Transfusion Medicine and Hemotherapy

Research Article

Transfus Med Hemother 2023;50:270–276
DOI: 10.1159/000528888

Received: July 5, 2022
Accepted: December 28, 2022
Published online: February 8, 2023

# Effects of Different Hemoglobin Levels on Near-Infrared Spectroscopy-Derived Cerebral Oxygen Saturation in Elderly Patients Undergoing Noncardiac Surgery

Achilles Delis[a] Derek Bautz[a] Heidi Ehrentraut[a] Karin Doll[a] Thomas M. Randau[b] Andreas C. Strauss[b] Ivana Habicht[b] Erdem Güresir[c] Holger Bogatsch[d] Peter Kranke[e] Maria Wittmann[a] Patrick Meybohm[e] Markus Velten[a]

[a]Department of Anesthesiology and Intensive Care Medicine, University Hospital Bonn, Bonn, Germany; [b]Department of Orthopaedic and Trauma Surgery, University Hospital Bonn, Bonn, Germany; [c]Department of Neurosurgery, University Hospital Bonn, Bonn, Germany; [d]Clinical Trial Center Leipzig, University Leipzig, Leipzig, Germany; [e]Department of Anaesthesiology, Intensive Care, Emergency and Pain Medicine, University Hospital Wuerzburg, Wuerzburg, Germany

**Keywords**
Regional cerebral oxygen saturation · Near-infrared spectroscopy · Red blood cell transfusion

**Abstract**

***Background:*** Near-infrared spectroscopy (NIRS) is a commonly used technique to evaluate tissue oxygenation and prevent harmful cerebral desaturation in the perioperative setting. The aims of the present study were to assess whether surgery-related anemia can be detected via NIRS of cerebral oxygen saturation and to investigate the effects of different perioperative transfusion strategies on cerebral oxygenation, potentially affecting transfusion decision-making. ***Study Design and Methods:*** Data from the ongoing multicenter LIBERAL-Trial (liberal transfusion strategy to prevent mortality and anemia-associated ischemic events in elderly noncardiac surgical patients, LIBERAL) were used. In this single-center sub-study, regional cerebral oxygenation saturation ($rSO_2$) was evaluated by NIRS at baseline, pre-, and post-RBC transfusion. The obtained values were correlated with blood gas analysis-measured Hb concentrations. ***Results:*** $rSO_2$ correlated with Hb decline during surgery ($r = 0.35$, $p < 0.0001$). Different RBC transfusion strategies impacted $rSO_2$ such that higher Hb values resulted in higher $rSO_2$. Cerebral desaturation occurred at lower Hb values more often. ***Discussion:*** Cerebral oxygenation monitoring using NIRS provides noninvasive rapid and continuous information regarding perioperative alterations in Hb concentration without the utilization of patients' blood for blood sampling. Further investigations are required to demonstrate if cerebral $rSO_2$ may be included in future individualized transfusion decision strategies.

© 2023 The Author(s).
Published by S. Karger AG, Basel

## Introduction

Transfusion of allogeneic red blood cell (RBC) units is frequently required during major surgery with elderly patient being at risk due to higher incidence of comorbidities including preoperative anemia and vascular disease predisposing to myocardial and cerebral ischemia [1–3]. Transfusion of RBC is the standard therapy of perioperative anemia with a broad Hb treatment range between 6 and 10 g/dL. However, existing evidence does not support a single criterion for transfusion and justification should depend on patients comorbidities, potential or actual on-

Achilles Delis and Derek Bautz contributed equally to this work.

Karger@karger.com
www.karger.com/tmh

© 2023 The Author(s).
Published by S. Karger AG, Basel

This is an Open Access article licensed under the Creative Commons Attribution-NonCommercial-4.0 International License (CC BY-NC) (http://www.karger.com/Services/OpenAccessLicense), applicable to the online version of the article only. Usage and distribution for commercial purposes requires written permission.

Correspondence to:
Markus Velten, markus.velten@ukbonn.de

going bleeding (rate and magnitude), volume status, cardiopulmonary reserve, and most notably signs of organ ischemia resulting in impaired tissue oxygenation [4].

Near-infrared spectroscopy (NIRS) is a commonly applied, noninvasive technique that uses the different absorption and dispersion spectrum of near infrared light to distinguish between oxygenated and deoxygenated hemoglobin, indicative of tissue oxygenation, in different tissues approximately 25 mm below the skull [5]. Therefore, any given NIRS presents a relative value that reflects a balance between oxygen demand and supply, within the evaluated tissue at current conditions. Furthermore, the assessed value depended on patient's individual baseline but also affected by various covariates including perfusion, oxygenation, and hemoglobin concentration [6]. While tissue perfusion is influenced by blood pressure and cardiac function, oxygenation is controlled during general anesthesia through the ventilatory settings. Hemodynamics and oxygenation are continuously monitored and kept within predefined ranges during anesthesia. Although hemoglobin concentrations commonly change during the course of major surgery with increased probability of blood loss, affecting tissue oxygenation, noninvasive techniques continuously evaluating hemoglobin concentration tend to be inferior to invasive blood gas analyses (BGAs). However, BGA is usually performed in response to clinical signs including blood loss and volume compensation and thus provides only intermittent information.

