Blood Flow Limits and Pulse Oximeter Signal Detection

DAN LAWSON, M.D.,* IAN NORLEY, M.B.B.,* GREG KORBON, M.D.,* ROBERT LOEB, M.D.,† JOHN ELLIS, M.D.†

The pulse oximeter has achieved widespread use as a noninvasive monitor of arterial oxygen saturation. The popularity of today's oximeter technology can be attributed to several facts: vascular bed "arterialization" is no longer needed, inexpensive high-speed microprocessors for data acquisition and processing are available, and set-up times are minimal.1 Pulse oximeters rely on the principle that fully oxygenated blood is only present during arterial pulsations.2 Pulse detection algorithms identify the arterial component of light absorbance in a vascular bed. Two wavelengths of light (660 nm and 940 nm) are used to detect the presence of oxyhemoglobin and reduced hemoglobin, and Beer's law is applied to determine the hemoglobin saturation. Modern pulse oximetry has been described as "multiple-wavelength plethysmography."3,4

In addition to its role in determining hemoglobin saturation, the pulse oximeter has been advocated as a monitor for the rapid determination of adequate blood flow to a limb, or as an indirect indicator of total body oxygenation.5-6 The physiologic basis for this recommendation has not been established. We employed a laser Doppler flow probe as a benchmark for determining the magnitude of peripheral blood flow. With this device, a rheometric study was performed to determine the pulse oximeter's sensitivity to pulsatile blood flow and its threshold for detecting arterial pulsation during artificially induced low-flow conditions.

MATERIALS AND METHODS

Ten human volunteers, age 25–38 yr, all healthy nonsmokers taking no medications, were studied. Approval by the Human Investigation Committee of our institution was obtained, and each participant provided an informed consent. One arm of each individual was stabilized on an arm rest, and a properly sized blood pressure cuff attached to a mercury manometer was placed on the upper arm. A Nellcor® D-25 pulse oximeter sensor was positioned over the isisilateral second finger and attached to a Nellcor® N100 pulse oximeter (software version 6.8). The pulse oximeter was judged to be functioning properly if the displayed pulse rate matched the heart rate of the subject in the absence of error messages or alarm indications. No in vivo measurements of blood oxygenation were made during this experiment.

A laser Doppler flow probe (LD 5000 Capillary Perfusion Monitor, MedPacific Corp., Seattle) was used to
compare blood flow with the response of the pulse oximeter. The laser Doppler flow probe is a low energy laser device which uses the Doppler principle to detect the velocity of red blood cells. This device can measure the pulsatile component of total blood flow (AC mode), and relative flow magnitudes can be easily documented (flow is arbitrarily measured in millivolts). The laser Doppler is a relatively new method for measuring blood flow to skin and mucosa, its ability to detect blood flow (as a relative magnitude), and the fact that the technique is totally different from that used by plethysmometers, makes the laser Doppler a useful noninvasive device for measuring flow in this study.

The laser Doppler transducer was positioned on the ipsilateral thumb and left undisturbed after baseline flow values were recorded. Calibration of the laser Doppler was performed as recommended by the manufacturer prior to each session. External calibrations are provided to properly set the laser Doppler sensitivity, zero flow, and maximum flow. Each subject's arterial blood pressure was measured by auscultation three times at 1-min intervals. Baseline flow was recorded, as was the laser Doppler voltage reading during total limb occlusion at a cuff pressure of 250 mmHg (table 1). The low voltage displayed during total limb occlusion was regarded as background noise; all measurements made during each experiment were referenced to it. To test the reproducibility of this approach, the cuff was inflated again to 250 mmHg and released; baseline flow voltage values with total limb occlusion were verified as remaining stable.

The pulse oximeter's ability to function without error indications, relative pulsatile blood flow by laser Doppler, and tourniquet occlusion pressure were recorded as the cuff was manually inflated in 2–5-mmHg increments. Cuff pressure and magnitude of flow were noted at the point where the oximeter stopped sensing a pulse. At this point, cuff pressure was maintained constant until the "pulse search error" condition displayed, or the pulse was detected again. After the oximeter displayed an "error," the cuff was inflated to 250 mmHg and then gradually deflated in 2–5-mmHg decrements. Cuff pressure and the relative flow were recorded when the pulse oximeter began to indicate a pulse rate with no error messages or alarm indications. The elapsed time taken for the pulse oximeter to accept a pulse signal and display a heart rate was noted. To minimize physiologic perturbations from limb ischemia, the cuff was not kept inflated for more than 180 s. The entire sequence was repeated after a 5-min rest period. Results were accepted if laser Doppler flows returned to within 10% of baseline within 5 min of tourniquet release, and if the subject's blood pressure remained within 5% of that measured prior to tourniquet inflation.

