Chapter 43
Monitoring of Filter Patency During Carotid Artery Stenting Using Near-Infrared Spectroscopy with High Time-Resolution

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Abstract We aimed to evaluate the usefulness of a newly developed, near-infrared spectroscopy (NIRS) device for monitoring hemodynamic changes during carotid artery stenting (CAS), as a means to detect filter obstruction due to distal embolism. We evaluated 16 patients with internal carotid artery (ICA) stenosis during the CAS procedure, using a NIRS system that can monitor not only changes in oxygenation of hemoglobin (Hb), but also the fluctuation of oxyhemoglobin (oxy-Hb) synchronized with heartbeat. The NIRS system detected a marked decrease of oxy-Hb and an increase of deoxyhemoglobin (deoxy-Hb) during ICA occlusion in patients without anterior cross circulation (ACC). Patients with ACC showed much smaller changes. The analysis of oxy-Hb fluctuation made it possible to detect occurrence of no-flow in the absence of Hb concentration changes. The amplitude of oxy-Hb fluctuation in the no/slow-flow group was significantly smaller than that in the normal-flow group. Our results indicate that the present high time-resolution NIRS device, which can measure oxy-Hb fluctuation, is superior to conventional NIRS for detecting filter obstruction.

Keywords Advanced imaging techniques • Carotid artery stenting (CAS) • Embolism • Intraoperative monitoring • Near-infrared spectroscopy (NIRS)

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1 Introduction

Carotid artery stenting (CAS) is a less invasive revascularization strategy than carotid endarterectomy (CEA) in patients with severe symptomatic or asymptomatic atherosclerotic carotid artery stenosis. A recently developed filter-type protection device is already widely used during CAS procedures; this device maintains blood flow in the distal internal carotid artery (ICA) [1]. However, obstruction of the filter pores by embolic particles could cause impaired distal blood flow in the ICA (i.e., no/slow flow phenomenon) [2]. According to the postmarketing prospective research in Japan, the incidence of embolic events was 17.5 % in the slow-flow group during the peri-procedural period [3]. In fact, intraprocedural embolic events are one of the factors influencing patients' outcome. Therefore, monitoring of hemodynamic changes during CAS is important to reduce adverse events.

Near-infrared spectroscopy (NIRS) has been employed to monitor changes in hemodynamic status induced by a variety of neurosurgical procedures, including CAS [4]. However, Hb concentration changes measured by NIRS are susceptible to collateral circulation and individual difference of vessel. This NIRS system has the potential to detect subtle changes in distal blood flow due to filter obstruction by measuring the fluctuation of oxy-Hb synchronized with heartbeat. Indeed, we found that this fluctuation was a more sensitive indicator of hemodynamic changes during CAS, as compared with conventional analysis of Hb concentration changes.

2 Methods

We investigated 16 patients with carotid artery stenosis (12 men and 4 women; mean age, 68.6 ± 7.8 years) who underwent CAS. We measured the hemodynamic changes in the bilateral frontal lobe using a newly developed NIRS device (Pocket NIRS, Hamamatsu Photonics K.K., Japan) (Fig 43.1a). The NIRS system uses light-emitting diodes (LEDs) of three different wavelengths (735, 810, and 850 nm) as light sources and one photo-diode as a detector; it has two channels. The common analysis of NIRS data uses the modified Beer–Lambert law. The sampling rate was 61.3 Hz. The NIRS probes were set symmetrically on the forehead with a flexible fixation pad.

CAS was performed by transfemoral catheterization with distal filter protection in all patients. Pre-stenting dilatation was performed with a controlled compliant balloon dilation catheter; the balloon was inflated at 7–10 atm for 20–30 s. Then, stent replacement was performed using a Precise® (Johnson & Johnson, Cordis, Japan). Post-balloon size was selected according to the normal luminal diameter of each ICA immediately distal to the stenotic lesion.

We evaluated the NIRS parameter changes during the CAS procedure by means of two analytical methods. First, we analyzed concentration changes of oxy-Hb, deoxy-Hb and, total-Hb by subtracting the mean value of the baseline from the mean value measured immediately after inflation and deflation of the balloon.

