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Cerebral Oxygenation and Neurocognitive Outcomes in Lumbar Surgery: A NIRS Study

Lomber Cerrahide Serebral Oksijenasyon ve Nörokognitif Sonuçlar: Bir NIRS Çalışması

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ABSTRACT

Objective: To evaluate whether management of cerebral desaturation using a near-infrared spectroscopy (NIRS) algorithms on the incidence of postoperative delirium (POD) and postoperative cognitive dysfunction (POCD) in patients undergoing prone lumbar surgery.

Method: Participants in this prospective trial were randomly assigned to either an intervention arm (receiving NIRS-guided care) or a control arm. We excluded individuals with pre-existing neuropsychiatric diagnoses. Baseline cognitive function was assessed, we administered the Mini-Mental State Examination alongside Addenbrooke's Cognitive Examination–Revised evaluated at one week, three months, and six months post-surgery.

Results: A total of 52 participants (comprising 27 males and 25 females) were enrolled, with an average age of 55.6 ± 7.1 years. Baseline demographic and clinical characteristics were comparable. Cerebral oxygen saturation drops of 20% or more occurred in 27% of the control group and 35% of the study group. Regarding neurocognitive outcomes, the study group demonstrated significantly improved test scores at the one-week (p=0.013) and three-month (p=0.018) marks compared to controls, though the difference at six months (p=0.064) was not statistically significant. Notably, POD was not detected in any patient across both groups.

Conclusion: While POD was not observed in our study population, our results indicate that reducing the duration of cerebral desaturation using a NIRS-based algorithm is associated with better neurocognitive outcomes. Conventional anesthetic management alone did not fully prevent postoperative cognitive decline in the control group, whereas NIRS-guided reduction of cerebral desaturation duration was associated with improved neurocognitive outcomes and a lower incidence of POCD.

Keywords: Cognitive dysfunction, spectroscopy, near-infrared, prone position, neurosurgical procedures, general anesthesia

ÖZ

Amaç: Prone pozisyonda lomber cerrahi geçiren hastalarda, yakın kızılötesi spektroskopi (NIRS) algoritması ile serebral desatürasyonun yönetiminin postoperatif deliryum (POD) ve postoperatif kognitif disfonksiyon (POCD) üzerine etkisini değerlendirmek.

Yöntem: Bu prospektif çalışmanın katılımcıları, rastgele bir müdahale grubuna (NIRS kılavuzlu bakım alan) ya da bir kontrol grubuna atandılar. Başlangıçtaki bilişsel işlevler değerlendirildi; ameliyat sonrası birinci hafta, üçüncü ay ve altıncı ayda Mini Mental Durum Testi ile Addenbrooke's Cognitive Examination–Revised testleri uygulandı.

Bulgular: Toplam 52 hasta (27 erkek, 25 kadın; ortalama yaş 55,6 ± 7,1) çalışmaya dahil edildi. Gruplar başlangıç özellikleri açısından benzerdi. %20 veya daha fazla serebral oksijen satürasyonu düşüşü kontrol grubunda %27, çalışma grubunda %35 oranında görüldü. Nörokognitif sonuçlar açısından, çalışma grubunda 1. hafta (p=0,013) ve 3. ayda (p=0,018) kontrol grubuna göre anlamlı iyileşme saptandı; 6. ayda ise fark istatistiksel olarak anlamlı değildi (p=0,064). Her iki grupta da POD gözlenmedi.

Sonuç: Çalışma popülasyonumuzda POD gözlemlenmemiş olsa da, sonuçlarımız NIRS tabanlı bir algoritma kullanılarak serebral desatürasyon süresinin kısaltılmasının daha iyi nörokognitif sonuçlarla ilişkili olduğunu göstermektedir. Kontrol grubunda, geleneksel anestezi yönetimi tek başına postoperatif kognitif gerilemeyi tam olarak önleyememişken, NIRS kılavuzluğunda serebral desatürasyon süresinin kısaltılması, nörobilişsel sonuçlarda iyileşme ve POCD insidansında azalma ile ilişkilendirilmiştir.

