Comparison of Extracapillary and Endocapillary Blood Flow Oxygenators for Open Heart Surgery in Dogs: Efficiency of Gas Exchange and Platelet Conservation

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ABSTRACT. The goal of the current study was to compare the efficiency of gas exchange and platelet conservation of a new extracapillary blood flow oxygenator versus an endocapillary blood flow oxygenator during open heart surgery with extracorporeal circulation in dogs. Dilatation and remodeling of the right ventricular outflow tract of dogs was performed using a patch graft technique to simulate pulmonary stenosis. Sequential pre- and post-operative blood analysis revealed that gas exchange efficiency and platelet conservation was significantly greater with the extracapillary blood flow oxygenator than with the endocapillary blood flow oxygenator. We conclude that while the extracapillary blood flow oxygenator provided benefits in terms of gas exchange and platelet conservation, development of a smaller extracapillary blood flow type oxygenator to reduce hemodilution effects would be beneficial.

KEY WORDS: canine, endocapillary blood flow oxygenator, extracapillary blood flow oxygenator, extracorporeal circulation.

Attempts to correct acquired and congenital heart diseases in small animals have led to the development of advanced veterinary surgical techniques. However, cardiopulmonary bypass (CPB) is not commonly used in clinical veterinary surgery, and only limited cases have been reported [1, 9, 16]. Current veterinary CPB in open heart procedures utilize endocapillary blood flow oxygenators, which cause less injury than other oxygenators because gas does not come in direct contact with blood [2, 13]. However, this oxygenator can cause blood cell destruction because of high pressure gradients across the apparatus [2, 6, 17]. We developed a new veterinary extracapillary blood flow oxygenator to circumvent these limitations. The present study compares the use of endocapillary versus extracapillary blood flow oxygenators on gas exchange efficiency and platelet conservation in dogs undergoing CPB with extracorporeal circulation.

MATERIALS AND METHODS

Animals: Fourteen clinically healthy beagle dogs were used in the study. All dogs were managed in accordance with the experimental animal guidelines of the Tokyo University of Agriculture and Technology. Animals were randomly divided into two groups: extracapillary blood flow oxygenator [Group A: body weight (mean ± standard error (M ± SE)) =11.0 ± 0.6 kg, n=7] and endocapillary blood flow oxygenator [Group B: body weight (M ± SE) =10.9 ± 0.5 kg, n=7] with two males and five females in each group. The dogs were vaccinated with a mixed vaccine and were negative for microfilaria and Brucella organisms. General hematological examination, blood chemistry, plain thoracic radiography, electrocardiography, and phonocardiography revealed no abnormalities.

Cardiopulmonary bypass system: An artificial heart-lung machine (NAPS-III) [18, 19], a heat exchanger, and a circuit were used in the present study.

Membrane oxygenator (Fig. 1): The extracapillary blood flow oxygenator utilized sheaves of polypropylene hollow fiber (inside diameter=200 µm, membrane diameter=30 µm) connected to inlet and outlet manifolds within a chamber. Oxygen was passed inside the fibers, while blood passed between and over individual fibers. To control blood temperature, the oxygenator incorporated a heat exchanger within the same unit. The surface area of the oxygenator was approximately 0.8 m², and priming volume was 150 ml. The endocapillary blood flow oxygenator (EC-100, MERA, Tokyo, Japan) also contained sheaves of polypropylene hollow fiber (inside diameter=200 µm, membrane diameter=22 µm) connected to inlet and outlet manifolds within a chamber, allowing blood to circulate through the fibers with the gas outside. The surface area of the oxygenator was approximately 1.0 m², and priming volume was 60 ml.

Priming solution: Before initiating extracorporeal circulation, the machine was primed with lactated Ringer’s solution with 5% glucose, 7% sodium bicarbonate and 20% mannitol. Whole blood was not used.

Surgical technique: The dogs were premedicated with atropine sulfate (0.04 mg/kg) and acepromazine maleate (0.4 mg/kg). Upon sedation, the dogs were anesthetized using thiopental sodium (5–10 mg/kg). Each dog was then intubated with an endotracheal tube, and inhalational oxygen and isoflurane mixture) and intravenous anesthesia (0.1% Ketamine micro-mini drip administration technique [3, 11]) was administered. While performing thoracotomy,
0.2 mg/kg of succinyldicholine chloride was administered intravenously under mechanical ventilation [11]. Heparin sodium was administered at 100 U/kg and titrated to an activated coagulation time (ACT) greater than 400 sec [4]. At the end of surgery, protamine sulfate was administered to neutralize heparin sodium.

