

A Novel Calculation to Estimate Blood Volume and Hematocrit During Bypass

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Abstract: Patient blood volume impacts most facets of perfusion care, including volume management, transfusion practices, and pharmacologic interventions. Unfortunately, there is a wide variability in individual blood volumes, and experimental measurement is not practical in the clinical environment. The purpose of this study was to evaluate a mathematical algorithm for estimating individual blood volume. After institutional review board approval, volumetric and transfusion data were prospectively collected for 165 patients and applied to a series of calculations. The resultant blood volume estimate (BVE) was used to predict the first and last bypass hematocrit. The estimated hematocrits using both BVE and 65 mL/kg were compared with measured hematocrits using the Pearson moment correlation coefficient

and the Bland Altman measures of accuracy and precision. There was a wide range of BVE (minimum, 35 mL/kg; mean \pm SD, 64 ± 22 mL/kg; maximum, 129 mL/kg). Using BVE, the estimated hematocrit was similar to the measured first ($24.7 \pm 6.4\%$ vs. $24.5 \pm 6.2\%$, $r = 0.9884$, $p > .05$) and last ($24.5 \pm 5.9\%$ vs. $25.1 \pm 5.7\%$, $r = 0.9001$, $p > .05$) bypass hematocrit. Using 65 mL/kg resulted in a larger difference between estimated and measured hematocrits for the first ($25.6 \pm 4.5\%$ vs. $24.5 \pm 6.2\%$, $r = 0.6885$, $p = .030$) and last ($23.8 \pm 3.6\%$ vs. $25.1 \pm 5.7\%$, $r = 0.5990$, $p = .001$) bypass hematocrits. Compared with using 65 mL/kg for blood volume, the BVE allowed for a more precise estimated hematocrit during CPB. **Keywords:** blood volume, cardiopulmonary bypass, hematocrit. *JECT. 2008;40:61–64*

Patient blood volume impacts most facets of perfusion care, including volume management, hemodynamic interventions, transfusion practices, and pharmacologic interventions. Unfortunately, there is a wide variability in individual blood volumes, and extremes (30–130 mL/kg) will be encountered in clinical practice (1–3). If an extremely low blood volume is encountered without identification, weight-based pharmaceutical concentrations will be higher than expected, and the effects of hemodilution will be more pronounced. An extremely high blood volume would be expected to have the opposite effect, potentially leading to under-heparinization and inappropriate transfusion (i.e., low hemoglobin treated with transfusion instead of volume removal through autologous priming).

Indeed, early knowledge of a patient's blood volume would empower the clinician to make more informed clinical decisions. Unfortunately, experimental measurements are not applicable to the clinical environment. The meth-

ods require either radioactive labeling or the measurement of plasma volume by injecting indocyanine green, subsequently measured by a specialty spectrophotometer, and measurement of red cell volume by labeling autologous red cells with sodium fluorescein and subsequent measurement by flow cytometry (3). Neither option could be considered viable in the clinical arena or justifiable for the information obtained. Less demanding techniques using new technology are being developed, but they are invasive and only moderately accurate and precise (4).

However, it is possible to estimate blood volume from the change in hematocrit during carefully controlled acute, normovolemic hemodilution (2). The estimated blood volume obtained by the Jacobs method correlated well with the measured values ($y = 0.912x + 560$; $r = 0.80$) (2). The Jacobs mathematical model was modified significantly and includes additional variables to allow a more dynamic, less time-dependent blood volume estimate. The purpose of this study was to evaluate the capacity of the blood volume estimate to predict hematocrit changes.

MATERIALS AND METHODS

An estimate for the post-induction blood volume [blood volume estimate (BVE); baseline (BVE_(B))] was devel-

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oped by applying a conversion factor (F) to a reference, or ideal, blood volume (BV_i):

$$BVE_{(B)} = BV_i \times F$$

Other groups have used BV_i (ideal blood volume), and it is calculated based on an ideal body surface area (2).

$$BSA_i = 0.01545 \times \text{height (cm)}^{0.54468} \\ \times (0.9 \times (\text{height} - 100))^{0.46336}$$

and

$$BV_i = BSA_i \times 2243$$

To calculate $BVE_{(B)}$, a conversion factor (CF) is applied to the BV_i . The conversion factor is calculated based on the change in hematocrit at two time points in relation to what the change would be with the BV_i :

$$\text{Conversion Factor (CF)} = \frac{(\text{HCT}_{i(\text{Post}A)} - \text{HCT}_{M(\text{pre}A)})}{(\text{HCT}_{M(\text{Post}A)} - \text{HCT}_{M(\text{pre}A)})}$$

where

$\text{HCT}_{i(\text{Pre}A)}$ = Ideal Hematocrit Before Change A;

