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The effects of end-tidal controlled low-flow anesthesia on anesthetic agent consumption in elective surgeries: randomized controlled trial

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Abstract

Purpose The environmental impact and cost of volatile anesthetics are significant concerns in modern anesthesia. Automated end-tidal control systems aim to optimize anesthetic delivery by reducing waste and improving efficiency. This study compared the effectiveness of end-tidal controlled (EtControl) low-flow anesthesia to manually controlled (MC) low-flow anesthesia in elective surgeries.

Design A randomized controlled trial.

Methods This study was conducted with 132 ASA Class I–II patients undergoing elective surgeries under general anesthesia. Patients were randomly assigned to the EtControl ($n=66$) or MC ($n=66$) groups. The primary outcomes included anesthetic agent consumption (mL).

Findings Anesthetic consumption was similar between the EtControl group (17.9 ± 2.63 mL) and the MC group (18.45 ± 2.44 mL) ($p=0.07$). The rate of anesthetic consumption per minute was also comparable (0.120 mL/min vs. 0.127 mL/min; $p=0.514$).

Conclusions EtControl and MC methods provide comparable safety and sevoflurane consumption during low-flow anesthesia. However, EtControl reduces manual adjustments, enhancing workflow efficiency and cost-effectiveness, with potential implications for reducing environmental impact.

Keywords End-tidal controlled, Low flow anesthesia, Sevoflurane consumption

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Introduction

Volatile anesthetics are essential for general anesthesia but contribute to environmental pollution. Low-flow anesthesia, which reduces fresh gas consumption, is gaining popularity for its economic and environmental benefits. However, when manually controlled, it requires continuous monitoring and adjustments by the anesthesiologist, increasing workload and cognitive demand [1, 2]. The resulting increased workload for the anesthesiologist may therefore divert attention away from other important tasks. As a result, modern anesthesia machines equipped with closed-loop control systems have been developed. These machines allow the anesthesiologist to set target values for EtO_2 and EtAA based on patient needs. The anesthesia machine then monitors these parameters and automatically adjusts gas delivery and total flow to achieve the preset target values [3]. This new technology significantly reduces the cognitive workload for the anesthesiologist. End-tidal controlled (EtControl) anesthesia offers a promising solution by improving efficiency and minimizing waste while reducing the anesthesiologist's workload. However, its effectiveness, safety, and environmental impact compared to manual low-flow anesthesia remain areas of study [4].

This study aims to compare the effects of end-tidal controlled and manually controlled low-flow anesthesia on anesthetic agent consumption. We hypothesize that end-tidal control systems reduce anesthetic agent consumption.

Materials and methods

This study was conducted with the approval of the Local Ethics Committee (Date: 02.10.2019, No: 2019/355) and in compliance with the ethical principles outlined in the World Medical Association's Declaration of Helsinki for medical research involving human subjects (2013). The patients provided informed consent to participate in the study. The study was retrospectively registered in the ClinicalTrials.gov trial registry under the identifier NCT06735937 on December 11, 2024, and adheres to CONSORT guidelines. A total of 132 patients aged 18–73 years, classified as ASA Class I–II, and undergoing elective surgery under general anesthesia in the operating room of Gaziantep University Faculty of Medicine between 01/09/2019 and 31/08/2020 were included in the study. Patients with heart failure, lung disease, liver disease, or kidney disease were excluded. Demographic data, such as age, gender, and body mass index (BMI), were recorded.

The included patients were divided into two groups. Group E consisted of 66 patients who received end-tidal controlled low-flow anesthesia, while Group M included 66 patients whose low-flow anesthesia was manually adjusted.

All patients were taken to the operating room without premedication and preoxygenated with 100% oxygen at a flow rate of 10 L/min via a face mask for three minutes. Standard hemodynamic monitoring was performed using continuous pulse oximetry, electrocardiography, and noninvasive blood pressure measurements taken every three minutes. General anesthesia induction was initiated with intravenous administration of 2 mcg/kg fentanyl and 2 mg/kg propofol. Following administration of 0.6 mg/kg rocuronium, endotracheal intubation was performed, and volatile anesthetics were started after the patients were connected to a ventilator. An anesthesia machine equipped with an end-tidal control module and electronic vaporizer (Aisys®, GE-Healthcare, Chalfont St Giles/Buckinghamshire/UK) was used in this study. The anesthesia machine used in this study are factory-calibrated and undergo regular maintenance following manufacturer guidelines. Routine calibration checks are performed to ensure the accuracy of sevoflurane consumption measurements, minimizing potential discrepancies in gas delivery readings.