Anahtar sözcükler: Kognitif disfonksiyon, spektroskopi, near infrared, pron pozisyon, nöroşirürjikal girişimler, genel anestezi

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INTRODUCTION

Postoperative delirium (POD) is characterized as an acute and possibly reversible neuropsychiatric disorder that manifests often in the post-anesthesia care unit or on the clinical ward (1). The term postoperative neurocognitive disorder (NCD) has recently replaced previous terminology to specifically identify a lasting decline in one or more cognitive domains (e.g., memory, attention, executive function) following surgical recovery. Any cognitive impairment that continues for up to 30 days is termed delayed neurocognitive recovery, while impairment lasting from 30 days to 12 months is identified as mild or major postoperative NCD. Diagnosis requires objective neuropsychological testing, evidence of functional or subjective cognitive decline, and comparison with preoperative baseline cognition (1). Among patients aged 60 or older, the incidence of POD is reported to be approximately 19% after elective and 32% after emergency non-cardiac surgery (2). A systematic review and meta-analysis (mean age ~70 years) reported a postoperative cognitive dysfunction (POCD) prevalence of 23% at day 7, 16% at 1 month, 10% at 3 months, and 3% at 1 year (3). In addition to patient-related factors, surgery type or duration, anesthesia type or depth, and perioperative complications play an important role in the development of POD and postoperative NCD (4,5).

Intraoperative monitoring of hemodynamics, oxygenation, and especially cerebral saturation may be helpful as a preventive strategy (6,7). Intraoperative cerebral oxygenation can be determined with a non-invasive near-infrared spectroscopy (NIRS) device that measures regional cerebral oxygenation (rSO_2). These advanced monitors, which are not among the standard methods, are recommended in coronary artery bypass grafting surgery (8). In this group of patients, decreased intraoperative NIRS values are associated with POD and postoperative NCD (9).

Since NIRS is not plethysmographic, it provides continuous rSO_2 measurement without relying on pulsatile flow. An rSO_2 level below 50% or a decrease of at least 20% compared to baseline is considered cerebral desaturation, which may be a sign of cerebral ischemia. Algorithms for patient management with NIRS data are based on studies conducted in cardiac surgery patients (10). The use of step-by-step intervention protocols for NIRS decline according to the cerebral oximetry algorithm may shorten hospital stay and reduce major organ morbidity and mortality (11). However, there are no evidence-based data showing that these protocols reduce the incidence of POD or postoperative NCD, and more studies are needed on this subject. Considering that cerebral desaturation may be affected by patient position, NIRS monitoring has been evaluated in some specific surgeries, such as shoulder surgery in the sitting position (12). Another position where the use of cerebral oximetry is discussed is the prone position. During spinal surgeries performed in this position, intra-abdominal and intrathoracic pressures increase due to direct pressure on the inferior vena cava, resulting in decreased cardiac output. This may lead to end-organ hypoperfusion and impaired cerebral perfusion. Studies indicate that cerebral desaturation is more common in patients undergoing surgery in the prone position compared with those in the supine position (13).

In this study, we aimed to evaluate the relationship between cerebral desaturation determined by NIRS monitoring and the development of POD or postoperative NCD in patients who underwent lumbar surgery in the prone position.

MATERIALS and METHODS

Patient Selection

Patients older than 18 years who were scheduled to undergo lumbar surgery in the prone position between August 2022 and March 2023 were included in this prospective randomized study. The inclusion criteria were American Society of Anesthesiologists physical status class I-III, no diagnosis of neuropsychological disease or use of medication that would affect neurocognitive functions, a secondary school education or higher, along with a Mini-Mental State Examination (MMSE) score of at least 25. Informed consent was obtained from each volunteer participating in the study. “Secondary school education” corresponded to a minimum of eight years of formal education in the national education system. This criterion was applied to ensure valid interpretation of neurocognitive testing, as educational attainment is a known determinant of baseline cognitive performance. While this approach may limit generalizability to populations with lower educational levels, it was necessary to reduce measurement bias in cognitive outcome assessment. Patients who agreed to participate were randomized using the sealed envelope method, opened by an independent anesthesia technician not involved in the study to ensure allocation concealment. Participants were divided into study (n=30) and control (n=30) groups. One of the 60 patients was excluded from the study due to the need for postoperative mechanical ventilation, three due to reoperation before the study was completed, and four due to the use of medication that would affect neurocognitive functions, and 52 patients were included in the analysis.

Study Protocol

This study was approved by the Ankara University Faculty of Medicine Clinical Research Ethics Committee (approval number: I11-672-20; date: 10 December 2020). There is no standard test to identify postoperative NCD. While the MMSE is

