Principles of Fluid and Blood Warming in Trauma

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Learning Objectives: 1) To discuss the importance of fluid warming. 2) To review the mechanisms of fluid warming. 3) To evaluate the types of fluid warmers available.

Abstract

Hypothermia is a frequent occurrence after trauma. In the natural history of the prehospital and hospital course, especially the initial hours, patients can experience a large heat loss. Administration of cold intravenous fluids and blood can produce substantial hypothermia, although the net effect of infusing cold solutions into the body depends on many factors such as tissue blood flow, rate of body heat generation, rate of heat loss to the outside environment, and temperature gradients within the body. A variety of commercial devices are available for warming intravenous fluids and blood. Many of these fluid warming devices do not deliver fluids at normothermia over a wide range of flows because of inefficient heat transfer of the warmer and heat loss along the length of the administration tubing after the fluid exits the heat exchanger. In this article we review principles of heat transfer, mechanisms of warming fluids and blood products, and the different types of fluid warmers available. Improvements made in rapid infusion devices are discussed, including some of the safety issues. The importance of safely and effectively warming intravenous fluids in the adult and pediatric trauma population should not be underestimated.

Hypothermia occurs frequently in trauma patients because of environmental exposure, infusion of cold fluids and blood, opening of body cavities, decreased heat production, and impaired thermoregulatory control.[1–11] Although hypothermia decreases metabolic function of the body and is neuroprotective, hypothermia is deleterious in traumatized patients because of coagulopathy, metabolic acidosis, and impaired immune response.[12] Injured patients with hypothermia are more likely to die than normothermic patients with a similar injury severity score.[4] Hypothermia and acidosis (base deficit >12 mEq/L) were strong predictors of death in exsanguinating trauma patients undergoing surgery.[13]

The mechanisms of heat loss are well described. Infusion of unwarmed or inadequately warmed intravenous (IV) fluids and cold blood is a well-known cause of hypothermia and may contribute to the multiple adverse consequences of hypothermia such as peripheral vasoconstriction and decreased tissue oxygen delivery, metabolic acidosis, coagulopathy, wound infection, and cardiac morbidity.[1,2,12,14–19] This article reviews the principles of fluid and blood warming as they apply to the trauma patient.

Importance of Warming Intravenous Fluids

Conclusive evidence demonstrating the harmful effects of cold fluid infusion was provided by Boyan and Howland[20] in 1961. In their study, infusion of 0.5 liter of cold blood reduced core temperature of anesthetized cancer patients by 0.5 to 1.0°C. When 3.0 liters or more of cold blood was administered, esophageal temperature decreased markedly and was associated with a high incidence of cardiac arrests (12 of 25 patients). When blood was warmed, the incidence of cardiac arrests in a matched group of patients with similar surgeries, blood loss, anesthesiologist, and surgeon was only 3 of 105 patients.[21,22]

Thermal Stress of Infusing Cold or Inadequately Warmed Fluids and Blood

The theoretical impact of infusing fluids on body temperature can be calculated as follows:

Change in body temperature = Thermal stress of infused fluids / (Weight x Sp heat)
where:
Thermal stress = temperature difference between core and infused fluids x specific heat of infused fluid x volume of fluid infused
Weight = weight of patient in kilograms
Sp heat = specific heat of the patient (0.83 kcal/L/°C)[23,24]

According to the specific heat of water, 1 kCal of heat is required to raise the temperature of 1 kg of water by 1°C. Assuming that 1 liter of crystalloid weighs 1 kg and that its specific heat is the same as water, one needs 16 kCal of energy to raise the temperature of 1 liter of crystalloid infused at 21°C to body temperature (37°C).[23–26] Similarly, infusion of 4.3 liters of crystalloid at room temperature to an adult trauma patient would require 71 kCal, the equivalent of 1 hour of heat production in an awake adult, or 1.5 hours of heat production in an anesthetized adult male (heat production decreased by 33%).

The negative thermal balance of 4.3 liters of room temperature fluids is thus equivalent to a decrease of 1°C body temperature in an awake individual and a 1.5°C temperature decrease in an anesthetized patient. Conversely, 30 kCal are required to raise the temperature of cold 4°C blood to 37°C, such that infusion of 2 liters could result in a body temperature decrease of between 1.0°C and 1.5°C.[23–26] Patients with smaller body surface areas would be expected to have a more significant temperature decrease with infusion of unheated fluids and blood.

Temperature Setpoints of Warmers

Blood can be warmed safely for infusion so as not to cause hemolysis using a temperature setpoint of 42°C in conjunction with an approved blood-warming device. This setpoint is based on

