SPECIAL ARTICLE

Intraoperative Blood Salvage: Fluid Replacement Calculations

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Intraoperative blood salvage (IBS) devices are used as adjuncts to blood conservation in spinal surgical procedures of increasing duration, complexity, and total blood loss. We applied existing information about the performance and efficiency of IBS devices together with existing information regarding the distribution of crystalloids and colloids to provide clinicians with guidelines for the prediction of the total blood loss implications of a given volume of IBS return. We also developed guidelines for estimation of the appropriate replacement volumes for the acellular component of blood loss when replacement is undertaken with either isotonic-iso-oncotic colloid or isotonic crystalloid solutions. When average hematocrit during blood loss is between 25% and 30%, total blood loss will be 3.4–4.0 times the volume of the IBS recovery. When replacement is undertaken with colloids or crystalloids, the appropriate replacement volume will be approximately 2.5 and 8.0 (respectively) times the volume of the IBS recovery. These volumes may be larger than have been appreciated by some clinicians.

(Anesth Analg 2005;100:645–9)

In an era of concern about transmission of infectious agents and the immunomodulatory hazards of blood products, intraoperative blood salvage (IBS) using so-called "cell saver" devices has become increasingly common (1). In parallel with this trend, there has been an increase in the duration and the complexity of spinal instrumentation procedures. Procedures of substantial duration with large total blood losses have become commonplace. Our anecdotal experience is that there have been circumstances in which an inaccurate understanding of the blood loss and fluid replacement implications of a given blood volume of blood return from the IBS device has led to physiologic mismanagement of patients. The purpose of this article is to review the "arithmetic" by which the practitioner can make reasonable estimates of the true blood loss represented by a given volume of blood return from the IBS device and simultaneously anticipate the approximate patient requirements for replacement of both the red cell and plasma components.

Stated very simply, the objective of this review is to provide the practitioner with rules of thumb to provide answers to three questions:

1. By what factor must one multiply the IBS return volume to achieve a realistic estimate of the patient's total blood loss? Total blood loss refers to all blood shed by the patient including blood that has previously been returned by the IBS device.
2. If fluid replacement of the noncellular component of the true total blood loss is undertaken using isotonic crystalloids, by what factor should the practitioner multiply the IBS return volume to achieve a reasonable estimate of the appropriate volume of crystalloid?
3. If fluid replacement of the noncellular component of the true total blood loss is undertaken using isotonic colloids, by what factor should the practitioner multiply the IBS return volume to achieve a reasonable estimate of the appropriate volume of colloid?

It should be understood at the outset that the authors do not intend that practitioners manage patients by formula. Rather, the formulas and factors that will evolve from this discussion should be used only to provide the practitioner with a warning of circumstances in which there is reason to be concerned that actual replacement volumes have been inadequate or excessive. Physiologic measurements reflecting the

Accepted for publication August 18, 2004.

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DOI: 10.1213/01.ANE.0000144069.36647.3D

0003-2999/05

adequacy of intravascular volume combined with laboratory determinations of hemoglobin, coagulation variables, and acid-base status should be the final arbiters of decisions regarding fluid and blood product administration.

Several items of information are essential for making estimates of true total blood loss and appropriate replacement. They include 1) the efficiency of cell salvage systems, 2) the typical average hematocrit of IBS return and, 3) the approximate volumes of distribution of the various acellular fluids (crystalloids and colloids) that may be used in the replacement regimen.

IBS Efficiency

By efficiency, we refer to the percentage of red blood cells (RBC) shed by the patient that is eventually returned intact to the circulation. This includes the effect of lost blood that does not reach the IBS device (sponges, drapes, non-IBS suction when nephrotoxic or procoagulant substances are in the field) as well as the effect of RBC destruction by collection and processing. There are regrettably few systematically derived data that provide reliable estimates of IBS efficiency. A single survey performed in the context of spinal instrumentation procedures reported an efficiency of 35% (2). A second survey, performed by Waters et al. (3), provides what is probably the most comprehensive information. That survey revealed an IBS recovery efficiency of 57% with a standard deviation of 20% (3). The patients studied in that survey were a mixed population of urologic, abdominal, aortic, and spine procedures (J. Waters, MD, personal communication). Practitioners should make note of the substantial variance. Numerous factors, many of which are given relatively little attention intraoperatively, influence efficiency. Chief among them are the rapidity with which blood is cleared from the surgical field and the negative pressures with which aspiration is accomplished (4). RBC within formed clots will be lost from the system. High vacuum pressures and, in particular, the agitation that occurs at the air/blood interface damage RBC membranes (5). The general principle is that if you can hear the suction device, cells are being damaged. It is recommended that the negative pressure be maintained at $<$150 mm Hg and that simultaneous aspiration of air be avoided when possible (5). For the purposes of the calculations and the estimates that follow, the authors have used a "benefit of the doubt goes to the patient" approach and assumed an IBS efficiency during orthopedic procedures of 50%.

