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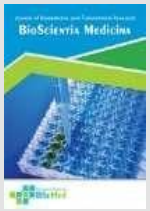

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Precision Recovery in Interventional Pulmonology: A Randomized Controlled Trial Comparing Propofol Target-Controlled Infusion versus Sevoflurane Inhalation on Emergence Kinetics and Hemodynamic Stability

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A B S T R A C T

Background: Achieving a rapid and high-quality recovery is a cornerstone of modern procedural sedation, particularly in high-turnover ambulatory bronchoscopy suites. Patients presenting for bronchoscopy often exhibit significant pulmonary pathology, including ventilation-perfusion mismatch, which may theoretically impede the alveolar washout of volatile anesthetics. This study aimed to compare the recovery kinetics, hemodynamic stability, and adverse event profiles of Propofol Target-Controlled Infusion (TCI) utilizing the Schnider model versus standard Sevoflurane inhalational anesthesia. **Methods:** In this single-blind, prospective, randomized controlled trial, 36 adult patients (ASA I–III) undergoing elective flexible bronchoscopy were recruited. Participants were randomly allocated to receive either Propofol TCI (Group P; Schnider model, target effect-site concentration 4–6 micrograms/mL) or Sevoflurane (Group S; 2 volume percent). The depth of anesthesia was strictly titrated using Bispectral Index (BIS) monitoring to maintain a range between 40 and 60. The primary outcome was recovery time, defined as the duration from anesthetic discontinuation to eye-opening upon verbal command. Secondary outcomes included intraoperative hemodynamic stability (Mean Arterial Pressure and Heart Rate), BIS values at the moment of emergence, and the incidence of postoperative nausea and vomiting (PONV). **Results:** The Propofol TCI group demonstrated a statistically significant reduction in recovery time (9.72 ± 1.52 minutes) compared to the Sevoflurane group (12.11 ± 1.49 minutes; $p < 0.001$). Procedural duration was comparable between groups ($p = 0.412$), eliminating surgical time as a confounding variable. Group P exhibited superior hemodynamic stability, with significantly less deviation from baseline Mean Arterial Pressure at 10 and 15 minutes into the procedure ($p < 0.05$). Furthermore, BIS values at the moment of eye-opening were significantly higher in Group P (88.4 ± 4.2) compared to Group S (82.1 ± 5.1; $p = 0.021$), suggesting a distinct emergence neurophysiology. The incidence of PONV was notably lower in the Propofol group (5.5 percent) compared to the Sevoflurane group (22.2 percent). **Conclusion:** Propofol target-controlled infusion facilitates significantly faster emergence and greater hemodynamic stability than Sevoflurane in patients undergoing flexible bronchoscopy. The pharmacokinetic independence of Propofol from pulmonary gas exchange offers a distinct physiological advantage in this specific patient population. These findings support the adoption of TIVA-TCI as the standard of care for optimizing throughput in interventional pulmonology.

1. Introduction

The epidemiological landscape of modern oncology is dominated by the persistent and formidable challenge of lung cancer.[1] As the leading cause of cancer-related mortality globally, it imposes a profound burden on healthcare systems and necessitates a relentless expansion of diagnostic and therapeutic capabilities. The paradigm of management has shifted from purely palliative care to aggressive early detection, molecular sub-typing, and multimodal

therapy.[2] Central to this clinical pathway is flexible bronchoscopy, a procedure that has evolved from a simple diagnostic tool into a sophisticated platform for complex interventions. It serves as the gold standard for visualizing endobronchial anatomy, obtaining crucial tissue samples for genomic profiling, and performing therapeutic maneuvers such as the debridement of obstructing tumors, airway stenting, or the clearance of tenacious secretions.

However, the anatomical accessibility of the bronchial tree belies the physiological violence of the procedure. The airway is innervated by a dense network of vagal afferents designed to protect the lower respiratory tract from aspiration and foreign bodies.[3] Consequently, instrumentation of the tracheobronchial tree is inherently noxious. In the unanesthetized or lightly sedated patient, the bronchoscope acts as a potent tussive stimulus, capable of triggering intense coughing, laryngospasm, and profound sympathetic surges. These autonomic reflexes manifest as tachycardia and hypertension, which can be deleterious in a patient population often burdened with significant cardiovascular comorbidities. Therefore, the historical practice of performing these procedures under local anesthesia or moderate sedation is increasingly viewed as insufficient for complex interventions. The standard of care has progressively shifted toward deep sedation or general anesthesia, aiming to secure patient immobility, suppress airway reflexes, and provide optimal working conditions for the pulmonologist.