Most studies investigating the perioperative impact of cerebral oxygenation saturation ($rSO_2$) on postoperative outcome are performed in cardiac or vascular surgery and report a correlation between $rSO_2$ and central venous oxygenation saturation. Current guidelines recommend monitoring of cerebral oxygenation during cardiac surgery to detect cerebral desaturation early, to increase oxygen supply, and thereby to improve neurological outcome [7]. Although, investigation showed that NIRS can be used for the detection of anemia in intensive care patients, no study has yet investigated the perioperative usage of NIRS for the detection of intraoperative bleeding and consecutive anemia and deoxygenation to potentially consider transfusion of RBC in adult patients undergoing major noncardiac surgery. Therefore, we hypothesize that anemia occurring during noncardiac surgery can be detected via NIRS evaluation of cerebral oxygen saturation and RBC transfusion improves cerebral oxygenation, potentially affecting transfusion decision-making (TDM) in elderly patients.

## Material and Methods

*Study Design*

The present analysis contains data of 67 consecutive patients, undergoing spine or hip surgery, recruited within the ongoing LIBERAL-Trial from 2020 to 2021. The LIBERAL-Trial is a prospective, multicenter, randomized, open, phase 4 trial, investigating the effects of a liberal transfusion strategy of RBCs on mortality and anemia-associated ischemic events in elderly patients undergoing noncardiac surgery [8]. In brief, patients ≥70 years scheduled for intermediate- or high-risk noncardiac surgery were included. Hemoglobin levels were monitored during the surgery and daily after surgery. If Hb level dropped below ≤9.0 g/dL during surgery or in the postoperative phase until postoperative day 3, patients were randomized either to the LIBERAL (receiving one single RBC unit each time Hb reaches ≤9.0 g/dL) or restrictive transfusion regime (a single RBC unit each time Hb reaches ≤7.5 g/dL). To investigate the impact of anemia severity on RBC transfusion-induced changes of cerebral NIRS, we grouped patients according to their pre-transfusion Hb concentration irrespective of their randomization group assignment: Hb <7.5 g/dL, Hb 7.5–8.5, and Hb ≥8.5 g/dL. This sub-study did neither unblind any data nor analyze any group differences of the large LIBERAL trial.

*Anesthesia Protocol*

Pulse oximetry, electrocardiogram, noninvasive blood pressure measurement, and a peripheral line were established upon arrival at the introduction room. Anesthesia was induced using fentanyl, propofol (2 mg/kg), and rocuronium (0.5 mg/kg). Following intubation, ventilation was adjusted to 8–10 mL/kg and respiratory rate was set to maintain $etCO_2$ at 35–40 mm Hg. Subsequently, the radial artery was cannulated for invasive blood pressure measurement and BGAs. Oxygen concentration was adjusted to $pO_2$ between 120 and 150 mmHg to maintain $SpO_2$ above 95%. Anesthesia was maintained using propofol and sedation dept was monitored using bi-spectral index monitoring (XP-sensor, Covidien plc, Dublin, Ireland) and bi-spectral index values were kept between 40 and 60, ensuring an appropriate anesthesia level. During the surgery, phenylephrine infusion has been used to maintain mean arterial blood pressure within 20% of pre-anesthesia level. To assess regional tissue oxygenation, the probe of an INVOS™ 5100C (Medtronic Inc., Minneapolis, MN, USA) was placed on the right forehead and cerebral oxygenation saturation ($rSO_2$) was continuously monitored throughout the surgery. Anesthesia regime and NIRS evaluation was performed in the present sub-study according to institutional standard and not specified in the LIBERAL-Trial study protocol [8]. Patients with carotid artery stenosis were not included due to its potential impact on cerebral perfusion. $rSO_2$ values were assessed through NIRS prior to and 10 min after transfusion of each RBC unit to investigate the impact of RBC transfusion on cerebral tissue oxygenation at different Hb concentrations.

*Statistical Analyses*

Statistical analyses were performed using Graph Pad PRISM 8. Data are expressed as mean ± standard deviation for normally distributed continuous variables. Differences between groups were determined using one-way ANOVA and Bonferroni post hoc analyses. Baseline, pre-, and post-transfusion differences were analyzed using two-way ANOVA and Bonferroni post hoc analyses.

## Results

The present study included 67 patients that received RBC transfusion during elective hip or spine surgery. Age, height, weight, and BMI were not different between groups (Table 1).

