Blood conservation in open heart surgery

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Attempts at blood conservation have been made continuously during the entire history of cardiac surgery. In the early days of cardiac surgery with cardiopulmonary bypass, 15 units of whole blood were typed and cross-matched before the procedure, and another 15 set up after induction of anesthesia. Large volume oxygenators were primed with 3 L or more of whole blood, initially heparinized and freshly drawn, and the incidence of reexploration was such that an anesthesia machine was reserved for the reexploration immediately after the patient was brought to the postoperative intensive care unit. The sheer logistical magnitude of obtaining so much blood represented a limit upon the amount of open heart surgery that could be performed. The incidence of hepatitis and other adverse responses to homologous blood transfusion were important factors of morbidity and mortality.

At present, the amount of blood used per case is only a small fraction of that used as recently as a decade ago. Many factors are responsible for this decline, including smaller priming volumes and nonheme blood primes, autologous blood transfusion, more exacting anticoagulation and coagulation reversal protocols, acceptance of postoperative normovolemic anemia, and recently, retransfusion of intraoperative suction and postoperative shed

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mediastinal blood. This discussion concentrates on the physiology of acute normovolemic anemia, with emphasis on work performed for many years at the Massachusetts General Hospital, and recent developments in retransfusion of shed blood.

Hemodilution

Hemodilution refers to the induction of acute anemia. In most instances, maintenance of normal intravascular volume (normovolemia) is implied. The conditions under which hemodilution occurs or is induced, however, must be described to anticipate the resultant physiologic effects. For instance, it is well known that blood volume will be reconstituted over a 24- to 48-hour period by transcapillary refill following a single, nonshocking hemorrhage. The hemoglobin and hematocrit values at the completion of reconstitution are less than before the hemorrhage. We shall not, however, consider this "hemodilution." For purposes of this presentation, hemodilution will refer to production of acute anemia by simultaneous withdrawal of blood and replacement by a volume of crystalloid and/or colloid in quantities sufficient to maintain circulatory stability, as judged by adequacy of pressure measurements. In the clinical setting, the withdrawn blood provides a source of fresh autologous blood which has not been exposed to the injury of cardiopulmonary bypass for reinfusion after major surgical blood loss has ceased.

The specific purposes of the described studies have been to decrease ultimately the morbidity of cardiopulmonary bypass, decrease blood loss, decrease incidence of hepatitis, decrease administration of bank blood products, decrease the logistical problems of blood procurement, and remove blood availability as a limiting factor in cardiac surgical practice.

It is crucial to note that all of the data presented (both animal and human) have been gathered in the unshocked state. It may be that the implications of colloid and crystalloid administration are different after a period of shock, particularly with reference to the integrity of the pulmonary capillary membranes.

Studies in animals: acute profound normovolemic anemia induced by crystalloid replacement of shed blood in spontaneously breathing dogs[1]

Methods

Mongrel dogs were anesthetized with intravenous thiopental. Anesthesia was maintained with 0.25% to 0.5% halothane in oxygen administered via a non-rebreathing system and endotracheal tube. Spontaneous ventilation was maintained throughout the experiment; deep breaths were administered each half hour.

Arterial blood gases were measured by polarography, pressures by transducers, cardiac output by indicator dilution, and blood volume by RISA dilution.

Hemodilution was accomplished by bleeding from the arterial line into standard ACD blood bags, simultaneously infusing warmed (37 C) Ringer's lactate solution to maintain central venous pressure several centimeters H_2O higher than control. This was associated with a systemic arterial blood pressure at a steady value somewhat lower than control. Bleeding and reinfusion were continued until a hematocrit of approximately 5% was achieved. The animals were maintained at this hematocrit for one hour by continued infusion of Ringer's lactate. At the conclusion of

this hour, the first unit of withdrawn blood was reinfused. The remainder of the dog's red blood cells (which had been separated from the supernatant) were then reinfused.

Results

PaO_2 was unchanged during or after hemodilution, in spite of the massive positive fluid balance and a total serum protein concentration averaging 0.9 g/dl at the time of maximal dilution (*Fig. 1*). There was no overt evidence of lung water accumulation. The cardiac output increased during dilution to two to three times the control value, without a significant change in heart rate. This increase was therefore due to an elevation of stroke volume. The average hematocrit achieved was 6%. Blood volume did not change significantly.
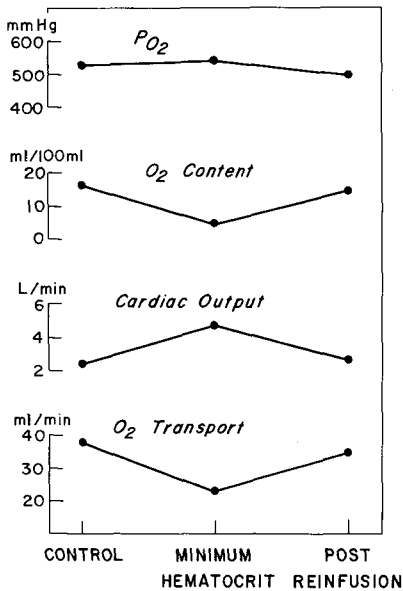
Fig. 1. Effect of Ringer's lactate hemodilution in anesthetized, spontaneously breathing dogs. No increase in alveolar-arterial oxygen tension gradient occurs, despite the large positive water balance. No metabolic acidosis is present during these conditions, despite the decrease in arterial oxygen content and oxygen transport. (Figure plotted from data of Reference 1).

