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Cerebral Autoregulation Assessment through Near-Infrared Spectroscopy and Arterial Monitoring: Advancements and Clinical Implications

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Abstract: Cerebral autoregulation, maintaining stable cerebral blood flow across varying arterial pressures, is vital in-patient care during surgery. Traditional views suggest a mean arterial pressure range of 50-150 mm Hg for effective autoregulation. However, patient-specific variations in autoregulatory patterns, particularly in cases of impaired autoregulation, call for personalized hemodynamic and blood pressure management during surgical procedures. In the evaluation of cerebral autoregulation, NIRS serves as a beneficial monitoring tool. The cerebral oximetry index, correlating cerebral oxygen saturation with perfusion pressure, aids in determining autoregulation limits. The literature shows varying impacts of vasoactive drugs on patients with different autoregulatory responses, emphasizing the need for individualized care. In summary, NIRS is crucial for monitoring cerebral autoregulation, and adjusting arterial blood pressure targets based on NIRS data could improve prevention of cerebral hyper/hypoperfusion. This approach, moving away from a generalized strategy, advocates for a more customized, physiology-based patient management. ©2024 NTMS.

Keywords: Cerebral Oxymetry; Near Infrared Spectroscopy; Cerebral Autoregulation.

1. Introduction

Monitoring oxygenation at the tissue level has been a prominent research focus in the field of clinical medicine for many years. Significant progress, including the development of the ear oximeter in the 1940s and the pulse oximeter in the 1970s, has been made in this field. These technologies are crucial for advancing cerebral oximetry by enhancing our understanding of how tissues, such as bone, interact with light in the near-infrared region [1]. Using near-infrared spectroscopy (NIRS) technology, it is possible to continuously and non-invasively monitor the level of oxygen saturation in a specific part of the frontal cortex. The implementation of these technology advancements has dramatically enhanced the quality of patient care in both cardiac and non-cardiac surgical procedures, as well as in critical care environments [2-4]. There is significant discussion about the possibility of cerebral oximetry monitoring being a regular anesthesiology practice in the near future [5]. The objective of this review is to examine the correlation between monitoring

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arterial hemodynamics and cerebral oximetry, with a particular focus on cerebral autoregulation.

1.1. Near-Infrared Spectroscopy

Near Infrared Spectroscopy is a commonly employed non-invasive technique in clinical practice. The method employs near-infrared light measurement within the range of 650-940 nm wavelengths to determine the cerebral oxygen saturation. The emitted light passes through the scalp and the underlying cerebral tissues, allowing for the assessment of regional oxygen saturation based on the difference between oxyhemoglobin and deoxyhemoglobin [6]. The system consists of two optodes, with one optode penetrating into superficial tissue at a depth of 3cm and the other optode penetrating into deep tissue at a depth of 4cm. Unlike the pulse oximeter, which predominantly monitors the arterial blood flow, the regional cerebral oxygen saturation (rScO2) value acquired using NIRS is derived from venous blood, which constitutes 70-75% of the blood flow in brain tissue [7].

Current challenges in NIRS technology are extracerebral signal contamination. NIRS signals can be affected by both intracerebral (non-hemoglobin chromophores, non-metabolized tissue oxygen saturation including capacitance veins) and extracerebral components, impacting accuracy. To address this, advanced algorithms are being developed to minimize extracerebral interference and enhance signal specificity. Spatial resolution is one of these. NIRS has limited spatial resolution, hindering precise localization of cerebral activity. Research on higher-resolution NIRS technologies or complementary imaging techniques to refine spatial accuracy is ongoing. Advances in the spatial techniques is slow due to restrictions on NIRS depth penetration, affecting monitoring in deeper brain structures. Also, variability in cerebral blood flow among individual patients challenges standardization. Although studies are conducted in volunteers and several critical patients, there is still need for establishing individualized baseline values for more accurate interpretation. Finally, fixed assumptions about the cerebral veno-arterial blood ratio affects the accuracy of NIRS techniques [8, 9, 10].

Near-infrared spectroscopy (NIRS) plays a critical role not only in monitoring cerebral perfusion but also in tracking the perfusion of the renal system and spinal cord. Although the fundamental limitation is the distance of subcutaneous tissue to the target structure, its use is highly beneficial in patients where this distance is suitable, especially in the pediatric population or in patients with low adipose tissue.

