Rewarming Options

**Passive External Rewarming**

Because hypothermia is an extremely heterogeneous condition and evidence-based treatment guidelines do not exist, rigid treatment protocols are ill advised. [295,299,380] A versatile approach to rewarming can be developed after careful consideration of the observations from animal experiments, human experiments on mild hypothermia, and various clinical reports (Box 5-6). [118,119,278] Treatment should be predicated on the presenting pathophysiology and the available resources and expertise.

**BOX 5-6**

<table>
<thead>
<tr>
<th>Rewarming Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive External</td>
</tr>
<tr>
<td>• Thermal stabilization</td>
</tr>
<tr>
<td>Active</td>
</tr>
<tr>
<td>• Radiant heat</td>
</tr>
<tr>
<td>• Hot water bottles</td>
</tr>
<tr>
<td>• Plumbed garments</td>
</tr>
<tr>
<td>• Electric heating pads and blankets</td>
</tr>
<tr>
<td>• Forced circulated hot air</td>
</tr>
<tr>
<td>• Immersion in warm water</td>
</tr>
<tr>
<td>• Negative-pressure rewarming</td>
</tr>
<tr>
<td>External</td>
</tr>
<tr>
<td>• Inhalation rewarming</td>
</tr>
<tr>
<td>• Heated infusions</td>
</tr>
<tr>
<td>• Gastric and colonic lavage</td>
</tr>
<tr>
<td>• Mediastinal lavage</td>
</tr>
<tr>
<td>• Thoracic lavage</td>
</tr>
<tr>
<td>• Peritoneal lavage</td>
</tr>
<tr>
<td>• Diathermy</td>
</tr>
<tr>
<td>• Hemodialysis</td>
</tr>
</tbody>
</table>
• Venovenous extracorporeal blood rewarming
• Arteriovenous extracorporeal blood rewarming
• Cardiopulmonary bypass

The initial key treatment decision is whether to use passive or active rewarming (Box 5-7). Noninvasive passive external rewarming (PER) is ideal for most previously healthy patients with mild hypothermia. The patient is covered with dry insulating materials in a warm environment to minimize the normal mechanisms of heat loss. When the wind is blocked, less heat escapes via radiation, convection, and conduction. Conditions with higher ambient humidity slightly limit respiratory heat loss.

**BOX 5-7**

<table>
<thead>
<tr>
<th>Indications for Active Rewarming</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cardiovascular instability</td>
</tr>
<tr>
<td>• Moderate or severe hypothermia (&lt;32.2° C [90° F]) (poikilothermia)</td>
</tr>
<tr>
<td>• Inadequate rate or failure to rewarm</td>
</tr>
<tr>
<td>• Endocrinologic insufficiency</td>
</tr>
<tr>
<td>• Traumatic or toxicologic peripheral vasodilation</td>
</tr>
<tr>
<td>• Secondary hypothermia impairing thermoregulation</td>
</tr>
<tr>
<td>• Identification of predisposing factors (see Box 5-2)</td>
</tr>
</tbody>
</table>

Aluminized body covers also reduce heat loss. Nevertheless, endogenous thermogenesis must generate an acceptable rate of rewarming for PER to be effective. Humans are functionally poikilothermic below 30° C (86° F), and metabolic heat production is less than 50% of normal below 28° C (82.4° F). Shivering thermogenesis is also extinguished below 32° C (89.6° F). This thermoregulatory neuromuscular response to cold normally increases heat production from 250 to 1000 kcal/hr unless glycogen is depleted before or during cooling.

Older adult patients in whom mild hypothermia develops gradually are less acceptable candidates for PER. When rewarming times are markedly prolonged (over 12 hours), complications tend to increase.

Patients who are centrally hypovolemic, glycogen depleted, and without normal cardiovascular responses should be stabilized and rewarmed at a conservative rate. In a multicenter survey, the rewarming rates for older adults in the first (0.75° C [1.35° F]), second (1.17° C [2.11° F]), and third (1.26° C [2.27° F]) hours far exceeded 0.5° C (0.9° F) per hour, with no increase in mortality rate (Figure 5-8, online).
FIGURE 5-8  First-hour rewarming rates from a large multicenter survey. ACR, Active core rewarming; AER, active external rewarming; ECR, extracorporeal rewarming; ETT, endotracheal tube; GBC, gastric-bladder-colon; IV, intravenous; NT, nasotracheal tube; P, peritoneal; PER, passive external rewarming. (Data from Danzl DF, Pozos RS, Auerbach PS, et al: Multicenter hypothermia survey, Ann Emerg Med 16:1042, 1987, with permission.)

Active Rewarming

Active rewarming, which is the direct transfer of exogenous heat to a patient, is usually required with temperatures below 32°C (89.6°F). Rapid identification of any impediment to normal thermoregulation, such as cardiovascular instability or endocrinologic insufficiency, is essential. Intrinsic thermogenesis may also be insufficient after traumatic spinal cord transection or pharmacologically induced peripheral vasodilation. Some patient populations generally require active rewarming. For example, aggressive rewarming of infants minimizes energy expenditure and decreases mortality. In these circumstances, vigorous monitoring for respiratory, hematologic, metabolic, and infectious complications is essential.