The volume of "blood" withdrawn averaged twice the animal's blood volume, and the volume of Ringer's lactate infused exceeded half the animal's control weight. Net weight gain averaged 36%. Two thirds of the excess weight was lost in the first 24 hours, and the remainder by the end of the second day.

Two groups of dogs were studied as survival experiments. These latter experiments were performed with sterile precautions, and without cardiac output or blood volume measurements. One group consisted of normal mongrel dogs, and the other of dogs with chronic aortic insufficiency, which had been surgically induced a minimum of 6 months previously. There was no evident difference in hemodynamic response, and all dogs were long-term survivors of the experiments without apparent harm.

Quantitation of lung water during acute hemodilution and colloid depletion: effect of reconstitution of oncotic pressure[2, 3]

Since the experiments described above implied a lack of lung water accumulation despite conditions that would be expected to produce it, the following studies were performed to specifically quantitate this aspect.

Methods

Mongrel dogs (17 to 22 kg) were anesthetized with 25 mg/kg intravenous thiopental. Anesthesia was maintained with halothane, 0.25% to 0.50%, in oxygen via a nonbreathing system and an endotracheal tube. Spontaneous ventilation was maintained throughout the experiment. Deep breaths were administered each half-hour. Appropriate cannulas were inserted to measure systemic, pulmonary artery, pulmonary capillary wedge, and right atrial pressures via electronic transducers, cardiac

output, and pulmonary extravascular water by indicator dilution; and to withdraw blood and infuse fluid.

Hemodilution was accomplished by bleeding from an arterial cannula and simultaneously infusing warmed Ringer's lactate solution (37 C) through a venous cannula. The infusion rate was adjusted to maintain right atrial pressure several millimeters of mercury above control, since previous studies had shown that this level was associated with a steady circulatory state. In general, removal of 2.5 to 3.5 L from the arterial line was required to achieve a hematocrit of less than 10%. This required approximately one hour.

Lung water was estimated in vivo at intervals by double indicator dilution (RISA and THO). At the conclusion of the experiment, the lungs were removed for determination of wet and dry weight and histologic examination (light microscopy). The main bronchi were clamped with the lung well inflated. Five pieces were removed from dependent and nondependent areas of both lungs, immediately frozen with an acetone-dry ice coolant, and subsequently prepared for sectioning by paraffin embedding. The remainder of the lungs were excised, drained by gravity, weighed, and oven-dried to constant weight at 105 C. The normal value determined in seven control dogs by this method was 3.88 ± 0.19 (SD) g H_2O/g dry lung; or a wet- to dry-weight ratio of 4.88. Dog blood at hematocrit of 40% had an average value of 4.0 g H_2O/g dry blood.

Protocol

Twenty-two animals were divided into three groups: Group I was killed when hemodilution was accomplished; Group II was maintained for one hour at the low hematocrit by continued infusion of Ringer's lactate; Group III was maintained at the low hematocrit for one hour by infusion of Ringer's lactate, followed by an infusion of 75 g human salt-poor albumin and maintenance for an additional hour prior to killing. In Group III, no additional Ringer's lactate was required after completion of albumin administration.

Results

Hematocrit was less than 10% in all groups after hemodilution. Total serum protein was less than 1 g/dl after Ringer's lactate in all groups. In Group III, serum protein concentration increased from 0.36 ± 0.1 g/dl to 3.6 ± 0.2 g/dl after colloid infusion.

Hemodynamic and blood gas consequences of hemodilution with Ringer's lactate were similar to those reported above. Cardiac output was increased significantly in the face of a significantly decreased systemic arterial pressure. Systemic and pulmonary vascular resistances were significantly decreased. Infusion of salt-poor albumin in Group III resulted in significant increases in cardiac index, pulmonary artery, pulmonary capillary wedge, and right atrial pressure compared to the values after hemodilution and maintenance for one hour prior to infusion of colloid. PaO_2 was unchanged throughout the experiment in all groups.

