REVIEW ARTICLE

Paul G. Barash, MD
Giovanni Landoni, MD
Section Editors

Preventive Strategies for Minimizing Hemodilution in the Cardiac Surgery Patient During Cardiopulmonary Bypass

Nian Chih Hwang, FFARCSI*†

HEMODILUTION IS INEVITABLE during cardiopulmonary bypass (CPB) and results from the mixing of the priming volume with the patient's blood in the extracorporeal circuit (ECC). Preoperatively, the hematocrit (Hct) value after commencement of CPB is estimated by taking into account the patient's preoperative Hct value, the estimated circulating blood volume (EBV) of the patient before surgery, and the volume of the priming solution for CPB.

Estimated hematocrit during CPB = (Preoperative hematocrit × EBV) / (EBV + Priming volume)

Priming volume is the amount of fluid added to prime the roller pump, the oxygenator, filters, and the tubing before connecting them to venous and aortic cannulas. This volume will mix with the patient's blood on commencement of CPB.

For most cardiac surgery patients, the preoperative calculation of Hct and hence prediction of whether the cardiac surgery patient will require addition of homologous blood during CPB is reliable. However, for some adult patients, despite their predicted Hct value being adequate for CPB, the first Hct value measured after commencement of CPB may be unexpectedly lower than the acceptable predetermined value.[1]

Even though homologous blood can be added to the ECC to improve oxygen delivery, red blood cell transfusion is a definite risk factor for postoperative renal failure and acquisition of nosocomial pneumonia.[2–11] On the other hand, excessive hemodilution and, particularly, Hct values less than 22% have been shown to be associated with increased complications, such as neurocognitive impairment, stroke, acute renal failure, and mortality.[2,12–17] Because of the adverse effects due to homologous blood transfusion and excessive hemodilution, it is necessary to reduce the risks for the patients whenever possible.

Preoperative hemoconcentration and excessive intraoperative volume expansion can lead to a lower-than-predicted Hct value after commencement of CPB. These situations and preventive strategies for minimizing hemodilution are explored in this review.

CHALLENGES IN THE ESTIMATION OF CIRCULATING BLOOD VOLUME

Different equations have been derived to estimate the circulating blood volume for male and female patients.[18–20] Allen et al[18] studied 81 Chinese healthcare workers and students; Baker et al[19] obtained their data from patients undergoing minor gynecologic procedures; and participants of the Nadler et al[20] study included healthcare workers, prisoners and patients. Because women have a higher fat content and lower body density than men, separate equations were derived for the estimation of circulating blood volume for males and females.[18–20] Using Gilcher's Rule of Fives, patients were classified as obese, thin, normal, or muscular (Table 1).[21] The perfusion team of each individual heart institute adopts the equations that best suit their patient population when estimating circulatory volume for their patients.[22]

Nevertheless, in cardiac surgery patients, circulating blood volume estimated from patient morphology can be different from the blood volume estimated by Hct dilution during CPB.[23,24] Estimation of "true" circulating blood volume is not possible. The intravascular volume at any time is a balance of fluid intake and loss, vascular tone, and plasma oncotic pressures. Vascular tone is regulated by the sympathetic nervous activity, which is influenced by factors such as anxiety and increased mental stress; these factors have been shown to cause contraction of the vascular volume.[25] Patterson et al demonstrated that acute psychologic stress (in the form of solving arithmetic problems for 10 minutes) can cause a rapid and substantial decrease in plasma volume, producing hemoconcentration.[25] The intravascular volume can be reduced by diuretic therapy, increased circulating natriuretic peptide concentrations after congestive heart failure, and via evaporative losses.[26] Hence, the timing of blood sampling for full blood count and the condition of the patient at that time will have an effect on the accuracy of the Hct value, which is, in turn, relied on for the prediction of Hct value after commencement of CPB. Figure 1 illustrates the factors that can influence the status of the intravascular volume.

INTRAOPERATIVE EVENTS PROMOTING HEMODILUTION AND REDUCTION OF HEMATOCRIT

The volume of fluid infusion administered up until commencement of CPB will affect the reliability of preoperative estimation of hematocrit expected during CPB. Mathematically,

*From the *Cardiothoracic Anaesthesia Service, Department of Anaesthesiology, Singapore General Hospital, Singapore; and †Department of Cardiothoracic Anaesthesia, National Heart Centre Singapore (NHCS), Singapore.*

Address reprint requests to Nian Chih Hwang, FFARCSI, Department of Anaesthesiology, Singapore General Hospital, Outram Road, Singapore 169608. E-mail: hwang.nian.chih@sgh.com.sg

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Table 1. Gilcher's Rule of Fives for the Estimation of Circulating Blood Volume[21]

Subject	Obese	Thin	Normal	Muscular
Male	60 mL/kg	65 mL/kg	70 mL/kg	75 mL/kg
Female	55 mL/kg	60 mL/kg	65 mL/kg	70 mL/kg

NOTE. The reason for the differences is secondary to the difference in vascularity between adipose tissue and muscle tissue. For very obese subjects, the circulatory blood volume can be estimated by using circulatory blood volume for lean body weight plus 20%.

this intraoperative volume adds to the denominator and will further decrease the actual hematocrit during CPB.

$$\text{Estimated hematocrit during CPB} = (\text{Preoperative hematocrit} \times \text{EBV}) / (\text{EBV} + \text{Priming volume} + \text{Volume infused before CPB})$$

Campbell et al found that patients who received $>1{,}600$ mL of fluid before CPB, compared to patients who received <1600 ml, had a decreased mean low CPB Hct (22.4% *v* 25.6%, $p < 0.001$), an increased incidence of CPB Hct $<25\%$ (74% *v* 38%, $p < 0.001$), and increased transfusion of homologous red blood cells during CPB (60% *v* 16%, $p < 0.001$), despite no significant difference in gender, age, patient size, baseline Hct, or CPB priming volume. [27]

The situations in which significant volumes of fluid may have to be infused before CPB are discussed in the following section.

