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Clinical Application of Near Infrared Blood Oxygen Monitoring in Cervical Spinal Cord Injury

Jamal Alshorman[1]*, Ruba Altahla[2], Gao Yana[1], Liu Xiangyan[1]

Abstract

Background: It has always been a challenge for orthopedic surgeons worldwide, to detect the blood flow after cervical spinal cord injury (CSCI). How to non-invasively, real time, and quantitatively evaluate the blood supply and injury degree of the spinal cord during the operation, and how to guide the selection of laminectomy and durotomy?

Objective: To investigate the feasibility of using NIR-SO_2 (Near infrared light-Oxygen saturation) monitoring for CSCI and to determine whether NIR can provide a non-invasive, real time, and quantitative assessment of the degree of spinal cord decompression and the need for a durotomy.

Methods: This study collected 37 CSCI cases from June 2023 to October 2024. Inclusion criteria: patients aged >18 years; patients with cervical fracture and/or dislocation, ASIA grades A, B, and C; treated with a posterior approach. Exclusion criteria: patients aged <18 years; ASIA grade D or E, no cervical fracture and/or dislocation; SCI treated conservatively; patients with normal MRI and no neurological symptoms; patients with spinal tumors. However, apply NIR-SO_2 technology to detect regional SO_2 under light-proof conditions.

Results: This study collected 37 patients; 23 males (62.2%) and 14 females (37.8%). The patients' ages was 51.4±9.7 years. The admission-to-operation time was 51.9±9.1 hours. The ASIA grades improved during the last follow-up. The NIR-SO2 in 22 patients before laminectomy was 53.7±1.6%, and after laminectomy was 65.1±1.6% (P<0.01). Therefore, in 15 patients before laminectomy, the NIR-SO2 was 39.7±1.6%, improving to 42.3±2.6% after laminectomy and increasing to 62.7±3.1% after durotomy and duroplasty with a statistical difference before and after durotomy (P<0.01).

Conclusion: NIR-SO_2 technology is safe and feasible and directly reflects the improvement of spinal cord blood supply. NIR-SO_2 technology can monitor the regional SO_2 of CSCI patients and assess spinal cord perfusion and compression in real time.

Keywords: Near-infrared light; Blood oxygen saturation; Cervical spinal cord injury; Laminectomy; Durotomy

Introduction

Several problems and difficulties remain associated with the diagnosis and treatment of CSCI. To manage CSCI effectively, early and adequate decompression is crucial [1, 2]. However, there is no uniform standard on whether further spinal canal decompression or even durotomy is necessary

Affiliation:

[1]Department of Orthopedics, The Second Affiliated Hospital, Hubei University of Science and Technology, Xiangning 437100, China

[2]Department of Rehabilitation, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan 430030, China

***Corresponding author:**
Jamal Alshorman: Orthopedcis department of the Second Affiliated Hospital, Clinical Medical College, Hubei University of Science and Technology, Xianning 437100, Hubei, China.

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following fracture reduction and internal fixation, particularly since a quantitative and non-invasive assessment method is not available to assess the blood supply to the spinal cord. Spinal cord decompression aims to relieve spinal cord compression, restore spinal cord blood flow, and improve the prognosis [3, 4].

Assessing the degree of spinal cord blood perfusion, ischemia, and hypoxia is essential for determining the degree of CSCI, selecting treatment modalities, and evaluating outcomes and prognosis. An important factor in the decision to decompress a patient with CSCI is the patient's preoperative signs and symptoms, CT, MRI, and intraoperative dural pulsation. The posterior approach is the main choice if MRI indicates extensive edema, hematoma, or softening foci. However, performed further durotomy if the dura is still not pulsating after laminectomy or there is a subdural hematoma (dural darkening).