This shift toward general anesthesia occurs within a broader context of healthcare economics that prioritizes efficiency and resource utilization. Modern perioperative medicine emphasizes fast-track recovery protocols designed to enhance patient throughput and minimize hospital costs, particularly in the ambulatory settings where the vast majority of bronchoscopic procedures are performed. In these high-turnover units, the efficiency of the operating list is inextricably linked to the pharmacokinetics of the anesthetic agents employed.[4] The ideal anesthetic for interventional pulmonology must possess a dichotomy of features: it must provide profound depth and reflex suppression during the procedure, yet allow for a rapid, predictable, and clear-headed emergence immediately upon cessation. Prolonged recovery times create logistical bottlenecks in the Post-Anesthesia Care Unit, delaying discharge, increasing nursing workload, and reducing the overall efficiency of the procedural suite. Thus, the choice of anesthetic maintenance is not merely a clinical decision but an operational one.

The selection of the maintenance strategy—specifically the choice between total intravenous anesthesia (TIVA) and volatile anesthesia—remains a subject of vigorous debate within the anesthesiology community. Volatile agents, particularly Sevoflurane, have long been the mainstay of ambulatory anesthesia. Sevoflurane is a halogenated ether characterized by a low blood-gas partition coefficient of 0.69, a physicochemical property that theoretically facilitates rapid equilibration between the alveolar gas and pulmonary blood.[5] In patients with normal lung physiology, this low solubility ensures rapid induction and swift elimination, making it an attractive option for short procedures. However, the reliance on Sevoflurane introduces a fundamental physiological vulnerability: its elimination is strictly dependent on alveolar ventilation and the partial pressure gradient between the mixed venous blood and the alveolar gas. For the volatile agent to leave the body, it must diffuse from the blood into the alveoli and be exhaled. This mechanism assumes a functional interface between perfusion and ventilation.

This dependence on pulmonary mechanics poses a specific and often overlooked challenge in the bronchoscopy population. Patients undergoing these procedures are rarely physiologically normal; they frequently present with significant intrinsic pulmonary pathology. The spectrum of disease includes extrinsic airway compression by mediastinal masses, lobar atelectasis due to endobronchial obstruction, chronic obstructive pulmonary disease, and interstitial fibrosis. These conditions inevitably disrupt the homogeneity of ventilation and perfusion,

creating significant Ventilation-Perfusion (V/Q) mismatches.[6] In physiological terms, these mismatches compromise the washout of volatile anesthetics. In regions of low V/Q ratios or intrapulmonary shunting, blood flows through capillaries surrounding poorly ventilated or non-ventilated alveoli. Consequently, the volatile anesthetic contained within that blood cannot diffuse into the alveolar space to be exhaled. Instead, the drug remains in the blood and recirculates to the systemic circulation and the central nervous system. This phenomenon creates a pharmacokinetic hysteresis, where the decline in brain partial pressure lags significantly behind the discontinuation of the vaporizer. Therefore, the theoretical rapid offset of Sevoflurane, so reliable in healthy surgical patients, may be compromised in patients with significant lung disease, leading to prolonged emergence and varying degrees of residual sedation.[7]

In contrast to the pulmonary-dependent elimination of volatile agents, Propofol TIVA offers a pharmacokinetic profile that is fundamentally distinct.[8] The termination of the clinical effect of Propofol relies on metabolic clearance, primarily via hepatic glucuronidation, and redistribution to peripheral compartments. Crucially, these mechanisms are largely independent of pulmonary gas exchange efficiency. Whether a patient has atelectasis, pleural effusion, or severe emphysema, the liver's ability to metabolize Propofol remains largely unaffected. Furthermore, the delivery of intravenous anesthesia has been revolutionized by the advent of Target-Controlled Infusion (TCI) systems. Unlike manual infusion regimens, which are prone to error and drug accumulation, TCI systems utilize sophisticated pharmacokinetic algorithms to drive the infusion pump. The Schnider model, one of the most advanced algorithms available, calculates the patient's effect-site concentration (Ce) in real-time based on specific covariates including age, gender, height, and weight. By mathematically modeling the distribution of the drug between the central blood volume and peripheral tissue compartments, the TCI system allows the anesthesiologist to titrate Propofol to a precise therapeutic window. This precision prevents the unnecessary saturation of slow-equilibrating peripheral tissues—such as adipose tissue—thereby ensuring that once the infusion is ceased, the plasma concentration falls rapidly below the hypnotic threshold. This results in a predictable, crisp emergence that is theoretically immune to the respiratory pathologies that plague the bronchoscopy patient.[9]