$\text{HCT}_{i(\text{Post}A)}$ = Ideal Hematocrit After Change A;

$\text{HCT}_{m(\text{Pre}A)}$ = Measured Hematocrit Before Change A;

$\text{HCT}_{m(\text{Post}A)}$ = Measured Hematocrit After Change A;

Change A is characterized by a blood volume change (ΔBV_A) and a red cell volume change (ΔRCV_A):

$$\Delta BV_A = \text{Volume Added (VA}_A) \\ - \text{Volume Removed (VR}_A)$$

where

$$VA_A = \text{mL Crystalloid Added} \times 0.65 \\ + \text{mL Albumin Added} \times 0.95 + \text{mL PRBC Added} \\ + \text{FFP Added} + \text{mL autotransfusion RBC added}$$

and

$$VR_A = \text{mL Urine Out} + (\text{mL autotransfusion added} \\ \times 0.65 / \text{HCT}_{m(\text{Pre}A)} / 0.80) + \text{Ultrafiltrate Removed} \\ + \text{Whole Blood Removed}$$

and

$$\Delta RCV_A = \text{mL PRBC Added} \times 0.65 \\ - (\text{Whole Blood Removed} \times \text{HCT}_{m(\text{Pre}A)})$$

then

$$\text{HCT}_{i(\text{Post}A)} = (\text{HCT}_{i(\text{Pre}A)} + \Delta RCV_A) / (BV_i + \Delta BV_A)$$

where

$$\text{HCT}_{i(\text{Pre}A)} = BV_i \times \text{HCT}_{m(\text{Pre}A)}$$

$BVE_{(B)}$ can now be calculated:

$$BVE_{(B)} = BV_i \times CF$$

or

$$BVE_{(B)} = (BV_i \times (\text{HCT}_{i(\text{Pre}A)} - \text{HCT}_{i(\text{Post}A)})) / \\ ((\text{HCT}_{m(\text{Pre}A)} - \text{HCT}_{m(\text{Post}A)}))$$

or

$$BV_i \times (\text{HCT}_{i(\text{Pre}A)} - \text{HCT}_{i(\text{Post}A)}) = \\ BVE_{(B)} \times (\text{HCT}_{m(\text{Pre}A)} - \text{HCT}_{m(\text{Post}A)})$$

The $BVE_{(B)}$ value gives the static blood volume of the patient at the first hematocrit sample; for this study, the sample was drawn immediately after the induction of anesthesia.

The $BVE_{(B)}$ was used to predict the first and last CPB hematocrit. Two additional periods were defined, change B (beginning when change A ended and ending when the first CPB hematocrit was taken) and change C (beginning when change A ended and ending when the last CPB was taken).

The first CPB hematocrit ($\text{Hct}_{e(\text{first})}$) and the last CPB hematocrit ($\text{Hct}_{e(\text{last})}$) were estimated by:

$$\text{HCT}_{e(\text{first})} = ((BVE_{(B)} \times \text{HCT}_{m(\text{Pre}A)} + \Delta RCV_B) / \\ (BVE_{(B)} + \Delta BV_B))$$

and

$$\text{Hct}_{e(\text{last})} = ((BVE_{(B)} \times \text{HCT}_{m(\text{Pre}A)} + \Delta RCV_C) / \\ (BVE_{(B)} + \Delta BV_C))$$

Both ΔRCV_B and ΔRCV_C were calculated in the same fashion as ΔRCV_A , and ΔBV_B and ΔBV_C were calculated in a similar fashion as ΔBV_A . For purposes of comparison, the same calculations were performed by substituting 65 mL/kg for the $BVE_{(B)}$.

All formulas were entered into a Microsoft Excel Workbook, and the variable data were collected in a prospective fashion on 165 adult (18–89 years old) patients undergoing cardiopulmonary bypass. The $\text{Hct}_{e(\text{first})}$ and $\text{Hct}_{e(\text{last})}$ were calculated using both $BVE_{(B)}$ and 65 mL/kg. The results using $BVE_{(B)}$ were compared with the results using 65 mL/kg using the Pearson moment correlation and the Bland Altman bias and limits of agreement. Significance was accepted at $p < .05$.

