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Hyperbaric oxygen therapy in emergencies: approaches to mechanical ventilation and anesthesia

Seyyid Furkan Kına[1], Osman Türkmen[2], Recep Özkan[3], Gizem Avcı[1], Atakan Sezgi[1], Altan Ecem Tönge[1], Ela Erten[4]

[1]Department of Anesthesiology and Reanimation, Ankara Etlik City Hospital, Ankara, Turkiye
[2]Department of Hyperbaric and Diving Medicine, Ankara Etlik City Hospital, Ankara, Turkiye
[3]Department of Hyperbaric and Diving Medicine, Van Training and Research Hospital, Van, Turkiye
[4]Department of Anesthesiology and Reanimation, Gülhane Training and Research Hospital, University of Health Sciences, Ankara, Turkiye

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Corresponding Author: Seyyid Furkan Kına, kinafurkan@gmail.com

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ABSTRACT

Aims: The aim of this study is to evaluate the epidemiology, anesthesia management, mechanical ventilator (MV) modes, sedative agents, drug dosages, and complications in mechanically ventilated patients undergoing hyperbaric oxygen therapy (HBOT).

Methods: This study was conducted retrospectively and observationally in a tertiary care center. Intubated adult and pediatric patients who received anesthesia and sedation under emergency conditions for HBOT between February 10, 2023, and May 15, 2024, were included. Data were obtained from the hospital information system, patient discharge summaries, and anesthesia observation forms. Patients' demographic data, indications, comorbidities, respiratory parameters, intravenous agents and their dosages, MV parameters, and complications were analyzed.

Results: HBOT was applied to 560 patients, of whom 3.75% (21 patients) received anesthesia and sedation. Among these patients, 29.4% (5 patients) were children, and 70.6% (12 patients) were adults, with an age range of 2 to 93 years. The indications included carbon monoxide intoxication (COI) (75%), COI with burns (17.6%), COI with synthetic cannabinoid intoxication (5.9%), and purpura fulminans (5.9%). A total of 44 sessions were conducted, ranging from 1 to 8 sessions per patient. The drugs used included midazolam (35.3%), dexmedetomidine (29.4%), remifentanil (23.5%), propofol, ketamine, and rocuronium bromide (64.7%). The ventilation modes utilized were SIMV-VC, SIMV-PC, PRVC, and PC. Increased sedation dose requirement was observed in 88.2% of the cases due to MV asynchrony. Complications included bradycardia, nausea and vomiting, hypo/hypertension, self-extubation, desaturation, and session incompletion. The in-hospital mortality rate was 29.4%.

Conclusion: Anesthesia management in a hyperbaric environment requires a multidisciplinary approach due to the unique physical conditions of the procedure. In intubated patients, the increased need for sedation must be met, and asynchrony should be prevented. During HBOT, propofol, ketamine, dexmedetomidine, remifentanil, and midazolam can be safely used in combination to optimize sedation. Anesthesia management should be individualized to prevent complications.

Keywords: Hyperbaric oxygen therapy, anesthesia, complications, mechanical ventilation, emergency

INTRODUCTION

Hyperbaric oxygen therapy (HBOT) is a medical treatment method in which 100% oxygen is administered under special conditions at pressures higher than sea level (2-3 atmospheres absolute [ATA]) (Figure 1).[1] HBOT is utilized as an emergency treatment for conditions such as crush injuries, carbon monoxide intoxication (COI), acute smoke inhalation, compartment syndrome, air-gas embolism, decompression sickness, retinal artery occlusion, cyanide intoxication, anoxic-hypoxic encephalopathy, gas gangrene, and necrotizing soft tissue infections.[2] The fact that patients with these indications reach HBOT as soon as possible increases the success of treatment.

Figure 1. The hyperbaric chamber used in our center

The general principles of HBOT are based on increasing the pressure and partial pressure of oxygen to enhance the level of oxygen delivered to tissues. The increase in dissolved oxygen improves oxygen delivery at the tissue level, compensating for defects in oxygen transport in related conditions.[3] Due to these effects, HBOT also exhibits bactericidal and bacteriostatic properties.[4]

HBOT is also administered to critically ill patients with conditions such as acute respiratory failure and sepsis, where the cardiovascular system is affected, and there is a need for mechanical ventilation (MV) and inotropic support. In critical patients, it is essential to monitor vital and respiratory parameters, ensure safe continuation of ventilation under high pressure, provide adequate sedation to achieve MV synchronization, and prepare hyperbaric-compatible equipment and devices, such as syringes and infusion pumps suitable for dose titration.[5] Considering the unique and specific conditions of HBOT, the preparation and anesthesia management of critically ill emergency patients must be conducted meticulously.