However, these criteria are sometimes invasive; when the dura mater is thick, about a 3 mm incision through the intact arachnoid is required to observe and confirm the presence of a hematoma. However, it remains a clinical challenge to monitor the local blood flow in a non-invasive, real time manner and assess whether the spinal cord's blood perfusion has improved and the decompression is completed. Invasive mean arterial and intradural pressure measurements have been indirectly used to extrapolate spinal cord perfusion pressure. For example, optical devices such as spectroscopy have been used to examine spinal blood flow and show real time blood flow. However, many risks are associated with the prolonged insertion of probes on the spinal surface, including aggravation of CSCI degree, risk of infection, and material toxicity [5]. Doppler ultrasound (US) is a non-invasive method for detecting blood flow, but it is not-real time and single-point monitoring with significant limitations [6]. On the other hand, NIR is a non-destructive method for monitoring the SO_2 level in various organs and tissues; it can continuously monitor cerebral perfusion status. Nevertheless, it has not been investigated whether NIR can be used to guide treatment for CSCI [7-10].

Treatment options for traumatized CSCI can result in poor outcomes. However, some patients improve with laminectomies, while others need durotomy with duroplasty. Durotomy-duroplasty may reduce intraspinal pressure (ISP) to avoid spinal cord compartment syndrome (SCCS) and improve spinal cord perfusion pressure (SCPP) [1, 11-14]. Durotomy can significantly restore cerebrospinal fluid (CSF) circulation, decrease intradural pressure, prevent edema, and treat the symptoms of SCCS [3, 4]. Some surgeons do not recommend performing a durotomy after a laminectomy because of the associated risks and complications. Yet, laminectomy alone cannot provide valuable results in some circumstances. The surgical intervention aims to improve blood flow at the injury site and achieve significant outcomes. However, CSF pulses do not recover after laminectomy in up to 25% of cases, while CSF pulses recover post-durotomy in approximately 75% of cases [3, 4, 13].

Many techniques are used to predict spinal cord blood flow, including mean arterial pressure (MAP), and postoperative ISP monitoring, optic device spectrectomy, NIR [7, 15-17]. Thus, NIR can be a helpful technique for checking blood flow in CSCI patients, ensuring the effectiveness of the surgical procedure, and predicting the prognosis [8, 9]. Due to these advantages, NIR is a convenient method, does not require sample preparation, requires a minimum strength, is less costly, painless, securely transfers data, and can be performed on children and adults. For an accurate prognosis and to avoid complications related to durotomies, it is imperative to find a safe and simple technique that provides more details about the return of blood flow in real time during the operation [1, 18]. Three main questions for patients with CSCI still exist clinically. Do these include how to improve blood flow? Whether laminectomy or durotomy should be performed, and how to monitor blood flow at the injury site?

Method

NIR-SO_2 Measurement

This study used the NIR-SO_2 technique in a non-invasive and real time manner to assess whether the spinal cord blood perfusion improved and decompression completed after laminectomy or if the patient required further durotomy with duroplasty. The patients were selected according to the inclusion criteria, which included patients with: traumatic CSCI, fracture and dislocation, >18 years old, patients with edema, hematoma, or contusion, and ASIA grades A, B, and C. In contrast, exclusion criteria included patients without fracture or dislocation, patients <18 years old, SCI treated conservatively, normal MRI and no neurological symptoms, patients with spinal tumors, and ASIA D or E.

The dural pulse was checked after the laminectomy procedure to assess blood reperfusion with a direct vision to confirm the existence of hematoma. However, to check the presence of hematoma when the dura is thick (dark), an about 3 mm incision was made. Moreover, inserted the probe to determine local blood SO_2 and microvascular blood flow. However, spinal blood SO_2 was determined in the dark and approximately 1 cm from the dural sac. Fibular flaps 295 are used to monitor the SO2 profiles of buried transferred tissue accurately and quickly at different tissue depths. The NIR probes are divided into 2 types (type A and type B) to meet the requirements of different age groups. According to NIR-SO_2, no dural decompression is required if the spinal cord blood SO2 level is between (58%~68%) (Figure 1). However, a durotomy with duroplasty is required if SO_2 <58%.