Hematocrit of IBS Return

Although hematocrits of up to 80% can be achieved, common clinical practices result in hematocrits in the 50%–60% range. There are, again, relatively few systematically derived data that provide specific information. In one bench evaluation of cell salvage devices, hematocrits of 45%–55% were reported (6). At one of our institutions, an informal random survey of multiple samples of IBS return revealed an average hematocrit of 53%, and, again on a benefit-of-the-doubt to the patient basis, we assumed a hematocrit of 50%. Some practitioners may work in institutions in which higher hematocrits are achieved. That can be accomplished if the centrifuge is filled relatively slowly, thereby allowing some settling of RBC to occur before complete filling of the centrifuge bowl. In our experience, the slow filling approach is clinically uncommon.

Crystalloid Volume of Distribution

For the purposes of the calculations that follow, we assume that one-third of isotonic crystalloids (0.9% saline, lactated Ringer's solution [LR], Plasma-Lyte) remains in the intravascular space. That number is clearly an overestimate of what actually remains in the vascular tree at final equilibrium, i.e., only 20% (7). However, as has been suggested by others (7), the assumption that one-third remains in the plasma volume is probably a reasonable reflection of the conditions that prevail 30 min after administration of an isotonic crystalloid solution. That estimate coincides very closely with the observations of Svensen and Hahn (8), who administered 25 mL/kg of LR to healthy volunteers over 30 min. Their data, derived using hemoglobin as the marker for expansion of the plasma space, indicated that approximately 30% of the infused fluid was within the vascular tree 30 min after completion of the infusion. In fact, because of the rapidity of blood loss in procedures in which there is a large volume of IBS return, it is probably inappropriate to use the final equilibrium ratio, i.e., 20% intravascular and 80% extravascular. In essence, the administered fluids are being lost before that final distribution ratio can be achieved. Accordingly, for the calculations that follow, we used the distribution ratio that prevails 30 minutes after administration (i.e., 33% intravascular and 66% extravascular).

In addition, although considered "isotonic" crystalloids, 0.9% saline, LR, and Plasma-Lyte differ in their osmolalities (310, 273, and 294 mOsm/L, respectively) and should have slightly different plasma expanding effects. Drobin and Hahn (9) confirmed that difference with their demonstration of a LR to saline plasma expansion ratio of 0.88 to 1.0. However, to simplify the calculations for what is at best an approximation, no distinction has been made among them in terms of distribution ratios.

Colloid Volume of Distribution

For the purposes of the calculations that follow, we assumed that 100% of isotonic colloid solutions (6% starch, 5% albumin) remains in the vascular tree (10,11). This is clearly physiologically imprecise. For instance, at least 5% of albumin leaves the vascular tree per hour (12). The various starches similarly leave the intravascular space by extravasation or metabolism, although somewhat more slowly than albumin (12,13). In addition, the volume expansion accomplished with 6% hetastarch (450,000; 0.7) is initially actually slightly more than 100% (11,12). However, the assumption of one for one plasma volume expansion serves the purposes of what is inevitably an approximation and simplifies the calculations.

Average Patient Hematocrit

Calculation of the blood loss represented by a given volume IBS return requires an assumption about, or knowledge of, the patient's hematocrit during the time of blood loss. Because currently common clinical practices entail maintenance of hematocrits between 25 and 30%, depending on the practitioner, we provide parallel calculations based on those two hematocrits. It is acknowledged at the outset that patients typically begin at a hematocrit greater than 30%. However, it is our empiric experience that because of preoperative autologous donation and many other medical factors, initial hematocrits after the postinduction fluid loading are commonly in the low 30s. In addition, the effect of that initially higher hematocrit washes out over the course of a lengthy procedure, during the majority of which the hematocrit is likely to be maintained in the range of 25%–30%. An average hematocrit of 30% during a lengthy spine procedure is probably common.

The Calculations

For the purposes of illustration, we will assume that 1000 mL have been returned to the anesthesiologist from the IBS device. What is the true total patient blood loss? We will use the previously defined assumptions of an IBS efficiency of 50% and a hematocrit of 50% in the IBS return.

One-thousand mL of IBS return with a hematocrit of 50% yields a packed RBC volume of 500 mL. A patient with a hematocrit of 30% must lose 1670 mL of blood to yield an RBC mass of 500 ($1670 \times 0.30 = 500$). With an average hematocrit of 25%, the requisite blood loss to yield an RBC mass of 500 mL would be 2000 mL ($2000 \times 0.25 = 500$). If the IBS efficiency is 50%, a 1000-mL IBS return corresponds to a true patient blood loss of twice those volumes, i.e., 3.4–4.0 L.