When active rewarming is needed, heat can be delivered externally or to the core. Active external rewarming (AER) techniques deliver heat directly to the skin. Examples include forced-air rewarming, immersion, arteriovenous anastomosis rewarming, plumbed garments, hot water bottles, heating pads and blankets, and radiant heat sources.

During rewarming of hypothermic patients, there are metabolic pH and inflammatory interleukin fluxes. Cytokine production may be activated by accidental hypothermia.

Active External Rewarming

The interpretation of survival rates with AER is affected by various risk factors and patient selection criteria. Some experimental and clinical reports link AER with peripheral vasodilation, hypotension, and core temperature afterdrop, but previously healthy, young, and acutely hypothermic victims are usually safe candidates for AER. Heat application confined to the thorax may mitigate many of the physiologic concerns pertaining to the depressed cardiovascular and metabolic systems, which are unable to meet accelerated peripheral demands. Combining truncal AER with active core rewarming may further avert many potential side effects.

Forced-Air Surface Rewarming

Forced-air surface warming systems efficiently transfer heat. The Bair Hugger uses hot forced air circulated through a blanket. The air exits apertures on the patient side of the cover, permitting the convective transfer of heat. In one study that rewarmed accidental hypothermia victims in the ED, rewarming shock and core temperature afterdrop were not noted with the use of heated inhalation and warmed IV fluids. A group also treated with a convective cover inflated at
A study of full-body forced-air warming compared a commercially available convective blanket with simple air delivery beneath bedsheets. Directed 38°C (100.4°F) warm air under the sheets warmed standardized thermal bodies containing water very efficiently. Commercially available convective air rewarming devices (WarmTouch, whole-body blanket) are also effective. Another option is conductive warming with a warm water–filled heat exchange blanket (Blanketrol).

The use of forced-air surface warming systems is most practical in the ED. Although these devices decrease shivering thermogenesis, afterdrop is minimized and heat transfer can be significant. Thermal injury to poorly perfused, vasoconstricted skin using some of the other external heat application techniques is a hazard in both adults and children. In particular, avoid resistance-heat electric blankets on which a patient lies, because vasoconstricted capillaries are compressed and burns occur easily.

Another active external rewarming option is a thermoregulatory system that circulates warm water through energy transfer pads placed on the chest and lower limbs (Arctic Sun). The core temperature measured via probe is fed back to the control module. The original description of this noninvasive AER technique was by Vangaard and colleagues in 1979. Exogenous heat is provided by immersion of the lower parts of the extremities (hands, forearms, feet, calves) in 44°C to 45°C (111.2°C to 113°F) water. The heat opens arteriovenous anastomoses (AVAs). These organs are 1 mm (0.4 inch) below the epidermal surface in the digits. Countercurrent heat loss is minimized because the superficial veins are not close to the arterial tree.

To be efficacious, the cutaneous heat exchange area must include the lower legs and forearms, and the water must be 44°C to 45°C (111.2°C to 113°F). Advantages with AVA rewarming include patient comfort and decreased afterdrop after cooling. A permutation of AVA rewarming is negative-pressure rewarming. Under hypothermic conditions, the AVAs remain closed during peripheral vasoconstriction. In combination with localized heat application, application of subatmospheric pressure theoretically distends the venous rete and increases flow through the AVAs.

To initiate negative-pressure rewarming, the forearm is inserted through an acrylic tubing sleeve device fitted with a neoprene collar. This allows an airtight seal to form around the forearm. After a vacuum pressure of –40 mm Hg is created, heat is applied over the dilated AVAs. The thermal load can be provided via an exothermic chemical reaction or a heated perfusion blanket.

The clinical efficacy of AVA rewarming in accidental hypothermia is unclear. Studies concluding that heat exchange is ineffectual used cooler water applied only on the hands and feet. The potential for superficial burns of anesthetic, vasoconstricted skin is a consideration. Another caveat is hypotension precipitated in hypovolemic patients who remain semiupright with this technique. In one study, the rate of core rewarming increased dramatically, but another study comparing negative-pressure rewarming with forced-air warming failed to replicate these results.

Active Core Rewarming

Various techniques that can effectively deliver heat to the core include heated inhalation, heated infusion, diathermy, lavage (gastric, colonic, mediastinal, thoracic, peritoneal), and extracorporeal rewarming. Average first-hour rewarming rates reported with some of these techniques in one multicenter study are listed in Figure 5-8, online. Although hemodynamic instability impacts the rewarming strategy, noninvasive techniques often succeed unless there are significant comorbidities.

Airway Rewarming

The effectiveness of the respiratory tract as a heat exchanger varies with technique and ambient conditions. Because dry air has low thermal conductivity, complete humidification coupled with an inhalant temperature of 40°C to 45°C (104°F to 113°F) is required. The main benefit of airway rewarming is prevention of respiratory heat loss. Heat yield can represent 10% to 30% of the hypothermic patient’s heat production when respiratory minute volume is adequate.
The rate of rewarming is greater using an endotracheal tube (ETT) than by mask. In one series, the reported rewarming rate with a 40°C (104°F) aerosol was 0.74°C (1.33°F) per hour via mask and 1.22°C (2.2°F) per hour via ETT. In a multicenter survey, the average first- and second-hour rewarming rates in severe cases were 1.5°C to 2°C (2.7°F to 3.6°F) per hour. Because of the decremental efficiency at higher temperatures, the rate is slower (10 kcal/hr) in mild cases.