**Table 1.** Patients characteristics were analyzed using one-way ANOVA with Bonferroni post hoc analyses and are expressed as mean ± SEM ($p < 0.01$)

| | <7.5 g/dL | 7.5–8.5 g/dL | >8.5 g/dL | *p* value |
|---|---|---|---|---|
| Age, years | 79±1 | 79±1 | 78±1 | ns |
| Height, cm | 170±2 | 167±2 | 171±2 | ns |
| Weight, kg | 78±4 | 72±3 | 81±4 | ns |
| BMI, kg/m$^2$ | 27±1 | 26±1 | 27±1 | ns |

Cerebral regional oxygen saturation ($rSO_2$) and Hb concentrations were evaluated after induction of anesthesia, prior to RBC transfusion, and 10 min after transfusion. As both hemoglobin concentrations and NIRS values changed during the surgery, the association between cerebral $rSO_2$ values and Hb concentrations at baseline, pre-transfusion, and post-transfusion were analyzed using Spearman's correlation. Our data indicate a positive correlation between Hb concentration and cerebral tissue oxygenation ($r = 0.35$, $p < 0.0001$) (Fig. 1).

Hb concentrations increased in all groups after transfusion of 1 RBC unit. However, post-transfusion Hb concentration remained lower in patients with pre-transfusion Hb concentrations <7.5 g/dL compared to 7.5–8.5 g/dL and >8.5 g/dL groups. Statistical analyses indicated effects of pre-transfusion Hb concentrations, transfusion, and an interaction of pre-transfusion Hb and RBC transfusion on post-transfusion Hb concentrations (Fig. 2).

Cerebral $rSO_2$ was lower prior to transfusion compared to baseline in patients transfused at Hb concentrations <7.5 g/dL, while there was no difference observed in other groups prior to transfusion compared to baseline values. Pre- to post-transfusion increases in $rSO_2$ were observed in all groups. Furthermore, $rSO_2$ was increased after transfusion compared to baseline values in 7.5–8.5 g/dL and >8.5 g/dL groups, while there was no difference observed in patients transfused at Hb concentrations <7.5 g/dL $rSO_2$ was not different between groups at baseline or post-transfusion. However, $rSO_2$ was significantly lower in patients transfused at Hb concentrations <7.5 g/dL compared to patients transfused at Hb concentrations >8.5 g/dL prior to transfusion. Two-way ANOVA indicated effects of transfusion, Hb concentrations pre-transfusion, and an interaction on $rSO_2$ (Fig. 3).

Delta $rSO_2$ baseline to pre-transfusion values were negative and significantly lower in patients transfused at Hb concentrations <7.5 g/dL compared to other groups. $rSO_2$ reduction from baseline values prior to transfusion was 12% in <7.5 g/dL, while 3% in 7.5–8.5 g/dL and >8.5 g/dL groups. Furthermore, delta pre- to post-transfusion $rSO_2$ was greater in patients transfused at Hb concentrations <7.5 g/dL compared to other groups ($p < 0.001$). However, neither baseline to pre- nor pre- to post-transfusion $rSO_2$ values were different between patients transfused at 7.5–8.5 g/dL and >8.5 g/dL (Fig. 4).

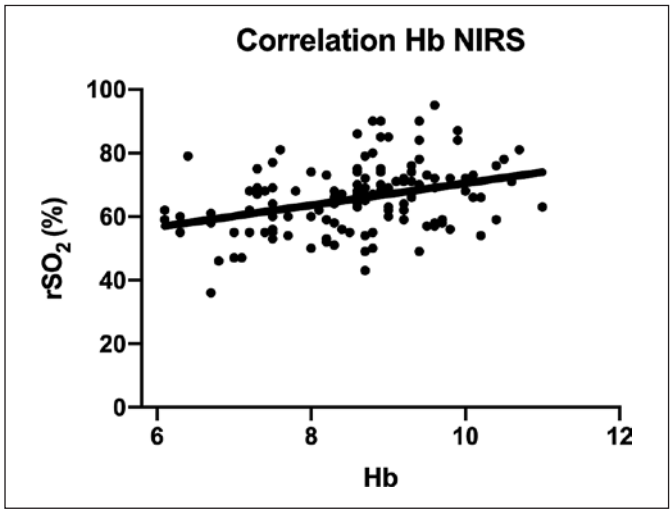


**Fig. 1.** Correlation between Hb concentration and NIRS-derived rSO2 measured after anesthesia induction, pre-transfusion, and posttransfusion. Data were analyzed using Spearman *r* test ($n = 129$, $r = 0.3479$, $p < 0.0001$).

Oxygenation parameters including arterial $pO_2$ and $pCO_2$ were not different between subgroups at any timepoint. Blood pressures were not different between groups but were higher after transfusion in patients transfused at Hb concentrations >8.5 g/dL (Fig. 5). Norepinephrine dosages were not different between groups pre- and post-transfusion (Table 2).

