A Convertible Cardiopulmonary Bypass System for Emergency Support Using a Hard-Shell Membrane Oxygenator

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ABSTRACT

Recently, several emergency cardiopulmonary bypass (ECPB) systems have been designed for the support of the arrested patient refractory to resuscitation. We have developed a compact ECPB system utilizing a Bio-Medicus centrifugal pump and a Bentley BCM-7 membrane oxygenator featuring rapid setup and prime. In contrast to other systems, our design provides a choice of configurations for ECPB which allow its continued use from initiation of membrane assist throughout any operative intervention. The safety and efficacy of this system has been tested using a canine model. Five animals were cannulated via the external jugular vein and the femoral artery, placed on ECPB (mean flow 80cc/kg/min), and monitored for 6 hours. Arterial and venous pressures and blood gases were easily maintained by standard manipulations. Serum hemoglobin, BUN, creatinine, and urine output remained stable at levels normal or bypass. Platelets, fibrinogen, and hemoglobin exhibited dilutional decreases at one hour, then stabilized. In summary, this system safely provides short term emergency metabolic and respiratory support while offering unique advantages in mobility, flexibility, and ease of use.

INTRODUCTION

During 1987, more than 200,000 percutaneous transluminal coronary angioplasty (PTCA) procedures were performed. Five percent of these PTCA's resulted in acute closure of a coronary artery, necessitating emergent surgical revascularization in approximately 6500 cases.[1-3] Mortality for this surgical group is estimated at 17% compared to 1.5-3.2% for all PTCA's and 1-6% for coronary artery bypass surgery.[1-5] Alternative methods of managing acute failed PTCA's have had minimal success in restoring target vessel patency.[6-7]

Approximately 1.5 million people will sustain a myocardial infarction this year. Cardiogenic shock will occur in 10-20% of all patients in cardiac failure and will be responsible for a 70-90% mortality rate in this group.[8]

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In the presence of ventricular failure the major limiting factor of current resuscitation procedures appears to be the inability to restore circulation.[9] The use of a cardiopulmonary bypass system (CPB) to provide circulatory function for the patient with acute refractory circulatory failure due to reversible myocardial or pulmonary collapse has been attempted often during the past two decades.[10-17]

Providing safe rapid bedside resuscitation with a emergency cardiopulmonary bypass (ECPB) system, until the patient can be taken to the operating room (OR) for corrective surgery, is still a challenge for the cardiopulmonary perfusionist.

Recent reports on ECPB systems demonstrate the lack of specific features which we think are necessary for remote institution and surgical suite maintenance of ECPB within one system.[16,18-21] We have designed a system that will safely provide short term ECPB as well as OR support, while offering unique advantages in mobility and flexibility. Using closed chest canines as a model, this study evaluates the efficiency of our ECPB system to supply hemodynamic and metabolic function.

ECPB SYSTEM

The ECPB system consists of a Bio-Medicus centrifugal pump, a Bentley[b] BCM-7 membrane oxygenator, a Travenol[c] normothermia unit, and standard CPB tubing. The system is assembled and transported on a custom built Bio-Cabinet[c] which houses all necessary ECPB supplies (**Figure 1**).

The BCM-7 membrane is constructed of 5.8 square meters of microporous polypropylene capillary fibers, which allow a maximum blood film thickness of 100 microns. The rated blood flow values range from 2-7 liters/minute (LPM) and dynamic priming volume at these flows ranges from 1100 to 1200cc. Maximum carbon dioxide transfer and oxygen transfer of the BCM-7 are 100 cc/min./LPM and 57 cc/min./LPM respectively.[22]

The Bio-Pump 80, a low prime, constrained vortex pump, which has been previously tested for long term use, was used.[23] For a control and power console, the Bio-Medicus [a] 540 with integral battery power source was selected. Arterial blood flow was measured using in line Bio-Medicus low probes with electromagnetic transducers.

a. Bio-Medicus, Inc., Minneapolis, MN
b. American Bentley, Inc., Irvine, CA

TABLE 1.