In the literature, there is limited data on the pharmacokinetics of anesthetics during HBOT and on patients monitored with MV. The aim of this study was to describe the incidence, demographic data, anesthesia management, sedation agents used, drug doses and complications in patients with MV who underwent HBOT under emergency conditions in our center.

METHODS

This study was conducted retrospectively and observationally in a tertiary training and research hospital. It was approved by the Ankara Etlik City Hospital Scientific Researches Evaluation and Ethics Committee (Date: 05.06.2024, Decision No: AEŞH-BADEK-2024/534) and conducted in accordance with the Declaration of Helsinki. Intubated patients who received anesthesia and sedation under emergency conditions for HBOT at our center between February 10, 2023, and May 15, 2024, were included in the study. There were no age restrictions for inclusion. Patient data were obtained from the hospital information system, patient discharge summaries, and anesthesia observation forms. The evaluated parameters included demographic data, HBOT indication, number of sessions applied, need for inotropic agents, presence of acute respiratory distress syndrome (ARDS) findings, sedative agents used, their requirements and dosages, MV mode, neuromuscular blockade requirements, complications, and in-hospital mortality. Sedation doses in the first sessions of intubated patients who underwent HBOT were compared. The routine protocol for HBOT administered at our center consists of a total duration of 120 minutes per session, including a 15-minute compression phase at the beginning and a 15-minute decompression phase at the end. The treatment pressure is 2.4 ATA. The therapy involves three 30-minute intervals of oxygen administration, interspersed with 5-minute air breaks. Patients with incomplete data in their records were excluded from the study.

Mechanical Ventilator Use

In the hyperbaric unit, the Maquet Servo-i® HBO Ventilator is utilized. This MV, approved for dives up to 30 meters and pressures up to 4.000 hPa, can be used for neonatal, pediatric, and adult patients. Tidal volume and other parameters are automatically adjusted during the compression and decompression phases. Both controlled and assisted ventilation modes are available (Figure 2).

Figure 2. Mechanical ventilator used in hyperbaric environment

Statistical Analysis

Statistical data will be evaluated with SPSS 22.0 (Statistical Program Social Sciences) package program. Continuous variables will be expressed as median (minimum-maximum) and categorical variables as number and percentage.

RESULTS

Between February 10, 2023, and May 15, 2024, a total of 560 patients underwent HBOT, of whom 3.75% (21 patients) received anesthesia and sedation. Data from these 21 patients were reviewed, but 4 patients were excluded due to incomplete data, leaving 17 patients for the study (Figure 3). The included patients ranged in age from 2 to 93 years, with a median age of 54 years (Table 1). Of the patients, 58.8% were female, and 41.2% were male (Table 1). All patients were intubated and admitted to HBOT under emergency conditions, with their status assessed as ASA 4E. Comorbidities were present in 82.4% of the patients, and the associated comorbid conditions are summarized in Table 1.

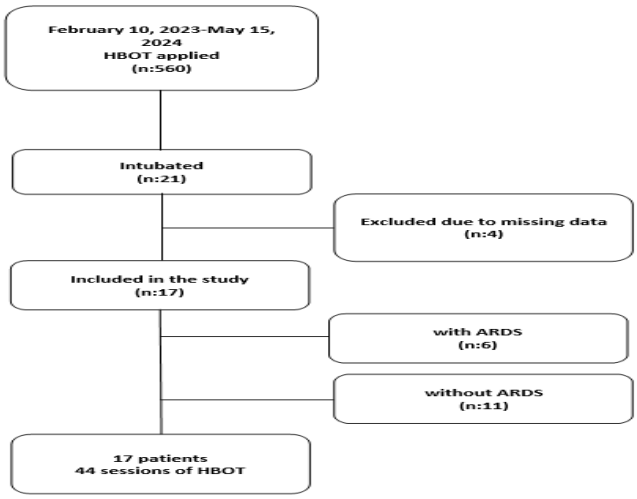

Figure 3. Working diagram
*HBOT: Hyperbaric oxygen therapy, ARDS: Acute respiratory distress syndrome, n: Number of patients.