## Discussion

The findings of the present study indicate a correlation between cerebral tissue oxygenation and blood loss-induced anemia and the subsequent effects of transfusion-induced changes of Hb concentrations in elderly patients undergoing intermediate- or high-risk noncardiac surgery. Substantial hemorrhage can occur during spine and hip surgeries.

Blood loss needs to be closely monitored through observation of the surgical field and calculations based on used sponges and collected volumes, but assessments are highly variable and affected by individual estimation [9]. Our study provides evidence that blood loss during hip and spine surgery and subsequent volume resuscitation

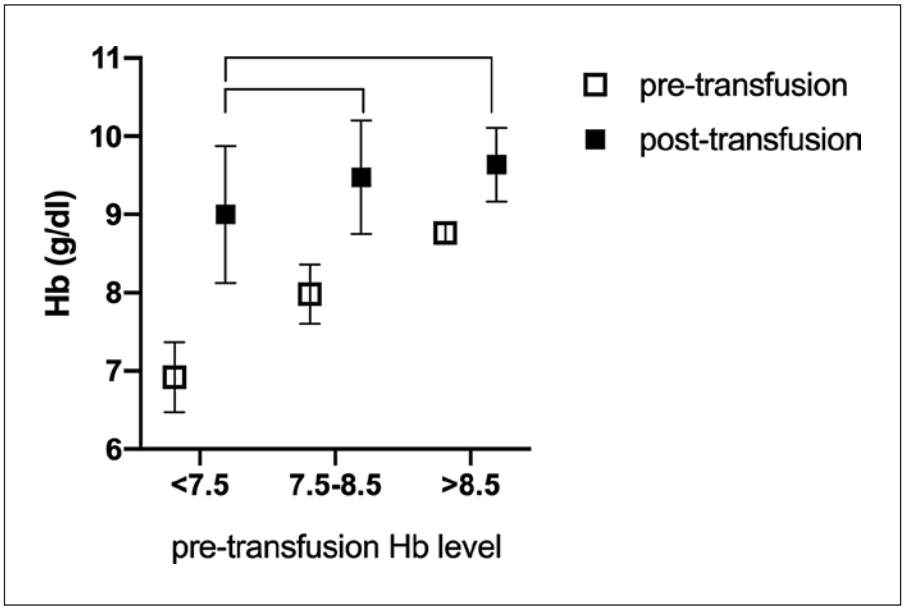


**Fig. 2.** Pre- and post-transfusion Hb concentrations in patients; RBC transfusion starting at Hb <7.5 g/dL, $n = 21$; 7.5–8.5 g/dL, $n = 21$; or >8 g/dL, $n = 25$. Data were analyzed using two-way ANOVA with Bonferroni post hoc analyses and expressed as mean ± SD. Lines indicate significant post-transfusion differences between groups ($p < 0.01$).

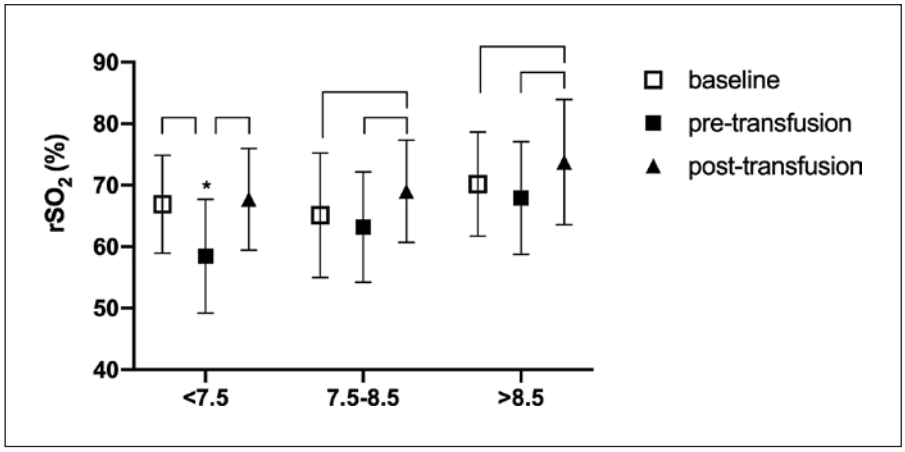


**Fig. 3.** $rSO_2$ values at baseline, pre-, and post-transfusion in patients; RBC transfusion starting at pre-transfusion Hb <7.5 g/dL, 7.5–8.5 g/dL, or >8.5 g/dL. Data were analyzed using two-way ANOVA with Bonferroni post hoc analyses and expressed as mean ± SD (<7.5 g/dL, $n = 21$; 7.5–8.5 g/dL, $n = 21$; >8.5 g/dL, $n = 25$; $p < 0.01$; *compared to >8.5 g/dL pre-transfusion; lines indicate significant post-transfusion differences between groups).