RESULTS

There was a wide range of BVE (minimum, 35 mL/kg; mean \pm SD, 64 \pm 22 mL/kg; maximum, 129 mL/kg). Using BVE, the estimated hematocrit was similar to the mea-

sured first ($24.7 \pm 6.4\%$ vs. $24.5 \pm 6.2\%$, $r = 0.9884$, $p > .05$) and last ($24.5 \pm 5.9\%$ vs. $25.1 \pm 5.7\%$, $r = 0.9001$, $p > .05$) bypass hematocrits (Figure 1). Using 65 mL/kg resulted in larger differences and less correlation between estimated and measured hematocrit for the first ($25.6 \pm 4.5\%$ vs. $24.5 \pm 6.2\%$, $r = 0.6855$, $p = .030$) and last ($23.8 \pm 3.6\%$ vs. $25.1 \pm 5.7\%$, $r = 0.5990$, $p = .001$) bypass hematocrits (Figure 1). The BVE also provided more precise prediction of first CPB hematocrit (limits of agreement: 1.0% vs. 3.4%) and last CPB hematocrit (limits of agreement: 2.4% vs. 4.0%) than the use of 65 mL/kg . Both blood volume estimates provided similar accuracy at the first CPB hematocrit (bias: -0.4% vs. 0.4%) and last CPB hematocrit (bias: 1.2% vs. 1.9%)

DISCUSSION

The BVE was used to calculate changes in hematocrit during CPB. However, the use of this value extends beyond its predictive capacity for hematocrit changes. For example, most pharmacologic interventions, including

anti-coagulation, are based on volume. In the absence of firm BVEs, weight is used as a reflection of blood volume. Unfortunately, weight seems to be a poor reflection of blood volume, because the estimated blood volumes (BVE) ranged from 35 to 129 mL/kg in this study. These were not unique findings, and other groups that have experimentally measured blood volumes have found similar diversity (1–3). Unfortunately, in the absence of valid estimates of blood volume, weight continues to be used in the majority of these calculations. Perhaps the principle hazard of this strategy is best illustrated by example: in this case anti-coagulation with heparin for a 70-kg patient. The standard heparin-dosing guidelines for CPB are 3 units heparin/mL of circulating blood volume. Using 65 mL/kg and 1700-mL prime volume, a target dose of $18,750$ units would be calculated. However, if this patient was a high blood volume patient (120 mL/kg), the circulating heparin concentration would only be 1.9 units/mL.

An accurate BVE could be useful beyond pharmacologic interventions. Discrepancies between measured and predicted hematocrit values could alert the perfusionist to