Table 1. Demographic data and comorbidities

	n=17
Age	
Median	54
Range	2-93
Gender n (%)	
Female	10 (58.8)
Male	7 (41.2)
Weight (kg)	
Median	70
Range	10-90
Height (mt)	
Median	161
Range	80-178
Presence of comorbidity n (%)	
Yes	14 (82.4)
No	3 (17.6)
Comorbidities n (%)	
Diabetes mellitus	2 (11.8)
Hypertension	5 (29.4)
Post-CPR	4 (23.5)
Coronary artery disease	5 (29.4)
Cerebrovascular disease	1 (5.9)
Hypothyroidism	2 (11.8)
COPD	2 (11.8)
CKD	1 (5.9)
Pregnancy	1 (5.9)
Ovarian malignancy	1 (5.9)
Meningitis	1 (5.9)

kg: kilogram, CPR: Cardio pulmonary resuscitation, COPD: Chronic obstructive pulmonary disease, CKD: Chronic kidney disease, n: Number of patients

Of the patients, 70.5% received HBOT due to COI, 17.6% due to COI with burns, 5.9% due to COI with synthetic cannabinoid (bonsai) intoxication, and 5.9% due to purpura fulminans (Table 2). The number of HBOT sessions ranged from 1 to 8, with a median of 2 sessions and a total of 44 sessions. Forty-two sessions were successfully completed, while 2 sessions were terminated early due to deterioration in vital signs. ARDS was observed in 35.3% of the patients, and 41.2% required inotropic agents (Table 2). For sedation, midazolam was administered to 6 patients, dexmedetomidine to 5 patients, and remifentanil to 4 patients. During the sessions, 8 patients also received additional sedative agents, including propofol and ketamine (Table 2). Patients were managed using various ventilator modes: 41.2% with pressure regulated volume control (PRVC), 29.4% with Synchronized intermittent mandatory ventilation volume control (SIMV-VC), 17.6% with pressure control (PC), and 11.8% with Synchronized intermittent mandatory ventilation pressure control (SIMV-PC). During the sessions, 88.2% of the patients experienced MV-patient asynchrony, and neuromuscular blocking agents (rocuronium bromide) were used in 64.7% of the patients (Table 2).

Table 2. Some evaluated parameters of HBOT

	n=17
HBOT indication, n (%)	
COI	12 (70.5)
COI+bonsai intoxication	1 (5.9)
COI+burn	3 (17.6)
Purpura fulminans	1 (5.9)
Number of HBOT session	
Median	2
Range	1-8
ARDS, n (%)	
Yes	6 (35.3)
No	11 (64.7)
Inotrope use, n (%)	
Yes	7 (41.2)
No	10 (58.8)
Sedative substance, n (%)	
Absent	2 (11.8)
Midazolam	6 (35.3)
Dexmedetomidine	5 (29.4)
Remifentanyl	4 (23.5)
*Propofol	
*Ketamine	
MV mode, n (%)	
PRCV	7 (41.2)
PC	3 (17.6)
SIMV-PC	2 (11.8)
SIMV-VC	5 (29.4)
MV compatibility, n (%)	
Compatible	2 (11.8)
İncompatible	15 (88.2)
Neuromuscular blocker use, n (%)	
Yes	11(64.7)
No	6(35.3)

HBOT: Hyperbaric oxygen therapy, COI: Carbon monoxide intoxication, ARDS: Acute respiratory distress syndrome, MV: Mechanical ventilator, PRVC: Pressure Regulated volume control, PC: Pressure control, SIMV-PC: Synchronized intermittent mandatory ventilation pressure control, SIMV-VC: Synchronized intermittent mandatory ventilation volume control, n: Number of patients
* Propofol or ketamine was not used as primary sedative agents in any of the patients

Complications were recorded in 76.5% of the 44 HBOT sessions. Among these complications, 50% were bradycardia, 10% nausea and vomiting, 10% hypotension, 5% hypertension, 5% self-extubation, 10% desaturation, and 10% session incompletion (Table 3). In one patient, the endotracheal tube cuff ruptured, resulting in self-extubation. The patient was reintubated inside the hyperbaric chamber. In two patients, vital parameters deteriorated due to pressure increases, and their sessions were terminated prematurely. None of the patients who developed complications required cardiopulmonary resuscitation during HBOT. Although none of the patients received cardiopulmonary resuscitation during HBOT, in-hospital mortality (due to various causes during intensive care follow-up) was determined as 29.4% (Table 3).