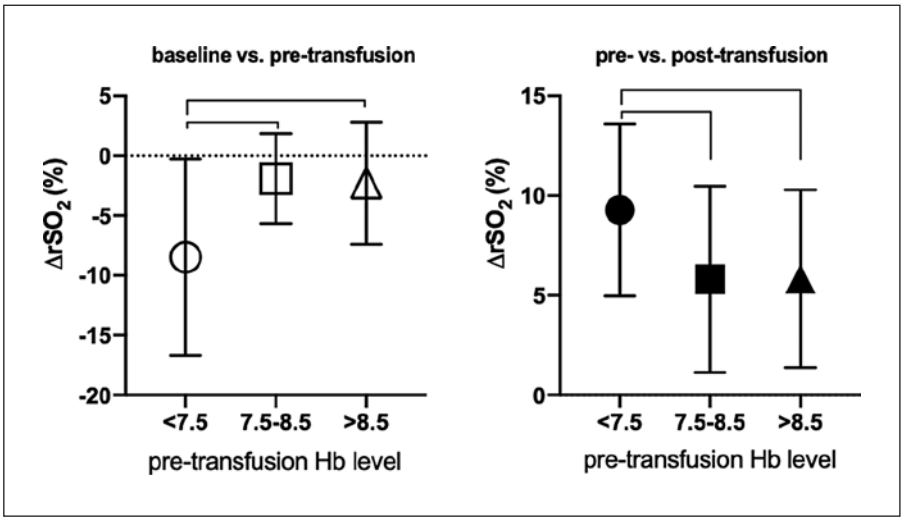


**Fig. 4.** $rSO_2$ changes from baseline to pre-transfusion (left panel) and pre- to post-transfusion (right panel) in patients receiving RBC transfusion starting at Hb <7.5 g/dL, 7.5–8.5 g/dL, or >8.5 g/dL. Data were analyzed using one-way ANOVA and expressed as mean ± SD (<7.5, $n = 21$; 7.5–8.5, $n = 21$; >8.5, $n = 25$; lines indicate significant post-transfusion differences between groups; $p < 0.01$).

using the corresponding volume led to a reduction of Hb, resulting in moderate to severe anemia that correlated with a reduction of NIRS-evaluated cerebral oxygen saturation.

TDM is based on the occurrence of transfusion triggers such as hemodynamic instability, lactemia, reduced mixed venous oxygenation, and reduced perfusion or deoxygenation of vital organs. However, anemia monitor-

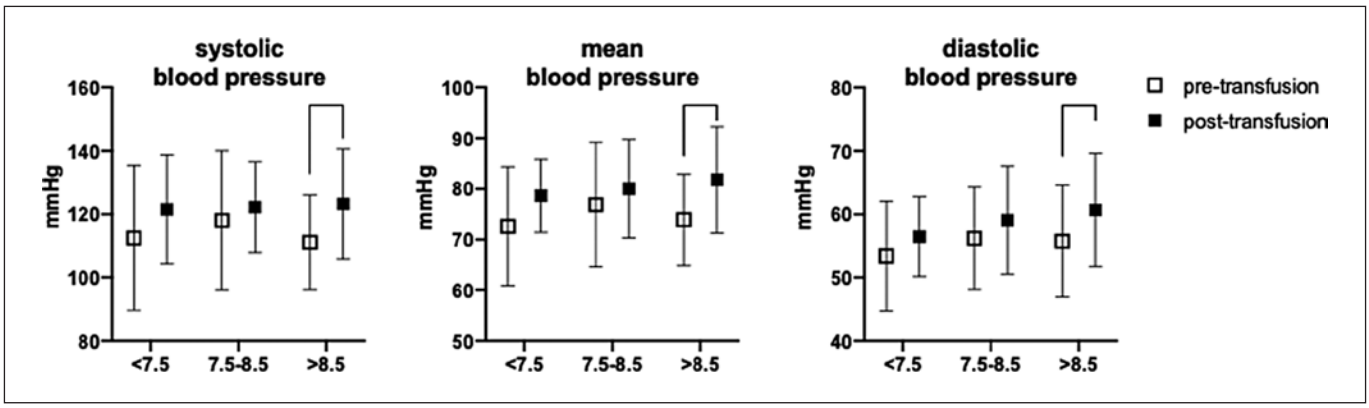


**Fig. 5.** Systolic, mean, and diastolic blood pressures assessed pre- and post-transfusion in patients receiving RBC transfusion starting at Hb <7.5 g/dL, 7.5–8.5 g/dL, or >8.5 g/dL. Data were analyzed using two-way ANOVA with Bonferroni post hoc analyses and expressed as mean ± SD (<7.5 g/dL, $n = 21$; 7.5–8.5 g/dL, $n = 21$; >8.5 g/dL, $n = 25$; lines indicate significant differences between pre- and post-transfusion; $p < 0.01$).