Net Ringer's lactate administered during hemodilution averaged 4.4 L during hemodilution, and 2.5 L the following hour. In a separate group of four animals maintained for a subsequent (2nd) hour, an additional 2.1 L Ringer's lactate was required to maintain vascular pressures within the required limits. In contrast, further Ringer's lactate infusion was not required in Group III dogs after reconstitution of oncotic pressure.

Gravimetric lung water content increased from 3.88 ± 0.19 to 5.67 ± 0.34 g H_2O/g dry lung at completion of hemodilution, and increased further to 6.70 ± 0.57 g/g during one hour of maintenance with Ringer's lactate. Reconstitution of oncotic pressure resulted in a decrease to 5.93 ± 0.46 g/g. Each change was significant. The calculated increase in extravascular lung water (including a correction for blood trapped in the lungs) amounts to 23% at conclusion of hemodilution, 47% after one hour, and 28% after albumin administration (*Fig. 2*).

An average of 18 bronchovascular units was examined in each animal of Groups II and III. Of peribronchial perivascular units of dogs maintained for one hour with Ringer's lactate, $80.9 \pm 12.1\%$ demonstrated cuffing. This was reduced to 23.2 ± 19.5 after colloid infusion ($p < 0.001$) (*Fig. 3*). In contrast,

INCREASE IN EXTRAVASCULAR LUNG WATER
WITH HEMODILUTION
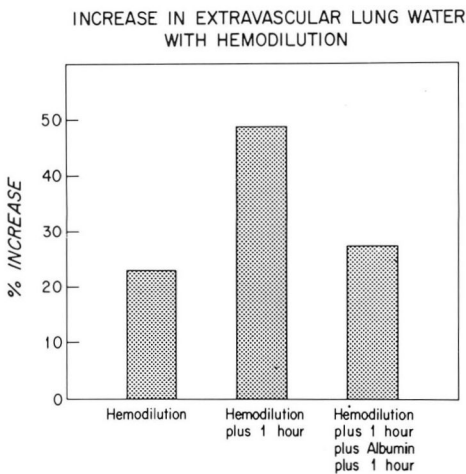
Fig. 2. Gravimetric estimation of the water content of the excised, drained lung demonstrates increasing water accumulation with increasing duration of Ringer's lactate hemodilution. Reconstitution of oncotic pressure was associated with a decrease in lung water content, despite an increase in left atrial pressure of 9 mm Hg. All changes are statistically significant ($p < 0.05$). (From Reference 2).
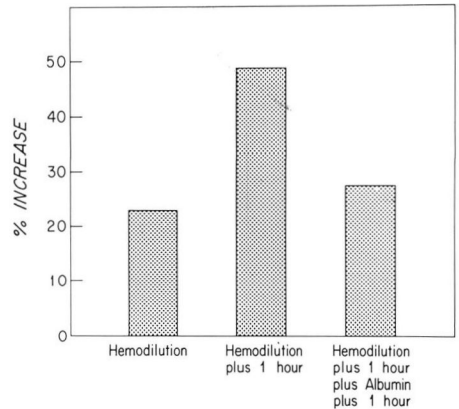
Fig. 3. The incidence of cuffing in perivascular-peribronchial units in which the pulmonary artery branch exceeded 25 μm in diameter was dramatically reduced by reconstitution of oncotic pressure. "Before-albumin" dogs were subjected to Ringer's lactate hemodilution and maintenance for one hour with additional Ringer's lactate. "After-albumin" dogs received 75 g salt-poor albumin. (From Reference 2).

indicator dilution failed to reflect the change in extravascular lung water content.

Quantitation of heart water during acute hemodilution with and without colloid depletion[4]

As the foregoing studies indicated that excess water was present in the lungs after colloid depletion of the plasma, the following studies were performed to quantitate the effect of similar conditions upon heart water. Unlike the lung, the heart is a "solid" organ.

Methods

Sixteen chloralose-urethane anesthetized dogs were ventilated mechanically. The heart was exposed through a left thoracotomy and suspended in a pericardial cradle. Heart water was estimated by wet- to dry-weight ratio of full thickness biopsies of left ventricular myocardium. The biopsies were obtained with a 3-mm OD, 2.1-mm ID steel tre-