According to the first session data of the patients in HBOT, the dose of sedative medication required increased in 88.2% of the patients, the dose of the sedative agent applied was increased, and propofol and ketamine were used in case of wakefulness. Details of the sedative agents used are provided in Table 4.

Table 3. Data on the complication and mortality

	n=17
Complication, n (%)	
Yes	13 (76.5)
No	4 (23.5)
Complication, n (%)	
Bradycardia	10 (50)
Nausea-vomiting	2 (10)
Hypotension	2 (10)
Hypertension	1 (5)
Extübation	1 (5)
Desaturation	2 (10)
Session interrupted	2 (10)
Mortality in hospital, n (%)	
Death in hospital	5 (29.4)
Discharge from hospital	12 (70.6)

*n: Number of patients

DISCUSSION

In our country, the number of patients undergoing HBOT is increasing with the increasing number of centers, and it is important that critically ill patients with emergencies such as fire, burns, trauma and crush injuries reach HBOT as quickly as possible. While some of these patients are monitored with spontaneous breathing, others require intubation due to compromised respiratory parameters, hemodynamic instability, or other conditions. Intubated patients, who are dependent on MV, pose unique management challenges due to the specific conditions of the hyperbaric environment. These challenges begin with the transfer process and extend to ensuring the maintenance and monitoring of vital signs within safe ranges during sessions, achieving synchronization with the MV, preventing ventilator-induced lung injury (VILI) caused by asynchrony, maintaining endotracheal tube cuff integrity, and sustaining continuous drug infusions.[6] In this study, we aimed to describe the incidence, demographic data, sedation status, complications, MV modes and anesthesia management of MV-dependent intubated patients who received HBOT in emergency conditions due to fire, smoke inhalation, burn and necrotizing tissue infection. We presented the experience of 44 HBOT sessions with anesthesia in 17 pediatric and adult patients meeting the inclusion criteria.

There is limited information in the literature regarding intubated patients undergoing HBOT, with only a few studies reporting incidence. In the study by Bessereau et al.[6], the incidence of intubated patients undergoing HBOT was reported as 14.65%. In Turkiye, there are no previous studies reporting incidence, and the incidence in our center was determined to be 3.75%. We anticipate that this difference in incidence may be attributed to several factors, including the relatively limited number of HBOT centers in Turkiye, challenges in the patient transfer process, lack of integration between emergency medicine and intensive care units, issues within the patient referral chain, and a relatively lower level of awareness about HBOT among physicians in Turkiye. While HBOT is integrated with emergency and intensive care medicine internationally, in Turkiye, it operates as a primary specialty service.[7-9] For these reasons, enhancing communication and collaboration among hyperbaric medicine, emergency medicine, intensive care, and anesthesia teams is crucial for the effective treatment of critically ill patients.

HBOT can be applied to pediatric and adult populations across various indications, regardless of age.[10] In our study, the population ranged from 2 to 93 years of age (Table 1). Comorbidities were present in 82.4% of the patients, and 23.5% (4 patients) had a history of successful cardiopulmonary resuscitation. The indications for HBOT included emergencies such as COI, burns, and purpura fulminans secondary to meningococcemia. Notably, 94.1% of the patients were intubated and underwent HBOT following forensic events (Table 2). The most common indication