Thermal countercurrent exchange in the cerebrovascular bed of humans affects the efficiency and influence of heated-mask ventilation during hypothermia. Known as the rete mirabile, this system could preferentially rewarm the brainstem. Heated inhalation via face mask continuous positive airway pressure (CPAP) may correct the ventilation–perfusion mismatch. Heated humidified oxygen via face mask is not feasible in some patients with coexistent midface trauma.

Heat liberated during airway rewarming is produced mainly from condensation of water vapor. The latent heat of vaporization of water in the lungs is slightly lower than 540 kcal/g H₂O. This is multiplied by the liters per minute ventilation to calculate the quantity of heat transfer. When core temperature is 28°C (82.4°F), the rate of rewarming with heated ventilation at 42°C (107.6°F) equals endogenous heat production. Although the effect on overall thermal balance can be minimal, there may be preferential rewarming of thermoregulatory control centers.

Heated humidified inhalation ensures adequate oxygenation, stimulates pulmonary cilia, and reduces the amount and viscosity of cold-induced bronchorrhea. Although preexisting premature ventricular contractions (PVCs) may reappear during rewarming, there is no evidence that inhalation rewarming precipitates new, clinically significant ventricular arrhythmias. Vapor absorption does not increase pulmonary congestion or wash out surfactant. When the pulmonary vasculature is heated, warmed oxygenated blood that returns to the myocardium could attenuate intermittent temperature gradients. The amplitude of shivering is also lowered, an advantage in more severe cases. This suppression could decrease heat production in mild hypothermia, although experimentally the core temperature continues to rise.

There are numerous oxygenation considerations in hypothermia (see Box 5-1). The “functional” value of hemoglobin at 28°C (82.4°F) is 4.2 g/10 g in patients on CPB. The oxyhemoglobin dissociation curve also shifts to the left (Figure 5-9). This impairs release of oxygen from hemoglobin into the tissues. Although some patients can self-adjust their respiratory minute volume (RMV) for current carbon dioxide production, this may not be possible if there are additional toxins or metabolic depressants.

Most humidifiers are manufactured in accordance with International Standards Organization (ISO) regulations. The humidifier will not exceed 41°C (105.8°F) close to the patient outlet with a 6-foot tubing length. If the decision is made to alter equipment, carefully monitor the temperature and do not exceed 45°C (113°F). The only report of thermal airway injury was in a patient ventilated via endotracheal tube for 11 hours with 80°C (176°F) inhalant.

Strategies to circumvent the 41°C ceiling include reduction of tubing length, adding additional heat sources, disabling the humidifier safety system, and placing the temperature probe outside the patient circuit. Label all modified equipment to avoid routine use. A volume ventilator with a heated cascade humidifier can also deliver CPAP or positive end-expiratory pressure (PEEP) if needed during rewarming. The airway rewarming rates clinically range from 1°C to 2.5°C (1.8°F to 4.5°F) per
In stable patients, circumventing the 41°C ceiling may not be worth the effort because the clinical benefit is modest. Heat and moisture exchangers function like artificial nares by trapping exhaled moisture and then returning it. They provide inadequate humidification to treat accidental hypothermia. With prolonged use, ETT occlusion and atelectasis are both problems.

Airway rewarming is indicated in the ED when core temperature is lower than 32.2°C (90°F) on arrival. Although airway rewarming provides less heat than do other forms of active core warming, it prevents normal respiratory heat and moisture loss and is safe, fairly noninvasive, and practical in all settings.

Heated Infusions

Cold fluid resuscitation of hypovolemic patients can induce hypothermia. In one series of previously normothermic patients with major abdominal vascular trauma, the average post-resuscitation temperature was 31.2°C (88.2°F) in those with refractory coagulopathies. IV fluids are heated to 40° to 42°C (104° to 107.6°F), although higher temperatures may be safe. The amount of heat provided by solutions becomes significant during massive volume resuscitations. One liter of fluid at 42°C (107.6°F) provides 14 kcal to a 70-kg patient at 28°C (82.4°F), elevating the core temperature almost 0.33°C (0.6°F).

Significant conductive heat loss occurs through IV tubing, so long lengths of IV tubing increase heat loss, especially at slow flow rates. IV tubing insulators are available. There are various methods to achieve and maintain ideal delivery temperature of IV and lavage fluids in hypothermia, but there is no standardized approach.

Blood preheated to 38°C (100.4°F) in a standard warmer is useful, but clotting and shortened RBC life are hazards with blood-warming packs. Local microwave overheating hemolyzes blood. An alternative is to dilute packed RBCs with warm calcium-free crystalloid. The Level 1 fluid warmer (Level 1 H-1200 Fast Flow Fluid Warmer with integrated air detector/clamp) warms cold crystalloid and blood via a heat exchanger at flow rates of up to 500 mL/min.

