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Combined Gas and Heat Exchange in Extracorporeal Circulation.* (28175)

NICHOLAS P. D. SMYTH, BRIAN B. BLADES AND WILLIAM F. BARTON
(Introduced by C. R. Treadwell)
Department of Surgery, George Washington University School of Medicine, Washington, D.C.

In extracorporeal circulation for heart surgery the heat exchanger is now considered an essential adjunct for maintenance of normothermia and induction of rapidly reversible hypothermia.

There would seem to be obvious advantages in combining the functions of gas and heat exchange in one unit, since each requires the dispersion of blood over a large surface area. Priming volume of the extracorporeal system would be reduced, and also the length of tubing and the number of connections used.

We selected the vertical screen oxygenator for modification, first, because of its efficiency (1); and second, because its absence of moving parts made the task theoretically easier. Since beginning this work we have become aware of the successful application of this principle of combined gas and heat exchange to the bubble(2,3), and the disc oxygenator (4,5).

In the proposed modification the wire screens of the oxygenator would be replaced by thin metal plates, through the center of which the heat exchange fluid would circulate, and on the surface of which the blood would be filmed for gas and heat exchange.

This report is concerned with the preliminary results obtained with a single plate.

Methods. The test plate was made from 2 pieces of No. 304 stainless steel measuring 12 in. in height × 16 in. in width × 64/1,000 of an inch in thickness. On one side of each plate mirror image halves of the central duct system were chemically milled to a depth of 15/1,000 of an inch. The plates were then welded together to form a single plate ⅛ of an inch thick containing a central duct system with a cross-sectional area of 30/1,000 of an inch × ¾ inch. On each side of this plate a pattern was chemically milled to form a "weir" 10/1,000 of an inch deep, and ⅞ of an inch high across the top of the plate, and a 3 mm × 1 mm diamond pattern 5/1,000 of an inch deep on the rest of the plate. The finished plate was the same size as the Kay-Gaertner screen(1), and its surface pattern resembled the standard Tyler #538 type 304 stainless steel Ton-Cap Screen (1,6). Inlet and outlet manifolds were then welded to the bottom of the plate using standard hose threads for connection to the heat exchange fluid system (Fig. 1). The plate was housed in the Lucite Box of a Kay-Gaertner Screen Oxygenator,† modified to take the single plate.‡ Temperature change was affected by a Thermo-Rite hypothermia unit.§ Blood and heat exchange fluid inflow and outflow temperatures were recorded electrically.‖

Oxygenation was studied by partial bypass from an anesthetized dog. The venous blood, obtained from the external jugular vein was circulated across the plate and returned to the femoral artery. Humidified oxygen was passed through the oxygenator casing at a

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† The Mark Company, Randolph, Mass.

‡ International Medical Instrument Co., Stoneham, Mass.

§ Therm-O-Rite Products Corp., Buffalo, N. Y.

‖ Yellow Springs Instrument Co., Yellow Springs, Ohio.