Table 4. Drug doses used before and during the first session

	Age	Sedation	Pre-session dose	Dose during session	Additional medicine	Additional medicine
1	2	Midazolam	0.04 mg/kg/h	0.07 mg/kg/h	30 mg propofol	
2	7	Dexmedetomidine	0.3 mcg/kg/h	0.45 mcg/kg/h	-	
3	7	-	-	-	-	
4	8	Midazolam	0.05 mg/kg/h	0.08 mg/kg/h	50 mg propofol	
5	16	Midazolam	0.05 mg/kg/h	0.1 mg/kg/h	-	
6	72	Remifentanyl	2 mcg/kg/h	3.2 mcg/kg/h	20 mg propofol	
7	93	Dexmedetomidine	0.2 mcg/kg/h	0.35 mcg/kg/h	-	
8	74	Dexmedetomidine	0.3 mcg/kg/h	0.5 mcg/kg/h	-	
9	54	Remifentanyl	5 mcg/kg/h	9.2 mcg/kg/h	50 mg propofol	25 mg ketamine
10	79	Midazolam	0.03 mg/kg/h	0.05 mg/kg/h	30 mg propofol	
11	87	Dexmedetomidine	0.2 mcg/kg/h	0.35 mcg/kg/h	-	
12	30	-	-	-	-	
13	86	Midazolam	0.04 mg/kg/h	0.06 mg/kg/h	-	
14	55	Remifentanyl	5 mcg/kg/h	10 mcg/kg/h	100 mg propofol	
15	53	Dexmedetomidine	0.2 mcg/kg/h	0.35 mcg/kg/h	40 mg propofol	
16	30	Midazolam	0.06 mg/kg/h	0.1 mg/kg/h	80 mg propofol	50 mg ketamine
17	74	Remifentanyl	2 mcg/kg/h	3.2 mcg/kg/h	-	

mg: Milligram mcg: Microgram, kg: Kilogram, h: Hour

was COI (%94.1). While HBOT is an effective treatment for COI, its use in cyanide poisoning associated with fires is less documented in the literature, though it is widely accepted by clinicians.[11] In case of fire, COI, smoke inhalation, and cyanide poisoning, patients should be transferred to hyperbaric treatment under emergency conditions as soon as possible.[12] In our study, HBOT was administered to three patients with COI and cyanide poisoning following burns, and we believe that HBOT provides significant benefits in intoxications occurring after fires. Centers have reported varying approaches regarding the number of sessions for intoxications and other indications. In our study, the median number of sessions was 2, ranging from 1 to 8. For MV-dependent patients, we believe that the decision on the number of sessions should be individualized, considering the patient's condition, indication, and the potential benefits and risks of HBOT.

The potential complications specific to anesthesia in the hyperbaric chamber stem from the physiological effects of this unique environment.[13] The efficacy, distribution, and safety of inhalation anesthetics in the hyperbaric setting are unpredictable. Since inhalation agents will almost always leak into the hyperbaric environment, they also pose potential risks for the operating team. Therefore, the use of intravenous (IV) anesthetics instead of inhalation agents is crucial due to the behavior of gases and the risk of contamination. In our center, IV agents such as midazolam, dexmedetomidine, remifentanil, propofol, and ketamine are used in combination, tailored to the individual needs of intubated patients undergoing HBOT. The current literature only reports the use of ketamine, benzodiazepines, and neuromuscular blockers.[14] The pharmacokinetics of IV agents in HBOT have been studied only in animal experiments, and there are no studies on their pharmacokinetics and dosage in humans.[15] The doses of IV agents used in this study are detailed in **Table 4**. According to the results of this study, compared to pre-session conditions, wakefulness and sedation dose requirements increased significantly, especially at high pressure levels. MV asynchrony was observed in 88.2% of the patients, particularly during diving and at high pressures, and neuromuscular blockers were used in 64.7% of the patients. We believe this asynchrony is due to the increased sedation dose requirements caused by the altered physiology and pharmacokinetics under high pressure. In patients with MV asynchrony, sedation doses were increased, and neuromuscular blockers were used to ensure synchronization with the MV. In MV-dependent patients, providing adequate sedation and, if necessary, using neuromuscular blockers is important to mitigate the risk of VILI in cases of asynchrony.[16] In our study, 35.3% of the patients had ARDS. ARDS is associated with high Ppeak pressures and an increased risk of pneumothorax during the decompression phase of HBOT.[17] For these reasons, intubated patients undergoing HBOT should be closely monitored with appropriate equipment, drug doses should be titrated individually, and the numerous challenges encountered in anesthesia management should be optimized and evaluated in detail.

