# Quantitative near-infrared spectroscopy on patients with peripheral vascular disease

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## ABSTRACT

We have used near-infrared spectroscopy to measure the hemoglobin saturation at rest and during exercise on patients affected by peripheral vascular disease (PVD). The instrument used in our study is a frequency-domain tissue oximeter which employs intensity modulated (110 MHz) laser diodes. We examined 9 subjects, 3 of which were controls and 6 were patients affected by stage II PVD. The optical probe was located on the calf muscle of the subjects. The measurement protocol consisted of: (1) baseline (~5 min); (2) stationary bicycle exercise (~5 min); (3) recovery (~15 min). The change in hemoglobin saturation during exercise ($\Delta Y$) and the recovery time after exercise ($t_{rec}$) were significantly greater in the PVD patients ($\Delta Y = -21\pm3\%$, $t_{rec} = 5.9\pm3.8$ min) than in the control subjects ($\Delta Y = 2\pm3\%$, $t_{rec} = 0.6\pm0.1$ min).

**Keywords:** peripheral vascular disease, near-infrared spectroscopy, hemoglobin saturation, skeletal muscle

## 1. INTRODUCTION

Peripheral vascular disease (PVD) is a progressive arterial narrowing or obstruction mainly caused by an atherosclerotic process which reduces blood flow to the lower limbs during exercise or also at rest. Iliac arteries (lower abdomen leading to the legs) and femoral arteries (legs) are among the peripheral vessels most commonly affected by the disease. The reduced oxygen supply (from the oxy-hemoglobin in the blood) to the muscle tissue results in a cramping pain in the thigh or calf muscles, and can limit walking capabilities. Current non-invasive diagnostic modalities for PVD include the ankle-arm blood pressure index[1] (AAI), plethysmography,[2] ultrasonic duplex scanning, and transcutaneous oxymetry.[3,4] Because of the sensitivity of near-infrared spectroscopy (NIRS) to the tissue hemoglobin content and to the hemoglobin oxygenation state, it has been proposed that NIRS may be a useful tool in the diagnosis of PVD and/or in the follow up of the patients after therapy.[5-7]

In this paper, we present initial clinical results obtained with our frequency-domain tissue spectrometer operating in the near-infrared.[8,9] The novelty introduced by this instrument with respect to previous applications of NIRS to PVD is the quantitative nature of the spectroscopic measurements. In fact, the absolute values of the tissue absorption and reduced scattering coefficients are measured, resulting in the quantitation of hemoglobin concentration ($[HbO_2]+[Hb]$) and saturation ($Y$). Furthermore, the multi-distance measurement protocol implemented in our multi-channel tissue spectrometer is weakly affected by movement artifacts or by changes in the optical coupling of the optical probe with the skin.[9] We present an initial clinical study on 9 subjects, 3 of which were controls and 6 were patients with stage II PVD.

## 2. MATERIALS AND METHODS

The frequency-domain tissue spectrometer employed in this study has been thoroughly described and characterized in Ref. 8 (the basic principles and first prototype), and in Ref. 9 (the newly engineered version used in this study). Briefly, this instrument employs eight intensity modulated (110 MHz) laser diodes, four emitting at 750 nm and four emitting at 840 nm. They are electronically multiplexed at a rate of 50 Hz, so that each laser diode is on for 20 ms. The four light sources at each wavelength are used to illuminate the tissue at four different distances from the detector fiber (range 1.5-3.0 cm), thus implementing the multi-distance measurement protocol for quantitative spectroscopy of turbid media.[10] The light sources are all coupled to optical fibers (600 μm core diameter), so that the optical probe placed on the skin contains only fiber optics and no electronics. In the measurements reported here, the acquisition time was set to 2.56 s, which results from the average over 16 cycles of acquisition from the eight laser diodes ($16 \times 8 \times 20$ ms = 2.56 s).