commonly used, it has a ceiling effect and low sensitivity for detecting mild cognitive impairment, particularly in executive dysfunction. We selected the Addenbrooke's Cognitive Examination-Revised (ACE-R) because it offers higher sensitivity (approaching that of the Montreal Cognitive Assessment) and includes specific subdomains for verbal fluency and visuospatial abilities. These domains are critical for assessing frontal lobe function, which is known to be particularly vulnerable to intraoperative hypoperfusion and hypoxia. The patients included in the study were assessed using the ACE-R 1 or 2 days before the surgery in a comfortable and quiet environment by the same anesthesiologist. Preoperative ACE-R results, patient demographics, and medical history [comorbidities, previous surgeries, medications used, body mass index (BMI), preoperative hemoglobin level, smoking history] were recorded. During the surgery, all patients underwent routine anesthesia monitoring (electrocardiography, pulse oximetry, non-invasive or invasive arterial blood pressure), bispectral index (BIS) (Covidien, Boulder, CO, USA), train-of-four (TOF) (GE HealthCare, Chicago, Illinois, USA) and NIRS monitoring. The NIRS monitoring was performed using an INVOS 5100C Cerebral/Somatic Oximeter monitor (Covidien, Somanetics, Troy, MI) with a sensor attached to the right frontotemporal region. For anesthesia induction, 1 μg kg^{-1} fentanyl and 1-3 mg kg^{-1} propofol were administered, titrated according to BIS. The patients were intubated after 0.6 mg kg^{-1} rocuronium was administered and the TOF response had reached 0%. Following routine anesthesia induction, patients were started on maintenance general anesthesia. Total intravenous anesthesia (TIVA) was strictly reserved for patients requiring neuromonitoring [somatosensory evoked potentials (SSEPs)/motor evoked potentials (MEPs)]. All other patients received volatile anesthesia with sevoflurane. The distribution of anesthesia type was balanced between groups. Anesthesia was maintained by keeping BIS values between 40 and 60 in both groups throughout the entire surgical period. Intraoperative heart rate, blood pressure, mean arterial pressure (MAP), peripheral oxygen saturation (SpO_2), rSO_2, end-tidal carbon dioxide, BIS, and fraction of inspired oxygen (FiO_2) were recorded at 10-minute intervals. Baseline rSO_2 was recorded while the patient was breathing room air prior to pre-oxygenation. Intraoperative hypotension was defined as a >20% decrease from baseline MAP. In the control group, intraoperative hypotension and other hemodynamic disturbances were managed according to the institutional standard anesthesia protocol, including fluid administration and vasopressor support when mean arterial pressure decreased by more than 20% from baseline. These interventions were applied equally in both groups; however, cerebral oxygen saturation values were not visible to the anesthesia team in the control group.

In the control group, the NIRS monitor screen was covered with an opaque shield to blind the anesthesia team to rSO_2 values. Routine approaches were applied to optimize hemodynamic values in these patients. In the study group, in addition, a NIRS-based cerebral oximetry algorithm was applied when rSO_2 decreased by at least 20% from baseline or fell below an absolute value of 50%. According to the scheme suggested by Denault et al., when rSO_2 decreased, the placement of the probes and head position were first checked (10). Then, if the patient's blood pressure was low, it was increased with volume or vasopressor support. When a decrease in SpO_2 values was observed, FiO_2 was increased. Erythrocyte transfusion was performed according to hemoglobin values and bleeding status. Invasive arterial blood pressure monitoring was used in patients undergoing multilevel lumbar surgery or those with an expected prolonged operative duration or anticipated significant blood loss, according to institutional anesthesia practice. Non-invasive blood pressure monitoring was used in less complex cases. The distribution of invasive and non-invasive monitoring modalities was comparable between the study and control groups, minimizing the risk of detection bias related to blood pressure measurement technique.

The time spent in the prone position, hypotensive periods, vasopressor requirements, blood loss, and transfusion volumes were recorded. The decrease in NIRS values and the duration of the decrease were noted for both groups. At the end of the operation, the patients were extubated and transferred to the postoperative recovery unit. Patients were evaluated for delirium according to the Nursing Delirium Screening Scale (Nu-DESC). Postoperative ACE-R assessments were performed face-to-face during hospital visits at week 1, month 3, and month 6 by the same anesthesiologist. Cognitive test results were interpreted by a psychiatrist to rule out accompanying psychiatric disease. Both the anesthesiologist administering the ACE-R assessments and the psychiatrist interpreting the results were blinded to group allocation.

Statistical Analysis

The sample size required for the study was calculated based on the use of the Student's t-test to evaluate the difference between two independent groups. Assuming a type I error rate of $\alpha = 0.05$, 26 patients per group were required to detect a large effect size (Cohen's $d = 0.80$) with 80% power using a two-sided independent-samples t-test. The power analysis was performed using the G*Power software package (version 3.1.9.4, Universitat Düsseldorf, Germany). All statistical evaluations were conducted using SPSS version 27.0 (SPSS Inc., Chicago, USA). Descriptive data are expressed as means ± standard deviations, medians (minimum–maximum), or frequencies (percentages) where appropriate. Comparisons of categorical variables were performed using chi-square or Fisher's exact tests. For continuous variables, independent

groups were analyzed using either the Student's t-test or the Mann-Whitney U test, contingent on the data distribution. Repeated ACE-R measurements were analyzed using repeated-measures analysis of variance within the general linear model framework, with assessment time as the within-subject factor and cerebral desaturation status as the between-subject factor. The main effect of time and the time × desaturation status interaction were evaluated separately within the control and study groups. Postoperative NCD was defined not merely by mean score differences, but as a decline of >1 standard deviation from preoperative baseline scores in any cognitive domain. A p-value of less than 0.05 was considered statistically significant.