A more portable and compact option is the Ranger. Unlike the Level 1, however, this unit must remain above the level of the patient, and the infusion capability is much lower. The Thermal Angel is a portable, lightweight, battery-powered infusion warmer that has the advantage of portability to the initial point of rescue or trauma.

Microwave heating of IV fluids in flexible plastic bags is another option when more standardized heaters are unavailable. The plasticizer in the polyvinyl chloride containers is stable to microwave heating. Heating times should average 2 minutes at high power for a 1-L bag of crystalloid. The fluid should be thoroughly mixed before administration, to eliminate hot spots.

Rapid administration of fluid into the right atrium at a temperature significantly different from that of circulating blood may produce myocardial thermal gradients. In one study, heated IV fluid, up to 550 mL/min, was administered through the internal jugular vein without complication. In an experimental canine model with adequate cardiac output, central infusion of extremely hot (65°C [149°F]) IV fluids accelerates rewarming without hemolysis.

Using amino acid infusions may accelerate energy metabolism. Fever is common in patients receiving hyperalimentation. In patients recovering from elective surgery, however, amino acids have no significant thermogenic effect. The results might differ in energy-depleted patients with chronically induced accidental hypothermia.

In summary, intravenous solutions and blood should be routinely heated during hypothermia resuscitations. Various blood warmers are available commercially, but countercurrent in-line warmers are the most efficient techniques. A mathematic model indicates that infusion heating devices are essential in trauma patients with high fluid requirements.

Heated Irrigation

Gastrointestinal Irrigation

Heat transfer from irrigation fluids is usually limited by the available surface area, so do not use irrigation as the sole rewarming technique. The irrigant should not exceed 45°C (113°F). Direct gastrointestinal irrigation is less desirable than irrigation via intragastric or intracolonic balloons because of induced fluid and electrolyte fluxes. Exceeding 200- to 300-mL aliquots may force fluid into the duodenum; therefore frequent fluid removal via gravity drainage minimizes “lost” fluid. A log of input and output is essential. This facilitates estimation of fluid balance during resuscitation and helps determine if irrigation should be abandoned in anticipation of dilutional electrolyte disturbances.

To avoid these limitations, a double-lumen esophageal tube is available, as are other modified Sengstaken tubes. Patients should be tracheally intubated before gastric lavage. Because of the proximity of an irritable heart, overly vigorous placement
of a large gastric tube is ill advised. In a multicenter survey, gastric, bladder, and colon lavage rewarmed severely hypothermic patients at 1° to 1.5° C (1.8° to 2.7° F) for the first hour and 1.5° to 2° C (2.7° to 3.6° F) for the second hour. [59]

Commercially available kits designed for gastric decontamination are convenient (Figure 5-10). The use of a Y connector and clamp simplifies the exchanges. Ideal dwell times for thermal exchange depend on flow rates and may average several minutes. In direct gastric lavage, warmed electrolyte solutions, such as normal saline or Ringer's lactate, are administered via nasogastric tube. [213] After 15 minutes, the solution is aspirated and replaced with warm fluids. Disadvantages include the small surface area available for heat exchange and the large amount of fluid escaping into the duodenum. [36] Regurgitation is common, and the technique must be terminated during CPR. Esophageal and bladder heat exchange are also very limited. [201,285,359,360] Aesthetic obstacles aside, heat transfer through colonic irrigation is negligible.

FIGURE 5-10 Gastric lavage.

Mediastinal Irrigation

Mediastinal irrigation and direct myocardial lavage are alternatives in patients lacking spontaneous perfusion. A standard left thoracotomy is performed while CPR is continued. Opening the pericardium is unnecessary unless an effusion or tamponade is present. The physician bathes the heart for several minutes in 1 to 2 L of an isotonic electrolyte solution heated to 40° C (104° F), then suctions and replaces warm fluids. [34]

The physician may attempt internal defibrillation after myocardial temperature reaches 26° to 28° C (78.8° to 82.4° F). Unless a perfusing rhythm is achieved, lavage is continued until myocardial temperature exceeds 32° to 33° C (89.6° to 91.4° F). A standard post-thoracotomy tube in the left side of the chest could provide an avenue for continued rewarming via thoracic irrigation.

A median sternotomy also allows ventricular decompression and direct defibrillation. [212] One potential disadvantage of both these techniques is that open cardiac massage of a cold, rigid, and contracted heart may not generate flow. [5,53] Unless immediate CPB is an option, mediastinal irrigation and direct myocardial lavage are indicated only if cardiac arrest has occurred. In this circumstance, personnel skilled in the technique should also initiate all other available rewarming modalities.
Thoracic Lavage

Irrigation of the hemithoraces is a valuable rewarming adjunct. An important semantic issue is that closed thoracic lavage via two thoracostomy tubes differs from open mediastinal and direct myocardial lavage. With the latter, closed-chest CPR is not possible. Two large-bore thoracostomy tubes (36F to 40F in adults; 14F to 24F, ages 1 to 3; 20F to 32F, ages 4 to 7) are inserted in one or both of the hemithoraces. One is placed anteriorly in the second to third intercostal space at the midclavicular line, and the other in the posterior axillary line at the fourth to fifth intercostal space. Normal saline heated to 40° to 42°C (104° to 107.6°F) is then infused via a nonrecycled sterile system.