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Ensure the Benefits of NIR

The dura was observed under direct vision to ensure the NIR advantages. Moreover, CSF pulse and dura darkening (hematoma beneath the dura) were examined to ensure no hematoma under the dura. In some cases, when the dura is thick, an incision of about 3 mm is necessary to confirm the existence of a hematoma, even though this method is noninvasive. The pulse and dura observation correlated positively with NIR-SO_2 and indicated the need for a durotomy or extensive laminectomy. After laminectomy, if no dural pulsation is seen, the dura should be opened to confirm the spinal cord's arachnoid membrane and internal pathological changes. In addition, the dura should be opened to check whether spinal cord surface hematoma is present.

Data analysis

Using IBM SPSS version 22 to analyze the results by t-test. Compared patients' age, gender, and follow-up time. In addition, analyzed the initial and final ASIA, sensory and motor functions, SO_2 values, and operation time. The mean and average were used for comparison values at different times and calculated the percentage for categorical data.

Ethics approval and consent to participate

The Ethics Committee of Clinical Medical College of Hubei University of Science and Technology granted approval for this study, Hbust-IRP202302001.

Working Principle of NIR-SO_2 Monitoring

The wavelength of NIR between 700~900 nm can detect blood and brain SO2. The NIR technique has acceptable tissue (skin, fat, and bone) penetrability and can detect blood oxygen parameters at a specific site. The measured parameters included local tissue SO_2, regional hemoglobin, regional oxy-hemoglobin concentration, and local tissue changes in total hemoglobin concentration. The NIR light penetrates tissues and reaches the injury site; the probe has 2 sides, 1 to send the light and the other as a detector. The SO_2 is collected continuously in real time, and there is no need to indirectly infer SO2 levels in topical tissues through the whole body's blood oxygen parameters.

Based on the fact that certain materials, including plants and human tissues, absorb light very efficiently in the NIR range of the electromagnetic spectrum. This allows the use of NIR light for a variety of applications, such as medical imaging, spectroscopy, and agricultural research. In medical imaging, NIR can create images of internal structures and blood flow in the body. Hemoglobin in the blood absorbs light, allowing indirect visualization of blood vessels and other structures (Figure 1).