phine mounted in a high-speed (15,000 rpm) drill. The tissue obtained was immediately removed from the trephine by a stylet, rolled gently on weighing paper to remove excess blood on the surface, and placed at once in a pre-weighed glass bottle, which was then closed and dried.
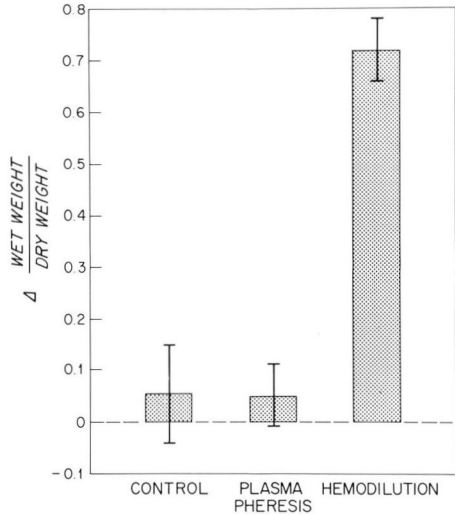
Hemodilution was produced with Ringer's lactate. Plasmapheresis was accomplished by removing blood into ACD blood bags, centrifugation, and returning the supernatant to the dog. The blood volume was supplemented with donor dog plasma and human 5% albumin in saline (two dogs) as necessary to maintain circulatory integrity.

Results

Hematocrit and total serum protein following hemodilution with Ringer's lactate solution were similar to those described above. Total serum protein was unchanged from control in the plasmapheresed dogs. Measurements obtained in paired biopsy specimens, determined in a separate group of dogs, were highly reproducible, with a coefficient of variation of 5%. Baseline wet-to dry-weight ratio was 4.33 ± 0.51 (or 3.33 ± 0.51 g H_2O/g dry heart). Neither control dogs nor plasmapheresed dogs demonstrated changes. However, wet-to dry-weight ratio increased to 5.04 ± 0.56 g/g ($p < 0.001$) immediately after hemodilution, and remained at that level thereafter (*Fig. 4*).

Effect of profound hemodilution on left ventricular performance[5]

In dogs studied on right heart bypass, left ventricular performance was assessed at constant left ventricular stroke work before and up to 150 minutes after hemodilution and oncotic pressure reduction were produced by crystalloid administration. Lowering hematocrit

Fig. 4. Heart water content was unchanged in control (sham-operated) dogs or dogs subjected to acute anemia by plasmapheresis. However, Ringer's lactate hemodilution was associated with an increase in heart water content. (Figure from data of Reference 4).

from $43.0\% \pm 1.3\%$ to $13.6\% \pm 1.7\%$ (SE) did not significantly change left ventricular end-diastolic pressure. After 80 minutes at low hematocrit, left ventricular end-diastolic pressure increased slightly by 1.7 ± 0.6 cm H_2O ($p < 0.05$) at stroke work of 17.3 ± 2.3 g · m. LV dP/dt did not change significantly throughout the studies.

When left ventricular function curves were generated by increasing cardiac output, the stroke work attained at a left ventricular end-diastolic pressure of 10 cm H_2O declined, though not significantly, by a mean of 13% (*Fig. 5*). Similar findings were obtained in vagotomized, ganglion and beta-adrenergically blockaded dogs. Coronary blood flow increased more than 300% during hemodilution, and myocardial oxygen consumption was unchanged throughout. Thus, profound crystalloid hemodilution is accompanied by slight, if any depression of left ventricular performance.
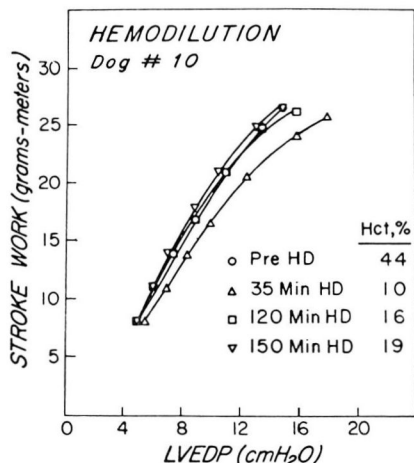
Fig. 5. Left ventricular function curves obtained in one representative dog on right heart bypass. This heart showed slight depression of function associated with reduction of hematocrit to 10%, and recovery when the hematocrit rose to 16%. (From Reference 5).

Effect of profound hemodilution upon experimental mycardial ischemia in the dog[6]

The development and widespread application of surgical procedures to revascularize the coronary arteries raised questions concerning any potential hazard of hemodilution and the attendant acute anemia in patients with ischemic heart disease. The following studies were undertaken in a dog model of myocardial ischemia, which has proven relevant to man with coronary artery disease.[7] We compared the effect upon the severity of experimental myocardial ischemia of a reduction of arterial oxygen content produced by hemodilution to a similar reduction produced by decreasing inspired oxygen concentration.

Methods

Sixteen dogs were anesthetized with chloralose and urethane, and ventilated with oxygen by a Harvard animal ven-

tilator. The heart was exposed through a left thoracotomy and suspended in a pericardial cradle, a branch of the left anterior descending coronary artery was isolated, and a snare placed loosely around it. The femoral artery and left atrium were cannulated and their pressures were continuously recorded.