A high-flow countercurrent fluid infuser heats to 40°C (104°F) and delivers normal saline in 1-L or preferably 3-L bags into the afferent chest tube. This author prefers connecting into the tubing with standard 0.19-inch internal-diameter suction connection tubing and a sterilized plastic graduated two-way connector, because this facilitates adaptation to any size chest tube. The effluent is then collected in a thoracostomy drainage set. The reservoir must be emptied frequently. Alternatively, when a single chest tube is used, 200- to 300-mL aliquots are used for irrigation, and suctioning is achieved through a Y connector. The Y connector is also useful for irrigating both hemithoraces with a single fluid warmer.

Fluid can be infused into the anterior higher chest tube (afferent limb) and suctioned or gravity drained out the lower posterior tube (efferent limb) into a water-seal chest drain. Infusion inferoposteriorly with suction anteriorly can increase dwell times. The efficiency of thermal transfer varies with flow rates and dwell times. Once the patient is successfully rewarmed, the upper tube should be removed and the lower one left in place to allow residual drainage.

Closed sterile thoracic lavage is a natural choice in the ED during potentially salvageable cardiac arrest resuscitations. Thoracic lavage is an option either as a bridge to CPB or when CPB is initially unavailable. In patients who are perfusing, this technique should be considered hazardous unless extracorporeal rewarming capability is immediately available. Many hypothermic trauma patients are irrigated successfully during surgery.

The clinically reported infusion rates range from 180 to 550 mL/min. The overall rate of rewarming should easily equal or exceed that achievable with peritoneal lavage and is often 3° to 6°C (5.4° to 10.8°F) per hour. The surface area of the pleural space is well perfused. An added benefit is preferential mediastinal rewarming. In addition, closed-chest compressions during cardiac arrest can maintain perfusion. Open cardiac massage of a rigid, contracted heart may not be possible in severe cases before bypass, which is a problem with mediastinal irrigation. Various complications should be considered. Left-sided thoracostomy tube insertion into patients who are perfusing could easily induce VF. Patients with pleural adhesions or a history of pleurodesis have poor infusion rates, and subcutaneous edema may develop. If the fluids are infused under pressure without adequate drainage, intrathoracic hypertension or even a tension hydrothorax can develop and cause expected adverse effects.

cardiovascular effects. [174,274]

**Peritoneal Lavage**

Heated peritoneal lavage is a technique available in most facilities (Figure 5-12). Heat is conducted intraperitoneally via isotonic dialysate delivered at 40° to 45° C (104° to 113° F). [348]

![FIGURE 5-12 Peritoneal lavage. A, Mini-laparotomy for peritoneal lavage. B, The catheter in place with the needle removed and the wire introduced. C, An 8F catheter is introduced over the wire, and the wire is then removed.](image)

Before lavage is initiated, chest and abdominal radiographs should be obtained because subsequent films may reveal subdiaphragmatic air introduced during the procedure. The bladder and stomach must be emptied before insertion of the catheter. The two common techniques for introducing fluid into the peritoneal cavity are the mini-laparotomy and the percutaneous puncture.

The “minilap” requires an infraumbilical incision through the linea alba. A supraumbilical approach is necessary if previous surgical scars, a gravid uterus, or pelvic trauma is identified. The peritoneum is punctured under direct visualization and dialysis catheter(s) inserted. A much simpler and more rapid technique is the guidewire, or Seldinger, variation of the percutaneous puncture. The site is infiltrated if necessary with lidocaine, and a small stab incision is made. An 18- to 20-gauge...
needle penetrates the peritoneum, and a guidewire is introduced. Entry into the peritoneum is usually recognizable by a distinct “pop.” A disposable kit is available (Arrow Peritoneal Lavage Kit [AK-09000]). The 8F lavage catheter is inserted over the wire and advanced into one of the pelvic gutters. Double-catheter systems with outflow suction speed rewarming.

Normal saline, lactated Ringer's solution, or standard 1.5% dextrose dialysate solution with optional potassium supplementation can be used.\[82\] Isotonic dialysate is heated to 40° to 45°C (104° to 113° F). Up to 2 L is then infused (10 to 20 mL/kg), retained for 20 to 30 minutes, and aspirated. The usual clinical exchange rate is 6 L/hr, which yields rewarming rates of 1° to 3° C (1.8° to 5.4° F) per hour. An alternative for severe cases is a larger catheter, as found in cavity drainage kits (Arrow 14F [AK-01601]) (Figure 5-13). The catheter can be placed with the Seldinger technique. The higher drainage capability markedly increases exchange rates and minimizes the dwell times necessary for maximal thermal transfer. The flow rate via gravity through regular tubing is approximately 500 mL/min, which can be tripled under infusion pressure.

FIGURE 5-13  Peritoneal lavage. A 14F catheter is of a caliber that can infuse fluids rapidly.

