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# Evaluation of a New Fluid Warmer Effective at Low to Moderate Flow Rates

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**Background:** The tendency of intravenous fluid exiting the heat exchanger of a fluid warmer to cool to room temperature increases as the rate of infusion slows and the length of tubing between the heat exchanger and the patient increases. Thus, slow to moderate flow rates result in the delivery of fluid near room temperature despite the use of a fluid warmer. The volumes infused even at low flow rates may be large relative to the size of infants and children and may result in a significant decrease in patient temperature.

**Methods:** A new warmer (Hotline<sup>®</sup>, Level 1 Technologies) that actively heats the fluid in the delivery tubing was evaluated and compared to two different conventional dry-wall warmers: the model DW1000A (Baxter Health Care) and the FloTem<sup>®</sup>IIE (DataChem). Cold blood (4–10° C) and room temperature saline (22° C) were pumped through the warmers and the delivered temperature was measured as the flow rate was varied from 50 to 12,000 ml/h.

**Results:** The Hotline<sup>®</sup> was more effective than the Baxter or the FloTem<sup>®</sup>IIE at flow rates between 50 and 6,000 ml/h for saline and at flow rates between 50 and 3,000 ml/h for blood. Insulating the tubing beyond the heat exchangers of the conventional warmers improved their performance, but the delivered temperatures were still less than those of the Hotline<sup>®</sup> at low flow rates.

**Conclusions:** The Hotline<sup>®</sup> is more effective than conventional warmers at slow flow rates, and may be useful for preventing hypothermia when large volumes of fluid relative to patient size are infused at slow rates. (Key words: Equipment: fluid warmer. Hypothermia, pediatric.)

THE tendency for intravenous fluids exiting the heat exchanger of a fluid warmer to cool to room temperature increases as the rate of infusion slows and the length of the tubing between the heat exchanger and the patient increases.<sup>1</sup> This is the result of heat transfer between the fluid and the environment across the wall of the tubing. Faries *et al.* found that fluid exiting the heat exchanger of a typical warmer with a temperature of 37.3° C at a flow rate of 100 ml/h cooled to 24.4° C

after traveling through 105 cm of tubing (a typical distance between the heat-exchanging portion of a fluid warmer and its connection to a patient).<sup>1</sup> Thus, slow to moderate flow rates result in the delivery of fluid near room temperature despite the use of a fluid warmer. As this fluid enters the patient, heat is transferred from the patient into the fluid and patient temperature is decreased. Although the volumes delivered at these flow rates may have little impact on the temperature of adult patients, even low flow rates may represent a relatively large delivered volume to small pediatric patients. Therefore, a warmer capable of delivering normothermic fluid at low to moderate flow rates would be potentially useful for prevention of hypothermia in small patients. We evaluated a new warmer (Hotline<sup>®</sup>, LEVEL 1<sup>®</sup> Technologies, Marshfield, MA) that actively heats the fluid in the delivery tubing and is thus potentially capable of providing normothermic fluid at low flow rates. The performance of this warmer was compared to two conventional dry-wall warmers, the model DW1000A (Baxter Healthcare, American Pharmascol Div., Valencia, CA) and the FloTem<sup>®</sup>IIE (DataChem<sup>®</sup>, Indianapolis, IN).

## Materials and Methods

### Warmer Design and Setup

The warmers were configured to meet typical clinical requirements: the tubing between the patient and the pole-mounted part of the warmers was long enough to permit adequate patient access (at least 100 cm) and could be connected to a standard female Luer hub. Each warmer was equipped with a blood recipient set containing an 80- $\mu$ m filter (Fenwal 4C7744, Baxter Healthcare, Deerfield, IL) and a disposable set supplied by the manufacturer. Although the performance of the warmers was decreased by any unheated tubing distal to the heat exchangers of the warmers, additional tubing was added, if necessary, to meet the requirements stated above. When this was necessary, tubing with the shortest possible length and smallest possible priming volume was added using commercially available com-

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ponents. The total length and volume of tubing distal to the heat exchangers is listed in table 1.

### *Baxter DW1000A*

This warmer is a dry-wall warmer with a 360-watt heater. Fluid is warmed as it flows through a thin plastic cuff that wraps around an electrically heated metal cylinder. This warmer was tested with an unmodified disposable set, because it met the requirements stated above.