A diagram of the coronary arteries was drawn, and between 15 and 18 sites were selected for epicardial electrographic mapping. The sites were located (a) within the area supplied by the branch that was to be occluded, (b) in immediately adjacent areas, and (c) in areas remote from the occluded artery. The electrocardiogram was standardized at 1 mV/mm. The epicardial electrogram was recorded twice in each location for the control mapping. The artery was then occluded and readings were recorded at each site 3, 6, 9, and 12 minutes following occlusion. The snare was then loosened to reestablish flow, and readings were subsequently recorded at each site at 3, 6, 9, and 12 minutes. Severity of ischemia was estimated by the sum of the ST-segment elevation (Σ ST) at each time interval.

Protocol

Each dog underwent three series of mappings. In 10 dogs, the first series (predilution) was obtained during chloralose and urethane narcosis alone. The dogs were then hemodiluted to an average hematocrit of 6.2% ± 0.4%, by simultaneous blood withdrawal and infusion of Ringer's lactate solution, and a second series (dilution) of recordings was obtained. The final series of recordings (postdilution) was performed after reconstitution of hematocrit (32.2% ± 4.0%). In six dogs, the studies were done before, during, and after production of hypoxia (PaO₂ 28.8 ± 2.2

mm Hg; CaO_2 6.8 ± 1.3 vol. %) by decreasing inspired oxygen concentration.

Results

Figure 6 represents the effect of hemodilution and hypoxia on the severity of myocardial ischemia, expressed as the sum of the ST-segment elevations (Σ ST). The data are compared with precontrol and postcontrol experiments. In the hemodilution experiments, there was no significant difference in the severity of ischemia during the three study periods—predilution, hemodilution and postdilution. However, during hypoxia (higher hematocrit same arterial oxygen content) the severity of ischemia produced by coronary arterial occlusion was significantly greater (p < 0.01) than during either the prehypoxic or posthypoxic periods.

The blood pressure, heart rate, and left atrial pressure were constant throughout the three study periods in those animals made hypoxic; however, systemic arterial pressure decreased and the left atrial pressure increased during the dilution period. Since these changes may influence myocardial oxygen supply and demand, they may have masked a potential change in the magnitude of ischemia.[8] We, therefore, performed similar experiments in five isolated dog
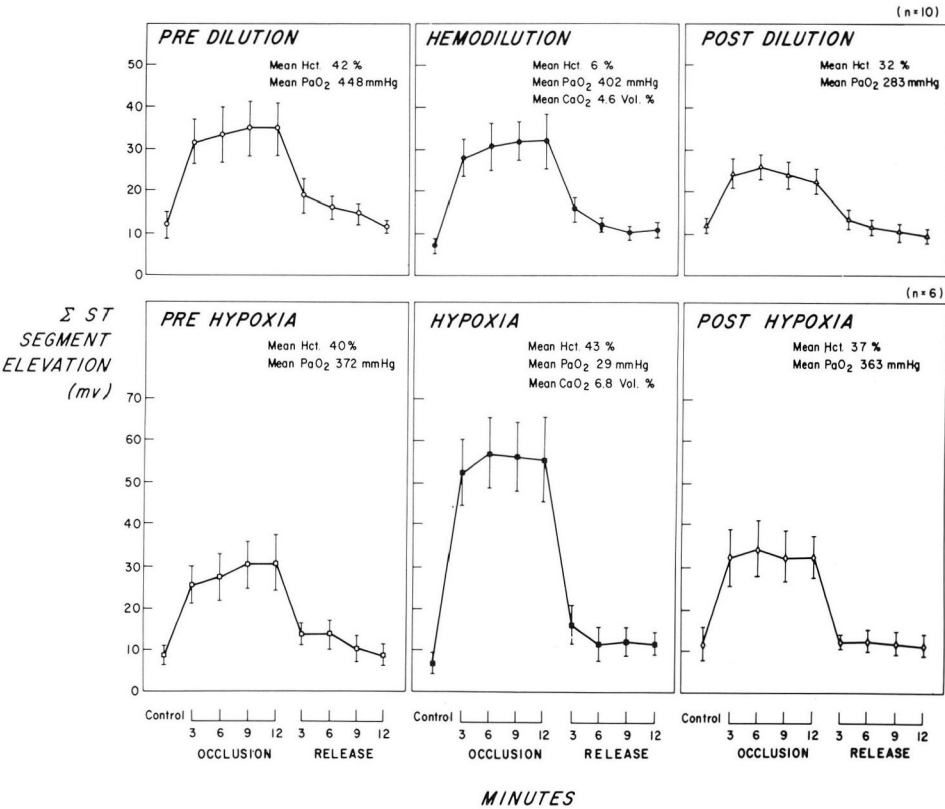

Fig. 6. Summary of ST-segment elevation data in the intact anesthetized dog. The extent of ischemia is not affected by hemodilution. However, ischemia is markedly increased by hypoxia. Φ = mean ± standard error. (Figure from Reference 6).

heart preparations in which these hemodynamic variables could be maintained constant. Under these controlled conditions, also, severity of ischemia was less during dilution than during hypoxia. Total coronary flow was essentially doubled during both hypoxia and dilution. However, coronary backflow (i.e., through the ischemic portion of the heart) was unchanged during hypoxia, whereas it was increased by 80% during dilution.