Fluid Therapy During General Anesthesia

Systemic vascular resistance usually decreases after induction of general anesthesia, either as a result of decreased autonomic sympathetic activity or direct peripheral effect of the anesthetic agent.[28,29] Fluid therapy usually is administered to maintain stroke volume and blood pressure. If the patient is hypovolemic before anesthesia, volume expansion to maintain preload certainly will contribute to hemodilution and lowering of the Hct value.

Patients who receive loop diuretic therapy for management of pulmonary edema, either as a result of acute decompensation of left ventricular function, myocardial infarction, or severe exacerbation of mitral valvular disease with subsequent acute rise in left atrial pressures, are more likely to experience a greater hemoconcentration before cardiac surgery.[26] These patients very likely will require fluid management after induction of general anesthesia.

Intraoperative management of patients with moderate mitral regurgitation contrasts sharply with other patients in terms of anesthetic and fluid replacement. Factors that determine regurgitant flow are pressure gradients across the regurgitant valve, the effective regurgitant orifice area, and duration of the phase of the cardiac cycle favoring regurgitation. The anesthetic management concept for patients with mitral regurgitation always has been "fuller, faster, and vasodilated."[30,31] In the presence of aortic regurgitation, a reduction in afterload encourages forward flow. After vasodilation and improvement in forward flow of blood from the left ventricle after induction of anesthesia, fluid commonly is administered to maintain preload and cardiac function. Preoperative diuretic therapy in these patients can result in an intravascular volume deficit that may become apparent after induction of general anesthesia.[32]

The arterial and aortic walls stiffen as a person ages.[33] Increased arterial stiffness in the elderly likely is a reason for the hemodynamic fluctuation and instability that often are observed during induction and maintenance of general anesthesia.[34,35] Hypotension during anesthesia induction has been shown to predict postoperative cardiovascular complications, such as stroke and renal failure; the management of hemodynamic instability inevitably involves fluid therapy.[36,37]

Regardless of the cause for volume expansion after induction of anesthesia, fluid therapy contributes to hemodilution.

Surgical Procedures

Catastrophic bleeding requiring rapid fluid management can occur with repeat surgeries on the heart.[38] Even with interposition of polytetrafluoroethylene surgical membrane as the "pericardium" in the previous cardiac surgery, cardiac injury during the second sternotomy still can occur.[39–41]

Videoscopically-assisted harvesting of the great saphenous vein and radial artery for conduits results in fewer sensory deficits and lower incidence of graft-site infections.[42–44] However, inadequate hemostasis while harvesting the great saphenous vein and radial artery can lead to insidious bleeding throughout CPB.[45] Occult blood loss is exacerbated if the leg or forearm is not bandaged before commencement of CPB. The internal mammary artery or its bed can be another cause of insidious bleeding throughout CPB.[46] With continuous blood loss from the graft harvesting sites, gradual reduction of venous return to the cardiotomy reservoir eventually will necessitate addition of fluid into the ECC to sustain circulatory volume. Hemodilution certainly will occur, further decreasing the hematocrit level.

Commencement of Cardiopulmonary Bypass

On commencement of CPB, large changes in arterial pressure and systemic vascular resistance commonly are observed.[47] In addition to the change in rheology, immune mediators are released when blood flows through the ECC, leading to a systemic inflammatory response syndrome and a decrease in systemic vascular resistance.[48,49] In practice, the

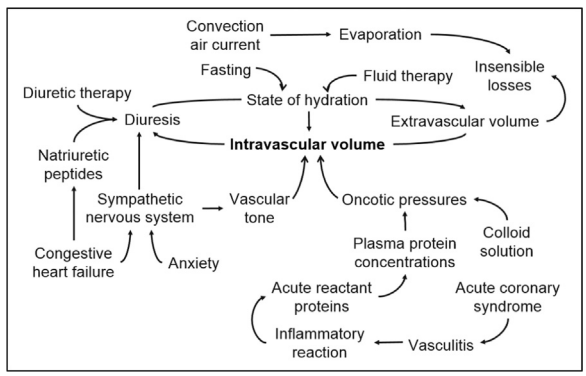

Fig 1. Factors that affect the status of intravascular volume. The intravascular volume at any time is a balance of fluid intake and loss, vascular tone, and plasma oncotic pressures. The vascular tone is regulated by the sympathetic nervous activity, which is influenced by factors such as anxiety and disease states. The intravascular volume can be reduced by diuretic therapy, increased circulating natriuretic peptide concentrations after congestive heart failure and via evaporative losses.