RESULTS

The mean age of the 52 patients (27 men and 25 women) included in the study was 55.6 ± 7.1 years. The baseline characteristics of the patients in the control (n=26) and study (n=26) groups were similar (Table I). Based on the predefined statistical criterion (a decline of >1 standard deviation from preoperative baseline ACE-R score in at least one postoperative assessment), postoperative NCD was identified in 11 patients (42.3%) in the control group and 3 patients (11.5%) in the NIRS-guided intervention group. The incidence of postoperative NCD was significantly lower in the study group compared with the control group (p = 0.026).

In the study group, patients with cerebral desaturation (≥20% decrease in rSO_2 from baseline) had a longer median anesthesia duration (p = 0.001), surgery duration (p = 0.001) and duration of prone positioning (p = 0.001), as well as a higher frequency of intraoperative bleeding (p = 0.011), than those without. No such differences were observed in the control group; in this group, only the mean intraoperative rSO_2 was significantly lower in patients with desaturation (p=0.019). Blood loss did not differ between subgroups in either group. Detailed information is given in Table II.

We compared patients with and without cerebral desaturation separately within the control and study groups using ACE-R test results obtained preoperatively and at the first week, third month, and sixth month after surgery. Repeated-measures analysis of variance showed a significant overall main effect of time on ACE-R scores in both the control and study groups (p < 0.001 for both). In both groups, ACE-R scores decreased from preoperative values in the first postoperative week and partially recovered at the third and sixth postoperative months. The time × cerebral desaturation status interaction was not statistically significant within either the control group (p = 0.097) or the study group (p = 0.299). Thus, a difference in ACE-R trajectories between patients with and without cerebral desaturation was not demonstrated within either group. Detailed information is given in Table III and Figure 1.

Among patients who experienced cerebral desaturation, the decline in ACE-R scores in the first postoperative week was numerically greater in the control group (from 78.4 ± 5.4 to 71 ± 2.6) than in the study group (from 80.4 ± 6.4 to 77.6 ± 6). At the sixth month, ACE-R scores in the study group had returned to above baseline (81.6 ± 6.7), whereas those in the control group remained below baseline (74.9 ± 6.5) (Figure 2).

Table I. Comparative Baseline Characteristics of the Study and Control Groups

Characteristics	Overall	Groups		p-value
		Control (n=26)	Study (n=26)	
Age, years	55.6 ± 7.1	56.9 ± 10.4	54.3 ± 7.1	0.304[a]
Male sex	27 (51.9)	13 (50)	14 (53.8)	0.781[b]
BMI, kg m^{-2}	27.8 ± 3.5	27.9 ± 3.7	27.6 ± 3.3	0.738[a]
Smoking history	23 (44.2)	10 (38.5)	13 (50)	0.402[b]
Comorbidity	39 (75)	19 (73.1)	20 (76.9)	0.749[b]
Medication use	34 (65.4)	17 (65.4)	17 (65.4)	1.000[b]
Previous surgery	34 (65.4)	17 (65.4)	17 (65.4)	1.000[b]
Preoperative hemoglobin, g dL^{-1}	14 ± 1.6	13.8 ± 1.8	14.1 ± 1.5	0.509[a]
Operation level				
I	20 (38.5)	10 (38.5)	10 (38.5)	0.539[c]
II	18 (34.6)	9 (34.6)	9 (34.6)	
III	11 (21.2)	7 (26.9)	4 (15.4)	
IV	2 (3.8)	0 (0)	2 (7.7)	
V	1 (1.9)	0 (0)	1 (3.8)	

Data are presented as n (%) or mean ± SD. **a:** Student's t-test, **b:** chi-square test, **c:** Fisher's exact test. **BMI:** Body mass index, **SD:** Standard deviation.