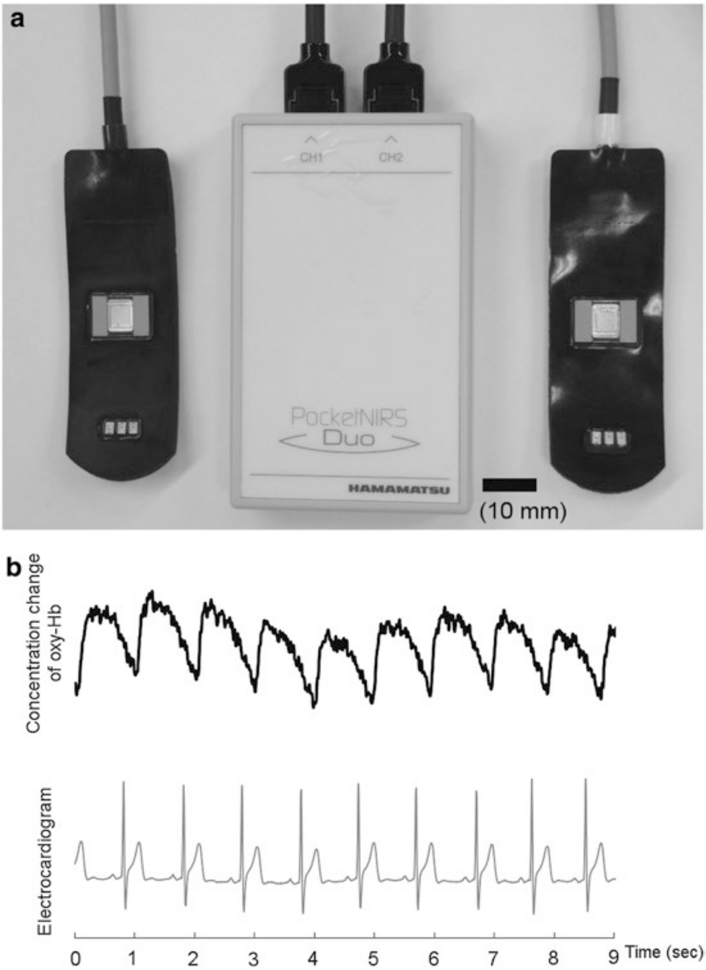

Fig. 43.1 (**a**) Appearance of the wearable NIRS device. The total weight of the controller and probes is 160 g. (**b**) Comparison of fluctuation of oxy-Hb measured by NIRS (*upper*) and ECG (*lower*). The *ordinate* indicates concentration changes of oxy-Hb in arbitrary unit (a.u.)

Second, we analyzed the fluctuation of NIRS parameters. In the preliminary study, we observed fluctuation in NIRS parameters in synchrony with heartbeat. Interestingly, oxy-Hb showed such fluctuations, while deoxy-Hb did not. Figure 43.1b compares the fluctuation of oxy-Hb and electrocardiography (ECG). We calculated the mean value of five peak-to-peak amplitudes of oxy-Hb using frequency analysis before and after stent replacement. In order to define no/slow flow and normal flow, common carotid artery angiogram was performed before and after balloon dilatation to provide information regarding transit time. Each value is expressed as mean ± standard deviation. Statistical analysis was performed by means of an unpaired Student's t-test for comparisons involving two groups; all p values were two-tailed. Statistical analysis was performed with the SAS system (version 8.2; SAS Institute, Inc). This study was approved by the Committee for Clinical Trials and Research at Nihon University School of Medicine and Sagamihara Kyodo Hospital, Japan. All patients or their relatives gave written informed consent.

3 Results

We investigated the effect of anterior cross circulation (ACC) on Hb oxygenation change during deflation of the balloon. The patients with ACC (7 out of 16 patients) showed prominent ischemic changes. In contrast, the patients with ACC (9 out of 16 patients) exhibited much smaller changes of Hb concentrations during deflation of the balloon, compared with the patients without ACC (Fig. 43.2). Change of Hb concentration decreases by development of ACC for the blood supply from the contralateral side. Hb concentration receives an effect of ACC easily.

No/slow flow was found in 6 out of 16 patients during CAS. We compared the sensitivity of the Hb concentration changes and the fluctuation of oxy-Hb for detection of the occurrence of no/slow flow caused by filter obstruction. The analysis of oxy-Hb fluctuation could detect occurrence of no flow even when there was no