Baseline relative blood flow values were calculated as the total limb flow (in mV) measured with the cuff deflated, minus the laser Doppler voltage when the tourniquet was inflated to 250 mmHg. Pulsatile flow (in mV) at the moment of pulse oximeter signal loss was also corrected for the laser Doppler voltage indicated with the limb totally occluded. Tourniquet occlusion pressures and calculated blood flows were averaged for each subject for each experimental condition; changes in flows and pressures were tested for significance using Student's paired t test.

### Results

The age and mean systolic and diastolic arterial blood pressure for each subject are shown in table 1. Also included are the mean baseline total blood flow readings displayed by the laser Doppler (in mV) and laser Doppler voltage indications during limb occlusion with the cuff inflated to 250 mmHg. Arterial pulsations were detected by the oximeter without error indications with no cuff pressure up until mean cuff occlusion pressure reached 106 ± 7 mmHg (mean ± SEM) (96% of control systolic pressure, P < 0.004). At that point, mean rela-
tive flow decreased to 8.6 ± 5.9% (mean ± SD) of the baseline (P < 0.001), and the pulse oximeter failed to detect a pulse, displaying its "pulse search error" indicator, followed by the audible alarm.

After total occlusion of the limb and subsequent slow release of the tourniquet, the pulse oximeter detected and displayed a heart rate at a mean cuff occlusion pressure of 104 ± 3 mmHg (93% of baseline systolic pressure, P < 0.001) and at a mean laser Doppler measurement of 4.0 ± 3.1% of the baseline (P < 0.001). The oximeter displayed a pulse rate within 6 s of sensing a pulse (mean heart rate 68 ± 12 bpm; one beat every 0.88 s; seven beats in 6 s). In all instances, no further changes in oximeter performance were noted with continued tourniquet release. There was no difference in mean cuff occlusion pressures with cuff inflation and loss of oximeter function, or cuff deflation and regaining of oximeter function (mean measured difference of 2 mmHg; P < 0.167). However, a small but significantly different relative flow was associated with the restoration of pulse oximeter pulse detection after tourniquet release as compared to the loss of pulse oximeter function during tourniquet inflation (mean difference 4.6 ± 2.7% of baseline flow; P < 0.02). Tourniquet occlusion pressures (expressed as percent of control systolic pressure) and the corresponding laser Doppler measurements (expressed as a percent of baseline) for each subject are shown in figure 1 at the time of pulse oximeter signal loss and at the time the oximeter resumed functioning.

**DISCUSSION**

The pulse oximeter was introduced in its current form in 1989. The precision and linearity of the Nellcor® oximeter has been the subject of several articles. Perturbations in accuracy occur if venous blood admixes with arterial blood during systole, if other hemoglobin moieties, such as carboxyhemoglobin, are present, if exogenous dyes are administered, or if ambient light of sufficient intensity interferes with sensor operation.

Pulse detection algorithms programmed into the oximeter evaluate the changes in light attenuation across a vascular bed. This is accomplished by measuring the optical path length of the diastolic tissue bed (d_{diast}) and the optical path length of the systolic tissue bed (d_{sys}). The difference between the two (Ad = d_{diast} - d_{sys}) is the optical path length of light being affected only by arterial blood. Nellcor's microprocessor continuously calculates the ratio of light absorption associated with both wavelengths of light emitted by the two source diodes on the fingertip. When preset thresholds for amplitude are exceeded, the signals are stored; artifacts are rejected after active comparison with historical data stored in computer memory. Once five to seven pulsations have been accepted, Beer's law is applied; pulse amplitude, pulse rate, and percent saturation of hemoglobin are then displayed. There is no attempt to measure blood flow or blood cell velocities with these pulse detection algorithms.

The laser Doppler flow probe measured pulsatile blood flow to the hand during this experiment. The output signal of these devices can be easily perturbed by excessive pressure on the sensor probe, desaturated blood, and low hematocrits. Kvietys et al. have compared laser Doppler measurements (in volts) to microsphere and hydrogen gas clearance techniques. They showed a correlation coefficient of 0.80 for the three techniques when used to estimate flow in mucosa and submucosa. There are no studies describing the correlation between laser Doppler measurements and actual
peripheral blood flow in the extremities. Pulsatile flow as measured by the laser Doppler does not demonstrate adequate tissue perfusion of the hand or the adequacy of oxygen delivery. One can only measure the relative change in pulsatile flow beneath the probe, assuming the probe has been left undisturbed once measurements have begun, a condition strictly adhered to during this experiment.

Our data show that the detection circuitry in the pulse oximeter accepts pulse signals in the presence of low relative flow as compared to baseline. The pulse oximeter continued to detect pulsations despite increasing interference with blood flow to a limb. At the critical point where pulse oximeter function ceased, the occluding tourniquet was at a pressure of 106 mm Hg, and relative blood flow had been reduced to 8.6% of that originally perfusing the limb. To restart the pulse oximeter, tourniquet inflation pressure was 104 mm Hg, and relative blood flow was only 4% of that measured at baseline.