Table 1. Selected Fluid and Blood Warmers

Instrument	Technology	Comments
Medi-Temp II FW400	Dry heat	Flexible plastic cassette inserts into warmer. Manual air eliminator and bubble trap. Manufacturer (Gaymar, Orchard Park, NY) still supports product.
Medi-Temp III FW600	Dry heat	Plastic cassette inserts into warmer. Adjustable temperature control between 30°C and 43°C. Bubble trap and air elimination.
Level 1 H-250, H-500	Countercurrent water bath	Tube in tube heat exchange. H-500 has larger heater than H-250 Product still supported by manufacturer (Smiths Medical, London, UK).
Level 1 H-1000	Countercurrent water bath	Tube in tube heat exchange combined with a 254-cm patient intravenous (IV) line with Hotline characteristics to prevent heat loss at moderate flow rates (<100 mL/min). Product still supported by manufacturer (Smiths Medical).
Level 1 H-1025	Countercurrent water bath	Tube in tube heat exchange. Can deliver between 75 mL/h and 60 L/h. Product still supported by manufacturer (Smiths Medical).
Level 1 H-1200	Countercurrent water bath	Automatic air detection system to prevent air embolism while still maintaining fast infusion and warming rates.
Hotline (Smiths Medical)	Countercurrent water bath	Entire 254-cm patient IV line is warmed to ensure delivery of warm fluids at flow rates between 5 and 80 mL/min (300–5,000 mL/hr)
Bair Hugger 2.4.1 (Arizant Healthcare Inc. Prairie MN)	Convective air	Spiral IV tubing suspended in same convective warming hose that delivers forced air to a warming blanket.
Ranger (Arizant)	Countercurrent metal	Cartridge-style plastic disposable set inserted between conductive warming plates.
FMS 2000 (Belmont Instrument Corp, Bellerica, MD)	Magnetic induction	Integrated peristaltic pump for flows up to 500 mL/min which eliminates requirement for pressurized infusion. Two air detectors and automatic air purge to prevent air embolism. Line pressure sensor automatically decreases flow if excessive pressure (e.g., small-gauge IV catheter, infiltrated IV). Cardiotomy option for large-volume infusion.
Belmont Buddy Fluid Warmer	Dry heat	Disposable cartridge inserts between two warming plates on the distal end of the IV tubing to prevent cool down at low flow. Automatically vents air that gets in the line. Cannot be used for pressurized flow.
R.I.S.	Countercurrent water bath	High-efficiency pump with 3-liter reservoir, three air/bubble detectors, line pressure sensor, and automatic flow rate control up to 1,500 mL/min. No longer being made, but still supported by manufacturer (Haemonetics Corp., Braintree, MA).
Nellcor Warmflo FW538	Countercurrent metal	Metal foil cassette inserted between two heated plates; IV tubing inserts directly into metal fluid channels within the cassette. For use with low-to-moderate flow rates. Formerly Mallinckrodt (Hazelwood, MO).
Alton Dean FW537	Countercurrent metal	Metal foil cassette inserted between two heated plates; IV tubing inserts directly into metal fluid channels within the cassette. Purchased by Mallinckrodt, supported by Nellcor (Pleasanton, CA).
Thermal Angel (Estill Medical Technologies, Dallas, TX)	Dry heat	Cartridge-style plastic disposable set inserted between conductive warming plates placed adjacent to IV infusion site to minimize heat loss. Portable, battery-powered.
Thermostat 900 (Microwave Medical System, Acton, MA)	In-line microwave	Direct microwave energy transferred to a disposable cartridge administration set for general purpose (ASH 100) and high flow/trauma (ASH 200-300) warming.
Enthermic EC770L Cabinet (Enthermics Medical Systems, Menomonee Falls, WI)	Dry heat	Has three heating coils in walls of cabinet and a fan to distribute air/heat evenly in main chamber by convection. Smaller warming cabinets available. Not for blood warming.
Astotherm (Stihler Electronic, Stuttgart, Germany)	Dry heat	Plastic disposable extension line IV tubing wraps around heat-exchange cylinder.
Animec (Futuremed America, Inc., Granada Hills, CA)	Dry heat	No disposable set. IV line inserted between warming plates at patient infusion site Only for low flows.
EnFlow (Enginivity LLC Lexington MA)	Dry heat	Disposable cartridge with low priming volume attaches close to patient infusion site to minimize cool down. Powered by AC or DC.

Note. Flotem IIe, DW-100, Fenwall, and Thermacyl fluid and blood warmers are no longer available.

observations by Uhl and colleagues[26] and is supported by a large body of experience with cardiac perfusion. In the study by Uhl et al,[26] red cells were incubated at 37, 40, 42, 44, 46, 48, and 50°C for up to 2 hours in a constant-temperature waterbath. Even subtle alterations in red cell integrity such as increased plasma hemoglobin and osmotic fragility were not apparent until 46°C.

Gore and Beaston[27] infused hot crystalloid fluids during operative burn wound debridement in an attempt to transfer heat to hypothermic patients. Temperature of crystalloid in their study was 54°C, which would theoretically transfer approximately 21 kCal/L to a hypothermic patient whose core temperature is 33°C. This technique was safe in their small series of patients undergoing burn surgery. There was no evidence of intravascular hemolysis, excessive bleeding or hyperkalemia.[27]

Judkins and Iserson[28] reported admixture blood warming in which very hot saline is mixed with cold red blood cells in order to infuse normothermic blood. With this technique, 250 mL 0.9% saline, maintained at a temperature of 70°C in an incubator, is quickly added to the cold blood. The resultant admixture has a temperature of approximately 37°C without evidence of red blood damage.[28,29]

Infusion of very hot fluids and admixture blood warming are considered experimental procedures. There is currently not enough information to recommend these techniques, and there is danger that very hot fluids may result in local vascular damage and hemolysis of cells. The maximum safe temperature for admixture blood warming is highly dependent on the relative volume of saline and blood. Use of unproven methods and unapproved approaches to warming fluids and blood can have catastrophic results, including death.[30,31]