This leads to rule of thumb #1. To achieve a reasonable estimate of true blood loss, (assuming average hematocrits between 30% and 25%) during the period of blood loss, multiply the cell saver return volume by 3.4–4.

RBC Replacement

The focus of this article is the calculation of estimated blood loss and nonsanguinous fluid replacement volumes. However, clinicians will inevitably also want to anticipate the need for RBC replacement. Based on the starting hematocrit, an estimate of starting blood volume (70 mL/kg), and the knowledge that only 50% of RBCs are salvaged and returned intact to the patient, the clinician can develop an estimate of when RBC replacement is likely to be necessary. For instance, in an 80-kg patient with a starting hematocrit of 35% and a blood volume of 5600 mL, RBC loss sufficient to reduce hematocrit to 25% will be reached after a true blood loss of approximately $(35 - 25)/35 \times 5600$ mL $= 1600$ mL. With the typical use of an IBS device (50% recovery of shed red cells), hematocrit will be reached after a true blood loss of 3200 mL. That true blood loss will have occurred after IBS return of approximately 3200 divided by $3.4 = 940$ mL (3.4 is the factor for an average hematocrit of 30%). That is to say that after approximately 940 mL of IBS return, an 80 kg patient with an initial hematocrit of 35% is likely to require RBC transfusion if further blood loss is probable and the objective is to prevent reduction of hematocrit to $<25\%$. The decision to transfuse RBCs should be driven or confirmed by measurement of hemoglobin concentration or hematocrit in the context of the patient's antecedent health and current physiologic state. Note that this approach should provide a very conservative estimate of the need for initial transfusion because the formula used above assumes uncompensated blood loss rather than the isovolemic replacement with crystalloid and/or colloid that will occur with ideal clinical management. In the patient above (weight 80 kg; starting Hct 35%), with continual maintenance of isovolemia during blood loss, a hematocrit of 25% will occur after a blood loss of 1884 mL (Appendix) rather than 1600 mL.

Colloid Replacement

The IBS return is composed of RBCs suspended in saline. The plasma element (and the platelets) should be viewed as having been entirely lost as a consequence of the cell salvage process. If the average hematocrit during blood loss has been 30%, then 70% of the true blood loss is composed of the plasma component. Accordingly, for example, after 1000 mL of IBS return and therefore a true blood loss of 3.4–4.0 L, the

plasma component lost will have been between $0.7 \times 3.4 = 2.4$ L and $0.7 \times 4.0 = 2.8$ L.

This yields the second rule of thumb. If replacement of the plasma component is undertaken with iso-oncotic solutions, the volume required is 2.5 times (as a simplification of the range of 2.4–2.8) the IBS return volume. For an IBS return of 1000 mL, approximately 2.5 L of iso-oncotic colloid replacement will be appropriate. For the purposes of the colloid replacement calculation, the RBC mass in the IBS return is retained within the vascular tree and can be counted as "colloid."

Crystalloid Replacement

Using the original assumption that one-third of isotonic crystalloid will remain in the vascular tree, if crystalloid rather than colloid is used as the replacement fluid, the appropriate crystalloid replacement volume will be three times that calculated for the iso-oncotic colloid. Accordingly, the appropriate crystalloid replacement will be between $3 \times 2.4 = 7.2$ and $3 \times 2.8 = 8.4$ times the IBS return.

This yields the third rule of thumb: If replacement of the plasma component is undertaken with isotonic crystalloid solutions, the volume required is 8.0 times (as a simplification of the range of 7.2–8.4) the IBS return volume. For an IBS return of 1000 mL, approximately 8 L of isotonic crystalloid will be appropriate.

Platelet and Coagulation Factors

The clinical investigation of Hiippala et al. (14) indicated that, in circumstances of isovolemic hemodilution, potentially critical depletion of fibrinogen (<100 mg%) is likely to occur with replacement of an average of 142% (95% confidence interval [CI], 117%–169%) of total blood volume; that critical depletion of prothrombin (reduction to 20% of baseline levels) is likely to occur with average blood loss of 201% of initial blood volume (95% CI, 160%–244%); that critical depletion of clotting factor V (reduction to 25% of baseline levels) is likely to occur with blood loss of 229% of initial blood volume (95% CI, 167%–300%), and that critical depletion of platelets (<50,000) is likely to occur with replacement of 230% (95% CI, 169%–294%) of blood volume. Accordingly, in an 80-kg adult with an initial blood volume of 5600 mL and an average hematocrit during blood loss of 30%, the clinician should be conscious that potentially critical dilutions may occur as follows: fibrinogen: IBS return volume,[1] 2270 mL; prothrombin: IBS return volume, 3200 mL; and, platelets: IBS return volume, 3680 mL. Replacement, however, should never be undertaken in response to formula but rather in response to evidence of clinical coagulopathy, ideally with verification by laboratory determinations. In addition, note the substantial variances, e.g., critical depletion of platelets occurring after replacement of 160% to 244% of initial blood volume.