TIME (Hrs)	1/2	1	2	3	4	5	6
ARTERIAL FLOW (l/min)	2.38 ± 0.45	2.36 ± 0.40	2.36 ± 0.27	2.26 ± 0.32	2.40 ± 0.33	2.18 ± 0.26	2.14 ± 0.22
PUMP RPM's (X 1000)	2.36 ± 0.51	2.42 ± 0.31	2.46 ± 0.26	2.34 ± 0.48	2.36 ± 0.30	2.42 ± 0.25	2.40 ± 0.25
RESISTANCE (mmHg)	184 ± 47	214 ± 30	210 ± 42	187 ± 23	173 ± 33	175 ± 21	168 ± 23
MAP (mmHg)	92.2 ± 12.4	85.0 ± 16.8	91.0 ± 13.0	85.6 ± 17.7	92.0 ± 11.7	95.4 ± 21.7	91.2 ± 14.2

All values ± St. dev.

W. Gil

ECPB Perfusion Parameters

TABLE 2.

TIME (Hrs)	0	1	2	3	4	5	6
HEMOGLOBIN (g/dl)	11.9 ± 0.3	7.0 ± 0.6	6.7 ± 0.8	6.9 ± 0.9	6.6 ± 1.2	6.8 ± 1.6	6.9 ± 1.4
HEMATOCRIT (%)	33 ± 2.9	22 ± 1.2	22 ± 1.0	21 ± 1.2	21 ± 1.8	21 ± 1.6	21 ± 3.0
PLATELETS x 10^3 (/mm3)	200 ± 34	118 ± 11	115 ± 10	116 ± 15	112 ± 9	109 ± 7	107 ± 9
FIBRINOGEN (mg/dl)	125 ± 27	108 ± 9	100 ± 6	109 ± 4	106 ± 6	106 ± 9	107 ± 9

All values ± St. dev.

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Hematologic Parameters Vs. Time

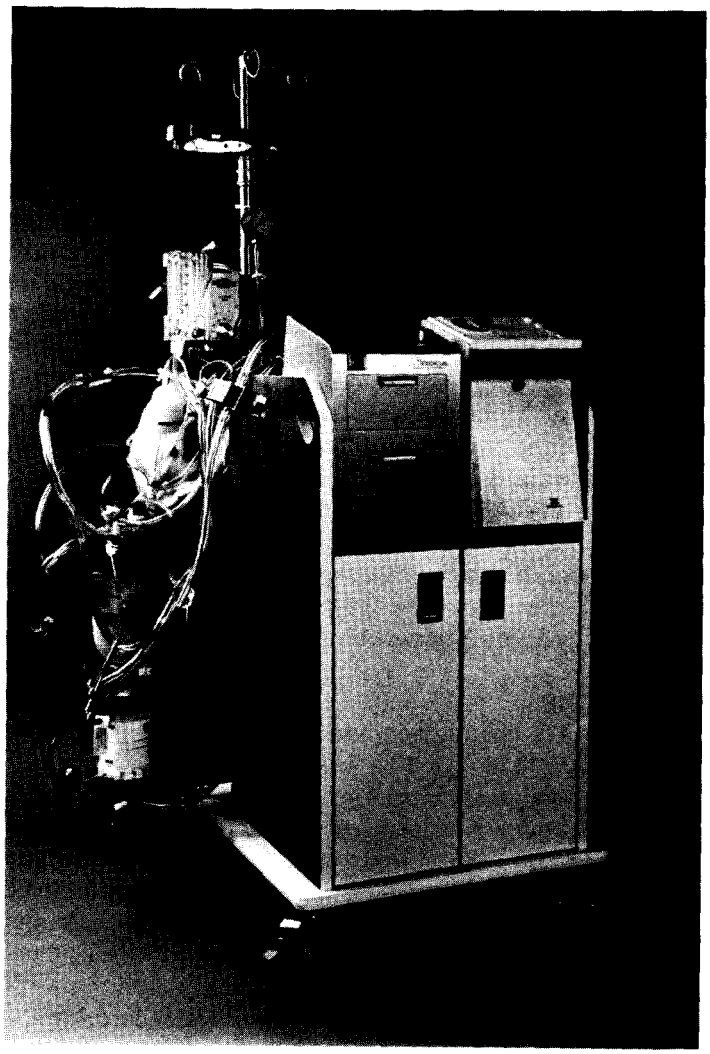

TABLE 3.

TIME (Hrs)	0	1	2	3	4	5	6
pH	7.35 ± 0.05	7.40 ± 0.04	7.39 ± 0.06	7.44 ± 0.03	7.40 ± 0.04	7.39 ± 0.04	7.43 ± 0.04
pCO2 (mmHg)	26.8 ± 5.7	30.9 ± 5.5	32.6 ± 4.7	28.9 ± 3.6	32.1 ± 5.4	30.2 ± 4.5	29.5 ± 4.4
pO2 (mmHg)	367 ± 111	586 ± 78	619 ± 96	662 ± 65	600 ± 94	655 ± 83	626 ± 99

All values ± St. dev.