Fluid and Blood-Warming Devices

Several methods to warm IV fluids and blood are currently available (Table 1). These include immersing coiled IV tubing in a warm water bath, microwaving the bag of fluid to be infused, adding heated saline to blood to be infused, passing the IV tubing through a heating block or through a plastic tube warmed with forced air, passing the IV tubing through a conductive surface interfaced with a countercurrent heated water bath, magnetic induction, prewarming fluids in a convection oven or in a microwave oven, and inline microwaving.[32–38]

The ideal fluid warmer should be capable of safely delivering fluids and blood products at normothermia at both high and low flow rates. At high flows, the device should be able to detect air and automatically shut off to prevent accidental infusion of air. The ability of blood warmers to safely deliver normothermic fluids over a wide range of flows is limited by several factors, including limited heat-transfer capability of materials such as plastic, limited surface area of the heat exchange mechanism, inadequate heat transfer of the exchange mechanism at high flow rates, erythrocyte damage, and heat loss after the IV tubing exits the warmer.[33,39–41]

Warming devices that use countercurrent heat exchange (Level 1 fast flow H-1200; Smiths Medical, London, UK) and magnetic induction (FMS 2000; Belmont Instrument Corp., Billerica, MA) are capable of warming fluids even at very rapid flow rates because of better conduction materials interposed between the heating elements and the infused fluid (Figures 1-3; Table 2).[41–44] Moreover, both the FMS 2000 and Level 1 H-1200 incorporate safety features to prevent accidental infusion of air (to be discussed in next section). Therefore, these warmers are appropriate for situations where rapid (>100 mL/min) volume resuscitation is necessary.

At moderate flows (<100 mL/min), there is significant heat loss after the IV tubing exits the warmer. The continual countercurrent warming of fluids in the tubing (Hotline and H-1000; Smiths Medical) essentially eliminates the loss of heat along the tubing distal to the warmer (Figures 4 and 5).[34,42] Alternatively, the fluid warmer can be placed adjacent to the infusion site to minimize in-line cooling at moderate flows (Buddy, Belmont; Figure 6).[45] Because of the marked inefficiencies of fluid-warming devices such

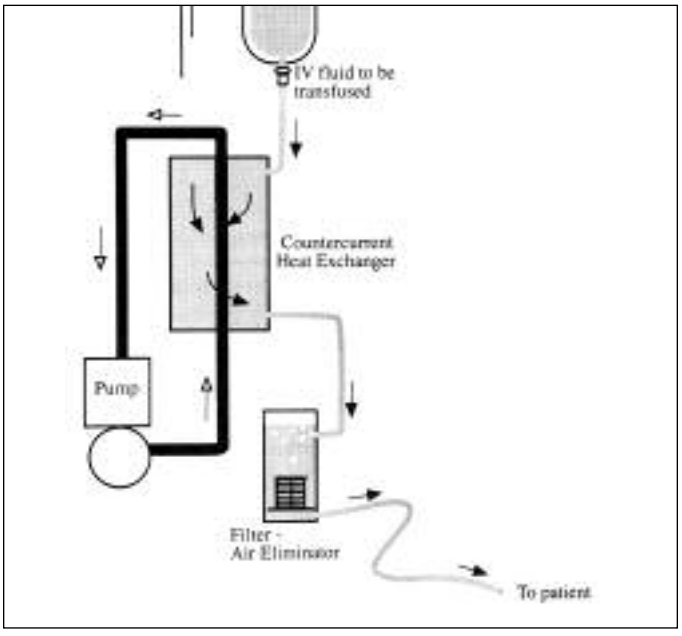

Figure 1. Schematic of the Level 1 fast flow warmers (H-series; Smiths Medical, London, UK). The device consists of a heater that warms water and circulates it through a pump and a heat exchange segment with a central tube for water flow (countercurrent heat exchange technology). Fluid flows through the outer sheath, which surrounds the water core.

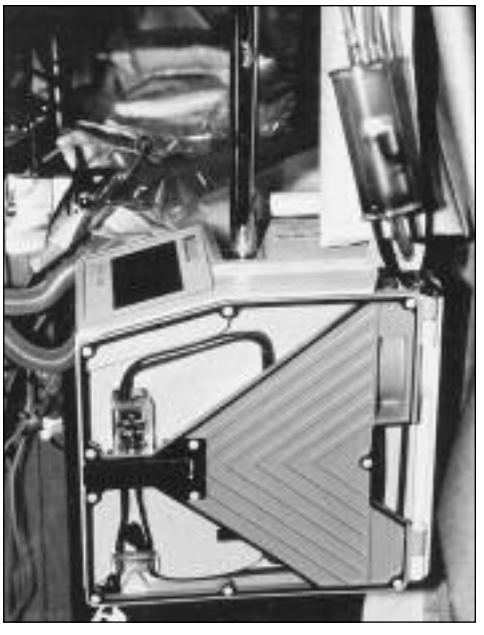

Figure 2. Belmont FMS 2000 warming system (Belmont Instrument Corp., Bellerica, MA). The system consists of an integrated volumetric infusion pump coupled with a high-capacity magnetic induction heater. There are two ultrasonic air detectors, one at the fluid inlet and the other at the outflow to the patient coupled to an automatic shut off.