**Table 2.** Phenylephrine dosages in microgram per kilogram body weight pre- and post-transfusion were analyzed using one-way ANOVA with Bonferroni post hoc analyses and expressed as mean ± SEM ($p < 0.01$)

| | <7.5 g/dL | 7.5–8.5 g/dL | >8.5 g/dL | *p* value |
|---|---|---|---|---|
| Pre-transfusion norepinephrine dosage, µg/kg BW | 0.08±0.02 | 0.10±0.03 | 0.08±0.02 | ns |
| Post-transfusion norepinephrine dosage, µg/kg BW | 0.06±0.01 | 0.07±0.02 | 0.08±0.02 | ns |

ing includes hemoglobin/hematocrit measurements prior to transfusion that is performed in a point-of-care fashion using BGAs that provide stable Hb and Hct values using 1-2 mL blood volume [4, 10]. Although Hb can be frequently determined during major surgery with high amounts of blood loss, BGA are still irregularly performed upon clinical assessment. In contrast, NIRS-based perfusion and oxygenation monitoring provides a continuous and high granular evaluation of cerebral tissue oxygenation in the absence of any blood utilization. Most notably, information regarding the oxygenation status of this crucial tissue may help TDM and in the absence of cerebral desaturation and subsequent transfusion triggers potentially prevent unnecessary transfusion. High expenses of the NIRS optodes compared to BGAs need to be addressed. However, tissue oxygenation monitoring may be a great adjunct to Hb concentration in making a clinical decision for RBC transfusion, or most importantly against a transfusion within currently recommended limits. Prevention of RBC transfusion reduces the risk for postsurgical complications, and improves outcomes, all according to current WHO recommendations on PBM [11]. Subsequent studies are required to evaluate the impact of tissue oxygenation monitoring on the reduction of perioperative RBC transfusion.

While baseline NIRS values were not different between groups, cerebral oxygenation was significantly declined in patients with pre-transfusion Hb <7.5 g/dL compared to 7.5–8.5 and >8.5 g/dL. After transfusion, $rSO_2$ increased and no differences were observed between subgroups. These data suggest that a restrictive transfusion strategy in elderly patients may result in minor cerebral deoxygenation episodes prior to RBC transfusion while patients receiving RBC transfusion at higher pre-transfusion Hb levels did not show $rSO_2$ decrease. These findings are in accordance with previous studies performed in neonatal critical care and perioperative pediatric patients that report a RBC transfusion-induced increase in cerebral oxygenation and correlation between Hb concentration and tissue oxygenation [12, 13]. Alternatively, Aktas and colleagues did not observe a transfusion-induced increase in cerebral oxygenation in neonatal intensive care patients, while abdominal and renal $rSO_2$ values increased after transfusion [14]. However, according to their study protocol NIRS values were assessed 24 h after transfusion and compared to pre-transfusion values, and cerebral changes could be more pronounced in the acute setting. Also, compensatory mechanisms may initiate within hours that maintain cerebral oxygenation at lower level. Our subanalysis focused on acute anemia due to acute surgery-related blood loss and transfusion in the perioperative setting where observed differences in cerebral oxygenation are likely to occur before compensatory mechanism is effective. Similar to the studies in neonatal intensive care

patients [14, 15], the most pronounced transfusion-induced increases in cerebral oxygenation were observed in patients with lower pre-transfusion Hb level <7.5 g/dL, potentially indicating physiologic severe anemia levels.

The observation that reduction in blood pressure was accompanied by a reduction in cerebral oxygenation has been reported in previous studies and the autoregulatory mechanisms of cerebral perfusion may be involved in this observation [16]. Furthermore, vasopressor treatment affects hemodynamics and tissue oxygenation in anesthetized patients [17]. However, the herein used norepinephrine dosages were not different between groups pre- and post-transfusion and are therefore unlikely to be responsible for rScO2 differences, but the assessment of physiological mechanisms of cerebral autoregulation is beyond the scope of our investigation.

NIRS evaluation of rScO2 provides an individual trend of tissue oxygen availability. Although the individual trend is precise, interindividual measurements are markedly variable; thus, this method has its limitations in the ratio of oxygen supply to oxygen consumption that need to be addressed. However, NIRS-evaluated tissue oxygenation has been proposed as an alternative method for TDM in pediatric intensive care patients [18]. However, the impact of NIRS on tissue oxygenation in the elderly patients has not yet been evaluated. Although noninvasive methods for Hb measurement tend to be inferior to invasive BGA, our data indicate that NIRS provides continuous information of cerebral oxygenation and has the potential to detect rapid changes during major surgery potentially being related to a critical Hb concentration without frequent utilization of patients' blood. TDM is an individual assessment that is based on the occurrence of distinct transfusion triggers and should not be made based on Hb values only [19, 20]. Therefore, a continuous monitoring that is not only providing changes in Hb concentration but also postulating information concerning the oxygen saturation and more important critical desaturation of a vulnerable tissue such as the brain seems reasonable as an individualized perioperative RBC transfusion strategy.

