THE USE OF OXIMETRY
IN DETERMINING INTESTINAL BLOOD FLOW

P. H. MacDonald, M.D., P. K. Dinda, Ph.D., I. T. Beck, M.D., and
C. D. Mercer, M.D., F.A.C.S., Kingston, Ontario

The intraoperative evaluation of intestinal ischemia and viability is often subjective and unreliable. The results of recent reports of pulse and surface oximetry have suggested that these techniques may be useful in assessing intestinal blood flow. In the current study, we evaluated and compared the ability of intestinal tissue oxygen saturation (as measured by pulse oximetry) and intestinal surface oxygen tension (as measured by surface oximetry) to determine the actual intestinal tissue blood flow (as measured with a radiolabeled microsphere technique). In five dogs, tissue oxygen saturation, surface oxygen tension and blood flow of the proximal and distal parts of the small intestine were measured under basal conditions.

A clamp placed around the root of the superior mesenteric artery was then tightened to decrease the blood flow through this artery (as measured by an ultrasonic flow probe) by 50 percent and then by 75 percent, repeating all measurements after each reduction. The two consecutive reductions in superior mesenteric artery blood flow resulted in an average 54 and 76 percent reduction in tissue blood flow, respectively. As a result of these reductions in tissue blood flow, the average intestinal tissue oxygen saturation (percentage), as determined by pulse oximetry, decreased significantly from a basal value of 93 ± 1 to 85 ± 1 (p<0.05) and then to 76 ± 1 (p<0.05) with the two progressive blood flow reductions. Intestinal surface oxygen tension decreased more steeply, from a basal value of 97 ± 1 to 80 ± 6 (p<0.05) and then to 64 ± 7 millimeters of mercury (p<0.05) with the same two reductions in tissue blood flow. Both techniques were capable of estimating tissue blood flow, but pulse oximetry was quicker and simpler to use. We conclude that the pulse oximeter has the potential to be of value in the intraoperative assessment of intestinal blood flow. Surg. Gynecol. Obstet., 1993, 176: 451-458.

The clinical evaluation of intestinal ischemia and viability is often subjective and unreliable. To date, there is no widely accepted and readily available intraoperative technique to quantify intestinal blood flow and thereby assess the viability. Not only would a reliable method of measuring intestinal blood flow be of importance in determining tissue viability, but it would also be useful in determining if an anastomosis had an adequate blood flow for healing. Recently, the technology of oximetry has been examined for the ability to estimate intestinal perfusion. Two types of oximeters are currently available for clinical use, the surface oximeter and the pulse oximeter. The surface oximeter is based on a modified Clark electrode (1), and when applied to the skin surface (usually in neonates) a determination of surface oxygen tension can be made. The results of studies using surface oximetry to measure intestinal oxygen tension have shown a direct correlation with tissue blood flow (1-4), but the equipment required to measure surface oxygen tension is not available in most operating rooms and thus, at the moment, this technique is not economically feasible in most centers.

Results of recent reports of the application of pulse oximetry to the surface of the intestine (5, 6) have suggested that this technique may be capable of estimating intestinal blood flow. Pulse oximetry is a noninvasive spectrophotometric technique used widely in the practice of anesthesia. When applied to the ear lobe or the fingertip, arterial blood oxygen saturation can be readily measured. A pulse oximeter is available in most operating rooms and thus, if indeed, is capable of measuring intestinal tissue blood flow and it could be a valuable tool for the surgeon faced with the question of intestinal viability.

The present study was done to evaluate and compare the ability of surface oximetry and pulse oximetry to determine the magnitude of intestinal tissue blood flow. A dog model was used in which local tissue blood flow was measured using a microsphere technique.

METHODS

Experimental design. Five healthy male or female mongrel dogs (weight ranging from 14.4 to 22.0
kilograms) were used in this study in accordance with the standards of the Canadian Council on Animal Care. Using pulse oximetry, the oxygen saturation of the intestine was determined at three separate sites—proximal part of the jejunum, distal part of the ileum and proximal portion of the colon. Intestinal surface oxygen tension was determined at a single site in the midjejunum using a surface oxygen electrode (1). Blood gas analysis (oxygen tension and saturation) of the arterial and venous intestinal blood was performed so that a comparison could be made with the tissue oxygen saturation (as measured by pulse oximetry) and the intestinal surface oxygen tension (as measured by surface oximetry). Blood flow through the superior mesenteric artery was measured using an ultrasonic flow probe placed at the root of this vessel. In addition, intestinal tissue blood flow was determined using a radiolabeled microsphere technique. To evaluate the ability of pulse oximetry and surface oxygen tension to detect the magnitude of intestinal blood flow, a clamp was used to reduce the superior mesenteric artery blood flow by 50 percent and then by 75 percent, repeating all the aforementioned determinations after each reduction in blood flow.