Thoracotomy was performed by median sternotomy, and the pericardium was exposed. Catheters were inserted through the right auricle and atrium to the anterior and posterior vena cava to drain the blood from the heart. The surgical field, NAPS-III and circuit were connected to perform extracorporeal circulation. During procedure, the dog's body temperature was reduced to 26°C. Following partial extracorporeal circulation for 20 min, total extracorporeal circulation was initiated, and cardiac arrest was induced by antegrade injection of cold Young’s solution once stable hemodynamics were achieved. The myocardium was protected by antegrade injection of cold cardioplegia solution, and the surface of the heart was cooled regionally using ice slush. Dilatation and remodeling of the right ventricular outflow tract in all dogs was performed using a patch graft technique to simulate pulmonary stenosis [10, 17]. After completing the necessary procedures, switching back to partial extracorporeal circulation, the heart was massaged manually, and cardiac activity was reinitiated using a defibrillator. Thoracic drainage tubes were placed, and the chest was closed by the conventional method. After surgery, all dogs received butorphanol (0.4 mg/kg) as necessary for analgesia.

**Sampling techniques:** Blood samples were collected at the following time points: just after switching to partial extracorporeal circulation (PRE), 20 min after switching to partial extracorporeal circulation (PARTIAL 1), 30 min after switching to total extracorporeal circulation (TOTAL 30), 60 min after switching to total extracorporeal circulation (TOTAL 60), 20 min after switching back to partial extracorporeal circulation (PARTIAL 2), 60 min after the completion of extracorporeal circulation (PUMP OFF), one day after surgery (DAY 1), three days after surgery (DAY 3), and five days after surgery (DAY 5). Arterial blood was collected through the artificial lung, and venous blood was collected at a point prior to blood entry into the artificial lung. Blood was analyzed using blood gas tests (arterial pH (pH(a)), venous pH (pH(v))), arterial oxygen tension (PaO₂), venous oxygen tension (PvO₂), arterial carbon dioxide tension (PaCO₂) and venous carbon dioxide tension (PvCO₂) from PRE to PARTIAL 2.

Effective pulmonary flow/total blood flow ratio (QP/QT), indicating efficiency of gas exchange in artificial lung, was calculated using the following equation [12]:

\[
\text{QP/QT} = \frac{(\text{CaO}_2 - \text{CvO}_2)}{(\text{Cc'O}_2 - \text{CvO}_2)},
\]

where

- \(\text{CaO}_2\): Oxygen content of arterial blood
- \(\text{CvO}_2\): Oxygen content of venous blood
- \(\text{Cc'O}_2\): Oxygen content of mixed venous blood

\[
\text{CaO}_2 = 1.34 \times \text{Hb(a)} \times \text{SaO}_2 / 100 + 0.003 \times \text{PaO}_2
\]

\[
\text{Cc'O}_2 = 1.34 \times \text{Hb(v)} \times \text{SvO}_2 / 100 + 0.003 \times \text{PvO}_2
\]

\[
\text{SO}_2\text{: Oxygen saturation}
\]

\[
\text{PO}_2\text{: Oxygen tension}
\]

To investigate efficiency of platelet conservation during extracorporeal circulation, blood was analyzed using quantitative platelet measurement (PLT) from PRE to DAY 5.

**Statistical analyses:** Data were expressed as M±SE. Statistical analyses were performed using the Mann Whitney U-test, and statistical significance was established at the p<0.05 level.

**RESULTS**

There was no significant difference in distribution of age or weight between the two groups. No postoperative complications occurred, and animals remained healthy (under general physical examination) at least for 4 months after the experiment.

**Blood gas findings:** Table 1 summarizes plasma pH measurements for the two groups. The pH(a) was significantly higher in Group B (alkalotic) than in Group A (normal range). The pH(v) was also significantly higher in Group B, except at the PARTIAL 1 time point.

Table 1 summarizes oxygen tension (PO₂) measurements with the two oxygenators. PaO₂ was significantly higher in Group A than in Group B, except at the TOTAL 30 time point. Furthermore, PaO₂ tended to decrease with time after PARTIAL 1 in Group B, but PaO₂ was maintained above 150 torr in both groups. PvO₂ did not significantly differ between the two groups. However, the PvO₂ was generally higher in Group A than in Group B, except at the TOTAL 30 time point.