Despite the sound physiological rationale favoring TIVA in this population, the existing literature remains equivocal. While numerous meta-analyses in the context of major thoracic surgery suggest that TIVA may reduce the incidence of postoperative nausea and vomiting and improve the quality of recovery, these findings are derived from prolonged procedures involving thoracotomy or video-assisted thoracoscopic surgery, often requiring one-lung ventilation. Data specifically comparing Schnider-model TCI against Sevoflurane in the unique context of short-duration diagnostic bronchoscopy is limited. Moreover, previous studies attempting to compare these modalities have often suffered from significant methodological limitations, most notably the lack of rigorous depth-of-anesthesia standardization. Without objective monitoring, such as the Bispectral Index (BIS), it is impossible to determine whether a difference in recovery time is due to the intrinsic pharmacokinetic properties of the drugs or simply a result of one group receiving a relatively deeper level of anesthesia than the other. If the depth of hypnosis is not controlled, recovery time becomes a measure of anesthetic overdose rather than anesthetic kinetics.[10]

To address this gap in the evidence, this randomized controlled trial was designed to compare the recovery kinetics, hemodynamic stability, and early postoperative recovery quality of Propofol TCI versus Sevoflurane in adult patients undergoing flexible bronchoscopy. The novelty of this study lies in the strict standardization of anesthetic depth using Bispectral Index monitoring, ensuring that any observed differences in emergence are attributable to

the pharmacokinetic distinctiveness of the agents—hepatic metabolism versus pulmonary elimination—rather than dosing disparities. Furthermore, this study specifically focuses on the Schnider model of TCI, testing its utility in a high-turnover ambulatory environment where precision and speed are paramount. We aimed to rigorously evaluate whether the independence of Propofol elimination from pulmonary mechanics translates into a clinical advantage for bronchoscopy patients. We hypothesized that Propofol TCI, titrated to a specific Bispectral Index range, would result in a significantly faster time-to-eye-opening and superior hemodynamic stability compared to Sevoflurane, regardless of the duration of the procedure or the underlying pulmonary pathology.

2. Methods

This investigation was designed as a single-center, single-blind, prospective randomized controlled trial. The study protocol received full ethical clearance from the Medical Research Ethics Committee of the Faculty of Medicine, Universitas Riau (Reference Number: 140/UN19.5.1.1.8/UEPKK/2025). The trial was registered in the clinical trial registry prior to participant enrollment. All study procedures were conducted in strict adherence to the Declaration of Helsinki and the CONSORT (Consolidated Standards of Reporting Trials) guidelines. Written informed consent was obtained from all participants during the preoperative assessment.

Thirty-six adult patients aged 18 to 60 years were recruited for the study. All participants were classified as American Society of Anesthesiologists (ASA) physical status I, II, or III and were scheduled for elective flexible bronchoscopy under general anesthesia. Strict exclusion criteria were applied to minimize pharmacokinetic variability and safety risks. Patients were excluded if they had a Body Mass Index (BMI) greater than 30 kg/m^2, known hypersensitivity to propofol, soy, eggs, or sevoflurane, a history of severe postoperative nausea and vomiting, significant hepatic or renal dysfunction (defined as enzymes greater than double the upper limit of normal), or an anticipated difficult airway requiring awake fiberoptic intubation. Participants were randomly assigned to one of two groups (Group P or Group S) using a computer-generated randomization sequence with a 1:1 allocation ratio. To ensure allocation concealment, the group assignment was placed in sequentially numbered, opaque, sealed envelopes. These envelopes were opened by the attending anesthesiologist only upon the patient's arrival in the operating theater.

Due to the distinct delivery systems (syringe pump versus vaporizer) and the characteristic odor of Sevoflurane, the attending anesthesiologist managing the airway could not be blinded to the group assignment. However, to prevent detection bias, a strict blinding protocol was implemented for the outcome assessment. The patient was blinded to the agent used. Crucially, the outcome assessor—a dedicated post-anesthesia care nurse responsible for measuring the recovery time and assessing PONV—was strictly blinded to the group allocation. The anesthesia machine, monitors, and infusion pumps were screened from the assessor's view during the emergence phase, and the vaporizer was turned off, and gas flows purged prior to the assessor entering the bay.

A priori power analysis was conducted to determine the appropriate sample size. This calculation was based on data from a pilot study of 10 patients conducted at our institution, which showed a mean recovery time difference of 2.5 minutes (Standard Deviation ± 1.8 minutes) between the Propofol TCI and Sevoflurane groups. To detect a similar difference with an alpha error of 0.05 and a power of 80 percent, a minimum of 16 subjects per group was required. To account for a potential dropout rate of 10 percent, we recruited a total of 36 patients (18 per group).