### *FloTem® IIE*

This warmer is a dry-wall warmer with a 300-watt heater. The electrically heated block of this warmer contains a channel that accepts standard-bore intravenous tubing. Fluid is warmed as it flows through the tubing within this channel. We used a tubing set manufactured for use with this warmer, but, because only 40 cm of the disposable set extended beyond the warmer, an additional piece of tubing was added (ET-30T extension, Burrn Medical, Bethlehem, PA, 76-cm length, 0.96-ml priming volume).

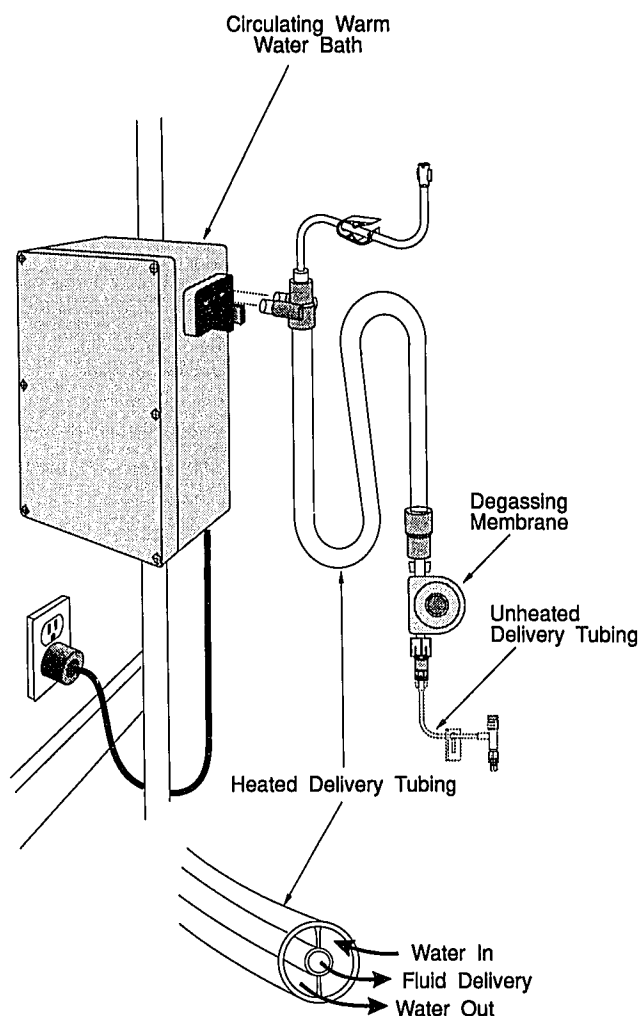
### *Hotline®*

Unlike the conventional warmers, the heat exchanger of the Hotline® is incorporated into the delivery tubing (fig. 1). This tubing contains a central fluid delivery channel surrounded by two outer channels through which warm water circulates. This tubing connects to a pole-mounted unit containing a 300-watt heater, a water bath warmed to 40° C, and a pump to circulate the water. This design provided more than adequate length (285 cm) but resulted in a disposable set that did not bend easily and, thus, could not be easily connected to an intravenous catheter in a clinical situation. Therefore, the Hotline® was tested with a small piece of extension tubing (ET-04TS extension, Burrn Medical, 10-cm length, 0.13-ml priming volume) added to the end of the degassing membrane located at the end of the disposable set. The degassing membrane is a hydrophobic Teflon-coated membrane that is permeable to gas but not liquid. Its intended purpose is to vent

**Table 1. Unheated Delivery Tubing**

Type of Warmer	Length (cm)	Volume (ml)
Baxter DW1000A	185	20
FloTem® IIE	116	3.8
Hotline®*	18	1.4

\* The numbers for the Hotline® include the degassing membrane.



**Fig. 1.** Diagram of the Hotline® warmer, including a cross section of the delivery tubing that is the heat exchanger of this warmer. Outer channels for circulation of warm water surround an inner fluid-delivery channel. Only a small piece of unheated tubing is needed to connect the warmer to a patient.

microbubbles that potentially could form in fluid when it is warmed; however, we did not evaluate the function of this device.