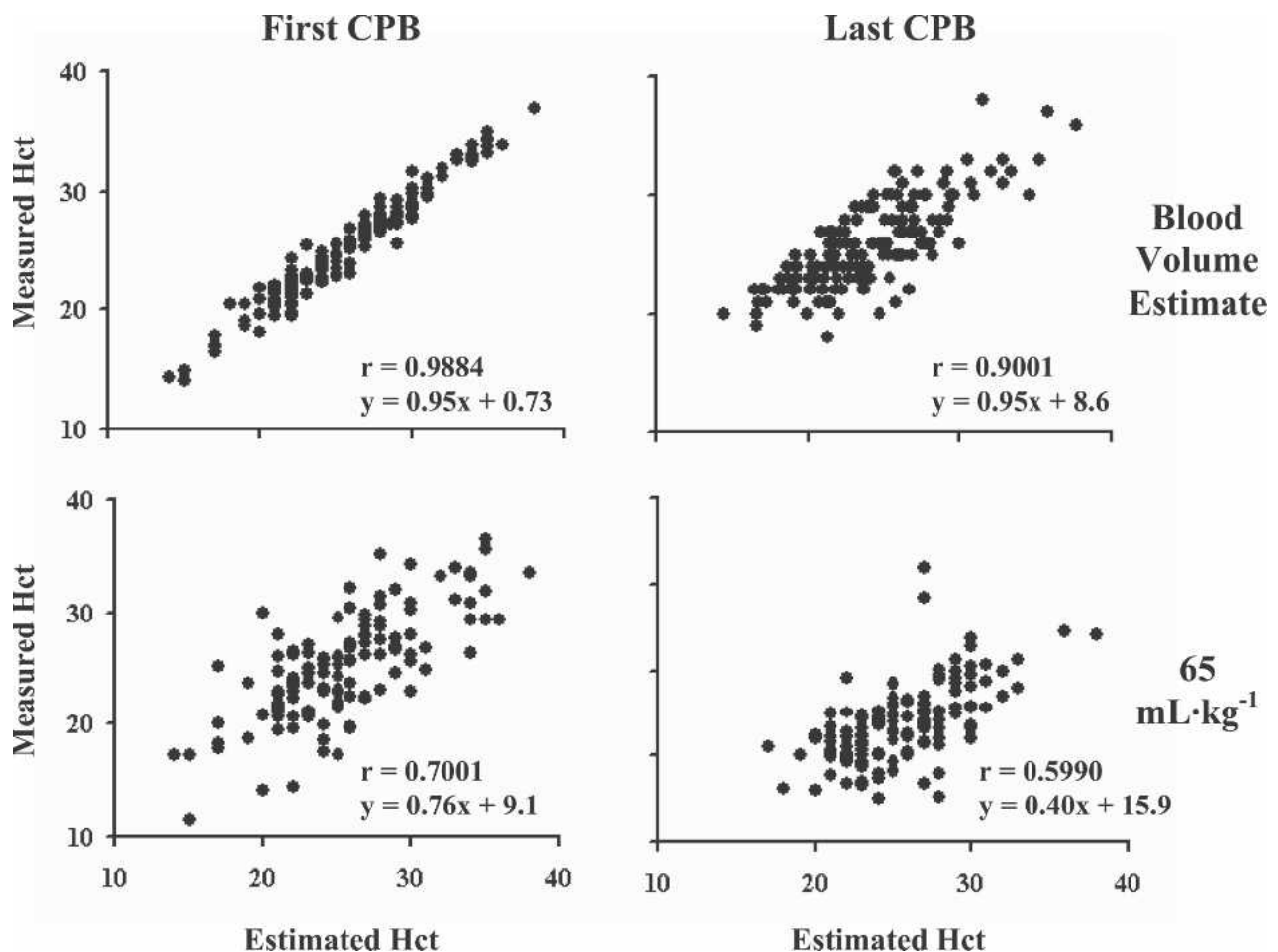


Figure 1. Estimate vs. measured hematocrit.

undetected blood loss, and excessive extravasation of fluid, and identify the need for volume replacement interventions. Likewise, dilutional coagulopathy could be more readily discriminated, allowing earlier detection and intervention.

Estimating blood volume by this method has two categories of limitations. The first group could be considered logistic or external limitations. For example, the formulas used to derive BVE and predict CPB hematocrits do not lend themselves to hand calculation or written charting methods. In the absence of automated data collection and calculation, the algorithms used would be too cumbersome and time consuming to be of clinical value. Furthermore, accurate capture of volume management values is essential to yield predictive results. The second category of limitations is internal and is a reflection of using a modified one compartment model in a biological system. The mobilization of capillary-based plasma layers and extravasation of fluid are not measured, but the effects are expected to be differential between individual patients. Conditions that alter vascular permeability or tone are not used in the calculations presented here but would be expected to diminish the functional capacity of them.

However, with modern computer technology and the national shift toward automated charting, a valid BVE may become a valuable clinical tool, used to guide volume replacement strategies, transfusion decisions, and pharmacologic interventions. The ability of the BVE to predict CPB hematocrit suggests that it is an accurate reflection of the patient's actual blood volume. The BVE did not require additional equipment, invasive techniques, or added laboratory samples. Rather, the estimate was derived from existing test data and patient information.

In addition, standard corrections were used for cell saver efficiency and distribution volumes. The other internal limitations seem to be systematic and did not impact the precision of predicted hematocrits. Indeed, aberrant results may indicate drastic deviation from normal conditions, such as excessive vascular permeability or unexplained blood loss. For example, if the predicted bypass hematocrit value is dramatically lower than the measured value, this may be evidence of large volumes accumulating in the third physiologic space.

This study was limited by design. It was designed to determine whether the range of variables currently collected could be used to predict BV-dependent changes in hematocrit. The method should be validated with double radiolabel measurement techniques. However, compared with using 65 mL/kg, using the blood volume resulted in more precise bypass hematocrit prediction that correlated better with measured results.

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