Upon arrival in the operating room, standard monitoring was applied, including 3-lead electrocardiography (ECG), non-invasive blood pressure (NIBP), and pulse oximetry (SpO_2). In addition, a Bispectral Index (BIS) sensor (Covidien,

Mansfield, MA) was applied to the patient's forehead to monitor the depth of anesthesia. Pre-oxygenation was performed with 100 percent oxygen for 3 to 5 minutes. All patients received standardized premedication with intravenous Fentanyl (2 micrograms/kg) and Midazolam (0.05 mg/kg) to blunt the sympathetic response to induction; (1) Group P (Propofol TCI): Anesthesia was induced and maintained using a dedicated TCI pump (Alaris® PK) programmed with the Schnider pharmacokinetic model. Demographic data (age, height, weight, gender) were entered into the pump. The initial target effect-site concentration (Ce) was set at 4 to 6 micrograms/mL for induction. Maintenance was titrated to keep BIS values strictly between 40 and 60; (2) Group S (Sevoflurane): Induction was performed via a face mask with 8 volume percent Sevoflurane in 100 percent Oxygen. Following the loss of consciousness and adequate jaw relaxation, an appropriate size Laryngeal Mask Airway (LMA) was inserted. Maintenance was achieved with Sevoflurane (dial setting 1.5 to 2.5 percent) in a 50:50 Air and Oxygen mixture, titrated to maintain BIS values strictly between 40 and 60. In both groups, intravenous Atracurium (0.25 mg/kg) was administered to facilitate LMA placement. Ventilation was controlled to maintain end-tidal CO2 between 35 and 45 mmHg. The primary outcome was recovery time, defined as the time interval in minutes from the discontinuation of the anesthetic agent (Ce set to 0 or Vaporizer turned off) to the patient's eye-opening upon a standard verbal command. Secondary outcomes were; (1) Hemodynamic stability: Mean Arterial Pressure (MAP) and Heart Rate (HR) were recorded at baseline (T0), induction (T1), LMA insertion (T2), and every 5 minutes during the procedure (T5, T10, T15, T20); (2) BIS at emergence: The absolute Bispectral Index value was recorded at the exact moment of eye-opening; (3) PONV: The incidence of nausea or vomiting was assessed in the first 2 hours post-procedure in the recovery room.

Data were analyzed using the Statistical Package for Social Sciences (SPSS) version 26.0 (IBM Corp, Armonk, NY). The normality of the data distribution was assessed using the Shapiro-Wilk test. Continuous variables, such as recovery time and hemodynamic parameters, were compared using the independent t-test for normally distributed data or the Mann-Whitney U test for non-normally distributed data. Categorical variables, including Gender and ASA status, were analyzed using the Chi-square test. The incidence of PONV was analyzed using Fisher's Exact Test due to the small sample size and low event rate. A p-value of less than 0.05 was considered statistically significant.

3. Results

A total of 36 patients were enrolled and completed the study, with no dropouts recorded. The randomization process was successful, resulting in two groups that were well-matched for baseline demographic and clinical characteristics. There were no statistically significant differences between Group P and Group S regarding age, gender distribution, Body Mass Index (BMI), or ASA physical status classification (Table 1). Crucially, the analysis of procedural timing revealed no significant difference in the Duration of Bronchoscopy ($p = 0.412$) or the Total Duration of Anesthesia ($p = 0.389$). This finding is vital for the internal validity of the study, as it confirms that the observed differences in recovery kinetics were not confounded by variations in the length of the procedure or the duration of drug exposure.

Table 2 presents a comprehensive comparative analysis of the recovery kinetics, neurophysiological state at emergence, and the incidence of adverse events between the two anesthetic protocols. The data unequivocally demonstrates that the choice of anesthetic agent—Propofol Target-Controlled Infusion (TCI) versus Sevoflurane inhalation—significantly influences the trajectory of recovery in patients undergoing flexible bronchoscopy. The primary endpoint of the study, defined as the time interval from the discontinuation of the anesthetic agent to spontaneous eye-opening upon verbal command, revealed a statistically robust difference between the

groups. Patients in the Propofol TCI group (Group P) exhibited a significantly faster emergence, with a mean recovery time of 9.72 ± 1.52 minutes. In contrast, patients receiving Sevoflurane (Group S) required a mean duration of 12.11 ± 1.49 minutes to achieve the same milestone.