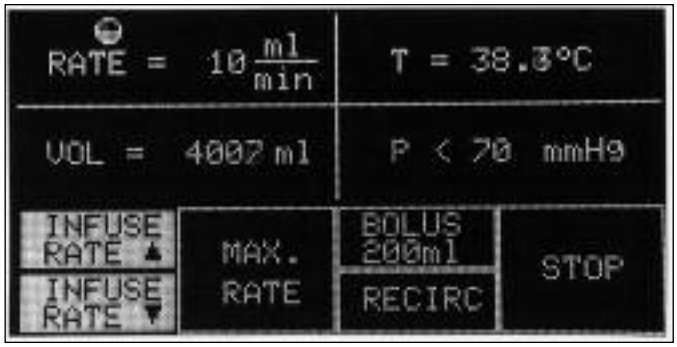

Figure 3. Graphical interface of the FMS 2000 showing flow rate (RATE), volume infused (VOL) temperature of the fluid distal to the heat exchanger (T), and line pressure (P). Flow rate is adjusted by pressing the increase or decrease rate button. Maximum unrestricted flow is 500 mL/min. However, flow is decreased automatically if line pressure is high (e.g., small-bore intravenous catheter). A fixed volume fluid bolus of 200 mL can be automatically delivered. (From Smith CE, Kabbara A, Kramer RP, Gill I. A new IV fluid and blood warming system to prevent air embolism and compartment syndrome. *TraumaCare* 2001;11:78–82.)

as the Flotem IIe (Datachem Inc., Indianapolis, IN), ASTOTHERM (Stihler Electronic, Stuttgart, Germany; Figure 7), and others (inadequate heat transfer at high flows, significant in-line cool down at moderate and low flows), these devices are no longer in use at the author's institution and have been replaced with the H-1025 (or H-1200) and FMS 2000 for rapid infusion (>100 mL/min or >6 L/hr) and the Hotline device for all other situations.

Table 3 summarizes the implications of using various fluid warmers during commonly encountered clinical situations: pressure-driven infusion, and gravity-driven infusion with the roller clamp wide open.[41,42] In the first situation, the patient presents with severe circulatory shock due to massive blood loss. Fluid resuscitation is required to prevent acidosis and irreversible shock. In the second scenario, the fluid and blood-volume deficit is not as severe, although ongoing blood loss may necessitate moderately fast infusions with the roller clamp wide open to maintain normovolemia and hemodynamic stability. It can be seen from the calculations in Table 3 that the thermal stress of infusing cold fluids may result in considerable changes in mean body temperature, especially if the patient is unable to increase heat production or prevent further heat loss. The larger the gradient between the temperature of the infused fluid and core temperature, the greater the drop in mean body temperature. As well, the greater the fluid requirement relative to body weight, the greater the potential drop in body temperature.

Table 2. Implications of Using Warming Devices for Crystalloid Fluid Resuscitation (5 and 10 L) in Anesthetized Adult Trauma Patients*

Device	Flow Rate (mL/min)	Outlet Temperature (°C)	Decrease in MBT† (5 L infusion, °C)	Decrease in MBT† (10 L infusion, °C)
Flotem IIe				
Pressure	260	24	-1.12	-2.24
Gravity	90	27	-1.03	-2.06
Astotherm				
Pressure	260	25	-1.03	-2.06
Gravity	90	30	-0.60	-1.20
Bair Hugger 2.4.1				
Pressure	360	24.2	-1.10	-2.20
Gravity	80	29.6	-0.63	-1.27
Hotline				
Pressure	220	29.8	-0.62	-1.24
Gravity	80	34.8	-0.19	-0.38
Level 1 250				
Pressure	600	33	-0.34	-0.69
Gravity	290	36	-0.09	-0.17
Level 1 H-1000				
Pressure	470	39.5	+0.22	+0.43
Gravity	150	39.4	+0.21	+0.41
FW537				
Pressure	580	38.9	+0.16	+0.32
Gravity	200	39.9	+0.25	+0.49
Cardioplegia Heat Exchanger				
Pressure	700	35	-0.17	-0.34
Gravity	150	35	-0.17	-0.34

*See Table 1 for manufacturer information.

†Change in mean body temperature (MBT) was calculated as $(T_F - T_P) \times S_F/Wt \times S_P$ where T_F = temperature of fluid delivered to the patient (outlet temperature of the warmer), T_P = temperature of the patient (assumed to be 37ºC), S_F = specific heat of infused fluid (1 kcal/1ºC crystalloid), S_P = specific heat of the patient (0.83 kcal/1ºC). Fluids were infused during two conditions: pressure-driven infusion and gravity-driven infusion with the roller clamp wide open.
Data from refs. 41 and 42.