Experience and studies in patients; profound hemodilution in patients of the Jehovah's Witnesses faith

The unwillingness of Jehovah's Witnesses to accept any stored blood products, either from other human beings or even from themselves, i.e., blood drawn prior to operation appeared to contraindicate performance of operations employing extracorporeal circulation for correction of heart defects. However, blood withdrawal and reinfusion does not contradict the tenets of the faith, if contact is not lost during the procedure. Therefore, heart-lung bypass and temporary blood withdrawal are feasible. A series of operations have been performed upon such patients, inducing with balanced saline solutions an average hematocrit of 11% during bypass.[9] The technique has the advantage of supplying autologous fresh whole blood, with all clotting elements intact, following performance of the repair and separation from heart-lung bypass. While a detailed report is beyond the scope of this paper, this condition is surprisingly well tolerated. It is noteworthy that clinical evidence of pulmonary edema has not been a problem in spite of extremely low levels of serum protein, and that postoperative bleeding also has not been prominent.

Conservation of bank blood products by blood withdrawal prior to cardiopulmonary bypass and reinfusion post-bypass[10]

The previous observations in animals and humans suggested that a less extreme form of blood withdrawal might be advantageous in all open heart surgery by making available to each patient a quantity of fresh autologous blood that has not been exposed to the trauma inherent in cardiopulmonary bypass. We anticipated that this source of blood might decrease the bleeding consequent to open heart surgery and therefore decrease the overall requirement for bank blood products, particularly fresh blood and its analogues. The following study was done after this thesis had been tested in several hundred cases.

Methods and protocol

Fifty adult patients were randomly divided into two groups according to hospital unit number. One group had two units (average 1254 ml) of blood withdrawn after induction of anesthesia, but prior to cardiopulmonary bypass. The blood was replaced with a combination of Ringer's lactate solution and 5% albumin in saline as required to maintain filling pressures and vital signs. If the hematocrit was unusually low, stored whole blood was administered. The heart-lung machine was primed in all cases with 2500 ml Ringer's lactate solution and 200 ml 25% albumin. Postbypass, the autologous blood was reinfused after reversal of heparin. Records were kept of intake and output, hematocrit, and clotting factors at each stage of the operation, and through the end of the first postoperative day. (A preliminary study had

indicated that virtually all bank blood products were administered during this period). Comparisons were made between the two groups.

Results

Hematocrit was lower in the autologous blood group after blood withdrawal, during cardiopulmonary bypass (18% vs 21%), and at the end of the operation. There was no difference in hematocrit from the time of arrival in the postoperative intensive care unit.

Total fluid volume administered was equal in the two groups of patients at approximately 8 L. Water balance was positive at 3200 ml in the autologous blood group and 2600 ml in the control group, a difference that did not achieve statistical significance. Significantly less plasma, packed cells, and total blood product units were utilized in the autologous blood group (*Fig. 7*). This amounted to 850 ml, or 25% of volume of blood bank requirements. An average of approximately 180 g of albumin was administered per patient, with no difference between the groups.

Quantitation of effect of albumin administration on water balance and blood use in open heart surgery[11]

The above study, plus variation of practice among the members of the Cardiac Anesthesia Group, raised the question of the cost-benefit ratio of albumin administration in this setting. A study was therefore instituted to examine the effect of omitting albumin as a volume expander while withdrawing blood, and the effect of omitting albumin from the priming fluid of the heart-lung machine. This report presents preliminary results.