The initial clinical study was performed at the Policlinico Monteluce, Perugia, Italy. We examined 9 male subjects. Six of them (mean age 70, range 66-75 years) were affected by stage II PVD confirmed by an AAI < 0.80 and ultrasonographic evidence of iliaco-femoral stenosis or obstruction. All patients were affected by typical intermittent claudication as treadmill test revealed. The other three subjects (ages 61, 61, 64 years), not affected by PVD, were taken as a control group. The optical probe was located on the calf muscle of each subject (on the pathological leg in the PVD patients). We acquired data continuously during a stationary bicycle exercise which consisted of 5-10 minutes of baseline (with the subject resting and sitting on the bicycle), about 5 minutes of exercise (at a power increasing every two minutes from an initial value of 25 W by steps of 25 W), and about 10-15 minutes of recovery (with the subject sitting on the bicycle). The exercise was interrupted as the PVD patients perceived muscle pain. A typical trace of hemoglobin saturation observed during the protocol is shown in Fig. 1. In Fig. 1, we also illustrate the definitions of the baseline hemoglobin saturation ($Y_{baseline}$), the change in $Y$ caused by the exercise ($\Delta Y = Y_{exercise} - Y_{baseline}$), and of the recovery time after exercise ($t_{rec}$).

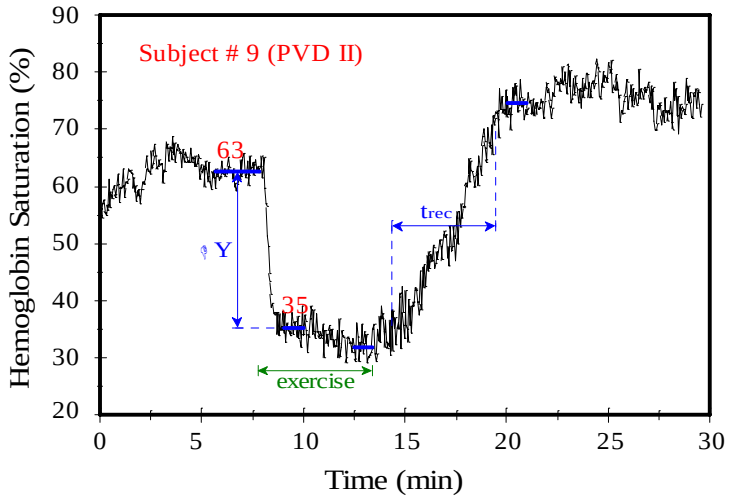


**Fig. 1.** Typical trace of hemoglobin saturation for a stage II PVD patient during the stationary-bicycle routine. In the figure we indicate the baseline value (63%), the value during exercise (35%), and the recovery time ($t_{rec}$).

## 3. RESULTS

The results of our measurements of hemoglobin saturation in the calf muscle are reported in Figs. 2, 3, and 4. The baseline value of $Y$ (Fig. 2) did not show a significant difference between the controls ($Y = 69 \pm 5\%$) and the PVD patients ($Y = 63 \pm 7\%$). As reported in Fig. 3, we found that the hemoglobin saturation was only slightly changed by the exercise in the controls ($\Delta Y = 2 \pm 3\%$). By contrast, the PVD patients showed a large decrease in hemoglobin saturation ($\Delta Y = -21 \pm 3\%$). The recovery time after exercise (Fig. 4) was also significantly different in the two subject groups. In fact, the recovery time was shorter than one minute in the controls ($t_{rec} = 0.6 \pm 0.1$ min), whereas in the PVD patients it was several minutes long ($t_{rec} = 5.9 \pm 3.8$ min).

