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# A REVIEW OF BLOOD WARMERS FOR MASSIVE TRANSFUSION

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## BLOOD WARMING IN CURRENT CLINICAL PRACTICE

### THE CASE FOR WARMING BLOOD

" With an animal as large as man, the rate of cooling made possible by using an external cooling circuit of blood is so much greater than the maximum rate obtained by cooling the surface of the body that immersion in a cold bath is almost certainly a superfluous complication " (Lovelock and Smith 1959). This commendation of the production of hypothermia by intravenous cooling was referring to those occasions when lowering the body temperature is required for surgery or as an adjunct to therapy. Unfortunately, cooling *via* the blood stream is equally effective when it is not intentional, and hypothermia can be caused easily by rapid infusion of cold blood.

Hypothermia has two effects which may jeopardize the patient's survival. It increases the risk of ventricular fibrillation, particularly below 28° C, and it impairs the ability of the body to withstand blood loss. Although Hegnauer (1959) considered 27° C to be a near estimate for a median lethal temperature ($LT_{50}$), the lowest temperature tolerable clinically is that just above the point where *any* fatalities occur. The highest fatal low temperature in healthy subjects would seem to be about 29° C, as Hegnauer reports two cases in water dying at 29·2° C and 28·7° C and two cases of exposure dying at 28·4° C.

In sickness, the danger level appears to be higher. Boyan and Howland (1961) describe a fatal case where cardiac upset began at an oesophageal temperature of 33° C. Dybkjaer and Elkjaer (1964) report severe arrhythmias developing in one patient at a rectal temperature of 34·8° C. Generally, supraventricular arrhythmias are common below 33° C (Golden 1973). During deliberate hypothermia Ozinsky (1963) observed spontaneous fibrillation in over 100 patients. The first cases fibrillated spontaneously at 35° C; by 33° C, 5 per cent of his subjects, all of whom had cardiac defects, had gone into ventricular fibrillation. Thus an ideal minimum temperature would be 35° C.

A 2° C loss is not uncommon during prolonged surgery, so that the body core is now 35° C and there is no spare heat to buffer a cooler blood infusion. Blood must be infused at 35° C to avoid any cooling effect. Certainly the temperature should remain above 33° C as 5 per cent of diseased hearts will fibrillate by this temperature, and also a deep body temperature of 33° C is considered to be the beginning of a progressive loss of physiological control (Hervey 1973).

The danger to a patient when hypothermia and blood loss are present together was well illustrated by Ferguson *et al.* (1958). In control experiments in dogs they showed that a 35 per cent loss of blood volume had an 80 per cent mortality (eight in 10 at 25° C), and they concluded that during surgery with hypothermia blood volume deficits are to be avoided.

If the body temperature is 35° C after some time in the theatre and the patient is in such a severe shock from sudden blood loss that he has a cardiac output of only 0·5 l/min, an infusion of 150 ml/min of blood at 32° C will give a cardiac temperature of not less than 34° C. This should be a safe temperature for most patients and is a minimum estimate, as such severe conditions should be rare in clinical practice today. Thus 32° C can be considered a crude estimate of the minimum acceptable output temperature for a blood warmer.

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Progressive cold infusion to replace a continuing loss can cause a low body temperature. There is a gradual fall with only small internal gradients. The decline in temperature is accentuated by anaesthesia, which prevents reflex responses such as shivering. The rate of cooling is increased if the patient is in a cool environment, if the patient's skin is wet, or if a large area of moist organs such as the bowel is exposed.

Even a patient who is not generally hypothermic to any severe degree may have a cardiac arrest from a rapid infusion of cold blood. Blood given intravenously reaches the heart very quickly, and thus blood which is at 4° C from the blood bank may not have warmed very much when it reaches the right ventricle. The biochemical abnormalities which are present in stored blood will not affect the heart until the blood enters the coronary circulation after it has passed through the lungs and the left ventricle. However, cold affects the heart when the transfused blood is in the right ventricle; the right ventricular muscle is cooled and conduction within the heart is disorganized (Hoffman 1959).

