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# Relation between blood flow and tissue blood oxygenation in human fingertip skin

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ABSTRACT

*Background:* Tissue blood flow (BF) is thought to be involved in the regulation of tissue blood oxygenation ($StO_2$). The purpose of the present study was to show the relation between BF and $StO_2$ by measuring them simultaneously under different conditions.
*Methods:* Twenty-one healthy subjects (age 21–30 years) participated in this study. We measured BF and $StO_2$ in a small area of skin (fingertip, palm, forearm) simultaneously using a laser Doppler flowmeter and a tissue oxygenation monitor. Three measurements were made at rest while performing mental arithmetic and during constriction of the ipsilateral upper arm.
*Results:* At rest, BF and $StO_2$ were higher in the fingertip than in the palm or forearm ($p < 0.01$). Performing mental arithmetic produced significant decreases in BF, oxygenated hemoglobin, and $StO_2$ in the fingertip ($p < 0.05$). Constriction of the ipsilateral upper arm produced significant decreases in BF and $StO_2$ ($p < 0.05$) and an increase in oxygenated hemoglobin ($p < 0.05$). Both procedures produced significant increases in deoxygenated hemoglobin ($p < 0.05$), which was in antiphase to the decrease in $StO_2$.
*Conclusions:* BF decrease produced a significantly decreased $StO_2$ in fingertip skin. The results show that simultaneous measurement of BF and $StO_2$ is beneficial for showing the close relation between them.


## Introduction

Tissue blood oxygenation ($StO_2$) reflects the balance between oxygen delivery to tissues and its consumption by those tissues. Imbalance between oxygen delivery and consumption can cause tissue dysfunction and pathological changes. For example, hypoxia is a reduction in oxygen delivery caused by blood flow below tissue demand, which causes well-known diseases such as diabetic retinopathy (Willard and Herman, 2012; Gao et al., 2014) and Raynaud's disease (Herrick and Clark, 1998). Tissue blood flow (BF) is considered to be essentially involved in regulating $StO_2$ (Kessler et al., 1976). It is of clinical and research importance to understand the relation between BF and $StO_2$ in the tissue. To examine the effect of BF increase on $StO_2$, Ohkubo et al. measured the amount of oxygenated hemoglobin (OxyHb), deoxygenated hemoglobin (DeoxyHb), and total hemoglobin (THb) in trapezius muscle during and after acupuncture (Ohkubo et al., 2009). They observed an increase in OxyHb and THb, whereas DeoxyHb was relatively unchanged. They suggested that acupuncture caused the increased arterial blood influx in the region, thereby producing an increase in $StO_2$.

As far as we could determine, the relation between BF and $StO_2$ in human fingertip skin has not been reported. There are two types of resistance vessels in skin: arterioles and arteriovenous anastomoses (AVAs) (Mescon et al., 1956; Krogstad et al., 1995). They are mainly under neural control. Finger skin BF decreases during an increase of sympathetic nerve activity, such as mental arithmetic (MA) (Abramson and Ferris, 1940; Wallin, 1988, 1990). Finger skin BF can be also decreased by external constriction, such as application of an upper arm constraint. We speculated that a transient reduction of BF reduces arterial blood influx to the tissue, causing a decrease in $StO_2$ in fingertip skin and that simultaneous measurement of BF and $StO_2$ could clarify the relation between them.

$StO_2$ has been measured in various tissues with several noninvasive optical methods clinically and in experimental animals (Frank et al., 1989; Chance et al., 1992; Hamaoka et al., 1996; Kakihana et al., 1998; Schmidt et al., 2001; Kashima, 2003; Benaron et al., 2004; Ferrari et al., 2004; Maxim et al., 2005; Kubo et al., 2008a,b; Thorn et al., 2009).

*Abbreviations:* AC, after upper arm constriction; AVA, arteriovenous anastomosis; BC, before upper arm constriction; BF, blood flow; BOLD, blood oxygenation level-dependent; C1–C4, control periods during the recording session; DC, during upper arm constriction; DeoxyHb, deoxygenated hemoglobin; L1–L6, measurement locations; LOM, laser tissue oxygenation monitor; MA, mental arithmetic; MRI, magnetic resonance imaging; OxyHb, oxygenated hemoglobin; $StO_2$, tissue blood oxygenation; THb, total hemoglobin.

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However, limited information is available of the $StO_2$ in human fingertip skin. Reported values are between 30% and 75% on the palm side of the index finger (Kakihana et al., 1998) and 63% on the dorsal side (Thorn et al., 2009).

With regard to BF measurement, several invasive measurement techniques (e.g., direct capillary pressure measurement, transcutaneous oxygen measurement) and noninvasive techniques (e.g., photoplethysmography, laser Doppler flowmetry) have been used (Swain and Grant, 1989). In recent years, laser Doppler flowmetry—noninvasive continuous measurement of BF—has been applied extensively to study various tissues including fingertip skin (Khan et al., 1992; Littleford et al., 1999; Abbink et al., 2001; Mayrovitz and Groseclose, 2002; Freccero et al., 2003; O'Brien, 2005; Tanaka et al., 2008; Hayashi et al., 2009). However, simultaneous measurement of BF and $StO_2$ in a small area of human fingertip skin has not been reported.