In Group M, the fresh gas flow was initially set to 4 L/min, and sevoflurane (4%) was delivered until the end-tidal gas mixture reached an age-adjusted 1 MAC (Minimum Alveolar Concentration) value. Once the target anesthetic concentration was reached, the fresh gas flow was reduced to 1 L/min. Maintaining at least 1 L/min fresh gas flow minimizes the risk of rebreathing unwanted gases and prevents potential hypoxic mixtures. Adjustments were made continuously to maintain the sevoflurane concentration at 1 MAC.

In Group E, the end-tidal control module was used to set the fresh gas flow to 1 L/min, targeting an age-adjusted 1 MAC concentration of sevoflurane in exhaled air. The end-tidal control system monitored expired O_2 and anesthetic agent concentrations, rapidly adjusting the fresh gas composition and delivery to minimize discrepancies between the measured and target values. All patients in both the EtControl and manually controlled groups received sevoflurane as the volatile anesthetic agent. No other inhaled anesthetics were used in this study, ensuring a consistent comparison between groups.

For both groups, volume-controlled ventilation was applied with a tidal volume of 7 mL/kg, a respiratory rate of 12/min, an end-tidal CO2 level of 35–45 mmHg, and an end-tidal oxygen concentration of 40%.

The amount of sevoflurane consumption (mL) measured by the anesthesia machine was recorded. The rate of sevoflurane consumption per unit time (mL/min) was also noted.

The allocation sequence was generated by an independent statistician using computer-based randomization software, assigning participants equally to groups in a 1:1 ratio. To prevent selection bias and maintain balance,

sealed, opaque, and sequentially numbered envelopes were used to implement the sequence. The anesthesiologists administering anesthesia were aware of the intervention group; however, the study coordinator, not the attending anesthesiologist, managed patient allocation to minimize bias.

Power analysis

A sample size of 66 patients per group was determined as the minimum required to detect a statistically significant difference of 0.36 ± 0.70 units in sevoflurane consumption between measurements ($\alpha = 0.05$, $1\text{-}\beta = 0.80$). The analysis was performed using G*Power 3.1.

Statistical methods

The Shapiro-Wilk test was used to assess the normality of numerical data. For variables following a normal distribution, Student's t-test was used to compare the two groups, while the Mann-Whitney U test was applied for non-normally distributed variables. For comparisons among three measurements, ANOVA was used for normally distributed variables, and the Kruskal-Wallis test for non-normal distributions. Relationships among categorical variables were assessed using the chi-square test, while correlations between numerical variables were tested using Pearson's correlation coefficient for normal distributions and Spearman's rank correlation coefficient for non-normal distributions. Analyses were performed using SPSS 22.0, with a significance level of $p < 0.05$.

Results

A total of 132 patients were enrolled in the study, with 66 assigned to Group 1 (end-tidal controlled) and 66 to Group 2 (manually controlled). The process of patient enrollment, randomization, and group allocation is depicted in the CONSORT diagram (Fig. 1).

The demographic data of the patients are presented in Table 1. The mean age and weight in Group M were 46.38 ± 11.53 years and 79.91 ± 14.46 kg, respectively, while in Group E, these values were 47.07 ± 13.36 years and 77.67 ± 17.19 kg. The average height was 162.79 ± 29.63 cm in Group M and 164.31 ± 21.2 cm in Group E. The BMI values were 28.07 ± 4.54 in Group M and 28.12 ± 6.08 in Group E. No statistically significant differences were observed between the groups regarding age, weight, height, or BMI ($p > 0.05$).