The heart can be cooled below 28° C while the rest of the body is still warm. Temperature gradients of 4° C and more have been recorded frequently with rapid cooling. Severinghaus (1959) shows a 5° C gradient developing between the oesophagus at atrial level and the rectum at 68 minutes. Bigelow (1959) found that even if blood is at room temperature it can still cause a fall in the oesophageal temperature when it is infused rapidly. Many authors have described this selective cooling of the heart by rapid transfusion. LeVeen *et al.* (1960), in mentioning two cases of cardiac arrest, noted that the cold so refrigerated the heart that there was a sensation of touching a cold metallic object when grasping the heart for massage. MacLean *et al.* (1961), in discussing defibrillation, noted that ventricular fibrillation occurred accidentally when large quantities of cold blood caused an unplanned hypothermia. Boyan and Howland (1961) observed a marked drop in the oesophageal temperature of patients receiving massive infusions of cold blood. In one of their cases ventricular ectopics developed at 31° C, and at 27·5° C cardiac arrest occurred. Other similar cases of cooling have been reported. In 1963 Boyan and Howland compared the incidence of cardiac arrest during blood replacement using warmed and unwarmed blood. Both at moderate (50–100 ml/min) and rapid (>100 ml/min) flows there were very significantly fewer cardiac arrests ($P<0{\cdot}01$) when blood was warmed.

Although many small transfusions are still done without warming, today blood is routinely warmed if an infusion which is large compared with the patient's blood volume is anticipated. This will mean warming a single unit of blood if the transfusion is for a newborn baby. The fundamental aim is to prevent the myocardial temperature from falling.

## The Specification for a Blood Warming Apparatus

Blood warmers must warm blood effectively, safely and conveniently. The warmer should not damage the blood even when used less carefully than prescribed by the manufacturer. It must be easy to use, must warm rapidly, and preferably be unobtrusive if used within the theatre area. Finally, it should be cheap to purchase and cheap to maintain.

To be effective, the apparatus must be able to provide the patient with blood at a temperature above 32° C at flows up to 150 ml/min. At this flow one unit of blood will be given in about three minutes; this is usually the fastest rate at which an infusion can be sustained. Preferably, the warmer should not reduce the rate of infusion and so should have minimal resistance. The ideal infusion would be capable of a free flow of 100 ml/min with blood; such a rapid rate without pumping would leave the anaesthetist's hands free for other tasks.

Generally, the warm blood will dilate the patient's veins, and this reduction in resistance helps to offset the loss of flow when the warmer is added into the line of the infusion apparatus. This dilatation of the patient's veins is much more important than the reduction in blood viscosity which occurs as the temperature rises. If the warm blood dilates the patient's veins to twice their former size, the resistance of the veins is reduced to only one-sixteenth of its former value. Warming blood from 4° C to 37° C reduces blood viscosity about two and a half times (Burton 1965). Thus, although improved flow can be observed *in vitro* when blood is warmed, the major part of the improved flow *in vivo* is usually the result of venodilatation. The amount of venodilatation varies from patient to patient, so an *in vitro* test is preferred for comparison between blood warmers. An approximate value for blood flow can be found if a warmer is tested with iced water and the flow rate divided by three (see Appendix 1). The resistance of the average 14 gauge cannula normally limits blood flow to about 50 ml/min

with a 150 cm head of pressure (i.e. blood level 150 cm above the cannula). In practice, any warmer which achieves a free flow of better than 200 ml/min with iced water is unlikely to impede seriously the flow of a blood transfusion. An alternative test for flow is to set up a drip apparatus with the blood warmer in the line and to use a bottle of dextran 70 in dextrose which has been stored in the blood refrigerator as the test fluid. Flows with this are more comparable to flows with blood (see Appendix 2).

The safety of blood warmers for the staff and the patient must be considered. Staff safety is achieved by ensuring that all electrical apparatus is adequately earthed and that any electrically live part of the apparatus cannot be touched or contaminated by blood or water; for example, it should not be possible to place a hand into a radio-frequency warmer while it is switched on, nor to pour water into the motor of a water-bath stirrer, or into the bath electronics (Shaw and Monk 1973).

Patients must also be protected from electrical hazard. Standard earthing alone may not be adequate, as only very small currents can be fatal when conducted along a central venous catheter (Monks 1971). Overheating of the infused blood may endanger the patient by haemolysis or by excessive temperature. The warmers should not allow the operating temperature to exceed 41° C (106·8° F), although this may be excessively cautious (Chalmers and Russell 1973). They should have at least one safety device which, when the set temperature is reached, prevents further heating and gives a clear indication of malfunction.