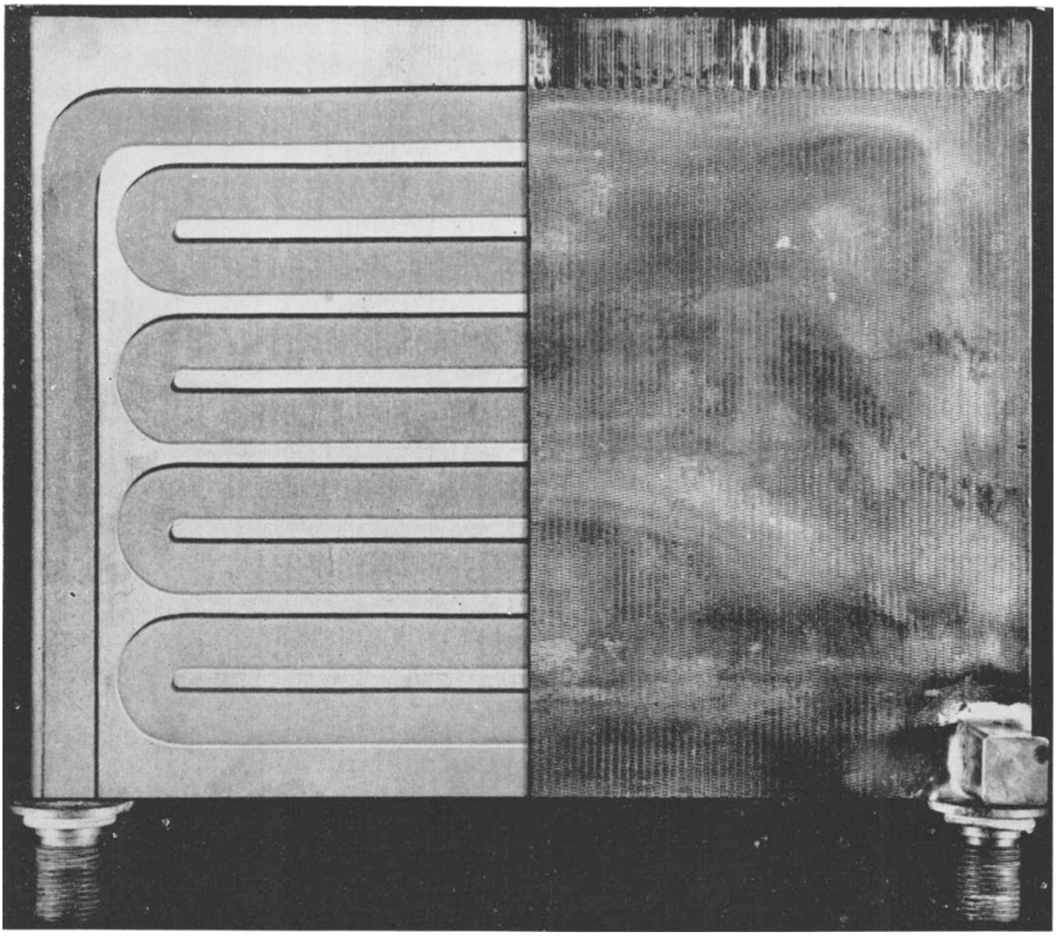

FIG. 1. Composite photograph of test plate, showing on left internal duct pattern, and on right surface pattern. Heat exchange fluid enters through manifold on left and leaves through manifold on right.

rate of 1½ liters per minute. Blood flow rates ranging from 75 cc/min to 280 cc/min were used in 22 studies on 8 dogs. After 15 minutes of bypass at each flow rate, to allow complete clearing of oxygenated recirculated blood from the system, blood samples were obtained simultaneously from the venous and arterial lines of the oxygenator. Oxygen determinations were made according to the method of Van Slyke and Neill(7).

Heat exchange was studied by circulating 1,000 cc of heparinized dogs' blood across the plate in a closed system. In 22 studies, blood at 22°C to 36°C was filmed on the plate at flow rates of 100 to 700 cc/min, and the heat exchange fluid at 0°C to 4°C, was circulated through the plate at a rate of 2,800 cc/min and a pressure of 4 lb/sq in. Higher flows and pressures were not used because of the risk of leakage in the plate.

Temperature recordings were made at one minute intervals until the blood leaving the plate reached a temperature of 2°C to 10°C. The heat exchange fluid system was then emptied and the cold alcohol-water mixture immediately replaced by water at 42°C. This was circulated through the plate and temperature recordings were again made every minute until the blood leaving the plate reached a temperature of 36°C to 38°C.

Heat exchange efficiency was calculated for each series of readings by expressing the change in temperature of the blood as a percentage of the difference between the inlet blood temperature and the inlet water temperature(4). The average value for each