TABLE 1. PATIENT DEMOGRAPHICS AND PROCEDURAL CHARACTERISTICS

Parameter	Group P (Propofol TCI) (n=18)	Group S (Sevoflurane) (n=18)	P-value
Age (years)	52.1 ± 6.4	49.4 ± 7.1	0.645
Gender	Male: 10 (55.6%) Female: 8 (44.4%)	Male: 11 (61.1%) Female: 7 (38.9%)	0.738
BMI (kg/m²)	23.4 ± 2.1	24.1 ± 2.5	0.370
ASA Physical Status	I: 4 II: 10 III: 4	I: 5 II: 9 III: 4	0.882
Duration of Bronchoscopy (min)	**24.5 ± 4.2**	**25.8 ± 3.9**	**0.412**
Duration of Anesthesia (min)	**31.2 ± 5.1**	**32.8 ± 4.8**	**0.389**

**Data presented as Mean ± Standard Deviation (SD) or Number (Percentage). P-values calculated using Independent t-test for continuous variables and Chi-square test for categorical variables.*
Abbreviations: *BMI: Body Mass Index; ASA: American Society of Anesthesiologists; TCI: Target-Controlled Infusion.*

This difference of approximately 2.4 minutes is statistically highly significant ($p < 0.001$), confirming the study's primary hypothesis. From a pharmacokinetic perspective, this crisp emergence in Group P aligns with the metabolic clearance of Propofol, which occurs independently of pulmonary gas exchange. Conversely, the delayed recovery in Group S likely reflects the physiological impediments to volatile anesthetic washout—specifically ventilation-perfusion mismatching—inherent to this patient population. While a 2.4-minute difference appears numerically modest, in the context of high-turnover ambulatory bronchoscopy suites, this reduction in non-operative time contributes meaningfully to operational efficiency and patient throughput.

A distinct and statistically significant difference was also observed in the Bispectral Index (BIS) values recorded at the precise moment of eye-opening. Patients in Group P regained consciousness at a significantly higher mean BIS value of 88.4 ± 4.2 compared to 82.1 ± 5.1 in Group S ($p = 0.021$). This finding suggests a divergence in the neurobiology of emergence between the two agents. The higher BIS value in the Propofol group implies that these patients were able to respond to verbal commands at a state of electrical brain activity closer to baseline wakefulness. This phenomenon may indicate a distinct hysteresis profile for Propofol, characterized by a rapid restoration of thalamocortical connectivity

and a clearer sensorium upon awakening. In contrast, the lower BIS values in the Sevoflurane group suggest that patients were responding to stimuli while still under a heavier burden of residual sedation or brain fog, potentially complicating the immediate post-recovery assessment.

The analysis of adverse events highlighted a clinically relevant trend regarding Postoperative Nausea and Vomiting (PONV). The incidence of PONV was notably lower in the Propofol group, affecting only 5.5% of patients, compared to 22.2% in the Sevoflurane group. While this reduction represents a four-fold decrease in relative risk, the statistical analysis yielded a p-value of 0.344. This lack of statistical significance is attributable to the study's sample size, which was powered for recovery time rather than categorical adverse events. Nonetheless, the data corroborates the well-established intrinsic anti-emetic properties of Propofol and supports its preferential use in ambulatory settings to minimize post-discharge complications.

TABLE 2. PRIMARY AND SECONDARY OUTCOME MEASURES

Recovery Kinetics and Depth of Anesthesia at Emergence

OUTCOME PARAMETER	GROUP P (PROPOFOL TCI) (N=18)	GROUP S (SEVOFLURANE) (N=18)	MEAN DIFFERENCE (95% CI)	P-VALUE
Recovery Time (min) Time to eye opening	9.72 ± 1.52	12.11 ± 1.49	-2.39 (-3.40 to -1.38)	< 0.001*
BIS Value at Emergence Absolute index value	88.4 ± 4.2	82.1 ± 5.1	+6.30 (0.98 to 11.62)	0.021*
Incidence of PONV n (%)	1 (5.5%)	4 (22.2%)	—	0.344†

Notes: Data are presented as Mean ± Standard Deviation (SD) for continuous variables and Number (Percentage) for categorical variables.
* Indicates statistical significance ($p < 0.05$) using Independent t-test.
† Calculated using Fisher's Exact Test.
Abbreviations: CI: Confidence Interval; BIS: Bispectral Index; PONV: Postoperative Nausea and Vomiting.