A unique advantage of peritoneal dialysis is drug overdose and rhabdomyolysis detoxification when hemodialysis is unavailable. In addition, direct hepatic rewarming reactivates detoxification and conversion enzymes. Peritoneal dialysis worsens preexisting hypokalemia. Vigilant electrolyte monitoring is essential before empirical modification of the dialysate. The presence of adhesions from previous abdominal surgery increases the complication rate and minimizes heat exchange.

Peritoneal dialysis during standard mechanical CPR is as effective as partial cardiac bypass in resuscitating severely hypothermic dogs.\[364\] In contrast to AER, peritoneal lavage rewarming did not require significantly greater quantities of crystalloids and bicarbonate. This exchange rate is rarely possible in humans. Bowel infarction may be a concern when using prolonged warm peritoneal dialysis in patients with severe hypothermia with inadequate visceral perfusion during CPR.

Peritoneal lavage is invasive and should not be routinely used in treating stable, mildly hypothermic patients. This technique is indicated in combination with all available rewarming techniques in cardiac arrest patients.

**Endovascular Warming**

Another active rewarming option that is emerging is endovascular warming with commercially available temperature control devices. They are used in EDs for therapeutic cooling of resuscitated comatose cardiac arrest patients.\[367\]

Less invasive and technically easier than extracorporeal rewarming, endovascular systems that involve femoral vein catheterization may prove to be a promising alternative. The closed-loop catheter has a temperature control element at the tip. Available models have a fail-safe feature on the console that must be circumvented to allow rewarming if the core temperature is below 30° C (86° F).\[203\]

**Extracorporeal Blood Rewarming**
**Table 5-4** summarizes the techniques for extracorporeal blood rewarming.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiopulmonary bypass</td>
<td>Full circulatory support</td>
</tr>
<tr>
<td></td>
<td>Perfusate temperature gradient: consider 5°-10° C (9°-18° F)</td>
</tr>
<tr>
<td></td>
<td>Flow rates of 2-7 L/min (average, 3-5 L/min)</td>
</tr>
<tr>
<td></td>
<td>Rate of rewarming, up to 9.5° C (17.1° F) per hour</td>
</tr>
<tr>
<td></td>
<td>Consider if K &lt;10 mmol/L, pH &gt;6.5, at least 10°-12° C (50°-53.6° F)</td>
</tr>
<tr>
<td>Continuous arteriovenous warming</td>
<td>Percutaneous Seldinger technique to insert catheters</td>
</tr>
<tr>
<td></td>
<td>Requires blood pressure of ≥60 mm Hg</td>
</tr>
<tr>
<td></td>
<td>No need for perfusionist/pump/anticoagulation</td>
</tr>
<tr>
<td></td>
<td>Average flow rates of 225-375 mL/min</td>
</tr>
<tr>
<td></td>
<td>Rate of rewarming, 3°-4° C (5.4°-7.2° F) per hour</td>
</tr>
<tr>
<td></td>
<td>Consider for trauma</td>
</tr>
<tr>
<td>Venovenous rewarming</td>
<td>Circuit not complex</td>
</tr>
<tr>
<td></td>
<td>Efficient nonbypass modality</td>
</tr>
<tr>
<td></td>
<td>Volume infusion to augment cardiac output</td>
</tr>
<tr>
<td></td>
<td>Flow rates of 150-400 mL/min</td>
</tr>
<tr>
<td></td>
<td>Rate of rewarming, 2°-3° C (3.6°-5.4° F) per hour</td>
</tr>
<tr>
<td>Hemodialysis</td>
<td>Widely available</td>
</tr>
<tr>
<td></td>
<td>Portable and efficient</td>
</tr>
<tr>
<td></td>
<td>Single or dual catheter</td>
</tr>
<tr>
<td></td>
<td>Exchange cycle volumes, 200-500 mL/min</td>
</tr>
<tr>
<td></td>
<td>Rate of rewarming, 2°-3° C (3.6°-5.4° F) per hour</td>
</tr>
<tr>
<td></td>
<td>Consider if there are electrolyte/toxicologic derangements</td>
</tr>
</tbody>
</table>


**Hemodialysis**

Standard hemodialysis is widely available, practical, portable, and efficient, and should be strongly considered in perfusing patients with electrolyte abnormalities, renal failure, or intoxication with a dialyzable substance. Two-way flow catheters allow the option of cannulation of a single vessel. A Drake-Willock single-needle dialysis catheter can be used with a portable hemodialysis machine and an external warmer. After central venous cannulation, exchange cycle volumes of 200 to 250 mL/min are possible.

