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A Comparative Study of Blood Warmer Performance

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Massive transfusions of refrigerator-temperature blood may induce hypothermia and life-threatening arrhythmias; for this reason a variety of devices have been developed for rapid blood warming. Blood warmers available in the United States use one of three warming technologies: dry heat, water bath, or countercurrent heat exchange. In the current study we evaluated blood warmers representative of each technology for speed and extent of heat transfer: the Fenwal blood warmer (Fenwal Laboratories; dry heat), the DW-1000 (American Pharmaseal Co.; dry heat), the FloTem IIe (DataChem Inc.; dry heat), the Hemokinetitherm (Dupaco Inc.; water bath), and the H250 and H500 (Level 1 Technologies; countercurrent heat exchange). Only one countercurrent heat instrument (the H500) was able to heat blood ≥ 33° C at target flow rates ≥ 250 ml/min. Dry heat and water bath blood warmers were unable to warm blood ≥ 33° C at target flow rates ≥ 100 ml/min. High resistance to flow with the proprietary tubing required for one instrument (the Hemokinetitherm) prevented tests of blood warming at rates > 150 ml/min. We found that instruments that used countercurrent technology warmed blood and saline more effectively than did blood warmers that used either dry heat or water bath technology. Our study also demonstrated the need for close control and standardization of experimental conditions in the evaluation of blood warming devices. (Key words: Blood: transfusion. Complications. Equipment: blood warmers. Temperature: hypothermia.)

HYPOTHERMIA can result in serious complications for the patient, including metabolic derangements, abnormal hemostasis, and ventricular arrhythmias.[1–4] Because packed cells and whole blood are stored at 1–6° C until just before use, hypothermia can be a concomitant of rapid and massive transfusion.[4–7] In such situations, blood must be warmed if transfusion-induced hypothermia is to be prevented.

Because blood can be damaged by excessive heat, a variety of instruments have been developed to provide controlled and even heating of blood and other fluids. In the United States, all currently available blood warmers use one of three technologies for warming blood: dry heat, in which the blood is passed within disposable tubing through heating blocks; water baths, in which the tubing is submerged in warm water; and, most recently, countercurrent heat exchange, in which blood in a jacket passes outside a tube of heated water moving in the opposite direction. Instruments that use microwave (electromagnetic) heat are not sold in the United States; these units are unpopular because hemolysis due to hot spots within the heating units is difficult to prevent.[8,9]

Studies of individual instruments suggest that heat transfer, at the high infusion rates often required to resuscitate the trauma victim (≥250 ml/min), may be suboptimal. For example, at flow rates as low as 80 ml/min, one group reported that a dry-heat style warmer was unable to heat blood to greater than 30° C.[10] Another group showed that a water bath heater was unable to heat blood to greater than 30° C at flow rates greater than 100 ml/min.[11] In addition, small internal diameters of tubing associated with individual blood warming devices may prevent the rapid flow rates needed in resuscitation efforts.[12]

No study has systematically compared blood warmers representing all three technologies. The following study was therefore undertaken to evaluate devices representative of each technology with regard to their ability to heat blood at different flow rates. We also tested saline to determine whether this fluid could be substituted for blood in the evaluation of blood warmers.

Materials and Methods

Six different blood warmers were chosen for these tests and were operated in accordance with manufacturers' recommendations.

Three of these instruments use dry heat technology (table 1). The Fenwal Blood Warmer (model 4R4305, Fenwal Laboratories, Deerfield, Il) is composed of two rectangular leaves that house the heating elements (fig. 1). The temperature in the elements is maintained at 37–38° C. A disposable plastic bag, sandwiched between the two leaves, contains channels through which blood flows against gravity. The DW-1000 (American Pharmaseal Co, Valencia, CA) is a cylindrical device housing three heating units that maintain temperatures at 36.4–37.5° C. Blood flows through a disposable plastic bag that is wrapped around the heating cylinder. The FloTem IIe (DataChem

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TABLE 1. Blood Warmers Evaluated

Technology	Instrument	Manufacturer
Dry heat	Fenwal	Fenwal Laboratories
	DW-1000	American Pharmaseal
	FloTem IIe	Data Chem, Inc.
Water bath	Hemokinetitherm	Dupaco
Countercurrent	H250	Level 1 Technologies
	H500	Level 1 Technologies

Inc., Indianapolis, IN) consists of two rectangular leaves containing the heating elements, which maintain a temperature of 37° C. The device is designed to accommodate intravenous tubing, which is sandwiched in grooves between the two leaves. Pathways of various lengths can be used to insert tubing, with longer pathways recommended for higher flow rates; for our experiments, the longest pathway was chosen.