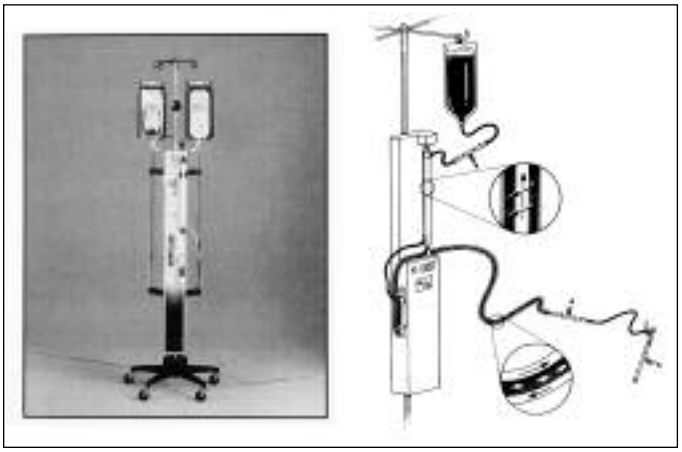

Figure 4, A and B. Level 1 H-1000 warmer (Smiths Medical, London, UK). The device consists of a cylindrical aluminum heat exchanger mounted on the warming unit and heated by a countercurrent water bath as in Figure 1. After the fluid exits this first heat exchanger, it enters a 254-cm patient line in which heat loss is prevented by surrounding the central lumen with warmed water circulating in a countercurrent direction, similar to the Hotline device. There is a double pneumatic external compressor that when activated, automatically squeezes the intravenous fluid or blood bag to increase flow.

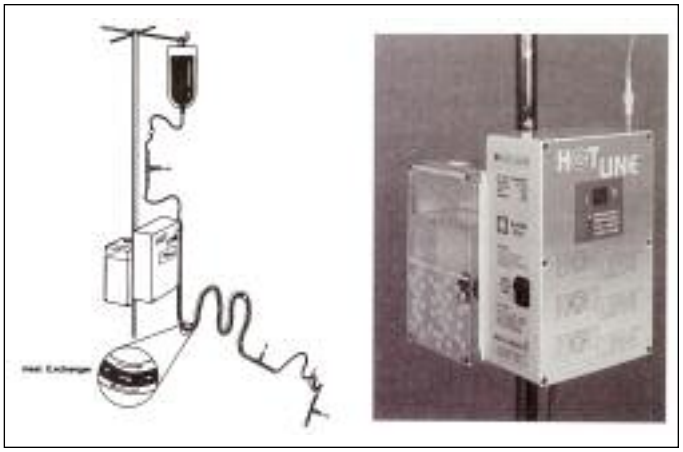

Figure 5, A and B. Hotline warmer (Smiths Medical, London, UK). The device consists of a water bath and a 254-cm disposable patient line. The central lumen for intravenous fluid is surrounded by an outer layer through which warm water circulates down one side and then back up to the warm water reservoir in a countercurrent fashion (countercurrent heat-exchange technology).

Infusion of fluids prewarmed in a fluid-warming cabinet (Enthermics, Menomonee Falls WI; Fig 8) is also effective, provided the fluid is kept in the cabinet for a sufficient time and infused using unrestricted gravity flow within 30 minutes on removal from the cabinet.[38] Crystalloid fluid temperature is related to time in and time out of the warming cabinet according to the equations:

1. T distal = T cabinet – (T cabinet – T room) * (1 – Exp (-ax)) where,
   T distal = distal fluid temperature
   T cabinet = temperature setting of the fluid warming cabinet
   T room = room temperature
   a = coefficient (0.53 for 40°C cabinet, 0.46 for 42°C cabinet)
   x = time out of the cabinet (time exposed to room air).

For example, if x is very short, T distal approaches that of T cabinet. As x increases towards infinity, T distal approaches T room.

And

2. T distal = T room + (T cabinet – T room) * (1 – Exp (-ax)) where,
   T distal = distal fluid temperature
   T cabinet = temperature setting of the fluid warming cabinet
   T room= room temperature
   a = coefficient (0.52 for 40°C cabinet, 0.42 for 42°C cabinet)
   x = time in the cabinet

   For example, if x is very short, T distal approaches T room. As x approaches infinity, T distal approaches T cabinet.

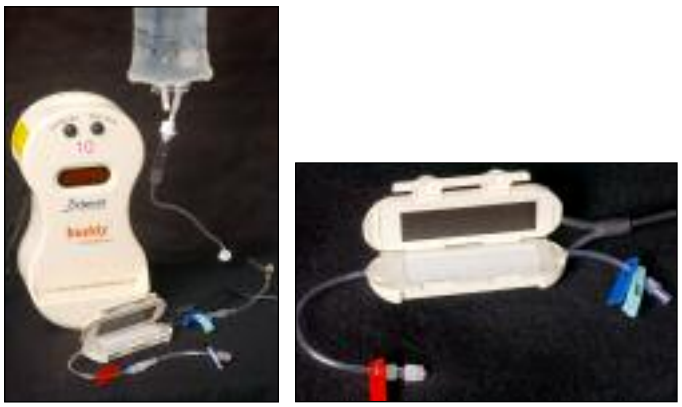

Figure 6, A and B. Belmont Buddy warmer (Belmont Instrument Corp., Bellerica, MA). The disposable set is attached close to the patient to minimize heat loss in the patient line. Priming volume is small (4 mL). The disposable set has microporous membranes that vent air from crystalloid fluid. Air is released through the side vents of the set to minimize the risk of air embolism.