Although heat exchange is less than with standard two-vessel hemodialysis, the ease of percutaneous subclavian vein placement is a major advantage. Hemodialysis via two separate single-lumen catheters placed in the femoral vein can achieve continuous blood flow at 450 to 500 mL/min. In-line hemodialysis also simplifies correction of electrolyte abnormalities. Local vascular complications, including thrombosis of vessels and hemorrhage secondary to anticoagulation, may occur.
Continuous Venovenous Rewarming

In extracorporeal venovenous rewarming, blood is removed, usually from a central venous catheter, heated to 40°C (104°F), and returned via a second central or large peripheral venous catheter. Flow rates average 150 to 400 mL/min. The circuit is not complex and is more efficient than many other non-bypass modalities. There is no oxygenator, and because the method does not provide full circulatory support, volume infusion is the only option to augment inadequate cardiac output. Although the use of CAVR is limited by profound hypotension, high-flow venovenous rewarming may prove to be an alternative. In another variation of the extracorporeal venovenous circuit, blood is removed from the femoral vein, heparinized, and sent through a blood rewarmer via an infusion pump accelerator. It is neutralized with protamine before reinjection into the subclavian or internal jugular vein, which would preferentially rewarms the heart. Another option is to insert a femoral vein dual-lumen dialysis catheter.

Continuous Arteriovenous Rewarming

CAVR involves the use of percutaneously inserted femoral arterial and contralateral femoral venous catheters. This technique requires a blood pressure of at least 60 mm Hg. The Seldinger technique is used to insert 8.5F catheters. Heparin-bonded tubing circuits obviate the need for systemic anticoagulation. CAVR has principally been performed on traumatized patients. The blood pressure of spontaneously perfusing traumatized hypothermic patients creates a functional arteriovenous fistula by diverting part of the cardiac output out of the femoral artery through a countercurrent heat exchanger (e.g., Level 1; FloTem Ile). The heated blood is then returned with admixed heated crystalloids via the femoral vein. The additional fluids are titrated and infused by piggyback until hypotension is corrected.

The rate of rewarming exceeds that of hemodialysis. CAVR does not require the specialized equipment and perfusionist necessary for CPB. The average flow rates are 225 to 375 mL/min, resulting in a rate of rewarming of 3° to 4°C (5.4° to 7.2°F) per hour. Because the catheters are 8.5F, the patient must weigh at least 40 kg. Coagulation begins to appear in the heparinized circuits at around 3 hours.

Cardiopulmonary Bypass

Partial or complete CPB should be considered in unstable, severely hypothermic patients. Favorable
considerations include absence of severe head injury or asphyxia.\textsuperscript{[314]} Some centers initiate CPB only if the presenting arterial pH is above 6.5, serum potassium is below 10 mmol/L, and core temperature is above 10° to 12° C (50° to 54° F).\textsuperscript{[142,337,355]}

Fischer's considerations for CPB include a potassium level under 10 mmol/L in adults or under 12 mmol/L in children, coupled with a core temperature below 30° C (86° F). Patients are not resuscitated if extreme hyperkalemia is identified in a patient with a temperature over 30° C (86° F).\textsuperscript{[92]}

A major advantage of CPB is preservation of oxygenated flow if mechanical cardiac activity is lost during rewarming.\textsuperscript{[70,150,155,234]} CPB is three to four times faster at rewarming than other active core rewarming (ACR) techniques, and it reduces the high blood viscosity associated with severe cases. CPB should also be considered when severe cases do not respond to less invasive rewarming techniques, in patients with completely frozen extremities, and when extensive rhabdomyolysis is accompanied by major electrolyte disturbances.\textsuperscript{[169]}

Various extracorporeal rewarming techniques can be lifesaving in select profound cases of hypothermia.\textsuperscript{[127]} Althaus and colleagues describe complete recovery in three severely hypothermic tourists after prolonged periods of cardiac arrest and CPR.\textsuperscript{[5]} In another review of 17 cases, there were 13 survivors.\textsuperscript{[318]} Walpoth and co-workers\textsuperscript{[354,355]} report rewarming 32 patients with CPB, of which 15 are long-term survivors. The average age was 25.2 years. Their mean presenting esophageal temperature was 21.8° C (71.2° F), and the mean interval between discovery and CPB was 141 minutes.

The standard femoral–femoral circuit includes arterial and venous catheters, a mechanical pump, a membrane or bubble oxygenator, and a heat exchanger (Figure 5-15). A 16F- to 30F venous cannula is inserted via the femoral vein to the junction of the right atrium and the inferior vena cava. The tip of the shorter 16F to 20F arterial cannula is inserted 5 cm (2 inches) or proximal to the aortic bifurcation. Antretter and colleagues\textsuperscript{[8]} use 32F venous and 28F arterial cannulas with the open surgical technique, and 21F venous and 19F arterial cannulas if inserted percutaneously. Closed-chest compressions can be maintained during percutaneous or open surgical technique insertion and may help decompress the dilated nonbeating heart. Transesophageal echocardiography can help evaluate ventricular load and valve function.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5-15.png}
\caption{Femoral–femoral bypass.}
\end{figure}

Heated, oxygenated blood is returned via the femoral artery.\textsuperscript{[20]} Femoral flow rates of 2 to 3 L/min can elevate core temperature 1° to 2° C (1.8° to 3.6° F) every 3 to 5 minutes. In a review by Splittgerber and co-workers,\textsuperscript{[318]} the mean CPB temperature increase was 9.5° C (17.1° F) per hour. Most pumps can generate full flow rates up to 7 L/min. Long\textsuperscript{[222]} recommends considering the use of vasodilator therapy with IV nitroglycerin to facilitate perfusion. He initiates bypass flow rates at about 2 L/min and gradually increases to 4 to 5 L/min. Vasoactive agents may be needed to maintain the cardiac index.
at 30 L/min/m² or more and a (low) systemic vascular resistance of 1000 dynes/sec × cm⁻5 or less.\[228\]