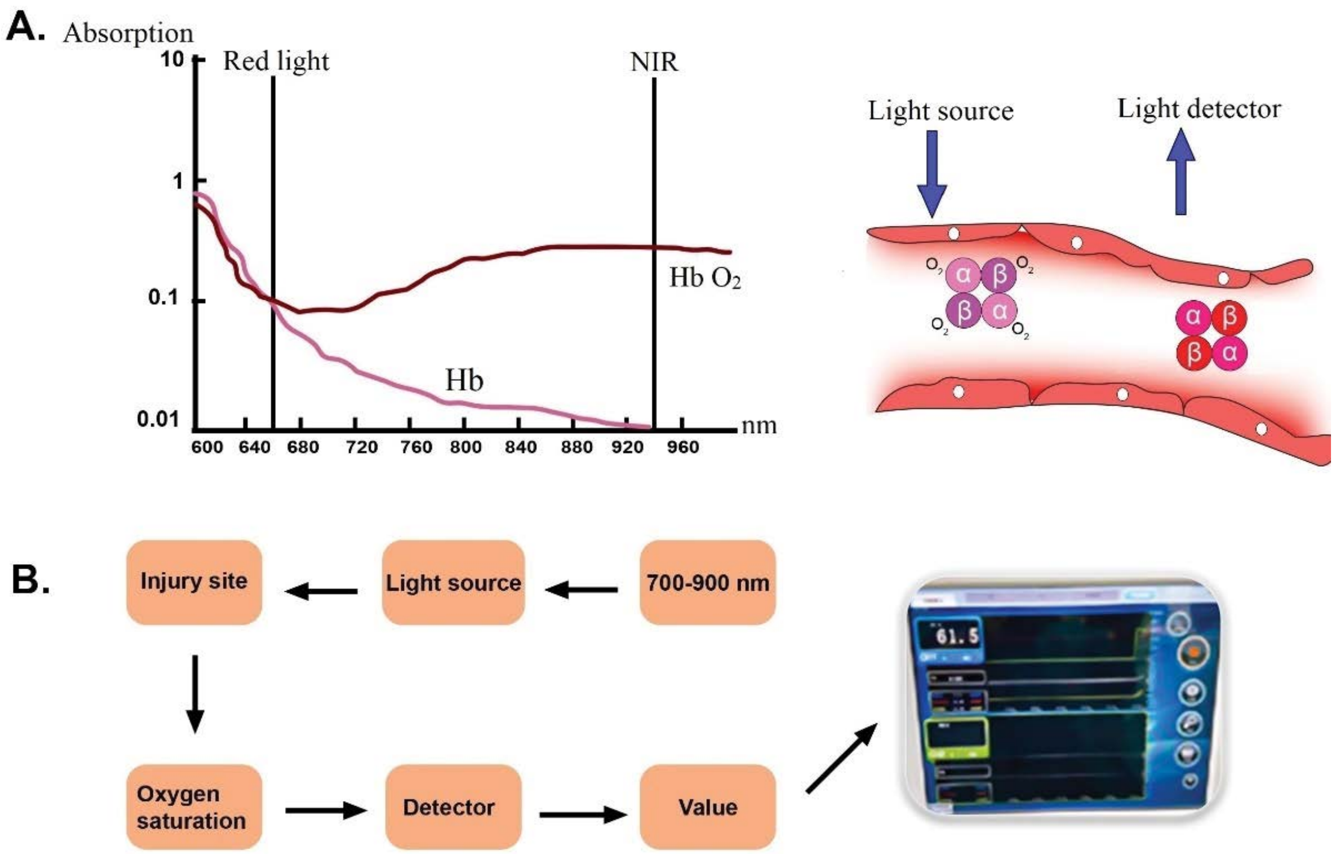

Figure 1: A: Showing the NIR technique: Oxyhemoglobin has a higher affinity for NIR between 700~900 nm. B: Showing the process of inserting the NIR probe and the SO_2 value

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Oxygenated and deoxygenated configurations lead to different electromagnetic absorption with different light emissions. The difference in the absorption and light emission of oxygenated and deoxygenated Hb is the principle of using the NIR. While oxygenated hemoglobin absorbs a greater amount of infrared light and allows a greater amount of red light to pass through, deoxygenated hemoglobin absorbs a significant amount of infrared light and a substantial amount of red light. The detector generates SO_2 values based on this ratio.

Results

General information

Between June 2023 and October 2024, 23/37 patients were male (62.2%), and 14 were female (37.8%). The patient's age was 51.4±9.7 years). The common MOIs were fall in 17 patients (46.0%), RTA in 15 (40.5%), and falling objects in 5 (13.5%). Admission to operation time ranged from 38~73 hrs with a mean of 51.9±9.1 hrs. (Table 2 and Table 3)

Table 1: Type of surgery and SO2 measurements for 37 patients. "First SO_2" refers to the values measured before laminectomy, "Second SO_2" refers to the values measured after laminectomy, and "Third SO_2" refers to the values measured after durotomy. "na" refers to the failure to perform a durotomy and measure a third SO2 because SO2 has reached the reference range after only a laminectomy