Surgical preparation. All dogs were fasted for 12 hours before the experiment. Each dog was anesthetized with pentobarbital sodium (30 milligrams per kilogram, intravenously) and then intubated with a No. 7F endotracheal tube. A mechanical ventilator (Harvard Animal Respirator, Model 613) using room air and a tidal volume of 15 milliliters per kilogram was used to maintain the arterial carbon dioxide partial pressure within normal limits (35 to 45 millimeters of mercury). A catheter was placed in the right femoral vein for injection of additional anesthetic. The right femoral artery was catheterized for continuous measurement of arterial blood pressure, removal of blood samples for blood gas determination and for withdrawal of the reference blood sample at the time of microsphere injection. A third catheter was inserted through the left femoral artery into the left ventricle for microsphere injection and the position of the tip was ascertained by pressure monitoring. Arterial catheters were perfused with heparinized saline solution (100 international units of heparin per 500 milliliters
Fig. 2. The effect of superior mesenteric arterial blood flow reduction on small intestine tissue blood flow (measured with microspheres), small intestinal oxygen saturation (measured with pulse oximetry) and small intestinal surface oxygen tension (measured with surface oximetry). The superior mesenteric artery blood flow (measured with an ultrasonic flow probe) was reduced by 50 and 75 percent by tightening a clamp around the root of the artery. Values are expressed as a percent of the basal value. SMA, Superior mesenteric artery.

of saline solution infused at 3 milliliters per hour to prevent clotting and each was connected through a pressure transducer (Model P1000b, Narco-Bio Systems) to a physiograph (Model RS 3800, Gould Inc.) for continuous recording. A midline laparotomy was then performed. The root of the superior mesenteric artery was exposed and a clamp was placed loosely around the artery. A 4 millimeter ultrasonic flow probe (Probe No. 2R568, Transonic Systems Inc.) was then placed on the superior mesenteric artery 2 centimeters distal to the clamp (Fig.1). Through a vein in the mesentery of the proximal jejunum, a small catheter was advanced into the superior mesenteric vein to be used for withdrawal of venous blood for blood gas analysis. A No. 4-0 chronic catgut suture was used to mark the intestine at the three sites (proximal jejunum, distal ileum and proximal colon), where pulse oximetry determined oxygen saturation would later be measured. An oxygen tension sensor probe (Kontron Instruments, Distributed through Medilogic Inc., Rexdale, Ontario, Canada) was secured to the antimesenteric serosal surface of the midjejunum by sticking an adhesive ring to the sensor and then suturing the edge of the adhesive ring to the serosa with a No. 5-0 polyglycolic acid suture (Fig. 1). Additional sodium pentobarbital was given as needed (10 to 15 milligrams per kilogram) to maintain anesthesia during the surgical preparation; however, once the operation was completed, no additional anesthetic was given and the dog was allowed to stabilize for a 45 minute period before the commencement of the experiment.

Experimental protocol. After the postsurgical stabilization period, the superior mesenteric arterial blood flow, as measured by the ultrasonic flow probe, was recorded. Intestinal oxygen saturation was then determined with a Nellcor N-100 pulse oximeter (Nellcor Inc.) at three separate sites (proximal jejunum, distal ileum and proximal colon) by folding a Nellcor D-20 Oxisensor transducer around the antimesenteric surface of the intestine (Fig. 1). The surface oxygen tension from the midjejunum was recorded with a Kontron Instruments Micro Gas 7640 oxygen sensor (Medilogic, Rexdale, Ontario, Canada) with the carbon dioxide partial pressure electrode heated to 44 degrees C. A 2 milliliter blood sample was withdrawn from the right femoral artery and a second from the superior mesenteric vein and each was analyzed for oxygen tension and saturation with a Corning blood gas analyzer (Model 178). Finally, intestinal tissue blood flow was determined using a radiolabeled microsphere technique as described previously [7] and as outlined here briefly. Approximately 2.5 million 15 mil-
limeter radiolabeled polystyrene microspheres (SM) were sonicated, vortexed and then injected into the left ventricle. A reference blood sample was withdrawn from the right femoral artery using a Harvard pump (Model 931, Harvard Apparatus) at a rate of 7.75 milliliters per minute. The withdrawal commenced five seconds before the microsphere injection and continued for 90 seconds. For accuracy, the actual withdrawal rate was later determined gravimetrically.