It is possible that near future may see advancements in multimodal imaging integration, improved signal processing techniques, machine learning applications, quantitative biomarkers, miniaturization and wearable devices.

1.2. Cerebral Autoregulation

Lasen described an auto-regulation plateau range of mean arterial blood pressures (MAP) between 50-150 mm Hg in young patients.[11] 8 At this plateau level, cerebral blood flow (CBF) is actively regulated by myogenic regulation of small cerebral arteries and arterioles and remains constant. When blood pressure exceeds these thresholds, the ability of myogenic vaso activity to adjust to these alterations is compromised, resulting in a correlation between CBF and blood pressure.

Although it remains valid due to its basic defining characteristics, it is recognized that CBF regulation involves a multitude of parameters beyond just blood pressure. It has been accepted that autoregulation mechanisms may be affected in certain situations, such as pharmacological medications and alterations in carbon dioxide levels of various diseases, such as prematurity [12-15]. However, in the presence of impaired autoregulation, there can still exist an optimal blood pressure range where the autoregulatory function is at its peak. Determining the optimal range of cerebral perfusion and personalizing blood pressure goals may shift the current clinical paradigm away from 'one size fits all' towards individualized, patient-specific, physiology-based blood pressure management.

Within the context of traditional knowledge, it is commonly recognized that a perfusion pressure of 50-60 mmHg in the arterial blood is considered acceptable during cardiopulmonary bypass (CPB) for patients undergoing cardiac surgery. However, studies have demonstrated that 35% of patients undergoing cardiac surgery show impaired cerebral autoregulation [15].

The mean arterial pressure, which constitutes the lower level of autoregulation, exhibits a significant range of variation ranging from 40 to 90 mmHg [16]. Consequently, as determined through the empirical selection of MAP goals, patients may experience different durations of time with MAP levels below the lower threshold of autoregulation during CPB.

1.3. NIRS Monitoring in the Evaluation of Cerebral Autoregulation

The cerebral oximetry index is obtained by calculating the Pearson correlation coefficient between cerebral oxygen saturation and perfusion pressure. In an optimal autoregulation curve, it is anticipated that this index will be less than 0.3 at the limits of autoregulation. Outside the limits of autoregulation, this correlation increases [17] (Figure 1).

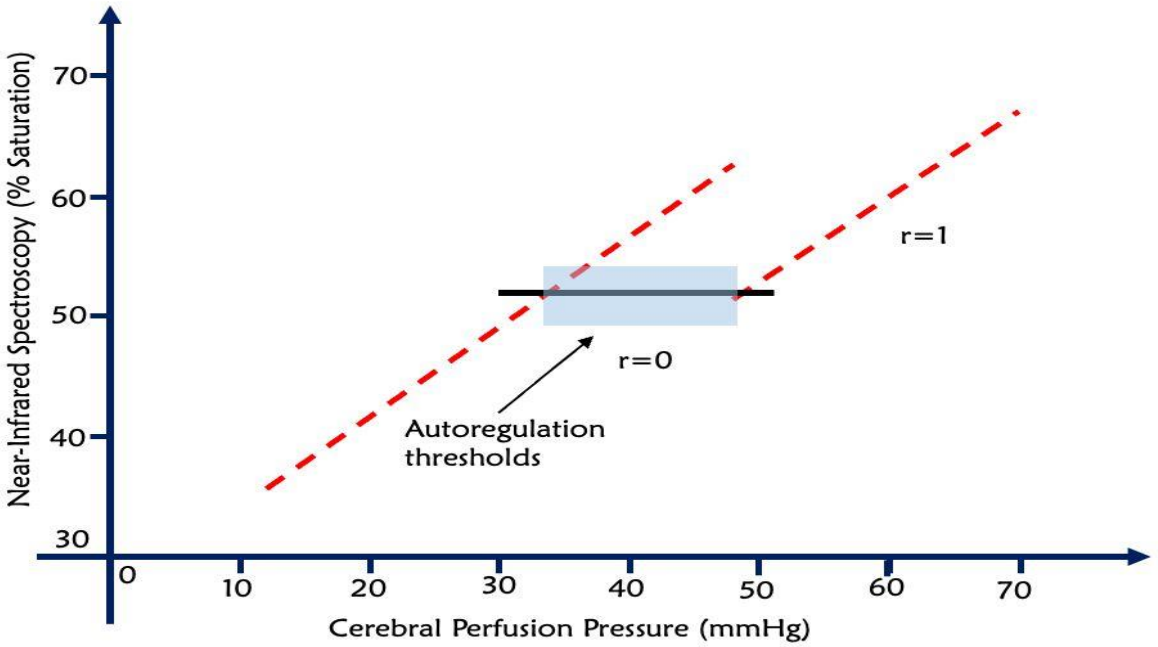

Figure 1: Calculation of Pearson correlation coefficient between cerebral oxygen saturation and perfusion pressure.