### *Data Acquisition*

Each warmer was studied in duplicate with both 0.9% saline and whole canine blood diluted to a hematocrit of 30% with 0.9% saline. These solutions were pumped (Masterflex 7522-10 roller pump, Cole Parmer Instrument, Chicago, IL) through a countercurrent heat exchanger (HE100, Bentley, Chicago, IL) into the warmers, then allowed to drain into a reservoir. The heat exchanger permitted us to recycle the infusate and still

maintain a nearly constant input temperature. Saline was infused at 22° C, approximately room temperature. Because of heat exchange across the tubing connecting the Bentley heat exchanger to the blood administration set, the temperature of the blood as it entered the blood administration set ranged from 3° C at the fastest flow rate to 10° C at the slowest flow rate. The flow rate through the warmers was varied from 50 ml/h to as high as 12,000 ml/h. Roller pump calibration was determined gravimetrically and was accurate  $\pm 1\%$  over the range of flows studied. Temperature was measured by thermocouples (Mon-a-therm skin temperature probes denuded of their foam covering, Mallinckrodt Medical, St. Louis, MO). These thermocouples were inserted into the fluid path at the start of the blood administration set, at the point where blood entered the heat exchanger of the warmer, at the point where blood exited the heat exchanger of the warmer, and at the end of the fluid path. Entry points were sealed with epoxy cement to prevent leaks. Thermocouple readings were checked against a mercury thermometer and were accurate to within 0.2° C at temperatures between 0 and 40° C. The Hotline® bath temperature and the FloTem® and Baxter plate temperatures were read from displays located on the warmers. Room temperature was measured by the same digital meter to which the thermocouples were connected (Mon-a-therm 6500, Mallinckrodt Medical). At each flow rate, temperatures were measured every 3 min until the readings were constant or until they were oscillating around a constant value. For each warmer, the highest flow rate studied was that at which both the infusion pressure exceeded 300 mmHg and the delivered temperature fell below 32° C.

As an alternative to the Hotline® design, we also studied the effect of insulating the tubing distal to the heat exchangers of the conventional warmers. This tubing was sandwiched between two strips of adhesive-backed foam rubber that were 1 inch wide and ½ inch thick (Reston®, 3M Medical-Surgical Div., St. Paul, MN). Thus, the delivery tubing was encased in a layer of foam rubber that was  $\geq ½$  inch in thickness. These warmers were then restudied with room temperature saline as described above.

The temperature readings we obtained allowed us to compare the warmers to each other over the range of flow rates studied, but did not directly quantitate the overall effectiveness of the warmers or allow comparison with studies where different flow rates were used. We quantitated the effectiveness of these warmers by

calculation of the apparent thermal clearance. The flow rate through a device at which the delivered temperature has reached 63% of the difference between the temperature of the infusate and the limiting temperature of the device ( $V_{TC}$ ; see Appendix) (e.g., for the heat exchangers of the warmers, this is the temperature of the water bath or heated block; for the unheated delivery tubing, this is room temperature).<sup>2</sup> The  $V_{TC}$  for a particular device varies with the solution tested. The higher the thermal clearance of the heat exchanger of a warmer, the higher the flow rate through the exchanger before output temperature falls below an acceptable level, and the more effective the warmer. On the other hand, a high  $V_{TC}$  for the tubing distal to the heat exchanger results in rapid cooling of the fluid. Thus, a high  $V_{TC}$  is desirable for the heat exchanger of the warmer, and a low  $V_{TC}$  is desirable for the tubing distal to the heat exchanger.

The delivered temperatures were tested for differences among warmers and flow rates with repeated-measures ANOVA.<sup>3,4</sup> Whenever there were differences among warmers, Fisher's least significant difference test was used to determine the flow rates at which they were different.<sup>4,5</sup> The  $V_{TC}$ s were tested for differences among warmers with one-way ANOVA followed by Tukey's HSD procedure.<sup>3,4</sup> For all comparisons,  $P < 0.05$  was considered significant. All values are expressed as means of the two trials for each warmer.