Immediately after all basal determinations were completed, the clamp around the base of the superior mesenteric artery was tightened to reduce the superior mesenteric artery blood flow by 50 percent (1/2 basal) and then 75 percent (1/4 basal).

The superior mesenteric arterial blood flow was reduced by 75 percent of original basal flow and again after a 15 minute equilibration period, all determinations were repeated as described previously.

The superior mesenteric arterial blood flow was reduced by 75 percent of original basal flow and then 75 percent (1/4 basal).

Immediately after all basal determinations were completed, the clamp around the base of the superior mesenteric artery was tightened so as to reduce the blood flow by 50 percent as measured by the ultrasonic flow probe (Fig. 1). After a 15 minute equilibration period, all determinations were repeated as described previously.

The superior mesenteric arterial blood flow was reduced by 75 percent of original basal flow and then 75 percent (1/4 basal). The microsphere determined tissue blood flow was calculated using the method of another investigator (8) as described previously (7). Tissue blood flow was expressed per gram dry tissue weight.

Statistical analysis. Data were compared using analysis of variance as applicable to repeated measures and regression. The Neuman-Keuls post hoc test was used to determine the statistical difference between any two means. All analyses were performed using a statistical software package (Systat version 4.1, Systat Inc.).

RESULTS

Superior mesenteric artery and intestinal tissue blood flow. The average basal blood flow through the superior mesenteric artery, as measured by the ultrasonic flow probe, was 104 ± 9 milliliters per minute with a range of 80 to 130 milliliters per minute (Table I). Mechanical constriction of the superior mesenteric artery in an attempt to reduce the flow by 50 percent and then by 75 percent resulted in an actual average blood flow reduction of 51 and 75 percent.

To interpret accurately changes in the pulse and surface oximeter measurements, it was important to quantify accurately blood flow at the tissue level using a microsphere technique. Reduction in superior mesenteric arterial blood flow resulted in an equivalent reduction in small intestinal tissue blood flow as determined by the microspheres. Specifically, a 51 percent reduction
in the superior mesenteric artery blood flow resulted in a 57, 50 and 54 percent reduction in the proximal jejunum, midjejunum and distal ileum tissue blood flow, respectively. With 75 percent reduction in the superior mesenteric artery blood flow, tissue blood flow to the same three segments of small intestine decreased by 78, 70 and 79 percent, respectively (Table 1).

In the proximal colon, reduction of the superior mesenteric arterial blood flow had less effect on the tissue blood flow. The 51 and 75 percent reduction in the superior mesenteric arterial blood flow resulted in only a 35 and 52 percent reduction in the proximal colon tissue blood flow, respectively. This observation of a discrepancy between the small intestine and the colon tissue blood flow will be important in the accurate analysis of the pulse oximetry data.

Pulse oximetry determined intestinal oxygen saturation. The tissue oxygen saturations, as measured by the pulse oximeter, are listed in Table I. The basal intestinal tissue oxygen saturation ranged from 91 to 93 percent, with no statistical difference among the three sites examined (proximal jejunum, distal ileum and proximal colon). The small intestine and colon pulse oximetry determined tissue oxygen saturation decreased significantly and progressively with the degree of reduction in tissue blood flow. In the proximal jejunum and distal ileum, where a 51 percent reduction in the superior mesenteric artery blood flow resulted in a respective 57 and 54 percent reduction in tissue blood flow, the tissue oxygen saturation decreased by 11.8 and 9.8 percent. When tissue blood flow was reduced by 78 percent in the proximal jejunum and 79 percent in the distal ileum, the tissue oxygen saturation decreased by 18.3 and 18.5 percent, respectively (Table 1).

In the colon, where superior mesenteric arterial blood flow reduction had less of an effect on tissue blood flow, a 35 and 52 percent reduction in tissue blood flow resulted in a 4.4 and 6.6 percent reduction in the tissue oxygen saturation, respectively (Table I). Note that these reductions in the pulse oximetry determined oxygen saturation of the colon were less than the corresponding reductions measured in the small intestine, where tissue blood flow had been reduced by a greater degree.

As mechanical constriction of the superior mesenteric artery resulted in a similar reduction in the proximal jejunal and distal ileal blood flow, pulse oximetry determined tissue oxygen saturation data for these two sites was combined and correlated with the reduction in the superior mesenteric artery blood flow (Fig. 2). It is apparent that the pulse oximeter determined tissue oxygen saturation is directly proportional to the degree of tissue blood flow \((r^2=78.6\text{ percent, } p<0.001)\) for the range of blood flow studied.