Materials and methods

Sixty-two adult patients were randomly divided into an albumin (n = 30) and a no-albumin (n = 32) group (*Fig. 8*). Two units of blood were withdrawn as in the previous study. Volume replacement included 500 ml of 5% albumin in the albumin group, whereas albumin was not administered during this period in the control group. Similarly, albumin (200 ml of 25% albumin) was added to the oxygenator prime only in
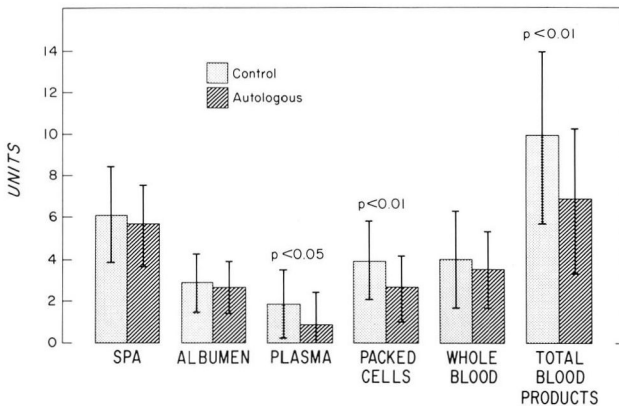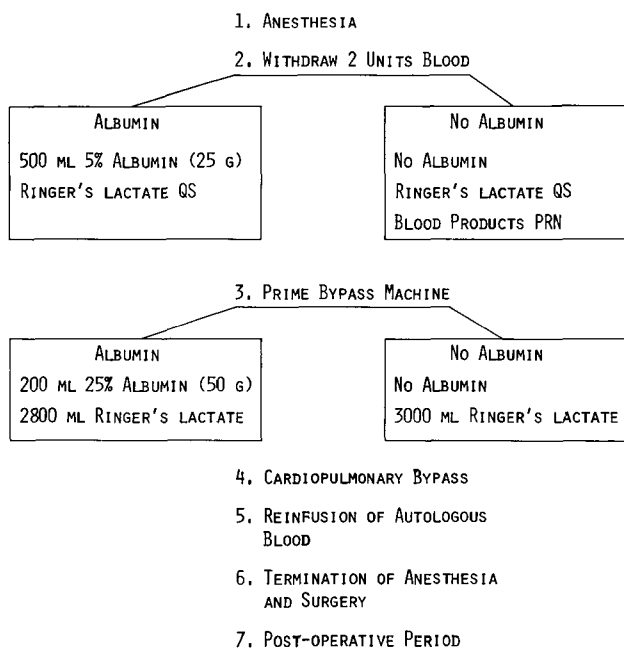

Fig. 7. Saving of bank blood products by blood withdrawal prior to cardiopulmonary bypass and reinfusion after completion of cardiopulmonary bypass. The volume of bank blood products administered during hospitalization was reduced by 25% by an autotransfusion program utilizing two units (1250 ml) of blood withdrawal. SPA = salt-poor albumin. (Figure from Reference 10.)

1. ANESTHESIA

2. WITHDRAW 2 UNITS BLOOD

ALBUMIN	NO ALBUMIN
500 ML 5% ALBUMIN (25 G)	NO ALBUMIN
RINGER'S LACTATE QS	RINGER'S LACTATE QS
	BLOOD PRODUCTS PRN

3. PRIME BYPASS MACHINE

ALBUMIN	NO ALBUMIN
200 ML 25% ALBUMIN (50 G)	NO ALBUMIN
2800 ML RINGER'S LACTATE	3000 ML RINGER'S LACTATE

4. CARDIOPULMONARY BYPASS

5. REINFUSION OF AUTOLOGOUS BLOOD

6. TERMINATION OF ANESTHESIA AND SURGERY

7. POST-OPERATIVE PERIOD

Fig. 8. Protocol of study to define effect of colloid administration during cardiac surgical procedures. (From Reference 11).

the albumin group. Albumin was administered postbypass and in the intensive care unit to both groups when considered indicated on clinical grounds. Detailed records were kept of intake, output, hematocrit and total protein concentration as in the previous study.

Results

Hematocrit was significantly lower in the albumin group from the time of blood withdrawal until the end of the operation. The lowest values were after initiation of bypass (15.1% vs 18.1%). At the conclusion of operation, the values were 25.7% vs 29.0%. There was no difference postoperatively.

Serum protein was lower in the no-albumin group only during bypass (2.7 g/dl vs 3.3 g/dl). While this difference was highly significant, it was small in magnitude.

Between the two groups, there was no difference in the volume of blood nor in the number of units of bank blood products administered. However, significantly less albumin was administered in the no-albumin group. The average difference was 61 g (127 vs 66 g), a saving of approximately 5 units of 12.5 g albumin each. In contrast, the no-albumin group had a significantly greater positive water balance than the albumin group, amounting to a difference of more than 1 liter (*Table 1*).