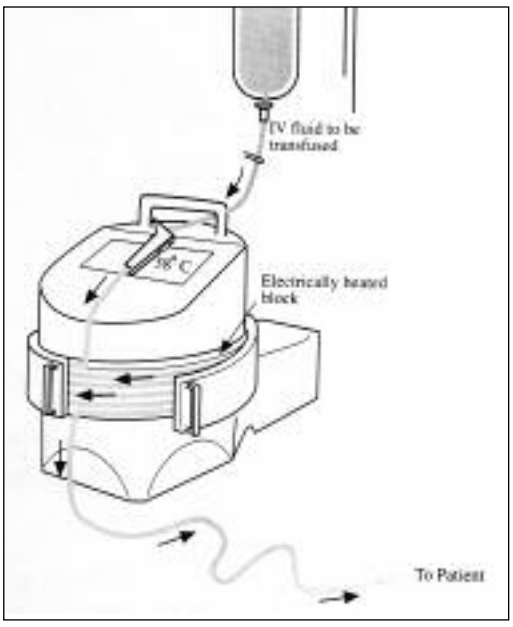

Figure 7. Schematic of the Astotherm warmer (Stihler Electronic, Stuttgart, Germany). This device consists of intravenous tubing coiled around a circular heating element (dry heat technology).

Table 3. Fluid and Blood Warming Using the Belmont FMS 2000 System*

Flow rate (mL/min)	Crystalloid T proximal, ˚C	Crystalloid T distal, ˚C	Diluted Red Blood Cells T proximal, ˚C	Diluted Red Blood Cells T distal, ˚C
Slow				
10	37.3 (0.3)	28.9 (0.4)	33.3 (0.8)	22.6 (0.2)
20	39.2 (0.4)	28.6 (0.2)	37.2 (0.8)	23.9 (0.8)
30	39.5 (0.4)	28.8 (1.2)	38.4 (0.4)	28.9 (1.7)
Moderate				
40	39.6 (0.4)	31.8 (1.2)	38.3 (0.5)	34.8 (1.2)
50	38.8 (0.9)	32.1 (1.0)	38.9 (0.5)	33.9 (0.9)
Rapid				
100	37.6 (0.3)	36.2 (0.6)	37.9 (0.9)	37.7 (0.5)
200	38.3 (0.4)	37.4 (0.1)	37.5 (0.6)	35.0 (0.8)
300	38.5 (0.8)	37.6 (0.2)	37.2 (0.6)	34.7 (0.6)
400	38.6 (0.5)	37.5 (0.5)	37.3 (0.5)	35.4 (0.8)
500	39.0 (0.3)	37.5 (0.3)	37.4 (1.1)	35.3 (3.0)

*Temperature was measured after the heat exchanger (T proximal) and at the point where fluid would enter the patient (T distal). Refrigerated packed red blood cells were diluted with 100 mL 0.9% saline. Data are means (SD).
Data from ref. 43

The warming cabinet cannot be used for blood. Injection fluid solution stability varies according to temperature, duration of storage at that temperature, composition, and storage container. Generally, fluids cannot be heated and stored longer than 14 days. Solution warm-up time varies depending on cabinet warmer load. Lau and Tsui[46] heated 1-liter bags of crystalloid in a microwave oven. They found that it is possible to predict the rise in temperature based on the power of the microwave and the set heating time. They developed a simple alogorithm as follows: temperature rise = 0.185 x output (kW) x time (seconds), which can be used to calculate the temperature rise of a 1-liter bag of fluid. Limiting the heating time to less than 80 seconds prevented overheating.[46]

Figure 8. Fluid warming cabinet (EC770L, Enthermics Medical System, Menomonee Falls, WI). The cabinet is warmed to 42°C using a low-heat-density electrothermal cable array to provide even heating of injection fluids. Solution warm-up time varies depending on cabinet warmer load. The cabinet cannot be used to warm blood.

Safety of Rapid Infusion Devices with Constant Pressure

Perioperative air embolism is a well-known complication of anesthesia and surgery. Symptoms and signs of air embolus include gasp, hypotension, arrhythmias, cardiovascular collapse, and death. Both the quantity of air and the rate at which it enters the circulation are important factors determining the severity of the embolic event. Accidental administration of air in IV fluid bags during use of pressurized infusion devices can be fatal because of the rapidity of flow. Gas vent filter assemblies of many commercial fluid warmers act merely to release gas bubbles produced by the warming of the liquid. Amount of air that could reach the patient would then depend on factors such as drip chamber volume, air volume, gas vent and filter performance, temperature, and flow.

Linden et al[47] showed in a simulated air- and fluid-containing administration system such as in a fluid resuscitation model, that 43 to 61 mL/sec of air can be delivered when the IV bag was externally pressurized to 300 mm Hg. This corresponds to as much as 200 mL of air entering the circulation in a little as 4 seconds, which is fatal. Because of the high flow rates generated by warmers when used with constant-pressure devices and large-bore IVs, the limiting factor in fluid resuscitation is the time required to identify red cell donor and recipient information, to spike and hang the fluid, and to ensure absence of air from the fluid system. In our experience, it is wise to have one individual solely responsible for pressurized infusion of fluids. This individual must use extreme vigilance and caution because of the danger of infusing air at these high flow rates and the danger of interstitial infiltration of blood and saline (compartment syndrome). Standard 1-liter bags of crystalloid contain between 40 and 85 mL of air.[45]

The authors are aware of seven cases of iatrogenic air embolism and two cases of forearm compartment syndrome following use of pressurized IV infusions. Adhikary and Massey[48] describe a case of massive venous air embolism during coronary artery surgery that occurred while infusing crystalloid under pressure. Air embolism was diagnosed using transesophageal echocardiography. A manufacturer and user facility device experience (MAUDE) database lists two cases of deaths during pressurized infusion of blood: one

after mitral valve replacement, the other during infusion to a major trauma patient. The frequency of fatal air embolism after pressurized administration of cell saver blood was 4 of 127,586 blood recovery procedures, or 1:31,300.[47] In a letter to the editor to the Anesthesia Patient Safety Foundation, mention is made of three cases of massive air embolism from pressure infusers that resulted in settlements of $385,000 to $1,600,000 according to the American Society of Anesthesiologists Closed Claims Study database.[49]

When infusing crystalloid under pressure, extra care must be taken to definitively expel air prior to placement of any pressurized infusion device, as human vigilance alone is insufficient given the possibility of rapid infusion rates. Use of an automatic air detector coupled to an automatic shut-off is desirable for rapid infusion devices. Pressurized infusion of recovered blood (e.g., cell-saver blood) should be avoided because these bags may contain considerable amounts of air and are difficult to vent.

