

Red Blood Cell Recovery and Reinfusion

Jonathan H. Waters, MD^{a,b,*}

^a*Department of Anesthesiology, Magee Women's Hospital of the University of Pittsburgh Medical Center, Suite 3510, 300 Halket Street, Pittsburgh, PA 15213, USA*

^b*University of Pittsburgh Medical Center, Perioperative Blood Management Program, 200 Lothrop Street, Pittsburgh, PA 15213, USA*

The process of collecting shed blood and its readministration is termed cell salvage. Cell salvage can occur both intraoperatively and postoperatively. In addition to the collection of blood, the process entails the readministration of blood following washing and filtration, or filtration alone. This article addresses the intraoperative washed cell salvage process. If this technique is used appropriately, several blood volumes of red cells can be recovered and readministered. In addition, this article educates the reader about the principles of cell salvage technology and describes the parameters that can maximize its effectiveness.

The physics of the cell salvage machine

There are many different manufacturers of cell salvage equipment. Generally, all of the machines depend on two basic principles for their function: the difference in density of blood constituents and a balance of centrifugal and hydraulic forces. The mechanics of the OrthoPat (Haemonetics, Braintree, Massachusetts), the AutoLog (Medtronic, Minneapolis, Minnesota), and the CATS (Continuous Auto Transfusion System) (Fresenius, Frankfurt, Germany) are slightly different than those in the following discussion, but the basic principles of centrifugation still apply.

* Department of Anesthesiology, Magee Women's Hospital of the University of Pittsburgh Medical Center, Suite 3510, 300 Halket Street, Pittsburgh, PA 15213.

E-mail address: watejh@upmc.edu

The process starts as blood is pumped from the collection reservoir into the centrifuge bowl. Blood enters the top of the centrifuge bowl through the bowl inlet and down a central straw. The blood exits the straw at the bottom of the bowl while the centrifuge is spinning (Fig. 1). The speed at which blood can be moved into and out of the bowl depends on the pumping pressure and the resistance of the straw through which the blood is pumped. The resistance (R) of this straw is defined by $R = (8 \times \text{length} \times \text{viscosity}) / (\pi \times (\text{radius})^4)$.

Thus, blood can be moved into the bowl faster or slower depending on the radius or the length of the straw and on the viscosity of the blood being pumped. One of the features that make the Baylor bowl ideal for trauma care is that the radius of its central straw is twice that of the radius of a standard Latham bowl's straw.

As blood is being pumped into the bowl, centrifugal force is applied. Centrifugation is a process used to separate or concentrate materials suspended in a liquid medium. The centrifugal force generated by a cell salvage processor is proportional to the rotation rate of the rotor (in rpm) and the distance between the rotor center and the sides of the centrifuge bowl. This relationship is described by the equation $F = m(\nu^2/r)$, where m is the mass of the particle, ν is rotation velocity, and r is the radius of rotation.

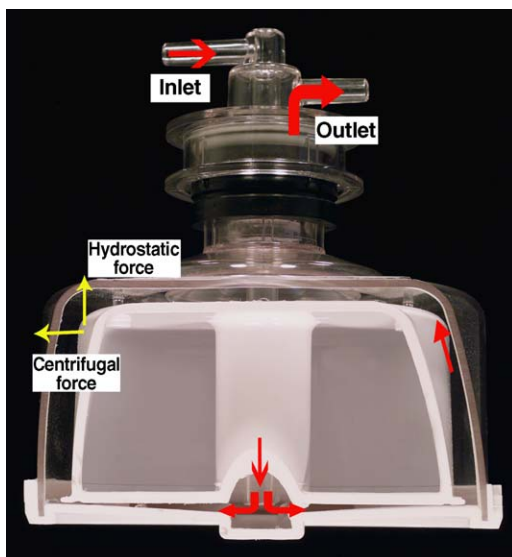


Fig. 1. This Baylor or square bowl shows the blood pathway as it enters the bowl through the inlet, passes down through the central straw, and then exits the bowl through the outlet. On the *left* of the figure are shown the vector forces that are applied to the blood in the bowl. Centrifugal force is applied to the cells, forcing them against the sides of the bowl. Hydrostatic force, or the force of blood being pumped into the bowl, pushes the contents out of the bowl. When the hydrostatic force overcomes the centrifugal force exerted on the red cells, the cells will be forced out of the bowl. This limits the speed at which processing can occur.