The data on the last two studies concerning albumin administration and net positive water balance are plotted in *Figure 9*. These data demonstrate that the use of albumin, as administered in these studies, does not decrease the blood requirement of cardiac surgical patients, but is associated with a lesser water balance. It also produces somewhat lower hematocrits intraoperatively than does Ringer's lactate replacement

Table 1. Effect of albumin administration upon water intake, output, and balance[11]

	Water intake L	Urine output L	Water balance L
Albumin	9.9 ± 0.4	3.6 ± 0.2	3.4 ± 0.3
No albumin	11.0 ± 0.6*	3.8 ± 0.3	4.5 ± 0.4*

* $p < 0.05$.
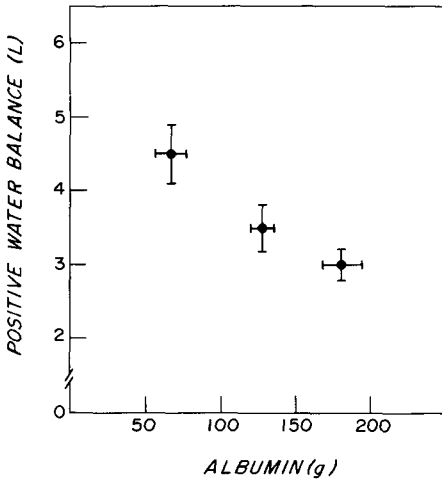
Fig. 9. Relationship of albumin administration to positive water balance in open heart surgery. (This figure represents data from two studies, References 10 and 11.)

of shed blood, probably because it is associated with less fluid loss into the extravascular space. There is an inverse relationship between the amount of albumin administered and net positive water balance.

Centrifugation and transfusion of oxygenator contents after separation from cardiopulmonary bypass

Simple, modified blood-washing centrifuges have recently become available for use in the operating room. The greater the volume of priming solution and the more profound the hemodilution, the greater apparent utility of these systems. The theoretical advantages are elevation of hematocrit as compared to reinfusion of oxygenator contents, less positive water balance, less reinfusion of heparinized blood and, if cell washing is performed, less infusion of cellular debris. A possible disadvantage is the loss of protein elements in the blood. These devices can also be used with local anticoagulation and field suction to salvage blood prior to heparinization and after heparin reversal.

Moran et al[12] reported a 33% decrease in postoperative bleeding and 25% decrease in bank blood transfusion with centrifugation alone, and greater decreases when centrifugation is combined with other methods of blood conservation.

Transfusion of shed mediastinal blood postoperatively

Schaff et al[13] have recently demonstrated the safety and the utility of reinfusing shed mediastinal blood whenever 400 ml or more was collected into a closed system within 4 hours. It is noteworthy that they did document an incidence of positive cultures from the blood thus collected. Furthermore, the blood is defibrinogenated. In a controlled study, they reduced their total blood use from 4.8 ± 0.6 to 2.4 ± 0.3 units per patient despite a similar volume of chest tube drainage.[14] There was no difference postoperatively in hematocrit between the two groups. The incidence of massive postoperative bleeding was similar in the two groups, but bank blood replacement was decreased from 8.8 ± 1.7 to 4.1 ± 0.7 units.

Discussion

Hemodilution

Unquestionably, hemodilution is the cornerstone of blood conservation in cardiac surgery. The tolerance to acute

normovolemic anemia in patients with heart disease is truly astounding. However, that there are limits is self-evident. Redistribution of coronary blood flow from endocardium to epicardium has been demonstrated experimentally.[15] The tolerance to anemia is decreased in the presence of supravalvular aortic constriction, and ischemia is evident on the endocardial electrocardiogram in the absence of changes in the epicardial electrocardiogram. Hagl et al[16] have shown regional impairment of ventricular function when constriction of a coronary artery prevents the normal increase of coronary blood flow associated with ischemia. Thus, anemia appears to be less well tolerated in the presence of narrowed coronary arteries. While the limits in an individual patient are problematical, a degree of caution is advisable in patients with unstable angina pectoris, individuals in whom revascularization has been incomplete, and those with ventricular hypertrophy.

Conclusion

The day when cardiac surgery with cardiopulmonary bypass can be performed on most patients without administration of homologous blood is undoubtedly near. A number of series have conclusively demonstrated the feasibility.[17, 18] Data accumulated at the Cleveland Clinic dramatically demonstrate the decline associated with conscientious attention to principles of blood conservation (*Table 2*).[19] Combining the different methods of blood conservation

has resulted in enhanced savings compared to the use of a single method. However, the less blood lost, the less that can be saved. The single most important step to initiate a program of blood conservation is a rigorous audit of blood use. Continued quantitation of bank blood use during conservation measures is vital to documentation of effectiveness, as well as to continued progress in minimizing homologous blood product administration.

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Table 2. Blood use associated with open heart surgery at the Cleveland Clinic (units per patient)*

1971	1972	1973	1974	1975	1976	1977	1978
11.4	9.1	6.4	5.3	7.4	5.6	4.2	2.7

* Derived from cohorts of 1000 patients per year.[19]

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