Brady demonstrated in his experimental investigation through a comparison of cerebral oximeter index (COx) and laser doppler (LDx) that spontaneous autoregulatory vasoreactivity can be assessed using the time-domain correlation between arterial blood pressure (ABP) and cerebral oximetry [18]. LDx-COx results were consistent, showing low values above and high values below a cerebral perfusion pressure (CPP) of 35 mmHg. In addition, LDx and COx changes showed a close correlation with every 5 mmHg increase in CPP.

1.4. Evaluation of Different Cerebral Autoregulation Patterns with NIRS

It is predictable and interpretable how blood pressure values outside these narrow autoregulation limits affect the cerebral perfusion of a patient with impaired cerebral autoregulation. In the NIRS monitoring algorithmic approach, the initial step in the course of cerebral desaturation is to increase MAP [19]. Demir et al. obtained an individual blood pressure value in a malignant hypertensive renal transplantation patient where cerebral autoregulation could be achieved by increasing the MAP upon developing cerebral desaturation when the patient became normotensive [20]. Nevertheless, individuals with normal cerebral autoregulation may exhibit paradoxical reactions in various hemodynamic situations [21].

Moerman et al. studied the COx using NIRS in 34 cardiac surgery patients, following the administration of phenylephrine and sodium nitroprusside [15]. COx was higher than 0.3 in 35% of the patients and remained similar after the administration of vasoactive drugs. Patients with impaired cerebral autoregulation were characterized by a pressure-passive cerebral circulation. In 18% of the patients, COx demonstrated a classic autoregulation pattern, remaining at 0 levels with both baseline and after vasoactive drug administration. However, in 10 patients with intact baseline autoregulation, following the administration of phenylephrine or sodium nitroprusside, cerebral blood flow was reduced, and COx became negative. Futhermore, in 6 patients with intact baseline autoregulation, cerebral blood flow decreased (COx became negative) after the administration of phenylephrine. Conversely, after the administration of sodium nitroprusside, COx increased above 0.3, resulting in an increase in cerebral blood flow. This group was defined by the divergent effects of vasoactive drugs.

2. Conclusions

The conventional definition of cerebral autoregulation is limited in its ability to capture the entire concept fully. The primary objective of cerebral oximetry monitoring extends beyond identifying impaired autoregulation. Studies have shown that patients with normal cerebral autoregulation may have paradoxical responses to commonly used medicines in our routine anesthetic procedures.

Variations in autoregulatory patterns directly affect the determination of blood pressure goals and the management of hemodynamics during surgery. Modifying arterial blood pressure targets through NIRS-based cerebral autoregulation monitoring could be a more efficient approach to preventing cerebral hyper/hypoperfusion than the current standard of treatment.

Limitations of the Study

This review acknowledges several limitations that may

impact the generalizability and applicability of its literary findings. Firstly, the reliance on near-infrared spectroscopy (NIRS) for the assessment of cerebral autoregulation, while valuable, presents inherent limitations in terms of sensitivity and specificity. NIRS data can be affected by extraneous factors such as movement artifacts and variations in skin pigmentation, potentially leading to variability in the measurements. Secondly, this review inherently draws heavily from existing literature and theoretical frameworks, which may not fully capture the complexity and individual variability of autoregulatory mechanisms in different patient populations. Additionally, the effects of various vasoactive drugs on cerebral autoregulation have been discussed; however, the adequacy of existing experimental or clinical study data to validate these claims remains debatable. Lastly, the emphasis on personalized hemodynamic management necessitates advanced monitoring equipment and expertise, which may not be readily available in all clinical settings, potentially limiting the widespread applicability of these recommendations. Addressing these limitations in future research could enhance the accuracy and applicability of NIRS-based monitoring in clinical management.

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None.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

Consent to participate

None.

Informed Statement

None.

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