Because the force applied to the various components of blood varies with the mass of the components, the heavier, larger particles (red cells) will sediment against the walls of the bowl, whereas the smaller, lighter particles (plasma) sediment closer to the core of the bowl. As blood is pumped into the bowl, the hydrostatic force of pumping will also be applied to the fluid. Thus, the contents of the bowl will have two forces applied to it, centrifugal force and hydrostatic force. As is described by the second equation, heavier particles will have more centrifugal force exerted on them. As the hydrostatic force increases, the first material to leave the bowl will be the plasma and lighter particles, which have less centrifugal force applied to them. If blood is pumped at too fast a rate or with too great a force, the hydrostatic force of the pumping will overcome the centrifugal force on the red cells, thus pushing them out of the top of the bowl. This limits the speed at which filling of the cell separation bowl can take place.

Following filling of the cell separation bowl, a wash solution is introduced into the red cell pack by pumping it through the central straw of the processing bowl. This wash solution is generally normal saline. One investigator suggests that a more balanced isotonic solution such as lactated Ringer's solution may offer a slight advantage in the prevention of hyperchloremic metabolic acidosis, which occurs when large quantities of normal saline are used [1,2]. This wash solution percolates through the cell pack, carrying lighter debris and irregular agglomerates out of the pack and into the wash bag. Washing is considered complete when the effluent line appears clear to the observer's eye and a wash volume of at least three times the bowl volume has been used. Again, the speed at which the saline wash is pumped into the bowl is limited by a balance of centrifugal and hydrostatic forces.

To empty the washed blood, the roller pump is reversed, and clean, packed red cells are aspirated from the bowl through the central straw and into the holding bag. Simultaneously, sterile air is drawn from the waste bag back into the bowl. Once the bowl is emptied of blood, another cycle may begin, and the washed red cells can be administered to the patient.

Optimizing red cell return

Small changes in red cell processing efficiency can make large differences in the blood loss that a patient can sustain before allogeneic transfusion therapy. Mathematical modeling [3] of a 70-kg patient with a starting hematocrit of 45% would suggest that the patient could sustain blood loss of 9600 mL if a transfusion trigger of 21% is used and cell salvage captures 60% of lost red blood cells. If 70% of the red cells are captured and returned to the patient, the sustainable blood loss rises to 13,750 mL. Thus, small changes in red cell recovery can result in large differences in the ability to avoid allogeneic transfusion. For this reason, every effort should be made to optimize the cell salvage process. Optimizing the cell salvage process can occur at multiple points in the

processing. The following discussion elucidates some of the areas where optimization can occur.

Suction

As blood is lost, suction is applied to clear the blood from the surgical field. The technique used to apply this suction pressure effects the degree of red cell return to the patient. Generally, turbulence destroys red cells. High turbulence results from high suction pressure. So, the lowest suction pressure that is tolerable to the surgeon should be applied. The vacuum pressure should be regulated from 80 to 120 torr, which is adequate for most surgical procedures [4,5]. The vacuum level can be temporarily raised to clear the field in the event of massive blood loss and then reduced to a lower level. It is important to remember that if multiple suction lines are attached to a collection reservoir both lines need to be used simultaneously, otherwise when one suction line is placed in blood and a second line is not then suction pressure will be halved.

The selection of the suction tip style and the method of use can also affect the degree of turbulence and red cell recovery rates. Tips that have small caliber openings create high degrees of turbulence at the tip, which can hemolyze cells during collection. If possible, the largest tip opening should be used. Suction tips should be immersed in the shed blood during collection. Skimming or sucking blood at a blood-air interface will lead to increased turbulence.