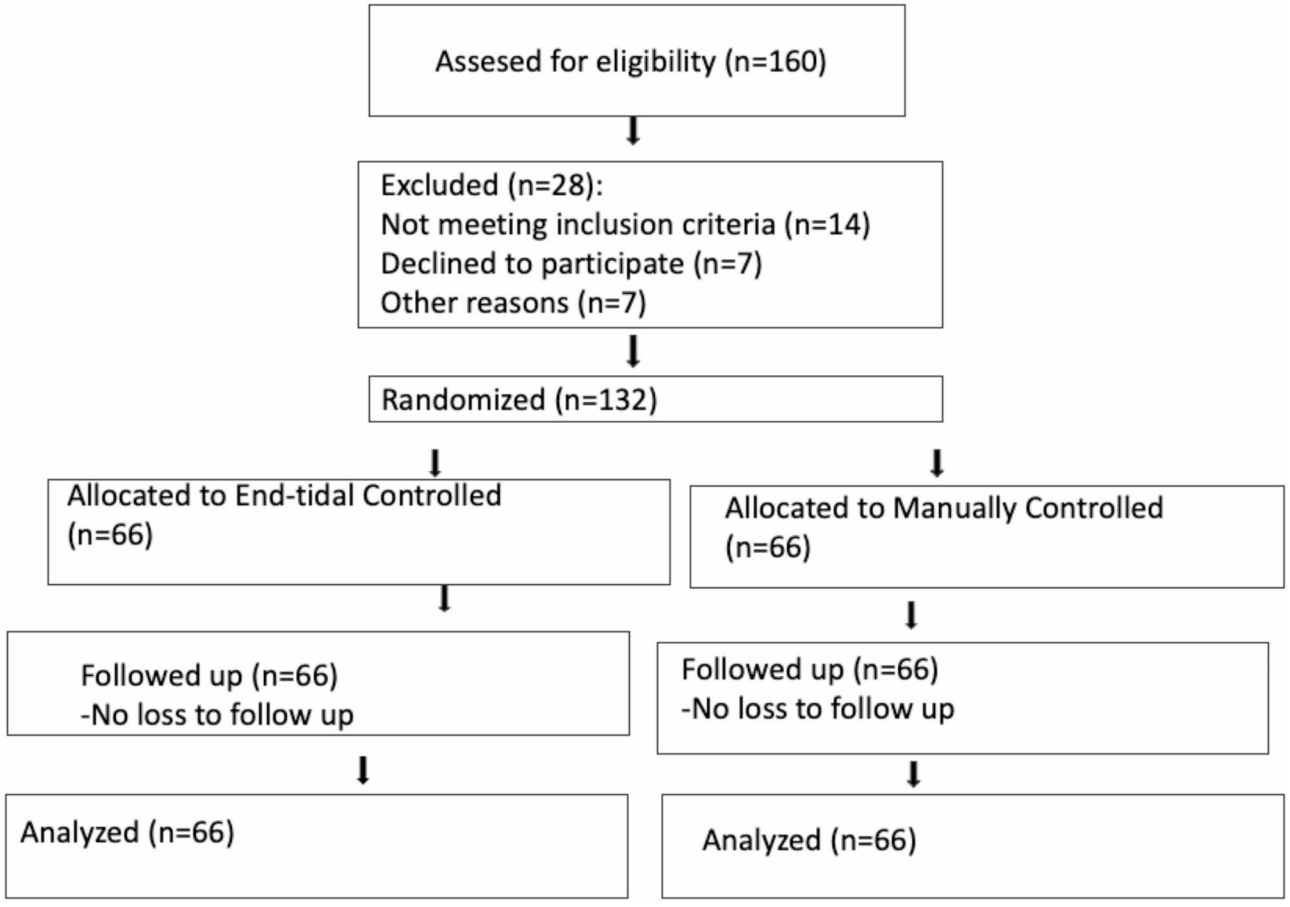

Fig. 1 Consort flow diagram of the study participating patients

Table 1 Demographic data of the groups

	Group M ($n=66$)	Group E ($n=66$)	*p*-value
Age (years)	46.38±11.53	47.07±13.36	0.75
Weight (kg)	79.91±14.46	77.67±17.19	0.23
Height (cm)	162.79±29.63	164.31±21.2	0.72
BMI (kg/m^2)	28.07±4.54	28.12±6.08	0.59

*Significant at $p<0.05$, BMI; Body mass index

Table 2 Anesthesia duration and anesthetic consumption of the groups

	Grup M ($n=66$)	Grup E ($n=66$)	*p* value
Anesthesia duration (min)	156.31±42.59	149.82±46.81	0.24
Anesthetic amount (mL)	18.45±2.44	17.9±2.63	0.07