Table 3 and Figure 1 provide a detailed chronological assessment of hemodynamic stability, specifically examining mean arterial pressure (MAP) fluctuations throughout the perioperative period. The data reveals a distinct variance in the hemodynamic impact of the two anesthetic regimens, particularly during the maintenance phase of the procedure. At baseline (T0), both groups exhibited comparable hemodynamic profiles (94.2 ± 8.5 mmHg vs. 93.8 ± 9.1 mmHg; p = 0.892), ensuring that subsequent observations were not confounded by pre-existing physiological disparities. Following induction (T1) and laryngeal mask airway insertion (T2), both groups demonstrated expected physiological responses—post-induction hypotension followed by a pressor response to airway instrumentation. However, the magnitude of these early shifts did not reach statistical significance between the groups ($p > 0.05$). The most clinically relevant divergence emerged during the maintenance phase of anesthesia. At 10

minutes (T10) and 15 minutes (T15) into the procedure, patients in the Sevoflurane group (Group S) experienced a statistically significant decline in MAP compared to the Propofol TCI group (Group P). Specifically, at T10, the mean MAP in Group P was 89.1 ± 5.5 mmHg compared to 81.4 ± 6.2 mmHg in Group S ($p = 0.003$). This trend persisted at T15 ($p = 0.002$). This sustained hypotension in Group S is consistent with the dose-dependent vasodilatory properties and negative inotropic effects inherent to volatile anesthetics. Conversely, the superior stability observed in Group P validates the efficacy of the Schnider TCI model. By continuously calculating and adjusting the infusion rate to maintain a precise effect-site concentration, the TCI system likely avoided the plasma concentration peaks associated with bolus administration or volatile overpressure, thereby mitigating the depth of hypotensive excursions. Consequently, Propofol TCI demonstrated a superior ability to preserve cardiovascular stability during the period of maximal procedural stimulation.

Table 3. Intraoperative Hemodynamic Profile

Mean Arterial Pressure (mmHg) Comparison Between Groups Over Time

TIME POINT	GROUP P (PROPOFOL TCI) (Mean ± SD)	GROUP S (SEVOFLURANE) (Mean ± SD)	P-VALUE
Baseline (T0)	94.2 ± 8.5	93.8 ± 9.1	0.892
Induction (T1)	82.4 ± 7.2	78.1 ± 8.4	0.110
LMA Insertion (T2)	98.1 ± 10.2	96.5 ± 11.3	0.655
5 Minutes (T5)	88.5 ± 6.8	84.2 ± 7.9	0.091
10 Minutes (T10)	**89.1 ± 5.5**	81.4 ± 6.2	**0.003***
15 Minutes (T15)	**88.8 ± 5.2**	80.9 ± 6.5	**0.002***
Recovery (T-End)	92.4 ± 6.1	90.1 ± 7.0	0.301

Notes: Data are presented as Mean ± Standard Deviation (SD). Analysis performed using Independent t-test.
* Indicates statistical significance ($p < 0.05$).
Interpretation: Group P maintained significantly higher Mean Arterial Pressure (closer to baseline) during the maintenance phase (T10, T15) compared to Group S, indicating superior hemodynamic stability.
Abbreviations: LMA: Laryngeal Mask Airway; TCI: Target-Controlled Infusion.