## Results

When the infusate was cold blood, the fluid temperature delivered by the Hotline® was higher than the Baxter at flow rates from 50 to 3,000 ml/h, but fell below the Baxter at a flow rate of 6,000 ml/h ( $P < 0.05$ , fig. 2). The fluid temperature delivered by the Hotline® was higher than that from the FloTem® at all flow rates studied ( $P < 0.05$ ). The fluid temperature delivered by the FloTem® was higher than that delivered by the Baxter from 250 to 2,000 ml/h, but fell below that from the Baxter when the flow rate was 3,000 ml/h or greater ( $P < 0.05$ ).

When the infusate was saline, the Hotline® delivered a higher temperature fluid than the Baxter at flow rates from 50 to 6,000 ml/h and was higher than the FloTem® at all flow rates studied ( $P < 0.05$ ), fig. 3). The FloTem® delivered a higher temperature than the Baxter from 250 to 2,000 ml/h, but fell below the Baxter when the flow rate was 3,000 ml/h or greater ( $P < 0.05$ ).

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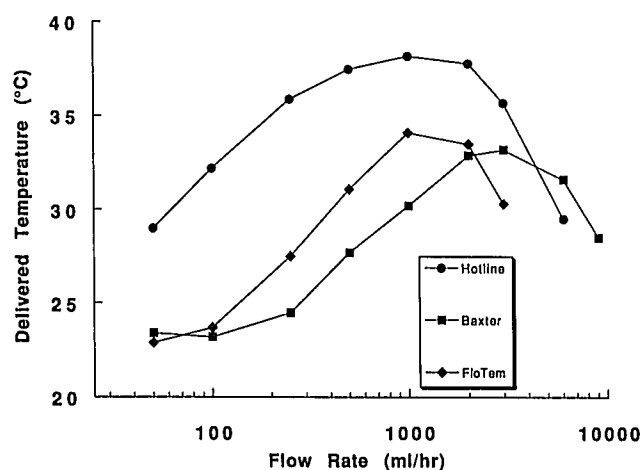


Fig. 2. The delivered temperatures of the three warmers for cold blood. Values are means of two trials for each warmer.

When the tubing distal to the heat exchangers of the conventional warmers was insulated, the delivered temperature of saline was higher than without insulation, but the Hotline<sup>®</sup> still delivered a higher fluid temperature than the Baxter below a flow rate of 6,000 ml/h and was higher than the FloTem<sup>®</sup> at all flow rates studied ( $P < 0.05$ , fig. 3). While the delivered fluid temperature of the Hotline<sup>®</sup> was  $>32^{\circ}\text{C}$  at a flow rate of 100 ml/h, the FloTem<sup>®</sup> with insulated tubing did not exceed  $32^{\circ}\text{C}$  until the flow rate was approximately 300 ml/h, and the Baxter with insulated tubing did not exceed this temperature until the flow rate was approximately 730 ml/h.

The  $V_{TC}$  for saline of the Baxter heat exchanger was greater than that of the Hotline<sup>®</sup>, which was, in turn,

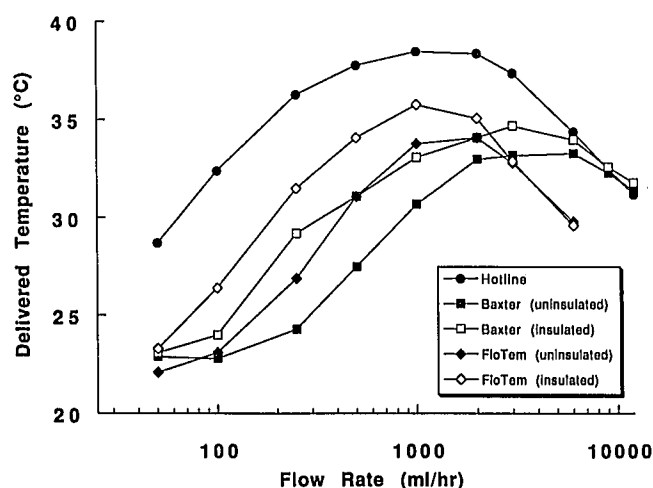


Fig. 3. The delivered temperatures of the three warmers for  $22^{\circ}\text{C}$  saline. Values are means of two trials for each warmer.

greater than that of the FloTem<sup>®</sup> ( $P < 0.05$ , table 2). When the infusate was blood, the order was the same, but the differences were not statistically significant. For blood or saline, the  $V_{TC}$  of the tubing beyond the Hotline<sup>®</sup> heat exchanger was the lowest, followed by the FloTem<sup>®</sup>, and then the Baxter ( $P < 0.05$ ). Insulation decreased the  $V_{TC}$  of the tubing beyond the heat exchangers of both conventional warmers by about 60%, but not lower than the tubing distal to the Hotline<sup>®</sup> heat exchanger ( $P < 0.05$ ).