*Significant at $p<0.05$

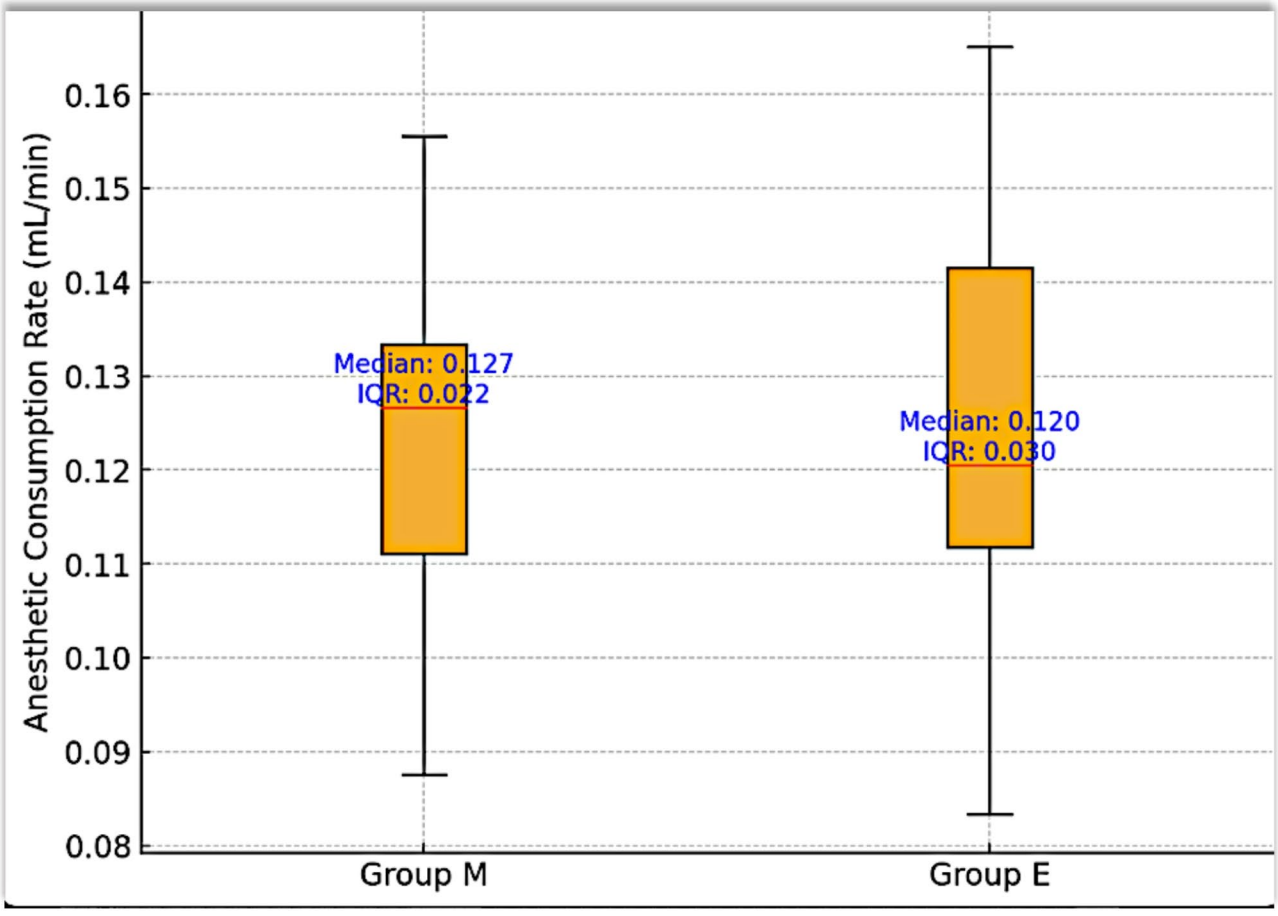

Fig. 2 Comparison of anesthetic consumption rates (mL/min)

The average anesthesia duration was 156.31 ± 42.59 min in Group M and 149.82 ± 46.81 min in Group E. No significant difference in anesthesia duration was observed between the groups ($p=0.24$)). As shown in Table 2, the amount of anesthetic consumed was 18.45 ± 2.44 mL in Group M and 17.9 ± 2.63 mL in Group E, which was not statistically significant ($p=0.07$).