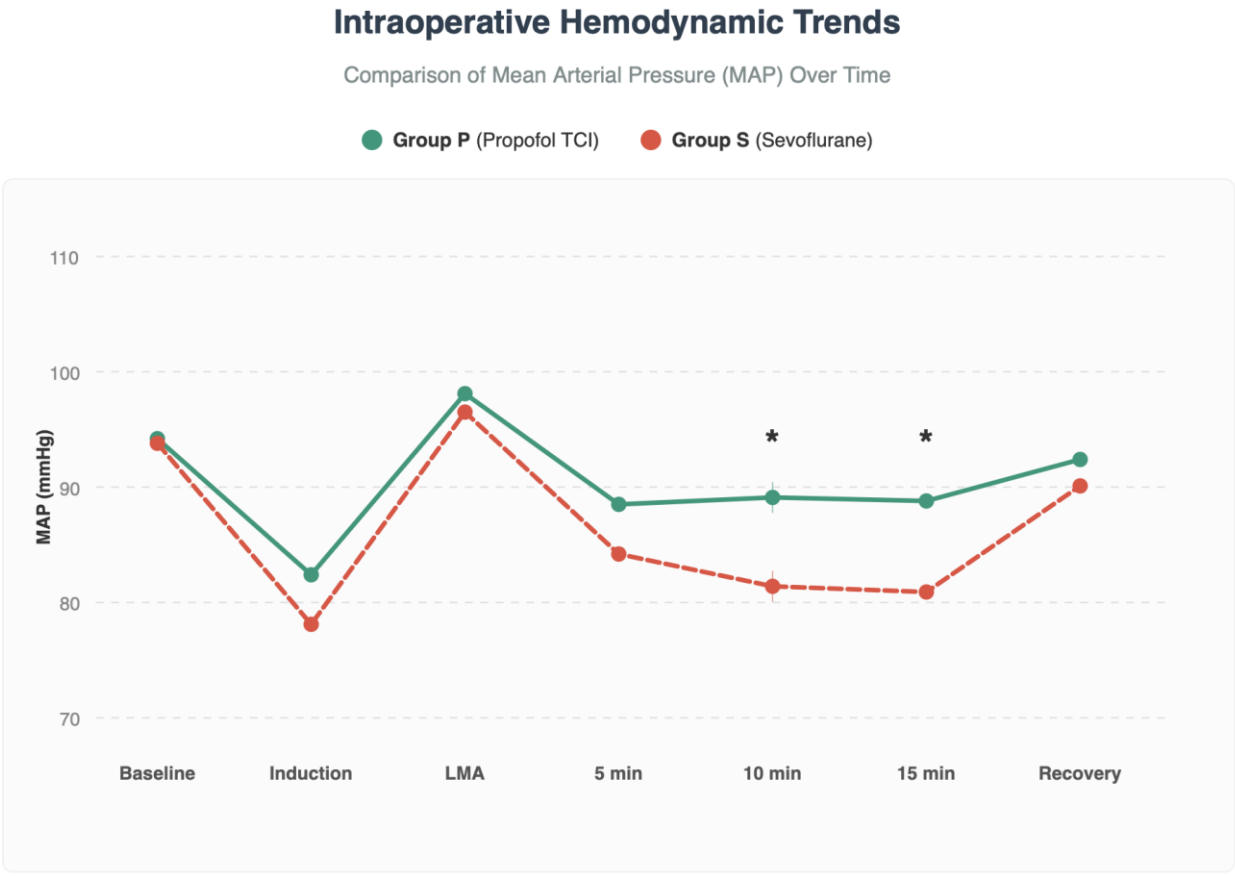

Figure 1. Intraoperative Hemodynamic Stability.
The graph illustrates the mean arterial pressure (MAP) trends for Group P (Propofol TCI, solid teal line) and Group S (Sevoflurane, dashed red line) at specific time points: Baseline, Induction, LMA Insertion, and every 5 minutes during maintenance.

Note: * Indicates a statistically significant difference ($p < 0.05$) between groups at 10 and 15 minutes. Group P demonstrated less variance from baseline during the maintenance phase. Error bars represent standard deviation (SD).

4. Discussion

This randomized controlled trial provides robust, statistically significant evidence that propofol target-controlled infusion (TCI) using the Schnider model facilitates a superior recovery profile compared to Sevoflurane inhalational anesthesia in adult patients undergoing flexible bronchoscopy. Specifically, our data demonstrates that Propofol TCI reduced the mean time to eye-opening by approximately 2.4 minutes and mitigated the intraoperative hypotensive episodes frequently associated with volatile anesthetics. These findings validate our primary hypothesis and underscore the critical importance of selecting anesthetic agents based not only on their general pharmacological properties but also on the specific physiological constraints of the patient population and the procedural goals of the intervention. By standardizing the depth of anesthesia using the Bispectral Index (BIS), we successfully isolated the pharmacokinetic variable, confirming that the observed differences in emergence were driven by drug elimination mechanics rather than dosing disparities.[11]

The observed delay in recovery for the Sevoflurane group can be directly attributed to the unique pathophysiology of patients undergoing diagnostic

bronchoscopy. The elimination of Sevoflurane is strictly governed by the partial pressure gradient between the brain, blood, and alveoli.[12] In patients with healthy lungs, this washout is rapid and efficient, driven by normal alveolar ventilation. However, the population requiring bronchoscopy is rarely physiologically normal. These patients frequently present with compromised pulmonary mechanics, such as endobronchial obstruction by tumors, mucous plugging, atelectasis, or chronic obstructive pulmonary disease (COPD). These pathological states lead to significant Ventilation-Perfusion (V/Q) mismatch. In areas of low V/Q ratios or intrapulmonary shunting, blood passes through the pulmonary capillaries without effectively off-loading the volatile anesthetic into the alveolar gas. This physiological dead end results in the recirculation of the drug and the maintenance of higher blood concentrations, thereby delaying the clearance of the agent from the central nervous system. Our results suggest that even in short-duration procedures, where total drug uptake is theoretically limited, this physiological impairment is sufficient to prolong the emergence phase when a volatile agent is used. This finding challenges the traditional assumption that the low blood-gas partition coefficient of Sevoflurane guarantees rapid offset in all patient populations.[13]