## Discussion

At low enough flow rates, all currently available warmers are capable of heating fluids to  $37^{\circ}\text{C}$  as the infusate leaves the heat-exchanging portion of the warmer. However, the infusate temperature decreases as heat exchange with the environment occurs across the tubing leading from the warmer to the patient. Although this tubing is a poor heat exchanger compared to that of the warmer (table 2), slow flow rates allow the necessary time for the fluid in this tubing to approach equilibrium with the ambient temperature. One possible solution is to minimize the length and priming volume of tubing between the warmer and the patient. Faries *et al.* found that, at flow rates between 30 and

Table 2. Apparent Thermal Clearance of Devices Studied

Device	Fluid	$V_{TC}$ (ml/min)
Warmer heat exchangers		
Hotline <sup>®</sup>	Saline	135
	Blood	105
Baxter	Saline	215
	Blood	123
FloTem <sup>®</sup>	Saline	78
	Blood	73
Tubing distal to the warmer heat exchangers		
Hotline <sup>®</sup>	Saline	0.8
	Blood	1.0
Baxter	Without insulation	
	Saline	9.5
	Blood	9.3
Saline	3.9	
FloTem <sup>®</sup>	Without insulation	
	Saline	4.6
	Blood	4.6
Saline	1.9	

Values were determined by nonlinear regression of temperature versus flow (see Appendix) and are the means of two trials for each warmer.

$V_{TC}$  = apparent thermal clearance.

In all cases, the  $r^2$  was  $>0.95$ .

250 ml/h, it was necessary to shorten this tubing to 25 cm or less to deliver fluid at 32° C or above.<sup>1</sup> However, shortening the delivery tubing to this extent may not always be practical or even possible. In the case of the Baxter, this would require cutting the tubing of the disposable set and then attaching a male Luer adapter to the end of the modified disposable set. In the case of the FloTem,<sup>®</sup> the warmer could be positioned 40 cm (16 inches) from the patient using an unmodified disposable set. Because this would require positioning the warmer under the drapes with the patient, an extra length of tubing was added. However, the volume of this tubing (0.96 ml) was only 25% of the total volume of unheated tubing beyond the warmer (table 1) and, thus, accounted for only 25% of the time fluid spent in unheated tubing. If we approximate the  $V_{TC}$  of the unheated tubing of the unmodified FloTem<sup>®</sup> disposable set as being 75% of the  $V_{TC}$  for the configuration tested,<sup>2</sup> it can be calculated (equation 2, Appendix) that the additional piece of tubing lowered the delivered temperature by 1.6° C at a flow rate of 250 ml/h. The amount that the delivered temperature was lowered by this tubing would be less at higher and lower flow rates.

Instead of shortening the unheated delivery tubing, we insulated this tubing to decrease heat loss. We found that the effectiveness of this solution was limited. While insulation decreased the  $V_{TC}$  of the tubing by approximately 60% (table 2), it did not increase the delivered fluid temperature to acceptable levels at the lowest flow rates (fig. 3). Insulating the tubing was also time consuming and limited access to the tubing for drug injection. The Hotline<sup>®</sup> overcame these problems by incorporating the heat exchanger into the delivery tubing (fig. 1). While the heat exchanger of the Hotline<sup>®</sup> has a lower  $V_{TC}$  than some conventional warmers<sup>6,7</sup> (including the Baxter, table 2) and, thus, does not perform as well as these warmers at high flow rates, its design minimizes the length of unheated delivery tubing, thereby avoiding heat loss at low flow rates. The performance of the Hotline<sup>®</sup> was not flawless, however, because there was some heat loss from the degassing membrane and the small piece of tubing required to connect the disposable set to an intravenous catheter (fig. 1), causing the delivered temperature to fall below 32° C at flow rates below approximately 100 ml/h.