While acute severe normovolemic anemia at hemoglobin level between 6 and 5 g/dL is associated with cognitive dysfunction [21], intraoperative decreases in NIRS have also been shown to correlate with postoperative cognitive dysfunction, and a patient-specific algorithm that incorporates cerebral NIRS monitoring and a restrictive RBC transfusion threshold improve clinical outcomes while reducing costs [22, 23]. Further studies are required to investigate the potential of perioperative NIRS evaluation and prevention of cerebral deoxygenation through RBC transfusion on postoperative cognitive dysfunction in elderly patients undergoing major noncardiac surgery.

There are some limitations that need to be addressed. First of all, this is a sub-study to the ongoing multicenter LIBERAL-Trial. Therefore, the sample size was not calculated for the primary outcome and our results are exploratory. Second, the data are just from one single center and the number of patients is limited. However, our results show a stable and significant effect and to the best of our knowledge this is the first study reporting a correlation between perioperative anemia and NIRS in elderly patients undergoing noncardiac surgery. Further studies are required to investigate the potential prevention of postoperative cognitive dysfunction through the prevention of perioperative cerebral desaturation.

## Conclusions

In conclusion, cerebral oxygenation monitoring by NIRS indicates cerebral desaturation, but also provides valuable information regarding perioperative alterations in Hb concentration, implying blood loss-induced anemia, potentially providing the clinician information when anemia-related impaired oxygenation is still compensated or transfusion may be indicated, in the context of individualized medicine. Transfusion-induced increases in cerebral oxygenation are more pronounced at lower pre-transfusion Hb level. Further studies are required to investigate the impact of cerebral oxygenation measurement on individual TDM in the perioperative setting, potentially preventing postoperative cognitive dysfunction.

## Statement of Ethics

This study protocol was reviewed and approved by the Institutional Review Board of the Rheinische Friedrich-Wilhelms-University Bonn (Ref: 096/17-AMG) and the federal authority (Paul-Ehrlich-Institute) LIBERAL-Trial (NCT03369210). Written informed consent was obtained from all participants before being included into the study.

## Conflict of Interest Statement

The authors have no conflicts of interest to declare.


## Funding Sources

This work was funded by the German Research Foundation (Deutsche Forschungsgemeinschaft; Grant No. ME 3559/3–1).


## Author Contributions

Conceptualization: Patrick Meybohm, Markus Velten, and Maria Wittmann; data curation: Achilles Delis, Derek Bautz, Thomas M. Randau, Andreas C. Strauss, Ivana Habicht, and Erdem Güresir; formal analysis: Heidi Ehrentraut, Karin Doll, Hol-

ger Bogatsch, and Peter Kranke; investigation and visualization: Achilles Delis and Derek Bautz; project administration: Patrick Meybohm, Markus Velten, Maria Wittmann, Holger Bogatsch, and Peter Kranke; supervision: Heidi Ehrentraut, Karin Doll, and Holger Bogatsch; writing – original draft: Markus Velten and Patrick Meybohm; and writing – review and editing: Maria Wittmann, Achilles Delis, Derek Bautz, Thomas M. Randau, Andreas C. Strauss, Ivana Habicht, Erdem Güresir, Heidi Ehrentraut, Karin Doll, Holger Bogatsch, and Peter Kranke.

## Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

## References


1 Anderson SA, Menis M, O'Connell K, Burwen DR. Blood use by inpatient elderly population in the United States. Transfusion. 2007 Apr;47(4):582–92.
2 Cobain TJ, Vamvakas EC, Wells A, Titlestad K. A survey of the demographics of blood use. Transfus Med. 2007 Feb;17(1):1–15.
3 Khanna MP, Hébert PC, Fergusson DA. Review of the clinical practice literature on patient characteristics associated with perioperative allogeneic red blood cell transfusion. Transfus Med Rev. 2003 Apr;17(2):110–9.
4 American Society of Anesthesiologists Task Force on Perioperative Blood Management. Practice guidelines for perioperative blood management: an updated report by the American society of anesthesiologists task force on perioperative blood management. Anesthesiology. 2015 Feb;122(2):241–75.
5 Ikeda K, MacLeod DB, Grocott HP, Moretti EW, Ames W, Vacchiano C. The accuracy of a near-infrared spectroscopy cerebral oximetry device and its potential value for estimating jugular venous oxygen saturation. Anesth Analg. 2014 Dec;119(6):1381–92.
6 Marin T, Moore J. Understanding near-infrared spectroscopy. Adv Neonatal Care. 2011 Dec;11(6):382–8.
7 Habicher M, Zajonz T, Heringlake M, Böning A, Treskatsch S, Schirmer U, et al. S3 guidelines on intensive medical care of cardiac surgery patients: hemodynamic monitoring and cardiovascular system-an update. Anaesthesist. 2018 May;67(5):375–9.
8 Meybohm P, Lindau S, Treskatsch S, Francis R, Spies C, Velten M, et al. Liberal transfusion strategy to prevent mortality and anaemia-associated, ischaemic events in elderly non-cardiac surgical patients: the study design of the LIBERAL-Trial. Trials. 2019 Feb 4;20(1):101.
9 Gerdessen L, Meybohm P, Choorapoikayil S, Herrmann E, Taeuber I, Neef V, et al. Comparison of common perioperative blood loss estimation techniques: a systematic review and meta-analysis. J Clin Monit Comput. 2021 Apr;35(2):245–58.
10 Tanner L, Lindau S, Velten M, Schlesinger T, Wittmann M, Kranke P, et al. Factors influencing the bias between blood gas analysis versus central laboratory hemoglobin testing. A secondary analysis of a randomized controlled trial. PLoS One. 2020;15(10):e0240721.
11 Schmitt E, Meybohm P, Neef V, Baumgarten P, Bayer A, Choorapoikayil S, et al. Preoperative anaemia and red blood cell transfusion in patients with aneurysmal subarachnoid and intracerebral haemorrhage: a multicentre subanalysis of the German PBM Network Registry. Acta Neurochir. 2022 Apr;164(4):985–99.
12 Goldstein GP, Rao A, Ling AY, Ding VY, Chang IJ, Chock VY. Influence of enteral feeding and anemia on tissue oxygen extraction after red blood cell transfusion in preterm infants. Transfusion. 2020 Mar;60(3):466–72.
13 Whitehead HV, Vesoulis ZA, Maheshwari A, Rao R, Mathur AM. Anemia of prematurity and cerebral near-infrared spectroscopy: should transfusion thresholds in preterm infants be revised? J Perinatol. 2018 Aug;38(8):1022–9.
14 Aktas S, Ergenekon E, Ozcan E, Aksu M, Unal S, Hirfanoglu IM, et al. Effects of blood transfusion on regional tissue oxygenation in preterm newborns are dependent on the degree of anaemia. J Paediatr Child Health. 2019 Oct;55(10):1209–13.
15 Koyano K, Kusaka T, Nakamura S, Nakamura M, Konishi Y, Miki T, et al. The effect of blood transfusion on cerebral hemodynamics in preterm infants. Transfusion. 2013 Jul;53(7):1459–67.
16 Liu L, Qiang Z, Zhang J, Ren Y, Zhao X, Fu W, et al. Effect of hemoglobin content on cerebral oxygen saturation during surgery for scoliosis in pediatric patients. BMC Anesthesiol. 2021 Jun 1;21(1):165.
17 Meng L, Cannesson M, Alexander BS, Yu Z, Kain ZN, Cerussi AE, et al. Effect of phenylephrine and ephedrine bolus treatment on cerebral oxygenation in anaesthetized patients. Br J Anaesth. 2011 Aug;107(2):209–17.
18 Markham C, Small S, Hovmand P, Doctor A. Transfusion decision making in pediatric critical illness. Pediatr Clin North Am. 2017 Oct;64(5):991–1015.
19 Causey MW, Miller S, Foster A, Beekley A, Zenger D, Martin M. Validation of noninvasive hemoglobin measurements using the masimo radical-7 SpHb station. Am J Surg. 2011 May;201(5):592–8.
20 Lamhaut L, Apriotesei R, Combes X, Lejay M, Carli P, Vivien B. Comparison of the accuracy of noninvasive hemoglobin monitoring by spectrophotometry (SpHb) and HemoCue® with automated laboratory hemoglobin measurement. Anesthesiology. 2011 Sep;115(3):548–54.
21 Weiskopf RB, Kramer JH, Viele M, Neumann M, Feiner JR, Watson JJ, et al. Acute severe isovolemic anemia impairs cognitive function and memory in humans. Anesthesiology. 2000 Jun;92(6):1646–52.
22 Ellis L, Murphy GJ, Culliford L, Dreyer L, Clayton G, Downes R, et al. The effect of patient-specific cerebral oxygenation monitoring on postoperative cognitive function: a multicenter randomized controlled trial. JMIR Res Protoc. 2015 Dec 18;4(4):e137.
23 Soenarto RF, Hidayat JK, Eureka O, Auerkari AN. Can Near-Infrared Spectroscopy (NIRS) monitoring prevent post-operative cognitive dysfunction following open- heart surgery? J Pak Med Assoc. 2021 Feb;71(Suppl 22):S10–3.