Rinsing of surgical sponges

Fully soaked gauze pads or lap sponges may contain up to 100 mL of blood [6]. Of this amount of blood, approximately 75% is retrievable. To retrieve these red cells, each sponge should be rinsed in a basin of isotonic solution (normal saline, Ringer's lactate, or Hartmann's solution) and wrung out before they are discarded. The rinse solution is periodically sucked into the cardiectomy or collection reservoir when it is noted that the sponges are no longer losing their red discoloration on rinsing.

Objections to the practice of rinsing sponges arise from two fears. The first fear is that this practice may result in cotton fibers being entrained into the blood. The second fear is that the sponges might introduce bacteria into the collected blood. In unpublished data from the Cleveland Clinic, no cotton fibers were retrievable from rinse solutions. Discussion with the manufacturer of these sponges disclosed that no fiber is shed because sponges are manufactured by a tight weave and a double washing process that eliminates cotton fiber shedding. This processing is carried out to eliminate fiber shedding into the surgical wound. If cotton fiber were to be shed into the blood product, these macroaggregates would be captured at the point of the collection reservoir filter. If a concern for shedding still existed, a microaggregate filter could be used at the point of administration.

As for bacterial contamination that might result from sponge rinsing, any bacteria that would be on the sponges would have come from the surgical wound. Thus, the patient has already been exposed to the bacteria. It is well described that cell salvage blood is routinely contaminated [7,8]. This contamination has not been correlated with clinical sequelae. If sponges are suspected to be contaminated, they should simply be discarded rather than rinsed.

Anticoagulant

As blood is suctioned from the surgical field, an anticoagulant should be mixed with the blood. The purpose of the anticoagulant is to prevent clot formation in the collection reservoir or processing system. Clotting of blood in the collection system will result in the loss of otherwise recoverable blood as well as the need for reservoir and bowl replacement when large clots obstruct blood flow through the system. Either citrate or heparin can be used for anticoagulation during cell salvage. Because of its low cost and availability, heparin is most commonly used. Added to a carrier such as normal saline at a dose of 30,000 units/L heparin, the solution is titrated through the aspiration suction system at a rate of 15 mL per 100 mL of collected blood. It is better to err on the high side rather than risk under-administration and loss of red cells to clotting. Over-administration of heparin during shed blood salvage is of no consequence in a cell washing system. Adequate washout will remove all but a trace of heparin, with less than 10 units of residual heparin remaining in the final blood product.

Citrate has also been used as an anticoagulant. Some controversy exists as to which anticoagulant is best [9,10]. The administration rate for citrate-bearing anticoagulants (acid citrate dextrose and citrate phosphate dextrose, and other forms) is also 15 mL per 100 mL of collected blood. Again, the over-use of citrate anticoagulants is better than inadequate doses. On reinfusion, rapid liver metabolism makes citrate toxicity a difficult state to achieve. In compromised liver function, correction with small doses of calcium provides immediate and nontoxic reversal. At the Mayo Clinic (Rochester, MN), 15,000 units heparin is mixed with 1 L of the citrate solution. Use of this solution has been noted to eliminate the cellular and protein deposits that frequently will be seen coating the interior surface of the processing bowl.

If a leukocyte depletion filter is to be used during cell salvage processing, some thought might be given to the use of heparin rather than citrate. The degree of deformability of leukocytes is reduced in the presence of calcium [11]. If a leukocyte depletion filter is being used to remove bacteria, cancer cells, or amniotic fluid contaminants, this decreased deformability might also affect these contaminants. By decreasing the deformability of these cells, the ability to filter them out of the blood product may be enhanced. This is an area in which further research is needed.

Collection reservoir

The reservoir is the collection site for blood as it awaits processing. The collection reservoirs are generally available with filter sizes ranging from 40 to 120 μm . Many perfusionists prefer to use the 40- μm size filter because this is the size to which they have become accustomed during cardiac surgery. However, the smaller filter size will result in larger amounts of blood being trapped in the reservoir. When large amounts of residual clot form in the collection reservoir, red cells can be retrieved by mechanically agitating the reservoir while simultaneously infusing normal saline or Ringer's lactate solution into the collection reservoir. This can be performed by using one of the suction lines or by infusing saline directly into the reservoir through ports on the top of the reservoir. These ports are available on some but not all manufacturer's reservoirs. Surprisingly large quantities of red cells can be retrieved through this mechanical agitation.