One instrument uses water bath technology. The Hemokinetitherm (model 32300, Dupaco Inc., San Marcos, CA) warms a water reservoir to 39° C; disposable coiled tubing is immersed in the bath.

Two instruments, the H250 and H500 (Level 1 Technologies, Rockland, MA), use countercurrent heat exchange. In these instruments, a heater warms water to 40° C and circulates it *via* a pump. The H500 differs

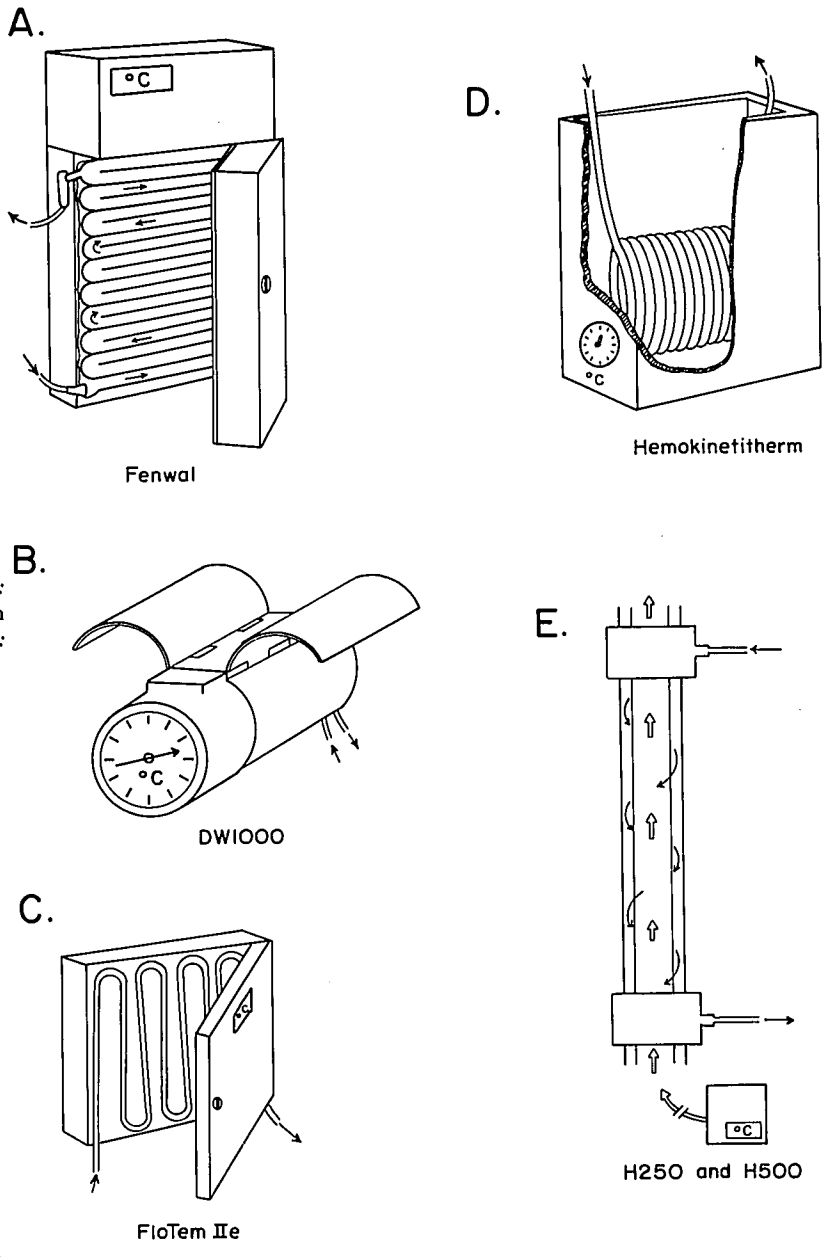

FIG. 1. The blood warmers tested in this study. *A:* Fenwal (dry heat). *B:* DW-1000 (dry heat). *C:* FloTem IIe (dry heat). *D:* Hemokinetitherm (water bath). *E:* H250 and H500 (countercurrent).