Patients number	Age	Initial ASIA	Final ASIA	Mechanism of injury	Operation	First SO_2(%)	Second SO_2 (%)	Third SO_2 (%)
1	67	A	B	Fall	Durotomy	37	40	64
2	47	B	B	RTA	Laminectomy	52	67	na
3	59	A	C	Fall	Durotomy	38	41	66
4	66	B	B	RTA	Laminectomy	53	64	na
5	52	A	A	Fall	Durotomy	40	43	64
6	57	B	D	RTA	Laminectomy	56	63	na
7	40	A	A	Fall	Durotomy	40	40	60
8	40	A	C	RTA	Durotomy	38	38	58
9	52	B	D	RTA	Durotomy	41	42	59
10	42	A	C	Fall	Laminectomy	52	63	na
11	42	B	A	RTA	Durotomy	41	45	61
12	51	A	A	Fall	Laminectomy	53	64	na
13	36	B	C	RTA	Durotomy	38	45	60
14	53	B	C	Fall	Laminectomy	53	64	na
15	50	A	C	RTA	Durotomy	40	40	65
16	62	B	D	Fall	Laminectomy	54	68	na
17	67	C	D	Fall	Durotomy	42	43	58
18	46	A	A	Falling object	Laminectomy	55	64	na
19	48	B	D	RTA	Laminectomy	57	63	na
20	51	C	E	Fall	Laminectomy	55	64	na
21	68	A	C	Fall	Laminectomy	56	64	na
22	55	C	E	Fall	Laminectomy	54	65	na
23	40	A	A	Falling object	Durotomy	42	47	63
24	51	B	D	RTA	Laminectomy	54	64	na
25	35	A	A	Fall	Laminectomy	54	66	na
26	64	A	A	Fall	Laminectomy	56	65	na
27	55	B	C	Fall	Laminectomy	52	65	na
28	55	C	D	Falling object	Laminectomy	52	65	na
29	43	C	D	Falling object	Laminectomy	52	66	na
30	64	A	A	RTA	Laminectomy	55	67	na
31	44	A	A	Fall	Laminectomy	52	65	na
32	69	B	C	RTA	Durotomy	39	43	64
33	36	A	A	Fall	Laminectomy	52	68	na
34	69	B	D	RTA	Durotomy	41	46	68
35	51	B	D	RTA	Durotomy	38	41	65
36	37	C	D	Falling object	Laminectomy	52	68	na
37	47	C	D	RTA	Durotomy	40	41	65

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Table 2: General data includes age, SO2, time from admission to operation, MOI, and operation types

Characteristics		Value	Percentage/P-value
Age (years)		51.4±9.7	-
Gender (cases)		Male 23	62.20%
		Female 14	37.80%
Admission to operation (hrs)		51.9±9.1	-
Operation types		**SO_2 (%)**	
Laminectomy (alone)	Before laminectomy	53.7±1.6	<0.01
n=22	After laminectomy	65.1±1.6	
Durotomy	Before laminectomy	39.7±1.6	<0.01
n=15	Before durotomy	42.3±2.6	
	After durotomy	62.7±3.1	
MOI (cases)			
Fall		17	46.00%
Falling object		5	13.50%
Road traffic accident		15	40.50%

Neurological Assessment

Preoperatively, 16 patients had ASIA grade A, 14 B, and 7 C. On the last follow-up (average time is 21 months), ASIA grade changed from A to B in 1 patient, A to C in 5; 10 remained the same. Fourteen patients with grade B improved to C in 4 and D in 7; turned to A in 1; 2 remained in grade B, while C turned to D in 5 and E in 2 patients (Table 4). The operation level in 17 patients was C2~C6 (45.9%), C3~C6 (21.6%) in 8, C2~C5 in 5 (13.5%), C3~C5 in 5 (13.5%), and C2~C7 in 2 (5.5%).

Oxygen Saturation Measurement

A total of 37 patients underwent laminectomy and NIR-SO2 monitoring. In 22 patients (59.5%), SO2 before laminectomy was 53.7±1.6% and increased to 65.1±1.6% after laminectomy (P-value <0.01). (Tab. 1-3). In 15 patients (40.5%), the SO_2 was still below 50% after laminectomy and required durotomy and duroplasty. The SO_2 before laminectomy was 39.7±1.6%; after laminectomy improved to 42.3±2.6%, and after durotomy and duroplasty raised to 62.7±3.1% (P-value <0.01). (Table 1-3) However, 22/37 patients showed returning pulse, and no hematoma was observed after laminectomy, but 15/37 underwent durotomy. Within a few seconds of inserting the probe in 1 patient, SO2 was 73.3%. Then, after a few more seconds, it decreased and stabilized at 67.8%. Laminectomy and NIR-SO_2 monitoring were performed on patients aged 35, 52, 55, and 65 years. During the operation, the SO_2 values were 59.9%, 60.6%, 61.5%, and 64.9%, respectively (Figure 2). NIR-SO_2 did not cause any trauma or pain.