A series of reports have appeared advancing the value of the pulse oximeter as a means for assessing tissue perfusion.4–6 In a report by Narang,7 an 11-month-old infant suffered an asystolic cardiac arrest and underwent cardiopulmonary resuscitation (CPR). The oximeter detected a saturation of 90% with a pulse display corresponding to the rate of external chest compression. CPR was clearly effective in generating a pulsatile blood flow adequate for the pulse oximeter to operate successfully. We have demonstrated that flows between 4% and 8.6% of the baseline are sufficient. However, Narang, in his conclusions, states that the pulse oximeter "... showed that resuscitation was effective..." by indicating adequate oxygen delivery to tissues. Tissue oxygen delivery is the product of blood flow and blood oxygen content. Therefore, Narang's conclusion must be viewed with caution. Adequate blood oxygenation requires pulmonary blood flow and ventilation. The adequate delivery of oxygenated blood is not measured by pulse oximetry. The knowledge that flows as low as 4–8.6% can trigger the pulse oximeter does not imply that, during CPR, vital organ flow is low. The relationship between central blood flow and peripheral blood flow during circulatory collapse is not well-defined in humans. This physiologic picture is complicated by the effects of the sympathetic nervous system and catecholamines (both endogenous and exogenous) and the circulatory effects of the anesthetics (both intravenous and volatile). Our study does not attempt to differentiate and explore the complex interactions of blood flow distribution during circulatory collapse. Some may argue that low flow in the periphery detected by devices such as the pulse oximeter may indeed indicate that vital organ blood flow is adequate. However, there is no evidence to support this conclusion.

A report by Nowak et al. describes the use of pulse oximeters as an aid to performing Allen's test.5 They suggest using the oximeter to ascertain adequate collateral perfusion to the hand; they accept a return of pulse rate and saturation readings within 15 s as adequate for cannulation. In light of our data, they essentially advocate relative flows as low as 8.6% of the baseline as acceptable for proceeding with arterial cannulation. A study correlating a delay of 15 s or greater in oximeter pulse detection with adequacy of total blood flow and subsequent tissue ischemia has not been done.

Finally, in a discussion of axillary artery compression, Skeehan and Hensley, Jr. note that their pulse oximeter alarmed after patient positioning.6 On physical examination, they found a pulseless left arm which, when repositioned, restored pulses to the arm. At the same time, the oximeter resumed functioning. Unexplained loss of pulse oximeter function is cause for concern; nonetheless, the regaining of a pulse signal does not necessarily imply the presence of adequate tissue perfusion. After restoring pulse oximeter function, the limb in question should be examined for pulse, nail bed capillary refill, and color, to assess its overall perfusion. It is possible to have a functioning pulse oximeter and diminished pulses in one limb as compared to the contralateral limb.

A study recently appeared that reported the use of pulse oximetry to monitor the viability of replanted or revascularized digits of the hand. Graham et al.15 observed that the pulse oximeter was useful for detecting early sub-clinical ischemia of a replanted digit caused by venous outflow obstruction. In experimental subjects, they occluded venous return with a digit tourniquet and discovered that the pulse oximeter rapidly indicated a hemoglobin desaturating trend. However, in their re plantation, population with postoperative venous outflow obstruction, a slow desaturation trend manifested over 2–3 h. Rather than attaching significance to the presence or absence of a pulse signal; it was the slow decreasing saturation trend over several hours that led to re-operation of these patients. For patient positioning in the operating room, a comparable condition might be the progressive deterioration of hemoglobin saturations and a widening gap between pulse oximeter readings and simultaneous arterial blood gases. The data provided by Graham et al. suggest that tissue oxygenation may be assessed by monitoring for a slow deterioration in hemoglobin saturation (i.e., poor perfusion) in addition to the sudden loss of pulsations (total loss of arterial flow).

The pulse oximeter's purpose remains the rapid non invasive evaluation of total blood oxygenation. Although pulse oximeters display pulse amplitude information, the conclusion that pulse oximeters monitor tissue perfusion and tissue oxygen delivery must be ap-
proached with caution. Our experimental data correlate blood flow, as measured in pulsatile mode by laser Doppler, with the sensitivity of the pulse detection algorithms programmed into the Nellcor® oximeter. From the rheometric standpoint, the pulse oximeter is a highly sensitive device for the detection of a pulsatile state. We conclude that, in a critical physiologic situation or emergency, the presence of a functioning pulse oximeter should not be construed as evidence of adequate tissue oxygenation or oxygen delivery to vital organs.

The authors would like to acknowledge the research assistance of Carlo LaScala, M.D. They are also grateful to David E. Longnecker, M.D., for his scientific and editorial insights.

REFERENCES