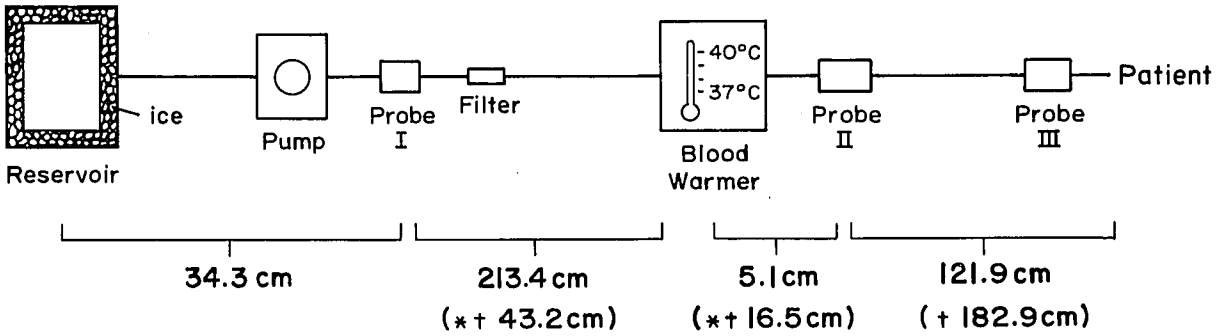

FIG. 2. Test system. Blood or saline was kept cold in a reservoir of ice, and the infusion temperature before the blood warmer was measured with an in-line thermistor (probe I). A pump controlled the rate of flow through the warmer. Temperatures were also monitored at the exit from the blood warmer (probe II) and at the end of the tubing intended for connection to a patient (probe III). The internal diameter of all tubing was 0.30–0.33 cm. Tubing lengths are shown under the figure; tubing lengths for the H250 (*) and H500 (†), where different, are shown in parentheses.

from the H250 in having a larger heater (1000 *vs.* 600 W) and pump capacity (9.8 *vs.* 5.3 l/min). The heat of the water is transferred to the blood *via* a countercurrent system accomplished by a tube-in-tube disposable heat exchange apparatus in which heated water is conveyed through a central conduit and the blood through a surrounding jacket.

To measure heat transfer, we designed the test system shown in figure 2. Bags containing either refrigerated saline or blood were connected *via* plastic tubing to a rotary pump (for flow rates up to 250 ml/min: Victor Pyrate Works, Essex, England; for flow rates of 500 ml/min: Cardiovascular Instrument Corporation, Wakefield, MA). For the Fenwal, DW-1000, FloTem IIe, and Hemokinetitherm, Y-type blood solution sets with an in-line 170-μm filter (Baxter, Deerfield, IL) connected the post-pump tubing to the proprietary disposable sets included with each blood warmer; intravenous tubing (Baxter) also was used for post–blood warmer connections. For the H250 and H500, proprietary disposable sets included input and patient-line tubing already connected to the disposable heat exchanger.

Fluid temperatures were measured using integrated circuit transducers (National Semiconductor, Santa Clara, CA) with a response time of < 15 s, placed at three different points in the test system (fig. 2). The preheat exchanger probe (probe I) was inserted within the tubing immediately beyond the rotary pump. The post–heat exchanger probe (probe II) was situated in the tubing directly beyond the blood warmer (between 5.1 and 16.5 cm from each blood warmer's outlet, depending on the configuration of each blood warmer's disposable tubing). Probe III was inserted at the end of the tubing, at the point where an intravenous needle would be attached. The temperature probes were calibrated to within 0.1° C of a National Bureau of Standards thermometer. Temperature data were collected every 10 s with an eight-channel analog-to-digital converter (CIO-AD08, Computer Boards, Inc., Mansfield, MA) using data acquisition software (LABLOG2, Quinn Curtis Inc., Needham, MA). At each flow rate, fluid was allowed to flow through the blood warmer until the post–heat exchanger (probe II) temperature had stabilized, after which 3 min of temperature readings (18 readings) were averaged.