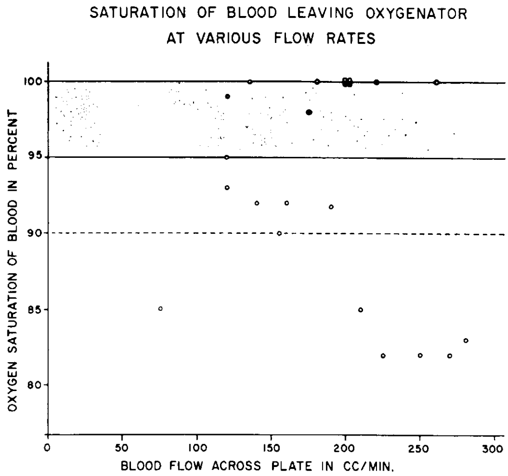

FIG. 2. Oxygenation obtained at various flow rates corrected to a standard venous saturation of 65%. In the range of 120 to 200 cc/min most of the arterial values are in the desired range of 95% to 100% saturation, and all are above 90% saturation. At higher flow rates satisfactory oxygenation was obtained in only 2 out of 7 studies.

cooling and heating cycle was then plotted against the blood flow rate.

Results. Satisfactory oxygenating capacity has been defined as the ability to raise the saturation of blood from 65% to 95%(6). The saturation of the venous blood of the anesthetized dog varied widely in different animals, and at different times in the same animal, making interpretation of the results difficult. When all values are corrected to a venous saturation of 65% as suggested by Theye and others(6), the results can be compared as shown in Fig. 2. There is still a considerable scatter in the oxygen saturation data, a phenomenon noted also by Theye and others(6), and attributed by them to unreproducible variations in film uniformity.

In constructing this plate, some distortion has always occurred in the welding process making it very difficult to maintain a stable film below a flow rate of 120 cc/min. It is hoped that improvement in the fabrication process will eliminate this source of error. Satisfactory oxygenation was obtained at flow rates of 120 to 200 cc/min. This is less than the 320 cc/min maximum flow rate claimed for the Kay-Gaertner Screen, but allowing for the difference in size, compares very well with the flow rates of up to 275 cc/min obtained by Theye and others using large screens measuring 12 × 24 inches(8).

At the optimal blood flow rate for oxygenation of 200 cc/min a heat exchange efficiency of 68% was obtained in the cooling cycle and 58% in the warming cycle. The difference between cooling and heating efficiency was due to the smaller thermal gradient generally available during rewarming(4) (Fig. 3).

Discussion. Since the complete unit will consist of a number of identical plates, its capacity is predictable, and will depend upon the number of plates used. For example, with an oxygenating capacity of up to 200 cc/plate/min, a 20 plate unit should provide adequate oxygenation for flow rates up to 4,000 cc/min, which is an adequate perfusion rate for most adults.

The heat exchange efficiency should be the same for 20 plates as for one. At a blood flow rate of 200 cc/plate/min, or 4,000 cc/20 plate unit/min, the cooling efficiency would be 68%. This figure is higher than that of any heat exchanger on which we have comparable data(4,9-13).

Summary. The advantages of combining oxygenation and heat exchange in a single unit are described. A modification of the vertical screen oxygenator is proposed in which the screens are replaced by plates, on the surface of which blood is filmed for oxygenation, and through the center of which liquid flows

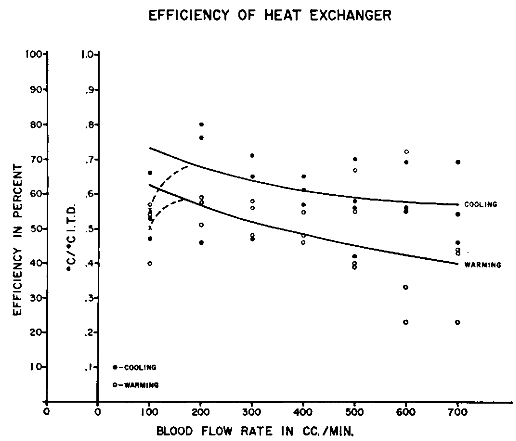

FIG. 3. At a blood flow rate of 100 cc/min the true values (×) are considerably lower than the expected values (solid line curve). This is due to warping of the plate in construction and resultant instability of the blood film. See text.

to effect heat exchange. The oxygenating and heat exchange capacity of one plate are studied and compared with similar functions in separate oxygenators and heat exchangers. The data suggest that a multi-plate unit should provide adequate oxygenating capacity and superior heat exchange capacity.

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