Table 1 summarizes carbon dioxide tension (PCO₂) measurements obtained in the two groups. PaCO₂ was generally higher in Group A than in Group B, and there were significant differences between the two groups at PRE and PARTIAL 1. PaCO₂ was generally lower than 35–40 torr, indicating adequate extracorporeal circulation. PvCO₂ was generally higher in Group A than in Group B, and there were
significant differences between the two groups at PRE and PARTIAL 1. QP/QT was maintained at all times in group A. QP/QT was lower at all time points in Group B than in Group A, and the difference in the QP/QT between the two groups increased with time. QP/QT after the PARTIAL 1 time point was significantly different between the two groups (Fig. 2).

Hematological findings: PLT decreased after the PARTIAL 1 time point in both groups. PLT between the PARTIAL 1 and DAY 1 time points were higher in Group A than in Group B, and there were significant differences between the two groups at PARTIAL 2 and PUMP OFF (Fig. 3).

**DISCUSSION**

Previous reports suggest that the extracapillary blood flow oxygenator provides for more efficient gas exchange than the endocapillary blood flow oxygenator [2, 5]. This is because the extracapillary blood flow oxygenator produces irregular blood flow patterns and turbulence, which increases oxygenation. In contrast, the endocapillary blood flow oxygenator produces laminar flow.

In this study, both oxygenators maintained PaO₂ at levels sufficient for heart surgery during extracorporeal circulation. However, PaO₂ was generally lower in Group B than in Group A, and PaO₂ tended to decrease in Group B with time. These values indicate greater gas exchange in Group
A than in Group B.

In addition, PaCO₂ was generally higher in Group A than in Group B. This can be due to an increase in the amount of carbon dioxide released from the blood, since the amount of oxygen flow to the artificial lung was higher in Group B. Plasma pH increased leading respiratory alkalosis because PCO₂ decreased in Group B.

QP/QT was also maintained at safe levels in Group A during extracorporal circulation. QP/QT was lower at all times in Group B compared to Group A, and the difference in the QP/QT between the two groups increased with time. Thus, consistent with previous reports [2, 5], long-term oxygenation was better when using the extracapillary rather than the endocapillary blood flow oxygenator, likely due to secondary blood flow pattern and turbulence generated by the extracapillary oxygenator. The surface area of extracapillary blood flow type oxygenator (0.8 m²) was 20% smaller than the surface area of the endocapillary blood flow oxygenator (1.0 m²), but the PaO₂ and the QP/QT were significantly higher at all times in Group A compared to Group B. These data support an increased efficiency of extracapillary blood flow oxygenator compared to its endocapillary counterpart. Further, PLT were lower in Group B than in Group A during extracorporeal circulation, because the platelets adhered to synthetic surfaces of the endocapillary blood flow oxygenator membrane. This may have contributed to the decrease in gas exchange efficiency over time.

Massive platelet loss and dysfunction are commonly observed during cardiopulmonary bypass [2, 15] and can lead to post-CPB bleeding. When blood comes in contact with foreign surfaces, platelet adhesion and aggregation [8] lead to platelet degranulation and accelerated aggregation [14], causing local thrombosis and distant embolization. However, pressure differences across the oxygenator are lower in the extracapillary than in the endocapillary blood flow oxygenator, because blood passes outside of the hollow fibers. Therefore, platelet injury is likely reduced when using the extracapillary blood flow oxygenator. However, because of secondary flow patterns and turbulence generated by the extracapillary blood flow oxygenator, platelet adhesion and aggregation may be increased.

In this study, PLT between the PARTIAL 1 and DAY 1 time points were higher in Group A than in Group B, and the difference in PLT between the two groups increased with time. Though platelet function and morphology were not evaluated in this study, these findings indicate greater platelet conservation with the extracapillary than with the endocapillary blood flow oxygenator.

In summary, the present findings suggest that use of the extracapillary blood flow oxygenator yield more efficient gas exchange than when using the endocapillary blood flow oxygenator. Platelet conservation was also greater when using in extracapillary than when using the endocapillary blood flow oxygenator. Use of the extracapillary blood flow oxygenator resulted in longer duration of CPB but hemodilution secondary to large priming solution volume. Excessive hemodilution reduces intravascular osmotic pressure, increases interstitial edema [2] and generates acid-base imbalances that decrease oxygen carrying capacity of the blood [7]. Therefore, effective use of the extracapillary blood flow oxygenator may benefit from a reduction in apparatus size and lower priming volumes.

REFERENCES