The purpose of the present study was to determine the relation between BF and $StO_2$ in a small area of human fingertip skin. For this purpose, we first measured the resting BF and $StO_2$ simultaneously in the skin of the fingertip, palm, and forearm. Then, we determined the effect of a transient decrease in BF on $StO_2$ using the following measurements: (1) before, during, and after MA calculations; and (2) before, during, and after interruption of BF by constriction of the ipsilateral upper arm.

## Methods

### *Participants*

The Research Ethics Committee of Tohoku University Graduate School of Dentistry (Ref. No. of the research project: 21-3) approved the experimental protocol of this study based on the guidelines set forth in the Declaration of Helsinki. A total of 21 students at Tohoku University School of Dentistry and Tohoku University Graduate School of Dentistry (11 men, 10 women; age range 21–30 years; mean $\pm$ SD 24.9 $\pm$ 3.2 years) participated in this study. All participants were normotensive, nonobese nonsmokers who were not taking any medications and had no history of autonomic dysfunction or cardiovascular disease. The experiments were conducted with the understanding and written informed consent of each participant.

### *Measurement of tissue blood volume and its oxygenation*

We measured $StO_2$ with a laser tissue oxygenation monitor (LOM) (Omega Monitor BOM-L1TRSF; Omega Wave, Tokyo, Japan) based on Kashima's method (Kashima et al., 1992; Kashima, 2003), which uses the large differences in absorption of three red laser light frequencies (630, 650, and 690 nm) by OxyHb versus DeoxyHb. The laser tissue oxygenation monitor measures the amount of OxyHb and DeoxyHb in the tissue. THb was calculated as the sum of OxyHb and DeoxyHb. $StO_2$ was calculated from the OxyHb and THb values using the following formula: $StO_2$ (%) $= 100 \times$ OxyHb / THb. This method measures the whole blood volume in arteries and veins in the measured region and has the advantage of estimating oxygen consumption in a small volume of tissue. Kubo et al. applied this method to the measurement of blood volume in the patellar tendon (Kubo et al., 2009) and $StO_2$ in the Achilles tendon during muscle contraction (Kubo et al., 2008a,b). Measurements were made at several sites on the ventral aspect of the middle finger, palm, and forearm of each subject's right arm. OxyHb, DeoxyHb, and THb were expressed in volts. $StO_2$ values were expressed as percentages (%).

### *Blood flow measurement*

Laser Doppler flowmetry (type FLO-C1; Omega Wave, Tokyo, Japan) was used to measure BF. The BF signals are expressed in volts.

### *A special probe*

A special probe (modified SF-DS probe; Omega Wave, Tokyo, Japan) was designed to simultaneously detect blood flow and tissue blood oxygenation. The probe was maintained in position with adhesive tape. The probe included six optical fibers (Fig. 1). Two of the six fibers were for the laser Doppler flowmetry measurement, one being for incidence light and the other for receiving reflection light from the tissue. The other four were for measuring the tissue blood volume and its oxygenation (Kubo et al., 2008a,b). These fibers were arranged in a line and mounted in a plastic mold with a diameter of 10 mm.

The distance between the probe's fibers for illumination (630, 650, and 670 nm) and detection for the laser tissue oxygenation monitor used for LOM was 3 mm. In this case, the measurement depth was estimated to be 3 mm (Kashima, 2003). For laser Doppler flowmetry (780 nm), the distance between the fibers for illumination and detection was 1 mm.

### *Data acquisition*

Data were input into a personal computer (iMac; Apple, Cupertino, CA, USA) at a sampling frequency of 10 Hz via an A/D transducer (Power Lab 4/20; ADInstruments, Dunedin, New Zealand). Mean values over a given duration were calculated with analytical software (LabChart 6; ADInstruments).

### *Experimental design*

Measurements were made in a slightly darkened, quiet room at a constant temperature of approximately 26 °C. Subjects sat in a comfortable chair with the right arm on cotton cloth placed on a small table (height 60 cm above the floor). BF, OxyHb, DeoxyHb, THb, and $StO_2$ were measured at several locations on the right arm. The maneuvers were performed as follows and in the following order.

In test 1, measurements were made at rest at six locations on the ventral skin of the subject's right arm: L1, fingertip of the middle finger; L2, middle phalanx of the middle finger; L3, palm over the distal metacarpal of the middle finger; L4, palm near the wrist; L5, at the midpoint of the forearm; and L6, near the elbow on the forearm (Fig. 2). The measurement probe was first attached to L1 and thereafter moved to L2 through L6 in turn.

In test 2, measurements were made only at the fingertip (L1) before, during, and after MA calculations. During the MA task, subjects were shown a piece of paper with one of the following two-digit multiplication problems: MA1, $12 \times 13$; MA2, $26 \times 16$; MA3, $34 \times 18$. Participants gave verbal responses and were encouraged to calculate the answer as


**Fig. 1.** Sensor probe (o.d. 10 mm). Six optical fibers are incorporated in a line at the center of the probe: (1) used to detect light for laser Doppler blood flow measurement; (2) used to produce light for laser Doppler blood flow measurement; (3) used to produce light for tissue blood oxygenation measurement; and (4–6) used to detect light for tissue blood oxygenation measurement.