Due to the risk of fire and explosion caused by high oxygen pressure in the hyperbaric environment, electrical equipment and batteries must be kept to a minimum for safety, and all equipment used must be compatible with the hyperbaric setting.[9] For intubated patients, the most critical equipment includes the MV, infusion pumps, and monitors for tracking vital parameters. Moon et al.[14] reported the use of the Monaghan 225 ventilator under hyperbaric conditions. At our center, we use the Maquet Servo-i® HBO Ventilator, with patients managed in PRVC, PC, SIMV-PC, and SIMV-VC modes. When selecting the MV mode in the hyperbaric environment, it is crucial to closely monitor Ppeak and Pplato pressures, avoid excessive pressures to prevent pneumothorax, and ensure the delivery of adequate tidal volumes. Patients' age, comorbidities and conditions such as ARDS should also be taken into consideration when choosing the MV mode. To counteract the increased airway resistance and turbulent flow disadvantages associated with high-pressure environments, the largest suitable endotracheal tube (ETT) should be used for the patient.[18] In addition to tube size, the ETT cuff of intubated patients undergoing HBOT should be deflated and filled with saline or distilled water before the session.[6] Similarly, Foley catheter cuffs must also be evacuated from the air before the session. This precaution is necessary to mitigate the risk of cuff rupture due to changes in ambient pressure. Despite the routine practice at our clinic of filling ETT cuffs with saline prior to sessions, a cuff rupture occurred in a 7-year-old patient during a session, resulting in extubating. The patient's saturation levels dropped to 50% due to probable saline aspiration and failed ventilation, but immediate intervention prevented further complications. This incident suggests the need to evaluate the suitability of ETT cuffs for hyperbaric environments. Similar case reports have been described in the literature.[19] Another consideration in the hyperbaric environment is gastrointestinal gas/air. Under pressure, gases can expand 2-3 times their original volume, potentially impairing ventilation and causing desaturation. At our center, nasogastric tubes were routinely placed in all patients before hyperbaric sessions to prevent such complications.

Due to altered physiology caused by increased pressure and hyperoxia in the hyperbaric chamber, several complications have been reported.[20] While diving bradycardia and reflexes represent protective physiological adaptations, the environment itself is non-physiological.[21] In critically ill intubated patients managed under emergency conditions, unpredictable complications can arise in this non-physiological setting. In our study, 76.5% of patients experienced complications, the most common being bradycardia (50%). One patient experienced self-extubation due to cuff rupture, and in two patients, sessions were terminated due to deteriorated vital parameters (**Table 3**). These findings underscore the need to carefully evaluate the potential risks and benefits of HBOT in intubated patients and ensure patient safety during its application. Even with thorough preoperative assessments, it must be remembered that certain complications, such as central nervous system oxygen toxicity, may be detected late under sedation. Neurological examinations should not be overlooked during the perioperative period.[22] The complications we encountered are detailed in **Table 3**, and no patients required cardiopulmonary resuscitation. Of the 44 total sessions, 42 were successfully completed, with only two sessions being terminated prematurely. Early detection and prompt intervention in response to complications are

critical in reducing morbidity and mortality. Mortality rates for intubated patients undergoing HBOT reported in the literature range from 11% to 87%, whereas the in-hospital mortality rate in our study was 29.4%.[6,23] To reduce complications and mortality, a deeper understanding of the effects of the hyperbaric environment on humans is essential. Our study holds potential as a pioneering effort in this context.

Limitations

Our study has several limitations. These include the retrospective design, with data obtained from the hospital information system and observation forms. Patients with incomplete data were excluded from the analysis. The study covered a time period of approximately 15 months. The depth of anesthesia could not be measured due to the incompatibility of the bispectral index monitor with the hyperbaric environment. Additionally, the results reflect the patient population of a single center.

CONCLUSION

As a result, midazolam, dexmedetomidine, remifentanil, propofol, and rocuronium bromide can be safely used to avoid the adverse effects of inhalation agents in intubated patients undergoing HBOT. It should be noted that sedation requirements increase due to the unique conditions of the hyperbaric environment. To prevent asynchrony, VILI, and complications, close anesthetic monitoring and supervision should be ensured with appropriate equipment. Further prospective, randomized clinical studies with larger sample sizes are needed to better understand the physiology and pharmacokinetics in the hyperbaric environment.

ETHICAL DECLARATIONS

Ethics Committee Approval

It was approved by the Ankara Etlik City Hospital Scientific Researches Evaluation and Ethics Committee (Date: 05.06.2024, Decision No: AEŞH-BADEK-2024/534).

Informed Consent

Because the study was designed retrospectively, no written informed consent form was obtained from patients.

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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