W. Gil

Arterial Blood Gasses Vs. Time

Standard polyvinyl tubing and polycarbonate connectors were used to construct a tubing configuration which provides the option of two different blood flow paths through the oxygenator. Configuration A (**Figure 2**) allows blood to follow the standard gravity drainage course into the venous reservoir of the BCM-7. Configuration B (**Figure 3**) excludes the hard shell venous reservoir and allows direct aspiration of blood from the right atrium to the vortex pump. When converting from configuration A to B, an occlusion clamp (**Figure 3, clamp A**) must first be placed on the venous outflow line just proximal to the inlet port of the venous reservoir. When converting from configuration B to A, this clamp (**Figure 2, clamp A**) must be the last one removed. This sequence of clamping is followed to prevent the negative pressure zone created by the vortex pump from being exposed to the ambient air of the venous reservoir. For continual use of the system during open heart surgery, a six inch tubing segment with a 3/8 inch straight connector placed distally, is connected to the cardiotomy return port of the venous reservoir. This tubing segment must be closed with a clamp until a cardiotomy is placed in line. Regardless of the venous configuration chosen, blood returning to the patient is filtered with a 40 micron arterial filter and resistance is measured distal to the filter.

A ventilating gas delivery system was designed to allow gas to be obtained from various sources. During extended bedside support, ventilating gases were obtained from regulated, in-wall, hospital supplies. Wall gas supplies pass through a set of hoses connected to MCV-4[d] one-way valves which then direct the gasses to an air-oxygen mixer. For mobility, two "E" cylinders, air and oxygen, are attached to the Bio-Cabinet. During patient transport, cylinder gases pass through the appropriate regulators, through a second set of hoses, also attached to the MCV-4 valves, and into the air-oxygen mixer. The MCV-4 one-way check valves permit gases to be supplied to a single air-oxygen mixer from multiple sources, while preventing gas leakage due to back flow into unused hoses. (**Figure 4**)

Normothermia during ECPB is achieved by intermittently converting to configuration A which allows blood to flow over the integral heat exchanger of the BCM-7. Once the patient is transported to the OR, the normothermia unit is replaced by a Sarn's[c] heater cooler.

METHODS

Five conditioned adult male mongrel dogs with an average weight of 25 + 1 kg were used for an ECPB model. The animals were anesthesitized with sodium pentothal (20mg/kg), intubated, and maintained with endotracheal anesthesia using halothane (0.7-1%), nitrous oxide, and oxygen. Rectal and esophageal temperatures were monitored by thermistor probes. Foley catheters were inserted for urine output measurements. Systemic arterial and central venous pressures were monitored by catheters in the right femoral artery and vein. The electrocardiogram was monitored by a standard limb lead arrangement. Hemodynamic parameters were continuously monitored.

Utilizing a trocar-guidewire system, percutaneous access of the right external jugular vein was made with a prototype 28F cannula. The cannula was advanced to the right atrium to ensure maximum preload reduction. The left femoral artery was also accessed for perfusion using a prototype percutaneous 16F cannula in two dogs and by open technique with a 16F standard CPB cannula in the remaining dogs. Prior to cannulation the dogs were heparinized systemically (300 units/kg). The arterial and venous cannulae were connected to the crystalloid primed arterial-venous loop of the ECPB and baseline data was collected, support was then initiated. Arterial perfusion was adjusted by 500cc increments until the pump flow was equivalent to 80-100% of predicted canine cardiac outputs. After stabilization on full bypass for 15 minutes, the dogs were converted to isolated membrane assist, configuration B, for five hours. Body temperature was allowed to drift until the last hour when configuration A was used intermittently to rewarm the dog. The paralyzed animals maintained an ejecting state with spontaneous heart beat. Activated clotting times [ACT] of 480-plus seconds were established using heparin administration. Blood volume, electrolytes, and arterial blood gasses (ABG) were stabilized using standard additives and manipulations.