It is our belief that constant pressurized infusion devices should not be used to accelerate flow unless the patient is in profound hemorrhagic shock and all air has been removed from the fluid to be infused rapidly. The use of air bubble and line pressure sensors and alarms coupled with a shut-off valve that automatically closes off all flow to the patient is a distinct advantage of the FMS 2000 and H-1200 fluid warmers. The FMS 2000 eliminates the risks normally associated with pressurized infusion by using an integrated peristaltic pump together with several features that detect air before it enters the system (fluid-out detector), purge air that is out gassed during warming (automatic air purge), and automatic shut-off that turns off the pump as soon as air is detected or line pressure is excessive (Figure 9; Table 4).[43,44]

With the H-1200, there is an air detector clamp that monitors for presence of air in the disposable gas vent-filter assembly (Figure 10).[50] An ultrasound signal is continuously passed through the fluid-filled gas vent-filter assembly. Because a bolus of air displaces the fluid in the gas vent-filter assembly, the ultrasound signal is broken, and the clamp automatically closes off the patient line. Audible and visual alarms are activated to alert the clinician that the fluid flow has stopped because of the presence of air. The operator is then prompted to follow a sequence of steps to purge the system of air before infusion of fluids can be resumed. It should be noted that the steps required to reprime the system with the Level 1 H-1200 following air detection and shutoff are very different from those of the Belmont FMS 2000. To restore flow after air detection with the FMS 2000, the operator follows a series of command prompts on the screen, which result in the semiocclusive rollerhead pump pushing a bolus of fluid to clear the air into the recirculate line and back up into the reservoir chamber.[43] With the Level 1 H-1200, multiple steps are required to reestablish fluid flow after the patient line clamps off because of air in the gas vent-filter assembly. The steps are as follows[50]:

1. Close the clamps under the IV bag, the roller clamp, and the clamp below the gas vent filter assembly.
2. Remove pressure from the pressure chamber.
3. Inspect the IV tubing for air.
4. Locate the air source and correct this condition.
5. Spike an air free bag of 0.9% saline.
6. Insert the IV bag in the pressure chamber.
7. Pressurize the chamber.
8. Prime the IV drip chamber and open the clamps above the gas vent-filter assembly.
9. If fluid flows freely through the IV tubing, air in the IV line is vented out through the gas vent-filter assembly.

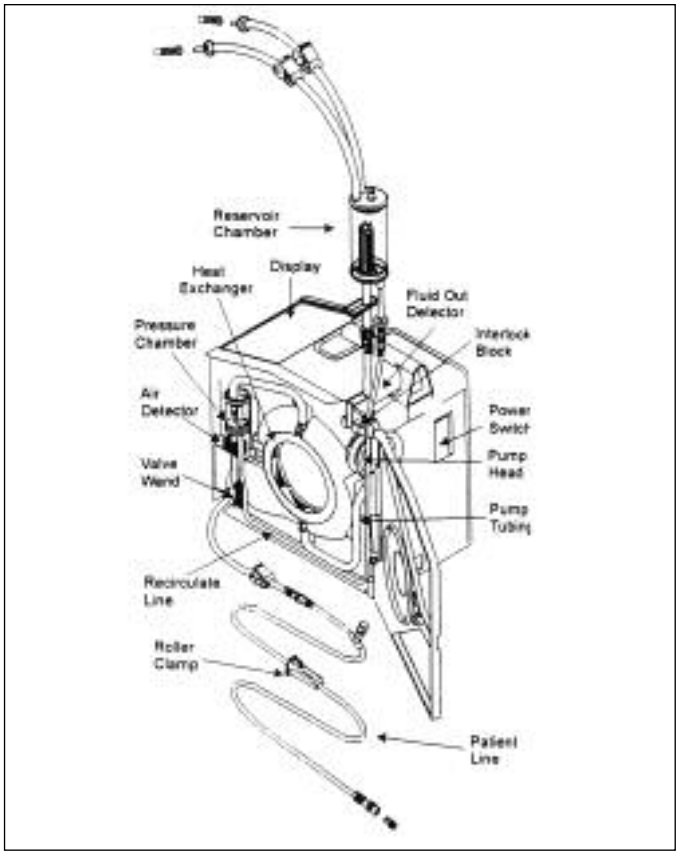

Figure 9. Belmont FMS 2000 disposable (Belmont Instrument Corp., Bellerica, MA). The set consists of a 120-mL reservoir chamber, fluid-out detector, pump tubing, pressure chamber, recirculating line, and patient line. Total priming volume is 220 mL. There is redundant air detection, automatic air removal, and sensors to alert the operator when the system is out of fluid, or a line is obstructed. (From Smith CE, Kabbara A, Kramer RP, Gill I. A new IV fluid and blood warming system to prevent air embolism and compartment syndrome. *TraumaCare* 2001;11:78–82.)