The effectiveness of any new device must be considered relative to its cost and clinical impact. Although the Hotline<sup>®</sup> is an effective warmer at slow flow rates, it is also costs more to own and operate than the conventional warmers tested (table 3). This increased cost

Table 3. Cost of Warming Fluid

Type of Warmer	Unit	Disposable
Baxter DW1000A	\$995	\$10.00
FloTem <sup>®</sup> IIE	\$1,075	\$2.50
Hotline <sup>®</sup>	\$1,500	\$15.00

Values are approximate prices of warmers studied and their disposable sets (March 1992).

must be balanced against the likelihood of clinically important hypothermia when a conventional fluid warmer is used. Hypothermia may result from a variety of causes other than the infusion of cold solutions, such as evaporative losses from the surgical site and respiratory tract, and convective and conductive losses to the environment. Because it is often difficult to isolate the effect of a single cause in a clinical situation, there is a lack of studies demonstrating the clinical impact of the infusion of cold solutions at slow flow rates. The possible clinical significance, however, can be approximated by a simple calculation:<sup>8</sup>

$$\frac{c_n m_n}{c_{pt} m_{pt}} = \frac{T_{end} - T_{start}}{T_n - T_{end}}$$

where  $c_n$  is the specific heat of the infused fluid ( $\approx 1$  cal/gm° C),  $m_n$  is the mass of fluid infused,  $c_{pt}$  is the specific heat of the patient ( $\approx 0.83$  cal/gm° C),<sup>9</sup>  $m_{pt}$  is the mass of the patient,  $T_{start}$  is the patient's temperature before the infusion,  $T_{end}$  is the patient's temperature after the infusion, and  $T_n$  is the temperature of the fluid infused. For example, consider a patient weighing 3 kg who receives 300 ml of fluid (100 ml/kg) during a laparotomy. If the fluid is infused at 100 ml/h over 3 h, the temperature of the fluid delivered to the patient is approximately 23° C when either the Baxter or the FloTem<sup>®</sup> is used. Equation 4 predicts that the patient's temperature will fall from 37° C to 35.5° C in the absence of heat production and other sources of heat transfer. This degree of cooling represents a thermal debt of approximately 1,200 cal/kg that must eventually be repaid at the cost of increased O<sub>2</sub> consumption. By comparison, the fluid temperature delivered by the Hotline<sup>®</sup> at this flow rate would be 32.4° C and the resulting patient temperature would be 36.5° C. If, instead of an infant, a 70-kg patient receives 300 ml of fluid at 23° C, the patient's temperature would only fall 0.1° C. To experience the same degree of cooling as the infant, this patient must receive 7,000 ml of fluid at 23° C. This volume of fluid, however, is likely to be infused rapidly enough to avoid significant

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cooling in the tubing between a conventional warmer and the patient. Thus, the Hotline® probably has less advantage over conventional warmers when used on larger patients.

Our calculations of temperature changes after infusion of cold solutions are based on several assumptions. Our assumption that heat production will not occur until the patient's temperature has fallen significantly is based on the observation that general anesthesia lowers the thermoregulatory threshold. For infants and children, the threshold is decreased to approximately 35.7 °C by halothane with or without caudal bupivacaine,<sup>10</sup> and is between 34.4 and 35.3 °C with isoflurane.<sup>11</sup> Thus, a significant degree of cooling may occur before heat conservation and production mechanisms are activated. We also assume that the specific heat of infants and children is approximated by the specific heat of adults. Although exact numbers for pediatric patients, or, for that matter, adult patients, have not been determined, it is possible that this value is higher in infants because of their higher total body water and lower total body fat contents. This introduces a small error, however, because a patient specific heat of 1 cal/gm° C would result in a final patient temperature only 0.2° C higher than that calculated using a patient specific heat of 0.83 cal/gm° C. Finally, we assumed that the entire mass of the patient equilibrates with the fluid, because the fluid was infused over a period of hours. To the extent that we have overestimated the mass of the patient participating in heat exchange, the fall in patient core temperature has been underestimated. Alternatively, mean body temperature, which is more important than core temperature in determining thermoregulatory responses, is much less affected by incomplete equilibration of all body compartments.<sup>12</sup>

Our calculation of thermal clearance was based on the assumption that heterogeneity of flow was preserved at different flow rates. Although we could not test this assumption directly, the coefficient of determination,  $r^2$ , from the regression of temperature against flow for each of the warmers was always  $\geq 0.95$ , indicating a very good fit between the data and the model (Appendix, equation 3).