A perfusion profile of arterial pump flow, pump revolutions per minute (RPM), blood flow resistance, urine output, temperature and ACT were recorded every 30 minutes. Hemodynamic and laboratory parameters were drawn and/or recorded immediately prior to ECPB and every 30 minutes for six hours. Laboratory tests included hemoglobin (Hgb), hematocrit (Hct), platelet count, fibrinogen, serum Hgb, electrolytes, creatinine, BUN, osmolality, and ABG's.

Results are expressed as the mean $\pm$ the standard deviation. ANOVA was used to compare the changes in observed parameters.

RESULTS

Priming of the ECPB system was accomplished in five minutes or less in all cases. Assembly with a custom ECPB tubing pack and priming were completed well within the time needed for prepping, draping and cannulation of the dog.

Mean arterial flow rates were maintained at 2.3 + .8 L/min. (range .9-2.7 L/min). The pump RPM required to produce the mean flow, blood flow resistance, and mean arterial pressure [MAP] are summarized in **Table 1.** There were no significant differences in mean values of these parameters in relationship to time interval of bypass. Pharmacological support of MAP was not necessary.

Central venous pressure decreased from a baseline mean of 4.6 mmHg to 3.2 mmHg after two hours of ECPB. It was subsequently stabilized in a range of 1-3 mmHg using volume replacement.

ABG's and acid-base balance remained stable and within baseline values for the six hour bypass interval. ABG's were maintained with a pH of 7.35-7.44, pCO2 of 26-30 mmHg, pO2 of 586-662 mmHg, and bicarbonate of 18-21 meq/L.

Pre-ECPB mean Hgb and Hct were 12 gm/dl and 33%

c. Sarns Inc/3M, Ann Arbor, MI

d. Western Enterprises, Inc., Ann Lake, OH

respectively. After one hour of ECPB, maximal decreases were found in all hematologic parameters due to initial hemodilution. **Table 2** represents the change in these values over time. Blood transfusions were not performed due to cost.

During six hours of ECPB, serum Hgb. remained low except in the first two dogs which were cannulated with prototype arterial cannulae. These animals developed serum Hgb. levels of 0.07 to 0.10 mg/dl at 4-6 hours of bypass.

Urine output ranged from a mean of 107 ± 25 cc/hr after one hour of bypass to a 218±45 cc/hr average at all other time intervals. Creatinine values stabilized to a mean of 0.68±.05 mg/dl after an initial dilutional decrease at one hour.

Body temperature drifted from a baseline mean of 34 ± .61°C to 31±.55°C after five hours of ECPB. Rewarming to a normal core temperature of 36.5±.74°C was accomplished during the final hour of support using the integral heat exchanger of the BCM-7. **(Figure 5)**

All animals survived the experimental ECPB sequence. There were no significant changes in any observed parameter other than changes due to hemodilution and routine CPB exposure.[24]

DISCUSSION

Gas exchange and blood flow resistance through the membrane are indicators of membrane performance and are useful in predicting membrane deterioration.[25] An increase in gas or blood flow resistance and/or a decrease in gas exchange is usually the result of blood and blood protein depositions forming on the membrane surface.[25] A significant increase in blood flow resistance through the membrane would demand an increase in pump RPM's to maintain an established blood flow rate. During 6 hours of ECPB, there were no significant changes in resistance or RPM's associated with a inverse change in flow and MAP. Gas phase water or proteinaceous exudate accumulation, referred to as membrane strike through, is also indicative of membrane capillary failure and was not observed in this series.[25-26] Gas flow rates through the membrane remained within expected limits in this study. The BCM-7 was clearly capable of maintaining arterial blood gasses within acceptable limits **(Table 4)**. We did not study the gas transfer efficiency of the polypropylene hollow fiber membrane oxygenator since this has been previously established.[21,27-29] Membrane failure was not observed in this series.

The ECPB system studied in this review provided sustained MAP's of 80 mmHg or greater and arterial pO_2 levels sufficient to preserve renal and cardiac function. An ECPB system must not only provide CPB sufficient to supply metabolic, respiratory, and hemodynamic demand but must do so easily and safely with maximum benefit to the patient. After transport the remote ECPB must also be capable of providing OR support. We believe the ECPB system, as compared to those in the literature, offers improvement in all of these functions. It is also the only system capable of providing remote and OR support.

The principle features of this system which improve mobility, safety, control, and priming time are the integrated reservoir/oxygenator with multiple blood flow circuits and the gas connect system.