Blood for the study came from ABO-identical outdated packed red cell components, collected in the anticoagulant-preservative solution AS-1 (Adsol; Fenwal Laboratories), and pooled into 3-l aliquots. Each aliquot was used only once. Saline and blood were refrigerated (1–6° C) until just before use. Eight target flow rates between 10 and 500 ml/min were chosen for study: 10, 25, 50, 75, 100, 150, 250, and 500 ml/min. Precise rotary pump flow rates were determined in each experiment by measuring the weight of fluid collected (model WB-6001-989061, Sartorius Instruments, McGaw Park, IN) over time, corrected in the case of blood for a specific gravity of 1.053 g/ml.§

Results

Heat Transfer to Saline

Five of the six blood warmers were tested up to the maximum target flow rate of 500 ml/min (measured flow rates ranged from 450–489 ml/min). However, the Hemokinetitherm (water bath technology) could only be studied up to a target flow rate of 250 ml/min (measured rate of 201 ml/min); at higher flow rates, leakage at tubing connection sites occurred because increased resistance to flow developed in the blood warmer tubing.

§ American Association of Blood Banks: Technical Manual. 10th edition. Edited by Walker RH. Arlington, VA, 1990, p 9.

Temperature data for the six blood warmers are shown in figure 3. Disparities in fluid warming were apparent at flow rates ≥ 50 ml/min. For example, at 50 ml/min, the FloTem IIe (dry heat technology) was able to heat saline only to 29° C at probe III. At 150 ml/min, only two of the six instruments (H250 and H500) were able to heat saline above 33° C. At the maximum target flow rate of 500 ml/min, the only instrument that heated saline above 33° C at probe III was the H500 (36.1° C). The next most effective warmer was the H250 (26.2° C), followed by the Fenwal (20.1° C), DW-1000 (16.9° C), and FloTem IIe (9.6° C). At 201 ml/min, the Hemokinetitherm was able to heat saline to 20.6° C.

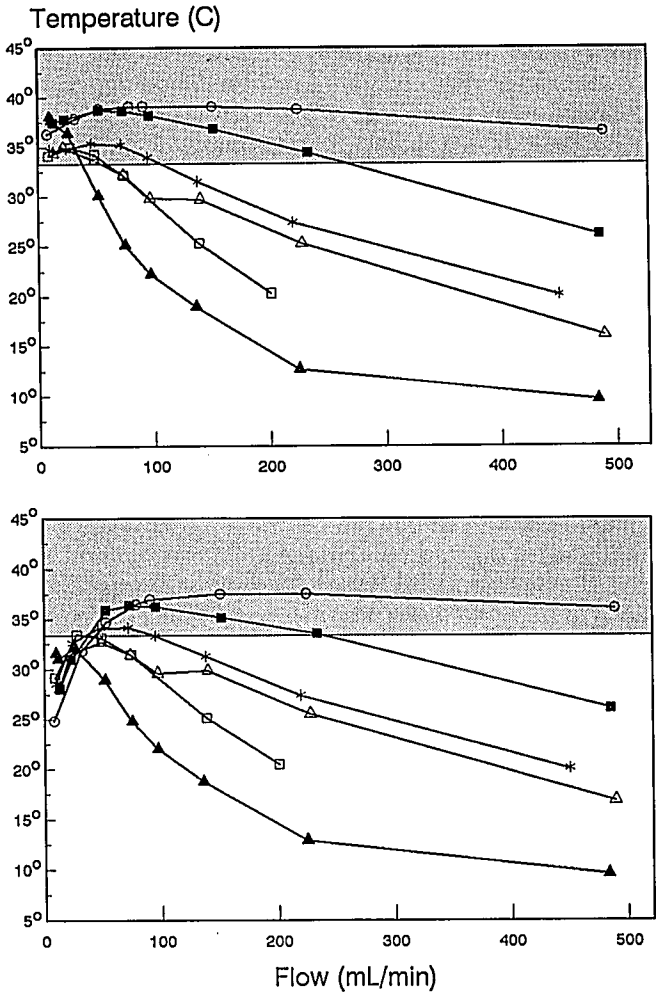

FIG. 3. Temperature of saline in relation to flow rate. The shaded area represents temperatures ≥ 33° C. *Top:* Probe II measured temperatures immediately after the blood warmer. *Bottom:* Probe III measured temperatures at the patient connection site. Asterisks = Fenwal; open triangles = DW-1000; filled triangles = FloTem IIe; open squares = Hemokinetitherm; filled squares = H250; circles = H500.