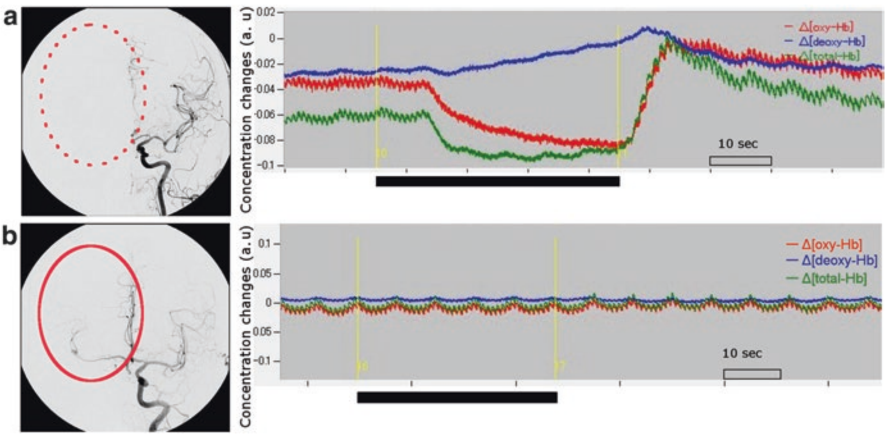

Fig. 43.2 Cerebral angiography and Hb concentration changes during right ICA occlusion. Cerebral angiography and Hb concentration changes during ICA occlusion in cases without anterior cross circulation (**a**: *dotted line*) and with anterior cross circulation (**b**: *solid line*). The *ordinates* indicate concentration changes of oxy-Hb (*red*), deoxy-Hb (*blue*), and total-Hb (*green*) in arbitrary unit (a.u.). The *abscissa* indicates time (s); *horizontal bars* indicate 10 s. *Thick black horizontal bars* indicate the period of ICA occlusion by balloon dilatation

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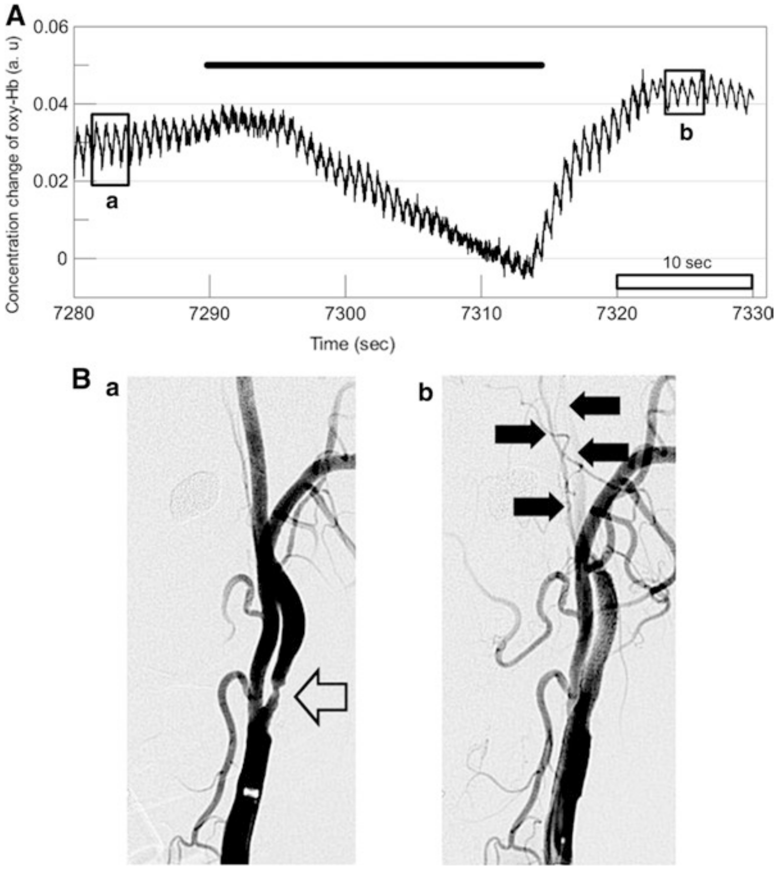

Fig. 43.3 (**A**) Changes of oxy-Hb concentration and fluctuation in patient with no flow during CAS. The *ordinate* indicates Hb concentration change (a.u.), while the *abscissa* indicates time (s). The *thick horizontal bar* indicates the period of balloon dilatation. The oxy-Hb fluctuation before balloon dilatation decreases markedly after balloon dilatation, while oxy-Hb concentration is still at control level. (**B**) Changes of common carotid artery angiogram before (**a**) and after (**b**) balloon dilatation. The *white arrow* in the angiogram (**a**) indicates severe stenosis of ICA. The *black arrow* in the angiogram (**b**) indicates no flow after balloon dilatation

apparent change in oxy-Hb concentration. Figure 43.3 shows a typical case with no flow after deflation of the balloon. It should be noted that oxy-Hb concentration increased abruptly after balloon dilatation, owing to vascular reconstruction; however, NIRS showed a decrease of oxy-Hb fluctuation 5 s after balloon deflation, while oxy-Hb concentration was still at the control level. The amplitude of oxy-Hb fluctuation in the no/slow flow groups was significantly smaller than that in the normal group ($P<0.001$). In contrast, there was no significant difference in oxy-Hb concentration after stent replacement between the two groups ($P=0.50$) (Fig. 43.4).