Mobility is facilitated by the compact design, which eliminates a remote reservoir and reduces the associated operational circuit area, by the flexibility of the ventilating gas connect system, and by the self contained Bio-Cabinet. Patient safety is improved by the ability to bypass the venous reservoir, by converting to configuration B, thus decreasing the amount of operating area subjected to movement which can cause microemboli production. The reduction in area also enhances ease of use by minimizing the area requiring constant surveillance.

In the A configuration, blood passes through a defoaming sponge which removes air from the blood. As a further safety feature, a vortex air separator located at the top of the membrane bundle collects air by centrifugal force and continuously shunts it through a one-way purge line back to the venous reservoir reducing the risk of air entering the membrane. Venous bag reservoirs which depend on flow patterns and air bubble buoyancy to remove air are capable of passing air to the membrane.[30]

Safety and control are also enhanced by utilization of configuration B, during remote support, which reduces the circuit fluid volume of this system. Other systems with in-line venous reservoirs must contain manufacturer's recommended minimal volume at all times to ensure the safety and performance of the system.[13,19,27]

Control of the system by the operator is augmented by having a choice of configurations. This choice deletes the dependency on the patient's peripheral IV lines for infusion of volume replacement. Large volumes can be rapidly administered to the patient by allowing the Bio-Pump to draw fluid from the venous reservoir while in configuration B.

Assorted bag type venous reservoirs in current systems demand more detail and effort in air removal during priming.[13,16,18,27,29] With our ECPB, air is easily and quickly evacuated through the open integrated hard shell reservoir.

All other systems require the use of a second CPB circuit after transfer to the OR. The pernicious effects of multiple exposure of the patient to hemodilution cannot be eliminated by these systems. Increased necessity for blood product administration is the most obvious risk of extreme hemodilution.[31,32] The principal, but not as obvious, deleterious effect is an increase in total somatic water content.[33] The myocardium and kidneys are adversely affected by a positive water balance. For the patient in acute circulatory collapse, exposure to sustained hemodilution may lead to post operative renal, pulmonary and/or cardiac dysfunction.[34,35]

Once in the OR the ECPB in this report adapts, after minimal changes, to function as a routine CPB system. First, the mobile system is positioned adjacent to a standard CPB pump base. A cardiotomy reservoir on the standard base is easily attached to a previously placed tubing segment and the ventilating gas sources are switched to OR wall supplies **(Figure 6)**. Within one minute and without interruption of support, the ECPB system can become to be the OR bypass system, thus eliminating the need to attach the patient to a second system. Continued use of one ECPB system from initiation of ECPB

support throughout surgical intervention provides physiological benefit as well as cost benefit for the patient.

Rapid resuscitation using CPB for bedside, transport and OR support is in a developmental era. This study supports the ability of our ECPB system to provide support that is safe, efficient, and cost effective. The unique design of this system allows it to be used continuously through all phases of support including operative support. ECPB systems, as described in this report, have potential application as an adjunct therapy for a group of patients with historically low salvage rates. We have initiated clinical trials with this system to further define the role of ECPB support.

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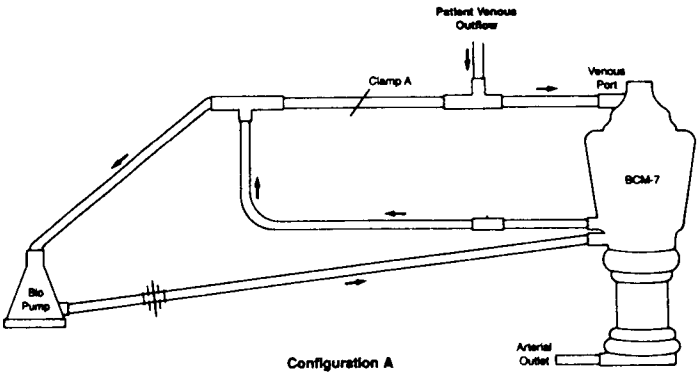
FIGURE 2