Calculation of blood loss during cell salvage

When performing cell salvage, blood that has been shed is suctioned from the surgical field into the collection reservoir and then processed and returned to the patient's circulation to potentially be lost again. This recirculation makes the calculation of blood loss during a surgical procedure difficult. For this reason, the equation [12] is used, $\text{blood loss} = ([H_s/H_p] \times V_b \times N_b)/SE$, where H_s is the average hematocrit of washed salvaged red cells, H_p is the average patient hematocrit during salvage, V_b is volume of the processing bowl, N_b is the number of bowls processed, and SE is the estimated salvage efficiency.

Salvage efficiencies can vary depending on vacuum levels, sucker tip size, diligence of salvaging efforts, contact time of blood in the wound, and other factors. With good procedural methodology, 60% of lost red cells can be recovered (SE). As the quality of the salvage effort declines, so does efficiency of recovery, and the assignment of lower values may be appropriate.

An example of how this equation can be applied is as follows, using a hip revision as an example. Five 125-mL bowls were processed. Small suction tips were used with elevated vacuum, and considerable blood was lost to drapes and gauze pads. Salvage efficiency was estimated at 40%. Hematocrit in the bowls was 66%, 70%, 68%, 65%, and 71%, respectively, averaging 68%. Concurrent patient values were 32%, 30%, 34%, 30%, and 28%, respectively, averaging 30.8%. Thus, $\text{blood loss} = (68\%) \times (125 \text{ mL/bowl}) \times (5 \text{ bowls}) / (30.8\%) \times (40\%) = 3450 \text{ mL}$.

Although this formula has not been compared with other techniques of estimating blood loss, routine blood loss estimates made by anesthesiologist, surgeon, and nursing personnel are well recognized to be grossly inaccurate. With this formula, some degree of accuracy can be obtained. If one is not

confident of the salvage efficiency, a range of possible blood loss can be calculated. For instance, the efficiency in the above example was estimated to be 40% but may have been better at 60%. For this same patient, the blood loss would be estimated to be 2300 mL at an efficiency of 60%, so the estimated blood loss can be reported as a range of 2300 to 3450 mL.

Wash quality

Attention to optimizing the quality of the product being readministered is required. Salvaged blood that has been poorly processed can result in adverse patient outcome. Inadequate washing has been described by Bull and Bull [13] and has been labeled “the cell salvage syndrome.” Inadequate washing and concentration of the cell-salvaged blood can lead to complications such as disseminated intravascular coagulation or acute renal failure. In a study of the “salvaged blood syndrome” incorporating 36,000 cases, Tawes et al [14] conclude that this problem occurs with inadequate bowl filling and inexperienced personnel.

The importance of having trained, dedicated workers operating the cell salvage equipment is highlighted by an article from the Cleveland Clinic. In an era before dedicated cell salvage personnel, O’Hara et al [15] reported on a lack of red cell avoidance with cell salvage during major vascular surgery. They report an average cell salvage unit hematocrit of 31%. Hematocrit levels of cell salvage blood should range between 40% and 75% if appropriate management of the processing has taken place. Lower hematocrit levels in the salvaged unit generally indicate inadequate filling of the centrifuge bowl. A lack of training and supervision of the personnel operating the machines led to processing on convenience by circulating nurses who would start the processing as they were walking by the machine while performing other tasks. Frequently, processing of the salvaged blood occurred before achieving enough red cells so that the final product was predominantly normal saline rather than red cells. An additional factor that may have caused these low hematocrit levels relates to the electronic sensor that detects the point at which the centrifuge bowl is full. The sensor works by detecting the red coloration of the red cell pack. In this era, a cell salvage machine was used that had an insensitive sensing mechanism. If careful observation of the filling of these bowls was not taking place, then the machine would trigger a wash cycle based on hemolyzed blood rather than intact red cells. In the above referenced study, the low hematocrit level was the result of this occurrence.