Surface oximetry determined intestinal surface oxygen tension. Data for the surface intestinal oxygen tension measured at a single site in the midjejunum are listed in Table I. The average basal surface oxygen tension was measured at 97±1 millimeters of mercury. The surface oxygen tension decreased significantly and progressively with the degree of tissue blood flow reduction. With
a 51 percent reduction in blood flow through the superior mesenteric artery and a resultant 50 percent reduction in the midjejunal intestinal wall blood flow, the surface oxygen tension decreased by 17.5 percent. With a 70 percent reduction in the midjejunal tissue blood flow, the oxygen tension decreased by 34.0 percent. The intestinal surface oxygen tension was directly proportional to the reduction in tissue blood flow ($r^2=60.3$ percent, $p<0.001$), with a regression slope greater than that for the pulse oximetry data (Fig. 2).

Comparison of pulse and surface oximeter measurements with the actual intestinal blood oxygen saturation and tension. The oxygen saturation and tension of the arterial blood supplying the small intestine were measured in a blood sample taken from the femoral artery, while the oxygen saturation and tension of the blood draining from the small intestine were measured in blood taken from the superior mesenteric vein. These data are illustrated in Figure 3 along with the pulse oximetry data (combined from the two small intestine sites—proximal jejunum and distal ileum) and the surface oximetry data (from the midjejenum). It is apparent that, as tissue blood flow was reduced, tissue oxygen extraction increased, as evidenced by a reduction in the venous blood oxygen saturation and tension. Comparison of the pulse oximetry determined tissue oxygen saturation with the actual oxygen saturation of the small intestine arterial and venous blood revealed that, as tissue blood flow was reduced, the pulse oximetry determined saturation approached the oxygen saturation of the venous blood. A similar trend was noted with the surface oximeter, in that, as tissue blood flow was reduced, the surface oximetry determined oxygen tension approached that in the venous blood.

DISCUSSION

Pulse oximeters use a spectrophotometric method to determine the proportion of unsaturated to saturated hemoglobin in arterial blood. A light-emitting diode shines light through a tissue bed onto a photodetector and thus the degree of light absorption is determined. Two different light sources are used in a high-frequency alternating manner, one emitting red light with a wavelength of 660 nanometers and a second emitting infrared light with a wavelength of 940 nanometers. Oxyhemoglobin absorbs less red light than does deoxyhemoglobin and at infrared wavelengths the opposite is true. Therefore, a ratio of red light absorbance to infrared light absorbance allows for the determination of the ratio of unsaturated to saturated hemoglobin (9–11). The pulse oximeter was designed to measure the oxygen saturation of arterial blood only; however, a tissue bed is composed not only of arterial blood, but also of venous blood and soft tissue, which will also absorb light. The pulse oximeter accounts for this “background” absorbance by the fact that, during diastole, the amount of arterial blood in a tissue bed increases and, therefore, total light absorbance will reach a maximum. The opposite occurs during systole, when light absorbance reaches a minimum. By calculating the ratio of maximum light absorbance to the minimum light absorbance a “pulse added” absorbance is determined. This “pulse added” absorbance represents the proportion of light absorbed just by arterial blood and this value is empirically related to arterial blood oxygen saturation (9–11).

Considering these principles on which the function of pulse oximetry is based, theoretically, the ability of a pulse oximeter to determine arterial blood saturation should be unaffected by tissue blood flow, provided an adequate pulse is present and the oxygen saturation of the incoming blood remains constant. However, in practice, this does not seem to occur and tissue blood flow does influence pulse oximetry measured oxygen saturation as reported in this study. As blood flow decreases and the venous blood oxygen saturation also decreases (as a result of increased tissue oxygen extraction), the pulse oximeter measured oxygen saturation will decrease in spite of an unchanged incoming arterial oxygen saturation. In tissue beds that are not very metabolically active and, thus, have a low tissue oxygen extraction, that is, the ear lobe or the tip of the finger, blood flow will have less effect on pulse oximetry determined oxygen saturation. However, in tissue beds that are very metabolically active, blood flow can have a significant effect on pulse oximetry measured oxygen saturation. It is on this principle that pulse oximeters may be useful in estimating intestinal tissue blood flow.

In the current study, we found that the oxygen saturation of the small intestinal wall, as measured by pulse oximetry, was directly proportional to tissue blood flow (Fig. 2). As the blood flow to the small intestinal wall was reduced, the pulse oximeter determined oxygen saturation decreased. The sensitivity of the correlation was such that a 50 percent reduction in tissue blood
REFERENCES