Table II. Comparison of Patients with and without Cerebral Desaturation

Parameters	Control group rSO_2			Study group rSO_2		
	Normal (n=19)	≥20% decrease (n=7)	p value	Normal (n=17)	≥20% decrease (n=9)	p-value
Age, years	55.9 ± 10.6	59.4 ± 10.5	0.462[a]	53.2 ± 5.9	56.3 ± 9.1	0.301[a]
Male sex	9 (47.4)	4 (57.1)	1.000[c]	9 (52.9)	5 (55.6)	1.000[c]
BMI, kg m^{-2}	28 ± 4	27.7 ± 2.7	0.832[a]	28.3 ± 3.5	26.3 ± 2.8	0.162[a]
Anesthesia duration, min	150 (100-310)	180 (90-260)	0.231[b]	150 (90-270)	260 (160-330)	**0.001[b]**
Surgery duration, min	120 (65-285)	160 (70-225)	0.094[b]	120 (75-240)	225 (135-290)	**0.001[b]**
Time in prone position, min	130 (75-295)	170 (80-240)	0.083[b]	130 (80-250)	240 (145-315)	**0.001[b]**
Intraoperative bleeding	10 (52.6)	5 (71.4)	0.658[c]	5 (29.4)	8 (88.9)	**0.011[c]**
Blood loss, mL	375 (300-600)	700 (300-1600)	0.254[b]	500 (300-900)	700 (300-2000)	0.354[b]
Blood transfusion	0 (0)	1 (14.3)	0.269[c]	0 (0)	2 (22.2)	0.111[c]
Vasopressor use	12 (63.2)	3 (42.8)	0.407[c]	5 (29.4)	6 (66.7)	0.103[c]
Anesthesia type Volatile TIVA	 14 (73.7) 5 (26.3)	 4 (57.1) 3 (42.9)	0.635[c]	 11 (64.7) 6 (35.3)	 3 (33.3) 6 (66.7)	0.218[c]
Baseline rSO_2, %	71.9 ± 7	72 ± 5.2	0.986[a]	71.3 ± 4.9	74.1 ± 7.9	0.274[a]
Mean rSO_2, %	70.5 ± 5.9	64 ± 5.4	**0.019[a]**	71.2 ± 7.2	67.2 ± 6.2	0.171[a]
Baseline MAP, mmHg	104.3 ± 12.5	100.6 ± 13.9	0.516[a]	98.2 ± 12.8	105.7 ± 12.2	0.165[a]
Mean MAP, mmHg	79.1 ± 6.2	83 ± 7.8	0.194[a]	85.8 ± 6.3	88.6 ± 7.4	0.323[a]

Data are presented as n (%), mean ± SD or median (minimum–maximum). **a:** Student's t-test, **b:** Mann-Whitney U test, **c:** Fisher's exact test. **BMI:** body mass index, **MAP:** mean arterial pressure, **SD:** Standard deviation, **TIVA:** Total intravenous anesthesia, **rSO_2:** Regional cerebral oxygenation.

Table III. Repeated ACE-R Measurements in Patients with and without Cerebral Desaturation

Parameters, mean ± SD	Control group rSO_2				Study group rSO_2			
	Normal	≥20% decrease	Subgroup p value	p values (b, c)	Normal	≥20% decrease	Subgroup p value	p-values (b, c)
Preoperative ACE-R	75.2±6.3	78.4±5.4	0.237[a]		77.5±8.2	80.4 ± 6.4	0.353[a]	
Postoperative 1st week ACE-R	72±6.1	71±2.6	0.682[a]	**<0.001[b]**	74.35±7.67	77.6±6	0.288[a]	**<0.001[b]**
Postoperative 3rd month ACE-R	71.7±6.5	72.7±4.1	0.713[a]	0.097[c]	75.6±8.1	79.9±6.1	0.180[a]	0.299[c]
Postoperative 6th month ACE-R	73.8±6	74.9±6.5	0.712[a]		77.1±8.4	81.6±6.7	0.184[a]	

a: Student's t-test comparing desaturation subgroups at each time point. **b:** Overall main effect of time across the four ACE-R assessments. **c:** Time × cerebral desaturation status interaction (with versus without a ≥20% decrease in rSO_2). Effects b and c were assessed using repeated-measures ANOVA. Analyses were performed separately within the control and study groups. **ACE-R:** Addenbrooke's Cognitive Examination-Revised, **SD:** Standard deviation, **rSO_2:** Regional cerebral oxygenation.