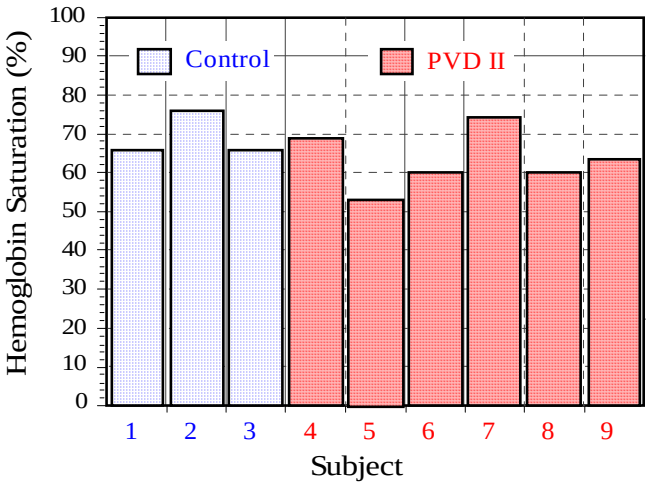


**Fig. 2.** Baseline hemoglobin saturation values in the controls and stage II PVD patients.

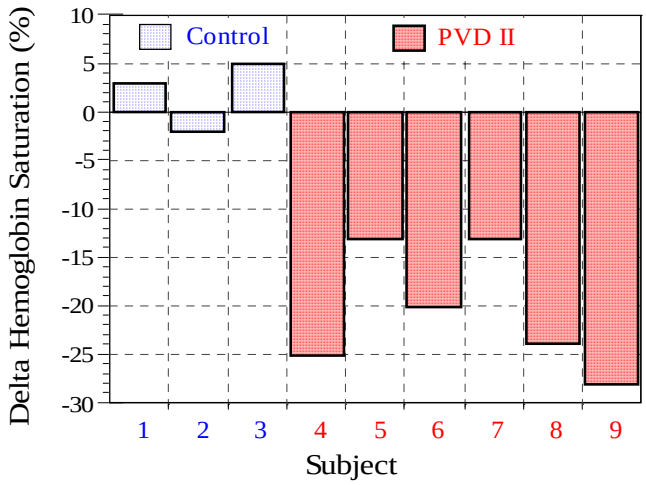


**Fig. 3.** Changes in the hemoglobin saturation caused by the exercise (exercise value - baseline value) in the controls and in the stage II PVD patients.

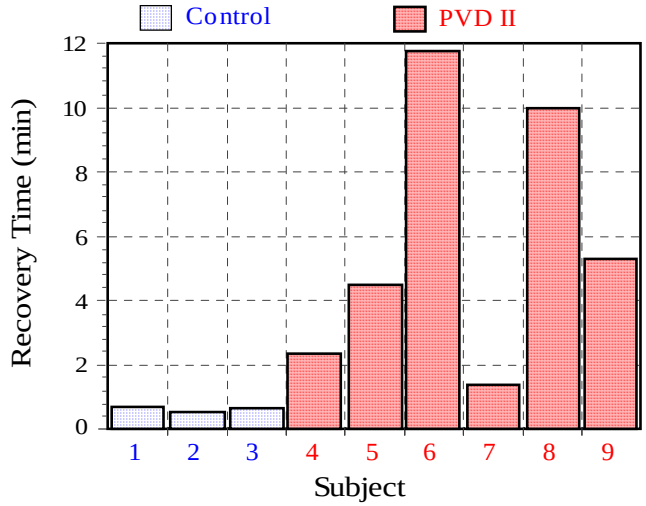


**Fig. 4.** Recovery time after exercise for the controls and for the stage II PVD patients.

## 4. DISCUSSION AND CONCLUSIONS

The stage II PVD patients considered in this paper did not show a significant difference in the baseline hemoglobin saturation values with respect to the controls. This is probably due to the fact that the disease is not at an advanced stage. In fact, initial measurements done on stage IV PVD patients (not reported in this paper) have shown significantly lower baseline saturation values. However, stage II PVD patients showed a much different response to the exercise routine with respect to the controls. The desaturation was much stronger, and the time required to recover the baseline saturation value was much longer than in the controls. These results indicate that near-infrared spectroscopy has significant potential in the diagnosis of PVD. Of course, its effectiveness needs to be more fully characterized, especially in conjunction with different measurement protocols (cuff ischemia,[5] seated calf raise exercise,[6] progressive walking test,[6] leg raising,[3] bicycle exercise, etc.). We point out that the quantitation of absolute values of hemoglobin saturation and concentration afforded by our frequency-domain tissue oximeter allows one to do simple baseline measurements. This capability appears to be especially important in stage IV PVD patients, who cannot perform exercise.

## ACKNOWLEDGMENTS

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