As shown in Fig. 2, the average rate of anesthetic consumption per minute (mL/min) was 0.127 (IQR: 0.022) in Group M and 0.120 (IQR: 0.030) in Group E, which was not statistically significant ($p=0.514$).

No complications were observed in both groups.

Discussion

This study demonstrates that end-tidal and manual control methods for low-flow anesthesia administration are comparable in patients undergoing elective surgery. The literature strongly supports the use of low-flow anesthesia techniques instead of "conventional" anesthetic gas delivery, citing benefits ranging from cost savings to reduced global pollution. Although low-flow anesthesia carries potential risks, modern anesthesia machines equipped with advanced monitoring tools ensure the safe implementation of these techniques [5].

Automated ET control can eliminate inadvertent hypoxic gas mixture in the circle system as a result of using low fresh gas flow. is a very significant risk when low fresh gas flow is employed manually.

Recent advancements in anesthesia technology have prioritized reducing volatile anesthetic consumption due to both ecological and economic concerns. Automated anesthesia workstations, such as those using end-tidal control systems, enable precise delivery of anesthetic agents at optimal fresh gas flow rates, minimizing waste. Studies have consistently shown that such systems can provide stable end-tidal concentrations with less intervention from the anesthesiologist [5].

Wetz et al. [2] demonstrated in their study with 64 patients that using EtControl resulted in more stable sevoflurane and oxygen target concentrations. They emphasized that end-tidal controlled modes not only support reliable anesthesia maintenance but also alleviate the workload of anesthesiologists in high-demand settings. Similarly, Lucangelo et al. [3] showed that automated end-tidal control systems are as effective as manual methods in maintaining anesthesia. These systems allow anesthesiologists to focus more on patient care by reducing the frequency of manual adjustments required.

Singaravelu et al. [6] evaluated the clinical effectiveness and inhalation anesthetic consumption of EtControl in their study. They reported that EtControl reduced the costs associated with inhalation anesthetics, benefiting both healthcare economics and the ecosystem. In their study, they highlighted that the desired end-tidal volatile anesthetic concentrations were achieved in 321 patients with reduced volatile agent use through EtControl. Tay et al. [7] noted that the use of anesthesia machines equipped with automatic end-tidal gas control options reduces volatile anesthetic consumption, offering both financial and environmental benefits.

Skalec et al. [8] demonstrated that manual and automated controlled general anesthesia provided equally stable and safe anesthesia for patients. In their study involving 74 patients, they found that the consumption of anesthetic and oxygen significantly increased in the EtControl module group. However, similar to other studies, they reported a significant reduction in the number of anesthesiologist interventions with EtControl use.

Recent studies have explored the efficacy and environmental impact of automated versus manual control methods in low-flow anesthesia. A randomized controlled trial by Mostad et al. [9] compared desflurane consumption using automated vapor control systems in two different anesthesia machines, highlighting the potential for reduced anesthetic agent usage with automated systems. Similarly, Jamil et al. [10] found that sevoflurane consumption and its rate were significantly lower in the Automatic Gas Control (AGC™) mode compared to the manual mode in the Maquet Flow-I anesthesia machine during adult laparoscopic surgeries. These findings suggest that automated control systems can enhance anesthetic delivery efficiency, leading to economic and environmental benefits.

A study comparing target-controlled (TC) and manual-controlled (MC) anesthetic delivery systems in 200 patients undergoing laparoscopic surgeries found that TC significantly reduced sevoflurane consumption and the number of adjustments needed to maintain anesthesia depth. TC also achieved desired end-tidal sevoflurane levels faster and at lower maximum inspired concentrations. These efficiencies translated to a cost reduction and decreased environmental pollution. These findings support TC as an effective and eco-friendly anesthetic delivery system [11].

McCabe et al. [12] demonstrated that the End-tidal Control (EtC) system on the Aisys CS2 was noninferior to manual control (MC) in maintaining target end-tidal anesthetic agent (EtAA) and oxygen (EtO2) concentrations. EtC achieved higher accuracy (98% vs. 45.7% for EtAA within 5% of the target) and shorter response times (75 vs. 158 s), underscoring its potential to improve precision and efficiency in anesthetic delivery.