DISCUSSION

In our study, the effect of cerebral oxygen saturation changes on postoperative delirium and cognitive functions in patients who underwent lumbar surgery in the prone position was investigated. When postoperative NCD was analyzed as an individual-level outcome rather than mean cognitive score change, NIRS-guided reduction of cerebral desaturation duration was associated with a significantly lower incidence of postoperative NCD. In patients with cerebral desaturation, ACE-R scores were found to be significantly higher in the study group treated with the NIRS-based algorithm than in the control group at the first postoperative week and third postoperative month. Postoperative cognitive dysfunction refers to cognitive functioning problems, which include memory, attention, or information analysis, that start within 30 days of surgery and can persist for up to a year (14). Although its pathophysiology is not fully known, it is associated with advanced age, comorbidities, multiple drug use, and low education level (15). To avoid influencing the cognitive tests, we only included patients who had an MMSE score of at least 25 and a secondary school education level or higher. Intraoperative depth of anesthesia may be associated with

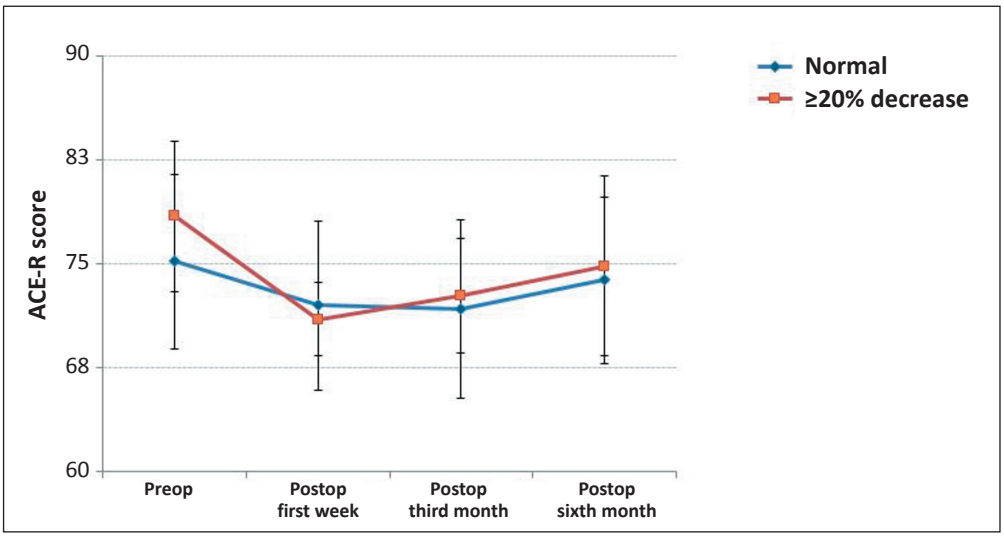


Figure 1. Addenbrooke's Cognitive Examination-Revised scores over time in patients with and without cerebral desaturation in the control group (ACE-R: Addenbrooke's Cognitive Examination-Revised, rSO_2: Regional cerebral oxygenation).

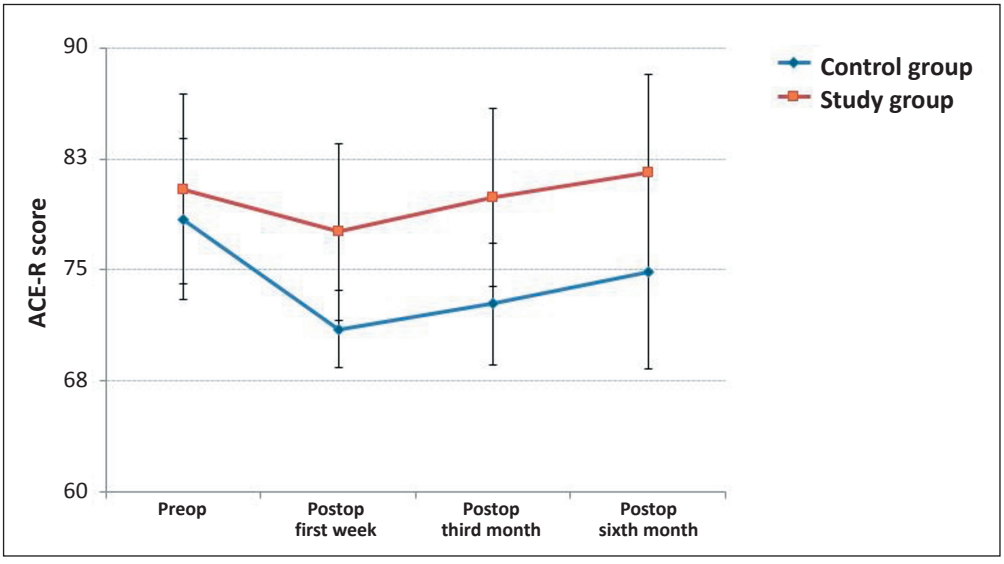


Figure 2. Addenbrooke's Cognitive Examination-Revised scores over time in patients with a ≥20% decrease in regional cerebral oxygenation in the control and study groups (ACE-R: Addenbrooke's Cognitive Examination-Revised).