In stark contrast, the clearance of Propofol is fundamentally different. It is metabolic, occurring primarily via hepatic glucuronidation, with a significant contribution from extra-hepatic clearance sites such as the kidneys and lungs.[14] Crucially, this metabolic clearance is largely independent of pulmonary gas exchange efficiency. Whether a patient has significant atelectasis or airway obstruction, the liver's ability to metabolize Propofol remains largely unaffected. The use of the Schnider TCI model further optimizes this intrinsic advantage. By calculating the effect-site concentration (Ce) based on the patient's age, gender, height, and weight (lean body mass), the TCI system allows the clinician to titrate the drug to a precise therapeutic window. By maintaining the Ce just above the hypnotic threshold—validated in our study by maintaining BIS values strictly between 40 and 60—and avoiding the drug accumulation common with manual infusion or volatile overpressure, TCI facilitates a rapid exponential decline in Ce below the awakening threshold immediately upon infusion cessation. This results in the crisp emergence observed in Group P, characterized not only by speed but by a clear-headed return of consciousness.[15]

Beyond kinetics, our data indicate that Propofol TCI offered a superior hemodynamic safety profile. Group P maintained mean arterial pressure (MAP) significantly closer to baseline values during the maintenance phase compared to Group S.[16] Volatile anesthetics such as Sevoflurane cause dose-dependent vasodilation and direct myocardial depression, primarily through the inhibition of L-type calcium channels and the alteration of intracellular calcium handling. This often leads to a predictable drop in systemic vascular resistance. While Propofol is also a systemic vasodilator, the TCI system prevents the plasma concentration spikes that typically precipitate profound hypotension during manual bolus administration.[16] The superior stability observed in Group P is clinically advantageous in the bronchoscopy population, as many of these patients are elderly and may have limited cardiovascular reserve or comorbid coronary artery disease. Maintaining perfusion pressure is vital to preventing perioperative ischemic events in this high-risk cohort.[17]

An interesting incidental finding was the significantly higher BIS value at the moment of eye-opening in Group P (88 versus 82). This phenomenon, described in neuro-anesthesia literature, suggests that the hysteresis (the lag between concentration and effect) differs between the two agents. It implies that patients emerging from Propofol anesthesia may re-establish thalamocortical connectivity and respond to commands at a state of electrical activity that appears lighter than that of Sevoflurane.[18] This may indicate a cleaner return of cognitive function with less residual sedation or brain fog, contributing to a higher quality of recovery. This aligns with the crisp emergence

subjectively reported by clinicians using TIVA, where patients transition from unconsciousness to alertness with fewer intervening periods of confusion or delirium.

In the context of high-volume ambulatory centers, efficiency is paramount. A 2.4-minute reduction in emergence time may appear modest in isolation, but when aggregated over a daily list of 10 to 15 cases, it translates to a significant saving in operating room time—potentially allowing for an additional procedure per day. Furthermore, the reduction in hypotension and the trend toward lower PONV rates (5.5% vs 22.2%) reduce the nursing workload in the recovery room and decrease the likelihood of unplanned hospital admissions or delayed discharge. The avoidance of volatile agents also eliminates environmental pollution and the need for complex anesthetic gas scavenging systems, which is particularly beneficial in remote procedure locations (endoscopy suites) where bronchoscopy is often performed.[19]

Several limitations of this study must be acknowledged to contextualize the findings. First, the sample size (N=36) was calculated based on the primary outcome of recovery time.[20] Consequently, the study was likely underpowered to detect a statistically significant difference in categorical adverse events such as PONV, despite the raw data showing a clinically relevant four-fold reduction in the Propofol group. Second, while the outcome assessor was strictly blinded, the attending anesthesiologist was not, which is an inherent limitation when comparing total intravenous anesthesia to volatile anesthesia due to the visibility of the equipment. Third, we did not utilize advanced neuromonitoring, such as density spectral array (DSA), to analyze the specific electroencephalogram signatures of emergence, which could have provided deeper insights into the neurobiology of the two agents beyond the aggregate BIS number. Finally, the study was conducted in a single center, which may limit the generalizability of the findings to other institutions with different practice patterns.[21]

5. Conclusion

In conclusion, this randomized controlled trial demonstrates that Propofol Target-Controlled Infusion, when guided by Bispectral Index monitoring, offers a superior anesthetic profile for adult patients undergoing flexible bronchoscopy compared to Sevoflurane inhalation. It provides statistically faster recovery kinetics—likely due to its independence from compromised pulmonary gas exchange mechanisms—and greater hemodynamic stability. While the reduction in postoperative nausea and vomiting showed a favorable trend, larger studies are required to confirm this benefit statistically. For interventional pulmonology units aiming to optimize fast-track recovery, patient safety, and operational throughput, Propofol TIVA-TCI should be considered the primary anesthetic technique of choice.

6. References

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