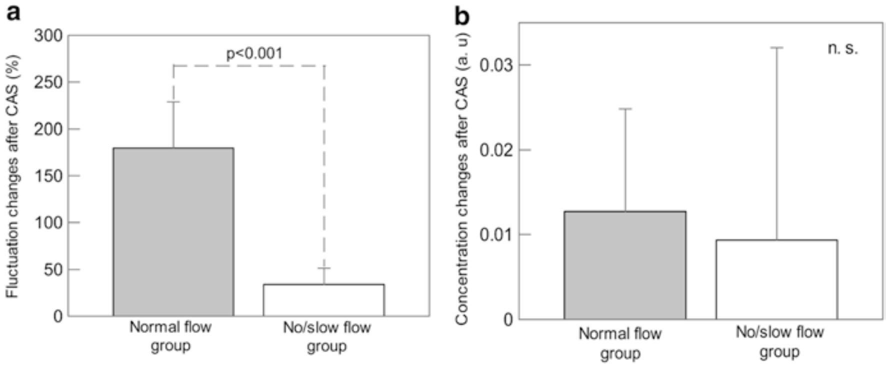

Fig. 43.4 (**a**) Changes of oxy-Hb fluctuation change after CAS in normal and no/slow flow group. The *ordinates* indicate % change of oxy-Hb fluctuation amplitude. The fluctuation amplitude of the no/slow flow group (n = 6) is significant smaller than that of the normal flow group (n = 10) (P < 0.001). (**b**) Changes of oxy-Hb concentration change after CAS in normal and no/slow flow group. The *ordinates* indicate oxy-Hb concentration change (a.u.). There was no significant difference between two groups (P = 0.50)

4 Discussion

NIRS has been employed to monitor changes in hemodynamic status induced by a variety of neurosurgical procedures, by measuring changes of Hb concentrations. For example, decreases of oxy-Hb associated with an increase of deoxy-Hb indicate ischemic changes, while increases of oxy-Hb associated with a decrease of deoxy-Hb indicate hyperperfusion following CEA.

The present findings indicate that NIRS has the potential to detect impaired distal blood flow due to filter obstruction by measuring the fluctuation of oxy-Hb synchronized with heartbeat, even when there is no change of hemoglobin oxygenation. Thus, the fluctuation analysis could detect blood flow reduction more sensitively, as compared with conventional NIRS data analysis, which measures Hb concentration change. Moreover, Hb concentration changes are susceptible to presence of ACC. No/slow flow is one of the factors influencing the patient's outcome. According to the postmarketing prospective study, the occurrence of major adverse events was 13.5 % in the no-flow group, 17.5 % in the slow-flow group, and 4.9 % in the normal-flow group [3]. Therefore, monitoring of subtle hemodynamic changes during CAS is important to reduce adverse events.

The origin of the fluctuation of oxy-Hb is not yet clear, but the following possibilities should be considered. First, the motion of the brain caused by heartbeat could cause the fluctuation of NIRS parameters. If so, all of the NIRS parameters should change; however, deoxy-Hb did not show fluctuation associated with heartbeat. Second, the pulsatile flow of cerebral arterial blood associated with heartbeat could cause the fluctuation of oxy-Hb. Changes of blood pressure could cause dilatation of the artery, resulting in an increase of oxy-Hb concentration without any change in deoxy-Hb concentration. Indeed, deoxy-Hb exhibited little or no fluctuation. In fact, recent NIRS studies have found fluctuations of NIRS signals associated with systemic blood pressure changes in pediatric, neurosurgical and cardiac patients [5, 6]. In fact, the fluctuation of oxy-Hb was associated with no/slow flow in the ICA. These results suggest that the oxy-Hb fluctuation originated mainly in the pulsatile flow of cerebral arterial blood associated with heartbeat.

In addition, the present NIRS system is compact enough to be attached to the patient's clothes, and is equipped with telemetric data communication, so that patients can be moved freely during CAS.

5 Conclusions

The fluctuation of oxy-Hb measured by the present NIRS system appears to reflect the oscillatory wave caused by heartbeat. Our results indicate that analysis of oxy-Hb fluctuation is a more sensitive tool than monitoring of oxy-Hb concentration changes, and that it is capable of detecting impaired distal blood flow due to filter obstruction during CAS even when monitoring of oxy-Hb concentration does not detect any hemodynamic change. We conclude that this high time-resolution NIRS system is useful to monitor intraprocedural no/slow flow during CAS.

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