the development of POD or postoperative NCD (16). In our study, the drugs used to maintain intraoperative anesthesia were titrated to keep the BIS value between 40 and 60. Postoperative delirium was not detected in either group. Given the zero incidence of POD and the limited duration of postoperative screening, no conclusions can be drawn regarding the preventive effect of NIRS, BIS monitoring, or hemodynamic management on POD. The absence of POD in this cohort is more likely related to the relatively young mean age of the population, strict exclusion of patients with pre-existing neuropsychiatric disease, and standardized perioperative care, rather than a specific intraoperative intervention. In addition, the Safe Brain Initiative program, which has been implemented in our hospital since 2020, formed part of perioperative care, although its contribution to POD prevention could not be assessed in this study. Also, this may be attributed to the relatively young mean age of our cohort (55.6 years) and the strict exclusion of patients with pre-existing neuropsychiatric conditions, rather than solely due to intraoperative management. Although POD was not observed during the postoperative screening period, postoperative NCD occurred in patients with decreased rSO_2, suggesting a possible association between cerebral desaturation and postoperative cognitive outcomes. In the study conducted by Radtke et al., it was re-

ported that BIS monitoring could prevent POD, but was insufficient to prevent postoperative NCD (17).

Cerebral autoregulation helps maintain relatively stable cerebral blood flow across a range of perfusion pressures. Cerebral perfusion pressure is calculated as MAP minus intracranial pressure. In healthy adults, the autoregulatory range is traditionally described as approximately 60-160 mmHg MAP, although these limits should not be assumed to apply uniformly to all patients (18). In a meta-analysis conducted by van Zuylen et al., which included 9 studies, it was reported that intraoperative hypotension should not be stated as the only risk factor for postoperative NCD, but should be evaluated together with other parameters (19). In our study, although there was no significant difference in mean MAP between the two groups, POCD occurred in patients whose rSO_2 value decreased by at least 20%. The absence of POD in both groups does not establish a preventive effect of maintaining MAP within 20% of baseline values. Many studies in the literature have shown that intraoperative hypotension and MAP fluctuations may be associated with POD, especially in elderly and frail patients (20,21). There are many studies comparing the use of inhalational anesthesia and TIVA in terms of postoperative complications. In their meta-analysis, Jiao et al. found no difference in mortality rates and cognitive status 1 year postoperatively between patients who received volatile anesthesia or TIVA (22). Another meta-analysis showed that the incidence of POCD on the 30th postoperative day was lower in patients treated with TIVA (23). There is no consensus on this issue due to the heterogeneity of studies and the differences in cognitive assessment tools. In our study, no difference in terms of postoperative NCD was noted between different anesthesia approaches. Near-infrared spectroscopy monitoring provides real-time trends in cerebral oxygenation, which may reflect changes in hemoglobin concentration, though our study protocol did not utilize a NIRS-specific transfusion trigger. Delis et al. investigated the relationship between cerebral oxygenation and intraoperative hemoglobin values in patients who underwent hip or lumbar surgery, and found a more significant increase in post-transfusion rSO_2 values in patients with lower pre-transfusion hemoglobin levels (24).

The prone position has important physiological effects, including hemodynamic changes (25,26). The incidence of cerebral desaturation is higher in the prone position than in the supine position (13). In addition, head position also negatively affects cerebral perfusion. Head and neck positioning in the prone position may influence cerebral venous drainage and intracranial pressure, thereby affecting cerebral perfusion. Neutral head alignment was standardized using the same positioning device in all patients to minimize positional effects on rSO_2 values (27). We found that the durations of anesthesia, surgery, and prone positioning were longer in patients with decreased NIRS values. However, it was determined that postoperative cognitive outcomes were better and the incidence of postoperative NCD was lower in the patient group with cerebral desaturation treated with the NIRS-based algorithm compared to the control group. Despite the study group experiencing longer surgical durations—a known risk factor for postoperative NCD—their cognitive outcomes were superior. These findings suggest an association between shorter desaturation duration during NIRS-guided management and better postoperative cognitive outcomes. Studies have also investigated the relationship between the duration of cerebral desaturation and postoperative NCD. In the study conducted by Jeongmin Kim et al., POCD was more common in patients with a longer duration of cerebral desaturation (28). In our study, the duration of cerebral desaturation in the control group was significantly longer than in the study group, and this was accompanied by poorer postoperative cognitive outcomes. The NIRS-based algorithm, which allows optimization of factors that may affect cerebral saturation, was first developed by Denault et al. and was studied mostly in cardiac surgery patients (10). The 2020 joint consensus statement from the American Society for Enhanced Recovery and the Perioperative Quality Initiative recommends cerebral oximetry to help detect and manage acute cerebral malperfusion during cardiac surgery, and an oximetry-guided intervention algorithm to shorten intensive care unit stay after cardiac surgery. However, the statement found insufficient evidence to recommend cerebral oximetry for reducing mortality or organ-specific morbidity after cardiac surgery, or for improving outcomes after noncardiac surgery (8). There are different opinions regarding the cut-off for rSO_2 reduction. Lin et al., in their study including patients undergoing total hip arthroplasty, showed that a >11% decrease in rSO_2 may be a potential risk factor for postoperative NCD (29). Despite different opinions, a decrease in rSO_2 of at least 20% from baseline or rSO_2 less than 50% is generally accepted as cerebral desaturation both in studies and in daily practice (10).