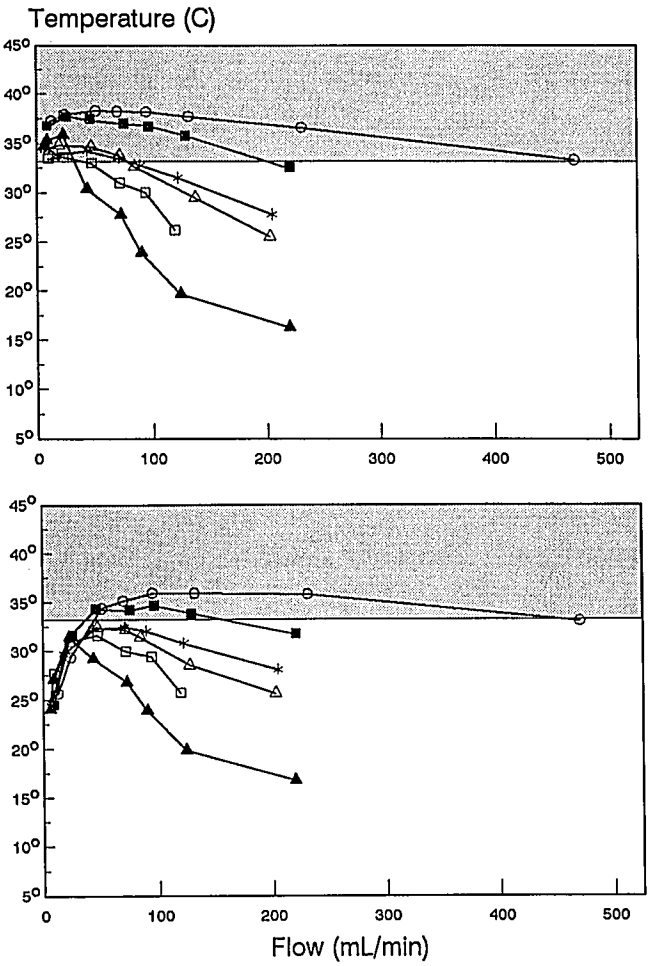

FIG. 4. Temperature of blood in relation to flow rate. The shaded area represents temperatures ≥ 33° C. *Top:* Probe II measured temperatures immediately after the blood warmer. *Bottom:* Probe III measured temperatures at the patient connection site. Asterisks = Fenwal; open triangles = DW-1000; filled triangles = FloTem IIe; open squares = Hemokinetitherm; filled squares = H250; circles = H500.

HEAT TRANSFER TO BLOOD

Temperature data are shown in figure 4. The Hemokinetitherm was tested only up to a targeted flow rate of 150 ml/min (measured rate 127 ml/min), because of increased resistance to flow at higher speeds. At this maximum flow rate, this instrument warmed blood to 25.8° C. All other instruments were tested up to a flow rate of 250 ml/min. At 250 ml/min, the instruments were ranked according to their heating ability at probe III as follows: H500, 35.8° C; H250, 31.8° C; Fenwal, 28.1° C; DW-1000, 25.7° C; and FloTem IIe, 16.8° C. The only instrument to heat blood above 33° C at 250 ml/min, the H500, was also tested at 500 ml/min, at which rate it warmed blood to 33.1° C.