In summary, the Hotline® was more effective than conventional warmers at slow flow rates, and this may be important when a relatively large volume is infused at a slow rate. It is important to remember that the effectiveness of this warmer is dependent on using tubing that is short and has a small priming volume to

connect the warmer to a patient. Likewise, when a conventional warmer is used, the tubing between the heat exchanger of the warmer and the patient should have a small priming volume, be as short as possible, and, perhaps, be insulated. In addition, when using a conventional warmer, consideration should be given to administration of fluid in boluses infused rapidly to minimize cooling in the delivery tubing, yet not so rapidly that the capacity of the heat exchanger of the warmer is exceeded.

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## Appendix

The  $V_{TC}$  for a simple heat-exchanging device is given by the following equation:

$$V_{TC} = -Q \ln \left\{ \frac{T_b - T_d}{T_b - T_i} \right\},$$

where  $Q$  is the flow rate through the device,  $T_b$  is the temperature of the water bath or warming plate of the heat exchanger of a warmer or room temperature for unheated delivery tubing,  $T_i$  is the initial temperature of the infusate entering the device, and  $T_d$  is the delivered temperature of the infusate as it leaves the device. Each configuration tested was actually three heat-exchanging components in series: the blood administration set (and any other tubing proximal to the heat exchanger of the warmer) that transfers heat from the room to the infusate when the infusate is cold, the heat exchanger of the warmer that transfers heat to the fluid, and the tubing beyond the heat exchanger of the warmer that transfers heat from the infusate to the room. Thus, the  $T_d$  of the blood administration set was the  $T_i$  for the heat exchanger of the warmer, and the  $T_d$  of the heat exchanger was the  $T_i$  of the tubing distal to the heat exchanger. For these three components in series, equation 2 becomes:

$$T_d = T_r + (T_b - T_r)e^{-A/Q} + (T_r - T_b)e^{-(A+B)/Q} + (T_i - T_r)e^{-(A+B+C)/Q}$$

where  $T_r$  is room temperature,  $A$  is the  $V_{TC}$  of the tubing between the heat exchanger of the warmer and the patient,  $B$  is the  $V_{TC}$  of the heat exchanger of the warmer, and  $C$  is the  $V_{TC}$  of the tubing proximal to the heat exchanger of the warmer. Although temperature measurements were available that could potentially permit calculation of  $V_{TC}$  for each individual component using equation 2, the readings

just proximal and distal to the heat exchangers of the warmers were affected by conduction of heat along the fluid path that became increasingly significant relative to bulk flow of fluid at the slowest flow rates. Therefore, approximate  $V_{TC}$ s were determined for each component and infusate by nonlinear regression (SYSTAT software, SYSTAT) of temperature and flow rate using equation 2. These  $V_{TC}$ s were then used as starting values for nonlinear regression using equation 3, which was dependent only on the temperature of fluid as it entered the blood administration set, the temperature of the warmer heat exchanger, and room temperature.

Because room temperature varied by as much as 1.1° C over the course of a study and by as much as 2.5° C between studies performed on different days, and because the delivered temperature we measured was a function of room temperature (equation 3), the measured  $T_d$  was corrected according to the following equation, which follows from equation 3:

$$T_{d,corr} = T_d - (T_r - T_{r,avg})(1 - e^{-A/Q} + e^{-(A+B)/Q} - e^{-(A+B+C)/Q}),$$

where  $T_{d,corr}$  is the delivered temperature corrected for changes in room temperature and  $T_{r,avg}$  is the average room temperature over the course of the studies being compared. Equation 4 resulted in a difference between  $T_d$  and  $T_{d,corr}$  that was close to, but did not exceed, the difference between  $T_r$  and  $T_{r,avg}$  (~0.6° C) at low flow rates and became smaller as flow increased.