Another comparative study of end-tidal control (EtCA) versus manual control (MCA) during low-flow anesthesia showed that EtCA significantly reduced anesthetic gas consumption, the number of adjustments required, and overall costs. After two hours, desflurane use and costs were lower in the EtCA group, and fewer adjustments were needed to maintain anesthesia depth. These findings highlight EtCA as an efficient system for optimizing resource use and reducing workload during low-flow anesthesia [13]. These results align with our study, the use of EtCA as a safe and efficient alternative to MCA, offering advantages in resource optimization without compromising the core goals of anesthesia. Reducing anesthesiologist intervention lowers cognitive workload, decreasing the risk of human errors, including inadvertent hypoxic gas mixtures. This is particularly relevant in high-demand clinical settings where multitasking can lead to sensory overload.

Beard et al. [14] demonstrated that EtControl can offer substantial cost savings and reduce greenhouse gas emissions by significantly decreasing the consumption of volatile anesthetic agents compared to manual administration. In their analysis, they estimated potential annual savings exceeding $95,000 (2023 USD) for a large academic medical center, primarily due to reductions in desflurane and isoflurane use. They mentioned that the reduction in sevoflurane usage was more modest, approximately 4%, or around $14,000 per year. They also estimated that the associated environmental benefit would be comparable to eliminating the annual emissions of nearly 100 U.S. motor vehicles. Beard et al. further suggested that additional reductions in both costs and emissions could be achieved by fully optimizing the low-flow capabilities of EtControl to minimize fresh gas flow rates.

We think that the automated system did not show a significant reduction in sevoflurane consumption because both techniques aimed to maintain the same end-tidal agent concentration. Although automated systems require an initial investment, their ability to minimize manual intervention and reduce the risk of dosing errors may justify their cost over time. A detailed economic analysis is beyond the scope of this study, but we acknowledge that future studies should address this aspect.

Our study was conducted in a single institution, which may limit the generalizability of the findings to other settings with different equipment or protocols. Given that the primary outcome did not reach statistical significance, a larger sample size might have provided more definitive results. The study focused on intraoperative anesthetic consumption without long-term evaluation of patient outcomes or complications related to low-flow anesthesia techniques. Although sufficient for statistical power, the sample size and restriction to ASA I–II patients undergoing elective surgeries might not represent populations with higher anesthetic risks. The study did not directly quantify the environmental benefits of reduced anesthetic agent consumption. Other limitations are that we did not evaluate the effect of the anesthesiologist on cognitive workload, as this is a very difficult issue to evaluate objectively and care providers were not blinded to the intervention, introducing potential bias.

Conclusion

This study demonstrates that end-tidal controlled (EtControl) and manually controlled low-flow anesthesia result in comparable sevoflurane consumption when fresh gas flow settings are standardized. Although the environmental or economic superiority of EtControl could not be demonstrated under these conditions, the study provides valuable real-world data confirming the feasibility of EtControl in routine clinical use. The findings highlight that EtControl can achieve similar anesthetic delivery outcomes. Future research should assess the clinical advantages of EtControl in more dynamic settings, including variable fresh gas flows and more complex patient populations, with a focus on safety, environmental, and economic outcomes.

Abbreviations

EtControl	End-tidal controlled
MC	Manually controlled
ASA	American Society of Anesthesiologists
EtO_2	End-tidal oxygen
EtAA	End-tidal anesthetic agent
BMI	Body mass index
MAC	Minimum Alveolar Concentration

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12871-025-03051-9.

Supplementary Material 1

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The authors have nothing to report.

Author contributions

E. S.Conceptualizm, Methodology, Software, Writing-Reviewing and EditingS.G. Supervision A.M.Data Curation, Writing-original draft preparationB.K.U. Visualization, investigationM.C. Software, ValidationF.Y. VisualizationL.P. Writing-Reviewing and Editing.

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Data availability

The datasets generated and/or analysed during the current study are not publicly available due to privacy but available from the corresponding author on reasonable request.

Declarations

Human ethics and consent to participate

This study was performed in accordance with the principles of the *Declaration of Helsinki*. It was reviewed and approved by the Clinical Research Ethics Committee of Gaziantep University (Date: 02.10.2019, No: 2019/355). The patients provided informed consent to participate in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Clinical trials

The study was retrospectively registered in the ClinicalTrials.gov trial registry under the identifier NCT06735937 on December 11, 2024.

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