Table 3: The initial and final ASIA

Initial ASIA	n	Final ASIA				
		A	B	C	D	E
A	16	10	1	5	-	-
B	14	1	2	4	7	-
C	7	-	-	-	5	2

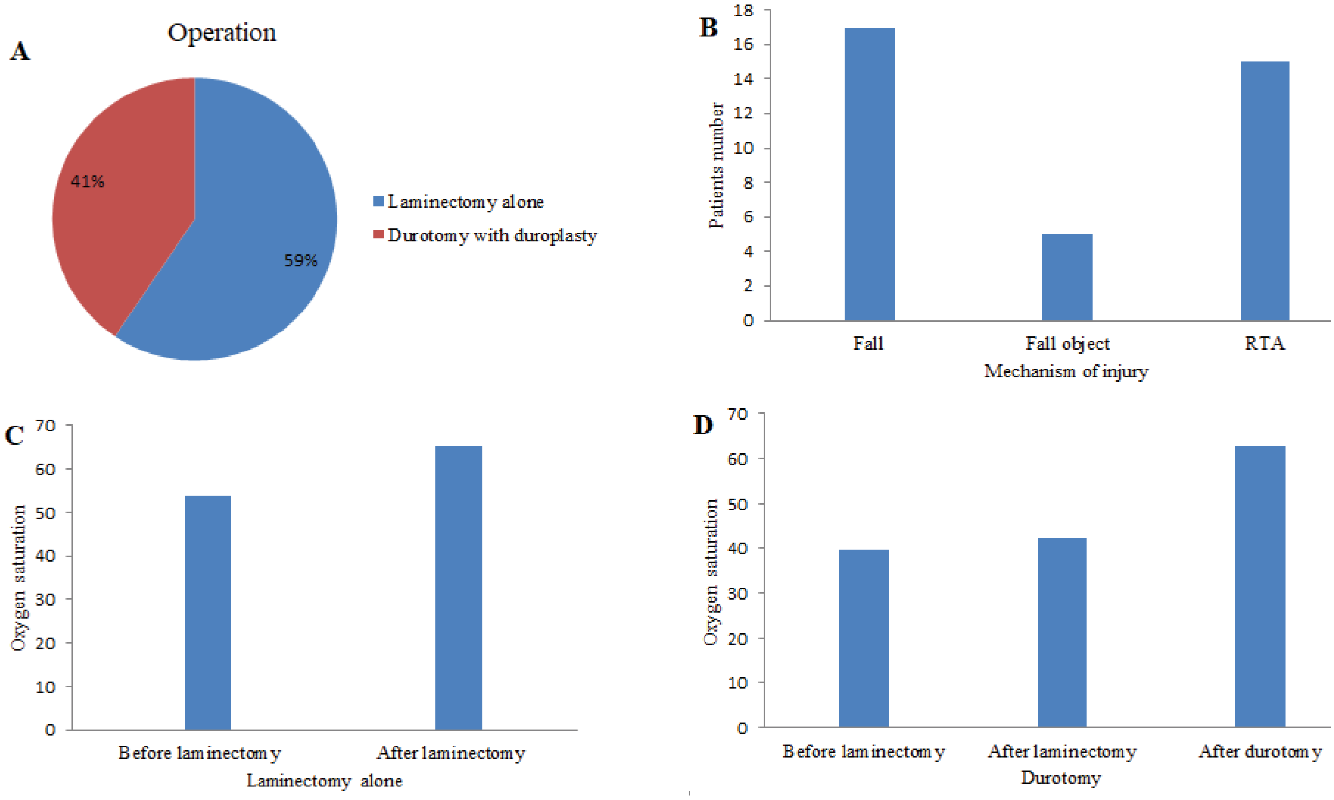

Figure 2: A: Shows the percentage of patients who underwent laminectomy versus durotomy; B: Presents the MOI among 37 patients; C: Shows the SO_2 values in a patient after laminectomy alone; D: Shows the changes in SO_2 during different measurement times in a patient after durotomy

Discussion

This study discussed the importance of finding a proper method of detecting blood flow at an injury site and shed light on the use of NIR-SO_2 during operating to confirm the success of the laminectomy procedure and if the patient required further durotomy with duroplasty. NIR-SO_2 is widely used in brain injury [17]. However, attempts to apply NIR-SO_2 to traumatic CSCI have never been investigated. For surgical treatment to be effective, it is crucial to evaluate spine blood reperfusion during surgery. At the same time, NIR has advantages in measuring the regional SO_2 of the bone, skin, and fat [9, 19].