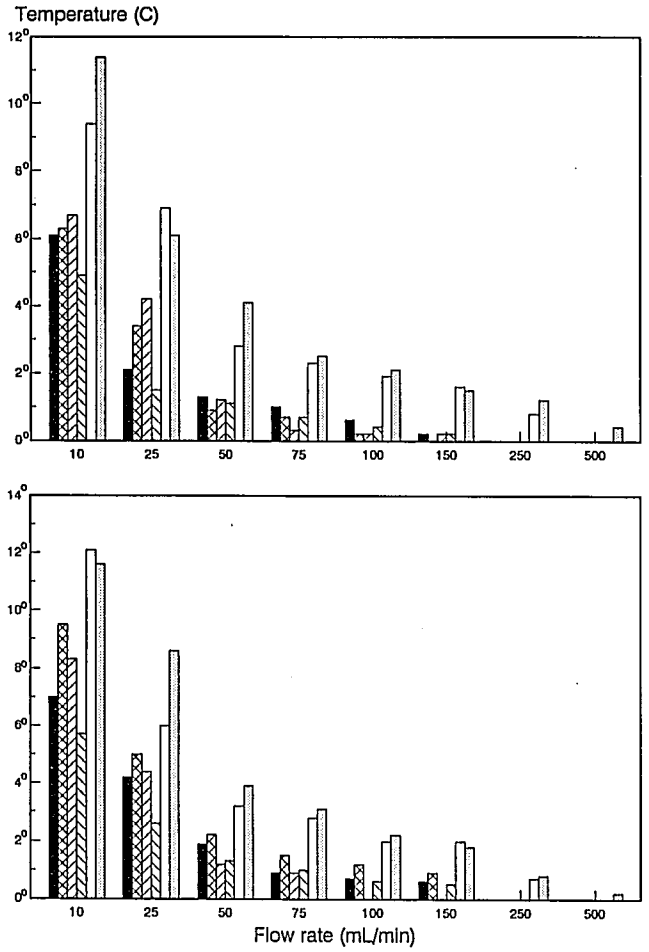

FIG. 5. Temperature difference between probe II and probe III at various flow rates. *Top:* Saline. *Bottom:* Blood. Solid bars = Fenwal; cross-hatched bars = DW-1000; hatched bars (left) = FloTem IIe; hatched bars (right) = Hemokinetitherm; open bars = H250; shaded bars = H500.

At low flow rates (<75 ml/min; fig. 3, top), all instruments except the FloTem IIe were able to warm saline to ≥ 33° C at probe II (just beyond the blood warmer); all instruments were able to warm blood to ≥ 33° C (fig. 4, top) at flow rates of <50 ml/min). However, the temperatures at probe I (just ahead of the blood warmer) were often already greater than 6° C because of partial equilibration of the temperature of the saline with room air during its slow passage through the tubing. Furthermore, at these flow rates, temperatures decreased at probe III because of heat loss in the tubing between probes II and III. For example, with the Fenwal at a target flow rate of 10 ml/min, a 6.1° C temperature decrease was noted with saline and a 7.0° C difference with blood (fig. 5).

Comparisons of temperatures of saline and blood at probe II for various flow rates are shown in figure 6. Four machines (Fenwal, Hemokinetitherm, H-250, and H500) warmed saline to higher temperatures than blood at most flow rates. The largest difference, 2.2° C, was noted at 250 ml/min with the H-500, which warmed saline to 38.8° C but blood to only 36.6° C. On the other hand, blood was warmed to slightly higher temperatures with the DW-1000 and FloTem IIe at most flow rates.

Discussion

At low flow rates (<50 ml/min), the performance of the six blood warmers in this study were nearly equivalent, in that all instruments were able to heat saline and blood to ≥33° C; however, heating was much more variable at higher flow rates. Blood warmers that used countercurrent heat exchange technology (H250 and H500) were the only instruments able to warm blood to ≥33° C at flow rates ≥ 100 ml/min; and only the larger of the two instruments (H500) was able to heat blood above this temperature at a flow rate of 500 ml/min. On the other hand, the FloTem IIe, a dry heat warmer, was unable to warm blood above 17° C at 250 ml/min, even though we followed the manufacturer's instructions for use of the longest pathway through the heater for maximum heat transfer. The Hemokinetitherm, which used water bath technology, also fared poorly in terms of heating: at a target flow rate of 150 ml/min, the temperature of blood at probe II was only 26.2° C, and high resistance precluded the testing of blood at flow rates greater than 150 ml/min. The other two dry heat warmers (DW-1000 and Fenwal) were equivalent in performance; at targeted flow rates of 250 ml/min, blood was warmed by the DW-1000 to 25.7° C and by the Fenwal to 28.1° C.

Our study demonstrated the need for close control and standardization of experimental conditions in the evaluation of blood warmers. For example, four instruments warmed saline to higher temperatures than blood at most flow rates. Studies that report the temperature of saline rather than blood may overestimate the heating efficacy of the warmer in transfusion situations and should therefore be interpreted with caution.[12,13] The temperature of the infusate should be sufficiently cold (1–6° C) to duplicate clinical conditions, in which blood components very recently removed from a refrigerator are used. In other studies in which the temperature of blood used for the tests was as high as 10–15° C, the resulting efflux temperatures may have been higher than those obtained with refrigerated components.[14] Although all blood warmer instruments provided good heating at slow rates (<100 ml/min), measurements of the efficacy of blood warmers at these rates are affected by partial equilibration of the testing fluid with ambient air, both before and after the heater.[15] Conclusions about the efficiency of heat transfer