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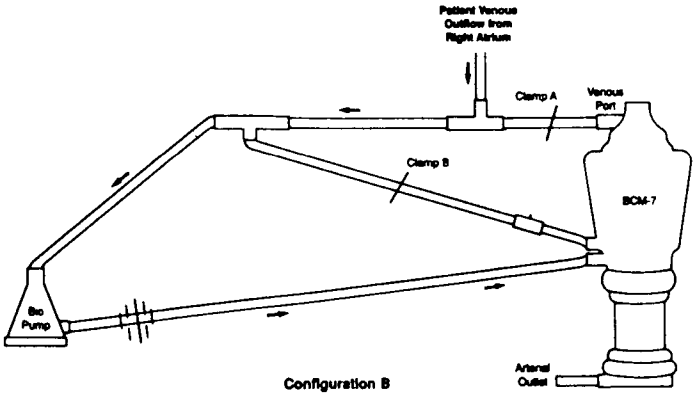
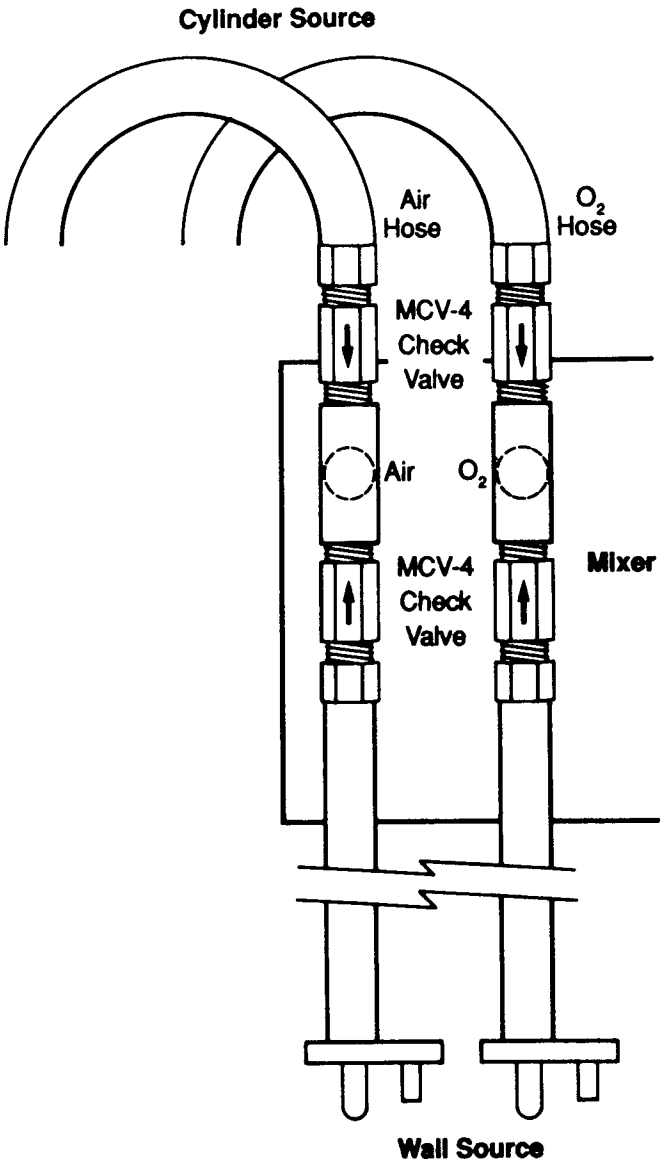


FIGURE 4



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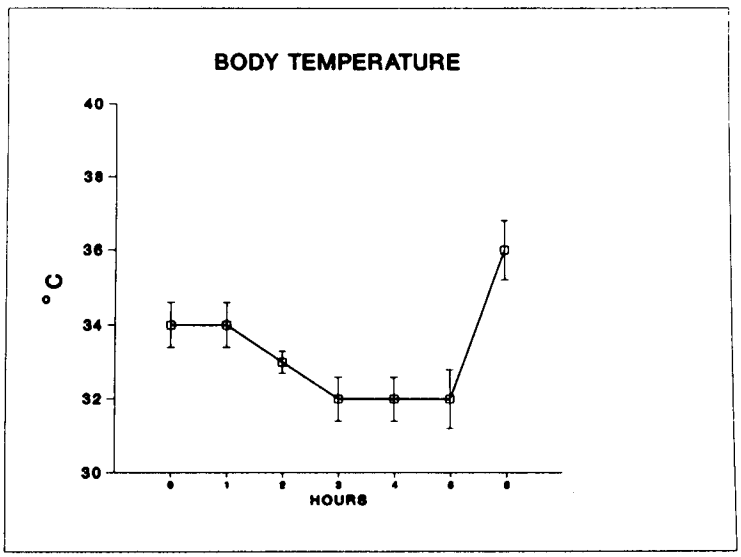

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