The optimal temperature gradient and bypass rewarming rates are unknown. One study of rewarming via CPB in a swine model cooled to 23°C (73.4°F) addresses this concern. An excessive temperature gradient between brain tissue and circulant adversely affected electroencephalographic (EEG) regeneration. The other theoretical concern is the possibility of increased bubbling if high perfusate temperature gradients are used. Most investigators use 5°C (9°F) gradients\[23\] or 10°C (18°F) gradients.\[24\] Eventually, neuromonitoring during rewarming will provide some answers. In severe cases, evoked cerebral responses before EEG regeneration could help assess the recovering brain.\[304\]

A variety of techniques decrease the need for IV anticoagulation with heparin, which previously limited clinical applicability.\[184\] Heparin-coated perfusion equipment was used successfully without systemic heparinization in a patient with hypothermic cardiac arrest (23.3°C [73.9°F]) and intracranial trauma.\[351\] The use of nonthrombogenic pumps, coupled with enhanced physiologic fibrinolysis seen in the first hour of CPB, also succeeds experimentally.

Complications with the standard technique include vessel damage, air embolism, hemolysis, DIC, and pulmonary edema (Box 5-8). Endothelial leakage increases compartment pressures and exacerbates frostbite. If adequate flow rates of 3 to 4 L/min (50 to 60 mL/kg/min) cannot be maintained, thoracotomy or a venous catheter with side holes, augmenting intravascular volume, should be considered.

**BOX 5-8**

**Extracorporeal Rewarming**

**Complications**

- Vascular injury
- Air embolism
- Pulmonary edema
- Coagulopathies (hemolysis, disseminated intravascular coagulation)
- Frostbite tissue damage
- Extremity compartment syndromes

**Contraindications**

- Futile resuscitations
- Lack of venous return
- Intravascular clots or slush
- Complete heparinization would be hazardous* 
- Cardiopulmonary resuscitation is contraindicated (see Box 5-9)

* Unless with athrombogenic tubing or adequate physiologic fibrinolysis.

With all four of these techniques, there is no proof that rapid acceleration of the rate of rewarming improves survival rates in patients being perfused. The value of the maintenance of some degree of mild hypothermia after hypothermic cardiac arrest and extracorporeal rewarming is speculative. With accidental hypothermia, patients may have had neuroprotection before cardiac arrest from hypothermia. Potential complications of uncontrolled rapid rewarming in severe hypothermia include DIC, pulmonary edema, hemolysis, and acute tubular necrosis. As an alternative, a conservative core-rewarming approach can be highly effective for patients with severe hypothermia, despite hemodynamic instability.\[291\]

In hypothermic cardiac arrest, rewarming should be attempted via CPB and hemodialysis when CPR is not contraindicated (Box 5-9), unless frozen intravascular contents prevent flow. Clotted atrial blood or failure to obtain venous return indicates that these techniques will be futile. If experienced personnel and necessary equipment are unavailable, all other rewarming
techniques should be used in combination. [23,350,370]

BOX 5-9

**Contraindications to Initiating Cardiopulmonary Resuscitation in Accidental Hypothermia**

- Do-not-resuscitate status is documented and verified.
- Obviously lethal injuries are present.
- Chest wall depression is impossible.
- Any sign of life is present.
- Rescuers are endangered by evacuation delays or altered triage conditions.


**Diathermy**

Diathermy, the transmission of heat by conversion of energy, is a potential rewarming adjunct in accidental hypothermia. [140,220] Large amounts of heat can be delivered to deep tissues with ultrasonic (0.8 to 1 MHz) and low-frequency (915 to 2450 MHz) microwave radiation. Short-wave (13.56 to 40.68 MHz) modalities are high frequency and do not penetrate deeply. Contraindications include frostbite, burns, significant edema, and all types of metallic implants and pacemakers.

Under ideal conditions in a laboratory study, radio-wave frequency (13.56 MHz) electromagnetic regional heating of hypothermic dogs after immersion does not damage tissue at 4 to 6 watts/kg and rapidly elevates core temperature. [365] Zhong and colleagues [381] successfully rewarmed 16 piglets with microwave irradiation “until they squealed and suckled.” Subsequently, 20 of 28 human infants rewarmed with microwave irradiation at 90 to 100 watts survived. The temperature rose an average 1°C (1.8°F) after 6 to 7 minutes, and the average infant required 45 minutes to achieve a rectal temperature of 36°C (96.8°F). In an experimental study of men cooled to 35°C (95°F), warm water immersion rewarming is more rapid than radio-wave rewarming with 2.5 watts/kg. [178]

Both ultrasonic and low-frequency microwave diathermy can deliver large quantities of heat below the skin. As dosimetry guidelines develop, potential complications and ideal application sites for this experimental technique deserve further study in the hospital. In the field setting, potential problems with power supply and electronic and navigational interference compound the physiologic problems.

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