There is no standard test to identify postoperative NCD. The MMSE is widely used for cognitive screening, but a study in cardiac surgery patients found that its ability to identify postoperative cognitive impairment was limited and depended on the cut-off score used (30). In our study, we used the ACE-R test, which is an expanded version of the MMSE, and compared the patients according to the attention, memory, verbal fluency, language, and visuospatial domains of this test. Experimental work in rats showed greater vulnerability of the frontal lobe than the thalamus to hypoxia and hypotension after traumatic brain injury (31). Different frontal regions contribute to cognitive control through processes such as task setting and monitoring (32). In our study, we observed that attention, memory, verbal fluency, and language

scores were better in patients who underwent NIRS-based intervention. However, in the control group, the significantly prolonged desaturation duration was accompanied by lower scores in these domains. In the visuospatial domain, on the other hand, similar results were observed between the groups, unlike the other domains. To ensure that postoperative cognitive impairments are not confused with other psychiatric disorders, and to assess cognitive test results unaffected by this condition, it is important to conduct a differential diagnosis. Therefore, the analysis and reporting of cognitive tests in our study were evaluated by a psychiatrist who served as an assisting researcher.

Study Limitations

There are some limitations to this study. Given the low number of patients in our study, definitive conclusions regarding the relationship between intraoperative hemoglobin levels and cerebral oxygenation could not be drawn; further studies with larger sample sizes are needed to clarify this issue. Regarding the cognitive evaluation, we observed similar results in the visuospatial domain between groups. The study did not include direct cardiac output monitoring or continuous arterial blood gas analysis. In the prone position, reductions in venous return and cardiac output may contribute to cerebral desaturation even when mean arterial pressure is preserved. Similarly, $PaCO_2$ was maintained within standard intraoperative targets but was not analyzed as an independent covariate. These unmeasured physiological determinants may have influenced rSO_2 values and limit mechanistic interpretation of cerebral desaturation events. The depth of anesthesia was guided by the BIS which was maintained between 40 and 60. Raw electroencephalographic waveforms and density spectral array were not routinely analyzed. We did not utilize advanced cardiac output monitoring or continuous arterial blood gas analysis, limiting our assessment of physiological determinants like cardiac output and $PaCO_2$. Delirium was screened using the Nu-DESC only in the recovery unit; fluctuating symptoms may have been missed. The sample size was relatively small, and while sufficient for cognitive score changes, it may have been underpowered for rare events like POD. Finally, blood pressure monitoring was not standardized to a single modality (invasive vs. non-invasive) for all patients. While the distribution of monitoring types was balanced between groups, continuous invasive monitoring in all patients might have provided more precise hemodynamic data. Although invasive arterial monitoring provides superior temporal resolution for hypotension detection, blood pressure monitoring modality was selected based on clinical indications rather than randomization. While the distribution of monitoring techniques was balanced between groups, intermittent non-invasive monitoring may have failed to detect brief hypotensive episodes, which represents a limitation. We believe that the memorization of questions related to the visuospatial domain during repeated tests (the learning effect) may have led to this outcome.

CONCLUSION

Our study demonstrates that while NIRS monitoring did not prevent the occurrence of cerebral desaturation events, the implementation of a targeted NIRS-based algorithm significantly reduced the duration of these events. This reduction was associated with improved postoperative neurocognitive outcomes and a lower incidence of postoperative NCD in patients undergoing prone lumbar surgery. These findings suggest that NIRS-guided management may be a valuable adjunct to standard anesthetic care for mitigating postoperative cognitive decline, although larger studies are needed to confirm causality and define its role in broader clinical practice.

AUTHOR CONTRIBUTIONS

Conception or design of the work: BCM
Data collection: AG
Data analysis and interpretation: OOA, SKE
Drafting the article: BCM
Critical revision of the article: SKE, BCM
Other (study supervision, fundings, materials, etc):
The authors (AG, SKE, OOA, BCM) reviewed the results and approved the final version of the manuscript.

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