[1] 100% of blood volume: $80 \times 70 = 5600$ mL; 142% of blood volume: $5600 \times 1.42 = 7950$ mL; IBS return corresponding to a blood loss of 7950 mL = 7950/3.5 = 2270 mL.

Discussion

We repeat the assertion that these calculations are only guidelines that clinicians should use to prompt physiologic verification of the appropriateness of their continuing blood and fluid replacement. Furthermore, these calculations have made many assumptions about physiologic conditions that may not apply precisely in individual instances. Those assumptions include the following:

Colloid Distribution

The colloid distribution formulas that have been used assume normal vascular endothelial integrity. In shock states or other conditions that damage the vascular endothelium, colloids may leave the vascular tree more rapidly and therefore have a larger immediate volume of distribution (15).

Crystalloid Distribution

The rationale for the use of a crystalloid distribution ratio of one-third in the plasma volume and two-thirds in the interstitial space was provided above. However, the rationale for that distribution ratio was based largely on observations made during brief fluid challenges in healthy individuals (8,10). That conservative estimate of crystalloid distribution nonetheless leads to a predicted crystalloid requirement of eight times IBS return (Rule 3). That volume will give many clinicians pause. In fact, it is entirely possible that as extracellular fluid space hydrostatic pressures increase with increasing crystalloid accumulation in the interstitial space, the percentage redistribution of crystalloid from the intravascular to the extravascular space may diminish with time. The assumption of a ratio of one volume intravascular to two volumes extravascular in a prolonged volume replacement situation during a lengthy spine procedure with very substantial crystalloid administration may not be a valid one. The authors are not aware of data that address this possibility. Accordingly, it should be acknowledged that the crystalloid rule of thumb may yield an overestimate in very lengthy procedures. This only serves to emphasize the importance of physiologic and laboratory determinations. Furthermore, considerations related to airway patency and the possibility that fluid accumulation within the orbit contributes to the postoperative visual loss phenomenon may discourage many clinicians from, in fact, using the large volumes dictated by the preceding arithmetic.

Table 1. Volume replacement guidelines for use with intraoperative blood salvage (IBS)

1. To achieve an estimate of the total blood loss, multiply the IBS return volume by 3.4–4.0.
2. If fluid replacement of the noncellular component of the true blood loss is undertaken using iso-oncotic colloid solutions, to achieve a reasonable estimate of the required volume of colloid, multiply the IBS return volume by 2.5.
3. If fluid replacement of the noncellular component of the true blood loss is undertaken using isotonic crystalloids, to achieve a reasonable estimate of the required volume of isotonic crystalloid, multiply the IBS return volume by 8.

Blood Salvage Efficiency

The large variance in IBS efficiency has already been acknowledged. That efficiency is in part a function of the nature of the procedure, which influences the amount of debris and/or the necessity to introduce foreign materials including irrigation, cement, and procoagulant substances that must bypass the IBS device. To a very great extent, IBS efficiency is also a function of user (surgeon) behaviors (immediacy of recovery, negative pressures used) over which the anesthesiologist does not have total control. In some hands, IBS efficiency may significantly exceed the 50% assumption made for the purposes of these calculations and in others (2) it may be less.

Platelet and Factor Replacement

The estimates of the percentage blood volume losses at which platelet and factor replacements may be necessary assume the maintenance of isovolemia during the loss and repletion process. In the event that isovolemia is not maintained and blood loss occurs during relative hypovolemia, the volumes at which critical levels are achieved will be smaller.

This presentation has focused very narrowly on the matter of blood and fluid replacement related to intraoperative blood salvage. Clinicians will, of course, have to address independently the fluid replacement relevant to deficits, maintenance requirements, and continuing third space losses.

The rules of thumb that have been derived in the preceding paragraphs are summarized in Table 1.

Appendix

Predicted blood loss after which a minimal acceptable hematocrit (Hct) is reached in conditions of continuous, isovolemic replacement and instantaneous mixing of patient blood and the replacement fluid.

$$X = -\text{Blood vol} \cdot \text{In}\left(\frac{1 - \text{Min Hct} - \text{Init Hct}}{\text{Repl Hct} - \text{Init Hct}}\right)$$

X = blood loss; Blood vol = patient's starting blood volume; Min Hct = Lowest acceptable final hematocrit; Init Hct = patient's starting hematocrit; Repl Hct = hematocrit of replacement fluid (= zero for crystalloids and colloids).

The authors are grateful to Mark M. Mitchell, MD, and Jonathan Drummond for the development and application of the isovolemic exchange formula.

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