To prevent the occurrence of processing as described above, the American Association of Blood Banks has developed standards for perioperative auto-transfusion [16]. Among the standards is a requirement for personnel who are trained and dedicated to the management of the equipment. In addition, monitoring of the quality of the product is required. A measure of adequate concentration of the blood is recommended, which would be reflected by the hematocrit

of the product, and a measure of the quality of the wash process is recommended. An appropriate measure of wash quality has not been agreed upon. Some of the suggested measures would include periodic measurement of heparin washout, potassium washout, or albumin washout, or measurement of free hemoglobin.

The red cell content of salvaged blood held in the collection reservoir is seldom known, so it is quite common to process what seems like an adequate amount of collected blood only to find that not enough cells are present to fill the bowl. This is termed a “partial bowl.” Attempts to wash and administer partial bowls as discussed above can be dangerous and lead to adverse consequences for the patient.

When partial bowls are encountered, one of three options is possible. Early in a case, when additional blood loss is anticipated, the processed blood should be pumped back to the collection reservoir for storage, using the “return” function key. When additional shed blood has been collected, the entire volume can be drawn back into the bowl for washing. At the end of a case, washed packed cells can be drawn back from the holding bag to fill the bowl using the “concentrate” function key. Reprocessing of washed cells does not harm them, and it ensures adequate washing of the residual blood while increasing the overall recovery rate. If a partial bowl remains at the end of a case, with no prospect of additional shed blood and no packed cells in the holding bag, a partial bowl should be discarded.

Complications to cell salvage

Air embolism

Readministration of blood to the patient from the holding bag puts the patient at risk for an air embolism. Transfer of the blood from the holding bag to a transfer bag and “burping” of the air in the transfer bag back into the holding bag will prevent the complication of air embolism. Under no circumstances should a pressure cuff be used on the holding bag when blood is being directly reinfused into the patient.

Wrong wash solution

Generally, normal saline is used as the wash solution. Using 3-L bags of the wash solution allows for minimal changing of the bag. Many types of solutions are used in the operating room, including normal saline, glycine, and sterile water. It is important to store these different solutions in different locations so that the appropriate solution is used. If sterile water is inadvertently substituted for normal saline, the red cells will be completely lysed during processing. Readministering lysed red cells in sterile water could be potentially fatal to the patient. Glycine-washed cells would still be intact, but glycine has been reported to cause transient blindness and death [17,18].

Comparison of cell salvage with other techniques of allogeneic red cell avoidance

Exposure to the risks of allogeneic blood comes from the administration of red blood cells, plasma, and platelets. Each of these components carries the risks inherent to allogeneic blood. Autologous alternatives to allogeneic blood include autologous preoperative donation, cell salvage, normovolemic hemodilution, and perioperative apheresis. These methods can be divided into two categories: avoidance of red blood cell transfusion (autologous predonation, cell salvage, and normovolemic hemodilution) and avoidance of clotting products (normovolemic hemodilution and apheresis). Although autologous preoperative donation and normovolemic hemodilution have components of both categories, their primary application is to avoid red cell transfusion.

Preoperative autologous donation

Currently, the favored choice of many patients is to donate their own blood before a surgical procedure. In autologous preoperative donation, the blood bank draws the blood and stores it until the need arises for it. Approximately 50% of these units are never used [19]. Thus, the cost of autologous predonation for the health benefit gained is expensive and has been estimated to be as much as \$23 million for every quality-adjusted year of life saved [20]. Although this cost may be exaggerated, multiple other disadvantages exist [21]. Medical conditions such as anemia ($Hb \leq 11$ g/dL), pregnancy, and indwelling intravenous lines may prevent preoperative donation. It has been suggested through mathematical modeling that, instead of preventing allogeneic transfusion, transfusion should occur at an earlier time during a bloody surgical procedure [22]. This would seem to negate the purpose of donation. Predonation also requires advanced planning and may result in mistransfusion (the administration of the wrong unit of blood to a patient), and storage causes some deterioration in the quality of the blood, in the same fashion that it does in allogeneic blood storage.

