.104.526350

Fitzgibbon, G. M., Kafka, H. P., Leach, A. J., Keon, W. J., Hooper, G. D., & Burton, J. R. (1996). Coronary bypass graft fate and patient outcome: Angiographic follow-up of 5,065 grafts. *Circulation, 93*(8), 1538–1545. https://doi.org/10.1161/01.CIR.93.8.1538

Harskamp, R. E., Lopes, R. D., Baisden, C. E., de Winter, R. J., & Alexander, J. H. (2013). Saphenous vein graft failure after coronary artery bypass surgery. *Annals of Surgery, 257*(5), 824–833. https://doi.org/10.1097/SLA.0b013e31827e7f6d

Taggart, D. P., D'Amico, R., & Altman, D. G. (2005). Effect of arterial revascularisation on survival: A systematic review of studies comparing bilateral and single internal mammary

arteries. *The Lancet, 366*(9482), 1882–1889. https://doi.org/10.1016/S0140-6736(05)67663-3