Depending on the injury intensity, injury type, operation time, and treatment method, many individuals with severe CSCI may remain paraplegic [10, 18]. Laminectomy is an effective technique to treat CSCI in some cases, and there is no need to perform another procedure. However, in severely swollen cases, the dura squeezes the spinal cord, increasing ISP, decreasing SCPP, creating SCCS, and worsening the prognosis [3, 14]. However, after fracture reduction and internal fixation, there is no method to confirm whether further extensive laminectomy or even durotomy is required because there is a lack of non-invasive and quantitative methods to assess whether the blood supply to the spinal cord has improved [1, 20].

Many surgeons suggest not using durotomy procedure because of risks and complications. Still, some severely injured individuals require this procedure to evacuate the hematoma, prevent secondary injury progression, and complete the spinal cord decompression [3, 4, 14]. However, reducing the blood flow can increase the secondary injury chance and worsen the prognosis by causing spinal tissue ischemia. Most patients remain paralyzed with involuntary bladder and bowel functions or sexual dysfunction, which require different management and lifelong special care [1, 3, 4, 11, 13, 14, 21].

SO_2 was more than 58% after laminectomy in 22 patients, and the final ASIA was significantly improved, which indirectly demonstrated the benefits of NIR. However, other patients had a value of <50%; these patients required durotomy with duroplasty to complete decompression and achieve significant outcomes; after durotomy, the SO_2 increased to >62.7%. In 1 patient, the SO_2 for the first few seconds was 73.3%, then 68.3%, and finally stabilized at 67.8% (Fig. 1-7). Therefore, upon inserting the probe at the spine surface, the surgeon should wait a few seconds and ensure the SO_2 values

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to avoid any errors. The probe should be inserted gently without force to prevent any complications. The Suzhou Aegean Biomedical Electronics Company has claimed that values of SO_2 between 58% and 68% are associated with a better prognosis and more efficient blood flow. Monitoring oxy and deoxy-hemoglobin can assess blood reperfusion, microcirculation, and macro-hemodynamics [22] and help to prevent hypoxemia-ischemia resulting from decreased blood flow in a specific region [22].

Different methods of monitoring blood flow can be ineffective and inappropriate for some patients. The surgical intervention aims to improve SCPP and prevent secondary injury by reducing ISP. In contrast, maintaining MAP between 85 mmHg and 90 mmHg for 7 days can assist in establishing an appropriate SCPP; however, this method does not work in all patients [22-25]. NIR-SO_2 can help determine whether a laminectomy is sufficient to restore blood flow to a near-normal level without complications, indirectly improving the ISP and SCPP.

The NIR technique was used to detect regional SO_2 in order to confirm complete decompression and verify blood flow restoration. Moreover, NIR provides a quantifiable, real time dynamic, and relatively non-invasive monitoring method for inferring the degree of spinal cord blood perfusion or ischemia and hypoxia, the severity of CSCI, the selection of surgical methods, curative effects, and prognosis evaluation [7-9, 16, 17, 19]. According to the NIR, if the SO2 is not between 58%~68%, then laminectomy is insufficient to improve blood flow, and the patient requires further procedures such as durotomy, myelotomy, or extensive laminectomy.

However, optic spectrectomy is a risky and complicated procedure for determining blood flow [12]. Doppler US can check the maintenance of blood flow and evaluate blood flow in the spine after trauma [24, 6]. In contrast, the NIR-SO_2 technique can monitor the SO_2 level of spinal tissue, real time continued monitoring of spinal SO_2, early detection of hypoxia and ischemia in the spinal tissue, evaluation of the short-term prognosis after SCI, evaluation of the safeness and significance of the treatment method, and evaluating the extent of spinal cord impairment after trauma [7, 17]. NIR during an operation can provide many advantages, like easy operation, ease of use, high accuracy, low cost, real time, non-invasive, and can be used in different departments.