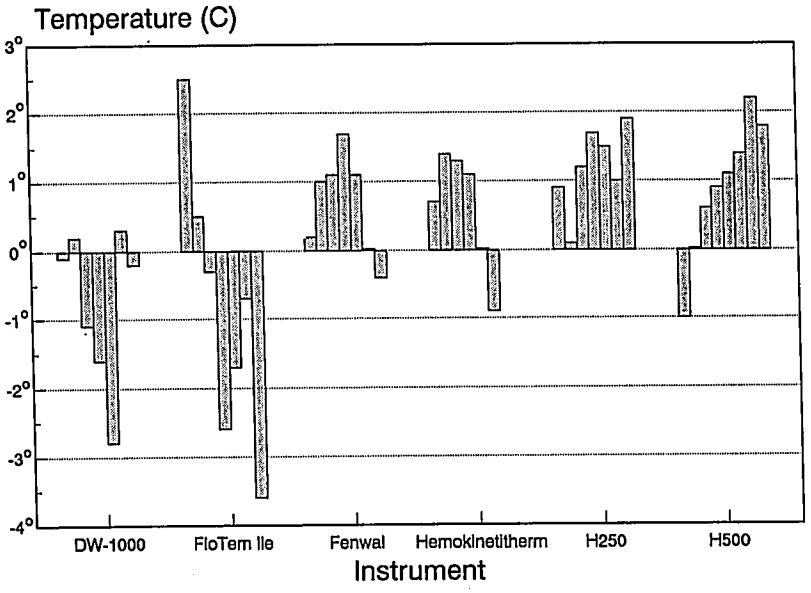

FIG. 6. Temperature difference between saline and blood at probe II at various flow rates for each instrument. Flow rates (*left to right*): 10, 25, 50, 75, 100, 150, 250, and (H500 only) 500 ml/min.

at such rates are therefore of questionable value. Furthermore, these flow rates are of no value in clinical situations requiring massive transfusion.

The better performance of the countercurrent blood warmers may have been due in part to their use of a water bath temperature of 40° C, which was 1–4° C warmer than the heat sources for other instruments in this study. The American Association of Blood Banks has raised concerns about potential red cell damage occurring with the use of blood warmers that exceed 38° C.¶ In our experiments, blood leaving the countercurrent warmers never exceeded a temperature of 38.3° C at probe II. Even if heat transfer had been fully efficient and the blood had reached a temperature of 40° C, no evidence exists that this level of heat is detrimental. Heat injury to normal red cells, as measured by *in vitro* parameters, occurs only when the temperature exceeds 47–49° C.[16–21] For example, abnormal osmotic fragility curves and increased plasma hemoglobin occurred in one report in which 3-week-old blood bank specimens were incubated at 48° C for 1 h.[17] Similar results were obtained by Ham *et al.*, who demonstrated increased osmotic fragility of human red cells incubated at temperatures greater than 47° C, as well as progressive morphologic changes (budding or dividing cells and formation of spherocytes) when the temperature was ≥48.6° C.[18] Membrane elasticity is decreased only when red cells are heated to 48° C.[20,21] Furthermore, *in vivo* red cell survival studies with chromium-labeled warmed red cells (using an older version of the H500 blood warmer) showed no difference in turnover as compared with unheated control cells.[22] In that study, there were also no significant differences between control and heated red cells with respect to plasma hemoglobin, potassium, or lactate dehydrogenase. Thus, 40° C heat appears to cause no problems to red cells and may be important to the effectiveness of the countercurrent blood warmer models that we tested.

The transfusion of large volumes of refrigerated blood components has caused irreversible ventricular fibrillation and other cardiac arrhythmias; such complications have been reported when the core body temperature decreased to 32° C or less.[4,7] For this reason, several authors recommend the use of warmed blood and other fluids to maintain the core body temperature significantly above this level.[8,23] Our studies demonstrate that, at the current time, only one commercially available blood warmer (the Level 1 H500) is able to transfer sufficient heat to refrigerated blood to exceed such temperatures when rapid transfusions, with flow rates > 250 ml/min, are needed.

¶ American Association of Blood Banks: Standards for blood banks and transfusion services. 14th edition. Arlington, VA, 1991, p 39.

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