10. Press the unclamp button once to enter the unclamp mode
11. Press the unclamp button again to enter automatic operation mode
12. If no warning signals are activated (e.g., no air detected, system primed and ready to go), open all clamps to reestablish fluid flow.

If fluid does not flow freely through the IV tubing in step 9, the gas vent-filter assembly needs to be replaced. Steps 1-8 are then repeated, followed by steps 10-12. During red cell infusion with air (simulated air embolism catastrophe), it was not possible to purge the Level 1 H-1200 disposable of air until the gas vent-filter assembly was removed from the unit.[50] Poor air venting performance of the gas-permeable membrane of the gas vent-filter assembly during red cell infusion may be due to proteins plugging the filter. Failure to properly remove all air prior to reestablishing flow, including replacing and repriming the gas vent assembly, may result in accidental air embolism. Existing rapid infusers by the same manufacturer (H-1000/1025 and H-275/H-525) can be upgraded with the integrated air detector/clamp device.

Table 4. Time (seconds) to Automatically Shut Off during Rapid Infusion Using the Belmont FMS 2000 Warming System

Flow rate (mL/min)	Time to Empty 120 mL Reservoir after Air Entrainment	Time to Detect Occluded 14-Gauge Intravenous Catheter
100	94.9 (0.9)	3.4 (0.9)
200	47.2 (0.8)	2.4 (0.6)
300	34.6 (1.5)	1.4 (0.2)
400	30.8 (0.8)	0.9 (0.2)

Data are mean values (SD).
Data from ref. 43.

Fluid Warming and Pediatrics

Trauma is a disease that is not limited to adults. The pediatric population encounters many of the same issues as do adults with regard to hypothermia and hemorrhagic shock. Moreover, hypovolemia can be relatively more severe as children have a lower total blood volume than adults. Both the Hotline and Buddy fluid warmers provide warming mechanisms close to the distal end of the IV line. This minimizes heat loss before the fluid enters the vein, at all but the slowest of flows.[33,42,45] The Buddy disposable set has microporous membranes that vent air from crystalloid fluid. Air is released through the side vents of the set. Use of this warming device might theoretically reduce the risk of accidental infusion of air during crystalloid resuscitation of pediatric patients.[45] The Buddy disposable does not, however, vent air during red blood cell infusion. The Hotline warmer does not have a mechanism for venting of air. The Hotline disposable tubing is inconvenient for use in neonates and infants because of its relatively bulky size and large priming volume. Of note, the FMS 2000 is unable to heat fluids at flows less than 10 mL/min, and is therefore not recommended for pediatrics. Serour et al[51] found that putting an IV line under a warming mattress was a good fluid-warming method, and was superior than their conventional fluid warmer because it prevented heat loss before the fluid entered the vien. Tseng et al[52] showed that simple wrapping of the IV tubing with superlon (which is an insulating foam rubber that is used to prevent heat exchange in air conditioners) maintains heat distal to the warmer preventing in-line cool down.

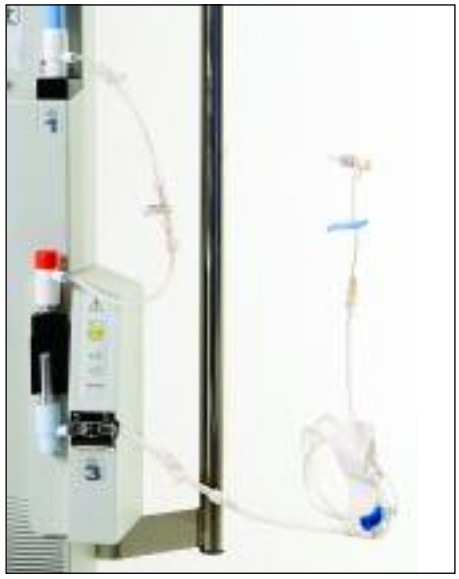

Figure 10. Level 1 H-1200 with integrated air detector/clamp (Smiths Medical, London, UK). The device consists of a heater that warms water and circulates it through a pump and a heat-exchange segment with a central tube (1) for water flow as in Figure 1 (countercurrent heat exchange technology). On detection of air in the line, the flow of blood and crystalloid is automatically stopped (3), allowing for removal of air and restoration of flow. There are audible and visual alarms when air is detected. The use of ultrasonic air detection coupled with automatic shutoff is a significant safety improvement.

Summary

Adverse consequences of perioperative hypothermia include myocardial ischemia, cardiac arrhythmias, coagulopathy, shivering, increased oxygen consumption during rewarming, alteration in drug metabolism, impaired offloading of oxygen from hemoglobin, and increased wound infection. Administration of cold or inadequately warmed IV fluids contributes to hypothermia, whereas administration of normothermic fluids may reduce both the incidence and complications of hypothermia. Therefore, infusion of adequately warmed fluids is important in order to minimize thermal stress and maintain thermal homeostasis. The choice of fluid warmer depends on patient needs, heat-transfer capabilities of the warmer, amount of in-line cool down expected, operator preference, and safety characteristics. There is no one ideal fluid warmer for use in all patients.

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