How to Ensure the Accuracy of NIR-SO_2 Technique?

NIR offers an assessment tool to monitor the SO_2 changes in tissues due to differences in light absorption by blood cells. However, NIR has been used for non-invasive monitoring of bone and blood perfusion in humans to develop an indirect blood flow index for further examinations. In addition, develop a guidance method to estimate the reperfusion velocity after short ischemia through the difference in the rates of oxy- and deoxy-hemoglobin concentrations. Does the NIR technique provide enough benefits to decide whether it is valuable or not? After laminectomy, should check the CSF pulse, and observe the presence of hematoma under the dura. In this study, 3 different surgeons checked the pulse and dural hematoma with direct vision. However, performing a further durotomy if the dura did not pulsate after laminectomy and there was a subdural hematoma (dural darkening). However, this criterion is sometimes invasive. When the dura mater is thick, and vision is not clear, an about 3 mm incision through the intact arachnoid is required to observe and confirm the presence of a hematoma.

In 22/37 patients, the SO_2 value ranged between 58%~68%, pulse return, and no hematoma observed after laminectomy, which provides an idea that blood flow return to normal status and laminectomy is sufficient and there is no need to perform durotomy, along with 15 patients showed the SO_2 value <50%, no pulse, hematoma observed in some after laminectomy, which means blood flow did not return and the decompression was incomplete. In addition, 15/37 patients required a durotomy procedure. The SO2 values returned to 62.7% after durotomy, ensuring that pressure had been released, blood flow had resumed, and decompression had been completed. Hence, SO_2 data can be supported by other methods to guarantee the benefits of NIR. We only examined blood flow during the operation in a dark field. This ensured that the light could reach the deep spinal tissues and did not affect the NIR process.

Moreover, if there is no dural pulsation after laminectomy, then SO_2 values help to make further decisions regarding durotomy to remove the hematoma and ensure the return of blood flow at the injury site. Moreover, according to neurological function improvements, 64.9% (24/37) showed improvement, and 5.4% (2/37) showed complete recovery (ASIA grade E). The improvements after the surgical procedure showed that NIR-SO2 was sufficient to complete the decompression. By measuring NIR-SO_2, you can indirectly measure blood flow improvements and ISP reduction. Recovery of neurological functions after CSCI depends on early and adequate decompression, which restores blood flow and prevents secondary injury progression. Meanwhile, predicting the blood flow level in the damaged region during the operation has significant value in choosing a proper treatment method, achieving better outcomes, and reducing intra and post-operative complications (durotomy complications). NIR-SO_2 is a safe and feasible technique for spine tissue that causes no pain or damage to the tissues of the patient [26, 27]. NIR is a valuable method for examining blood flow in tissues, including bone, cartilage, and the spinal cord. NIR can also show significant benefits without any intra-operative or post-operative complications. However,

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SO_2 values can be different among patients due to nutrition, weight, height, fitness, aging, gender, and growth scale. All these factors affect the NIR technique and lead to different SO_2 values.

Conclusion

Decompression in CSCI can result in considerable improvement, but not in all cases. In order to monitor blood flow during surgery, a unique technique is needed, such as NIR-SO_2. However, assessing spinal blood flow using NIR-SO2 can help determine whether decompression is achieved or if there is a need to perform an extensive laminectomy or durotomy with duroplasty. Intraoperative NIR provides more information about blood reperfusion at the injury site. The technique is also a quantitative, real time dynamic, and non-invasive monitoring technique that determines the level of spinal cord ischemia and hypoxia. When the SO_2 value ranges between 58%~68%, it ensures better recovery and prognosis without a durotomy, but if it is <58%, the patient will require a durotomy to achieve a significant outcome. Further, NIR is used to evaluate the severity of SCI, select treatment modalities, determine efficacy, and predict the patient's prognosis. NIR is a safe and feasible procedure with no complications.

Deceleration

Informed consent

Informed consent was obtained from all individual participants included in the study

Conflict of interest

The authors declare that they have no conflict of interest.

Funding: None

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (Hubei University of Science and Technology, No. 2023-02-001) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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