Normovolemic hemodilution

Normovolemic hemodilution is another method designed to avoid homologous blood transfusion. This procedure entails withdrawal of autologous blood and replacement with intravenous fluids [23,24]. The replacement of blood with asanguinous colloid or crystalloid solutions maintains the normal circulating blood volume and oxygen delivery [25]. The primary goal of this technique is to create a relative anemia in the patient so that blood shed during the operative procedure effectively has a reduced number of red cells in it. Once the threat of blood loss is diminished, the harvested cells are returned to the patient. This minimizes the loss of crucial blood during the operative procedure. The advantages of normovolemic hemodilution are that it may reduce

the need for allogeneic blood during surgery, no storage injury occurs to the blood, the blood contains viable clotting factors, minimal cost is incurred, and the circuit used for this procedure can be kept in constant contact with the patient, thus making it a viable option for many Jehovah's Witness patients. The major problem with this technique is that the most optimal situations need to exist to have any blood savings [26].

Cell salvage

In comparison with other methods of red cell avoidance, cell salvage offers the greatest flexibility of all of the red cell avoidance techniques. Generally, the more units of blood produced per case, the higher the level of cost effectiveness. A recent cost analysis performed at the Cleveland Clinic demonstrated minimal cost savings of \$9.87 when patients received 1 unit of salvaged blood when compared with the alternative of transfusing an allogeneic unit. A high level of savings occurred when 2 or more units of salvaged blood were transfused in each case. The level of savings rose dramatically with the number of required units (Fig. 2). Patients with very high blood loss of 10 units or more received each unit at a cost of only \$20.18. The reason for this decline in cost is that the majority of the cost exists in the disposables. Once the disposable cost is expended, then minimal additional expense is incurred with producing multiple units.

The applicability of this analysis to other institutions will vary depending on the choice of equipment and the type of manpower coverage that is desired. The choice of equipment can vary with the startup costs of an autotransfusion service. Additionally, many manufacturers offer lease programs, whereas some will supply machines "free" of charge. These programs will reduce the initial startup investment, but ultimately the cost of the machine gets bundled into the supplies.

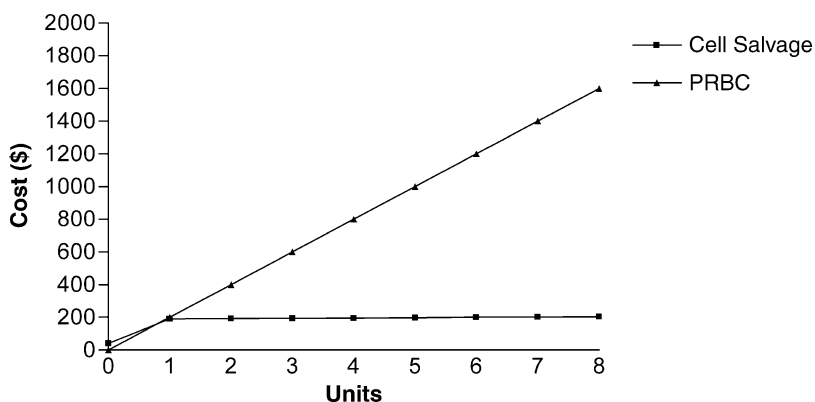


Fig. 2. A comparison of the cost of allogeneic blood to that of cell salvage. The cost per unit decreases as more units of cell-salvaged blood are produced.

Summary

The autotransfusion program at the Cleveland Clinic Foundation implements cell salvage in surgical procedures that average 2397 ± 2915 mL of blood loss per case, with 1030 ± 1247 mL being returned to the patient at an average hematocrit level of 57%. This highlights the ability of these systems to process and return red blood cells to a patient. An understanding of the parameters that can alter the efficiency is important to achieving maximum allogeneic transfusion avoidance. Furthermore, the knowledge of how to produce a quality product is mandatory before implementing this technology.

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