It is preferable that apparatus used in the theatre should not spark and should be safe when used in the presence of potentially inflammable anaesthetic agents such as cyclopropane and ether. One method is to enclose in an isolated gas-tight compartment all devices, such as bimetallic thermostats or microswitches, which might spark. However, a potentially hazardous situation can occur if the seal of the compartment is faulty. An alternative method is to design a circuit which uses electronic switches. This can be accomplished by the use of " triac " semi-conductor devices. However, unless the design is such that zero point switching is used electro-magnetic interference may upset other apparatus connected to the mains supply (see Appendix 3). Controls which require electro-magnetic switches, such as a water level safety cut-out, can be designed as magnetically switched reed relays if they are for modest current. The reed relay is a set of contacts sealed into a glass tube. When the relay opens, any sparking is isolated and cannot ignite an explosive anaesthetic mixture.

Cost is an important consideration for any hospital, but the initial cost is not the only consideration. The cost of maintenance can be very significant, particularly for equipment which must be cleaned and sterilized repeatedly. The cost of disposable items such as coils may also be a large part of the overall expense. Probably the best way of estimating the relative cost is to calculate the sum of the initial purchase price, two years' maintenance cost, and the price of the disposable items expected to be used in that time. Costing has not been done in this review as it will vary from hospital to hospital. Two variables which will affect cost are distance of the hospital from the supplier, and the discount for quantity.

## METHODS OF WARMING

The methods of warming blood have become more sophisticated since the 1960's, when Bennike and Hagelsten (1964) wrote of tubing in a bucket of water. The continued enthusiasm for blood warming in the last ten years attests that the importance of this aspect of management of massive transfusion is now clearly recognized. Two types of warmer are used: those which warm blood before infusion, and those which warm during infusion.

Today only the bucket of hot water and the radio-frequency warmer remain as examples of warming before infusion. Most warmers which are for use during infusion are disposable units in a heated container. However, there are some non-disposable metal warmers which are extremely efficient. These are used in certain special situations such as cardio-pulmonary bypass.

### *Warming before Infusion*

A bucket of hot water is the simplest and cheapest method of warming blood, but unless the water is dangerously hot it will take at least 20 minutes to warm a bottle of blood.

Radio-frequency blood warming works by a high frequency electro-magnetic oscillation which induces electrical eddy currents in the blood. The energy of the currents is converted to heat; the blood is warmed to above 32° C in about four minutes; the warming occurs throughout the blood. The original work on this was reported by Besseling, Bull, Du Plessis and Mason (1965) and a machine is now available commercially (Figure 1). However, the machine is bulky and separate machines are required

for bottles and for plastic packs. Only the machine for plastic packs is in current production. The volume of the blood inserted in the machine is important; if the volume is less than about 250 ml, proper contact may not be made with the temperature sensing probe in the plate in the door of the machine; overheating and haemolysis can then occur (McCullough *et al.* 1972). Once warmed, blood units should be used immediately or discarded. Because the machine works by electro-magnetic radiation, at 27 Mega-Hertz, any sensitive electrical apparatus such as an ECG or EEG machine may be temporarily upset if it is in close proximity. The machine warms blood without using disposable equipment, so that running costs should be low.

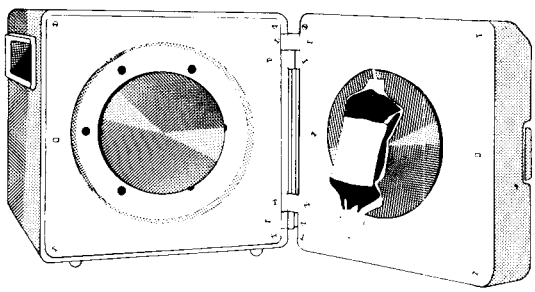

FIGURE 1.—Taurus radio-frequency blood warmer—Model 300. The dimensions are 41 × 40 × 51 cm. This model is designed for 450 ml blood packs. The full pack is hung on the door, which is then closed. The blood is sandwiched between the two plates, which position it in the centre of the high-frequency electromagnetic field, and rotate 180° during warming. The temperature sensing probe is in the plate on the right, and it would seem sensible to avoid thick paper labels on the side of the blood bag, which is against the plate.

A machine, Ohio model 987, operating by a similar principle, is made by Ohio Medical Products in the United States of America. Failure of mixing in this machine, which warms to about 32° C in one minute, has caused severe haemolysis (Staples and Griner 1971).

*Warming During Infusion*

All warmers which are plugged into the infusion line and warm while the blood is being infused depend on the blood coming into contact with a warm surface. Heat is supplied by an electrical element which usually heats a water bath. The water then heats one side of a plastic or metal wall, the other side of which is in contact with the blood. Thus the heat must pass across the wall into the blood; see Russell (1969*b*) for a more detailed discussion. It is this transfer of heat which is often a limiting factor in the performance of the blood warmer.

When blood has been warmed, some heat is lost through the output line as the blood flows

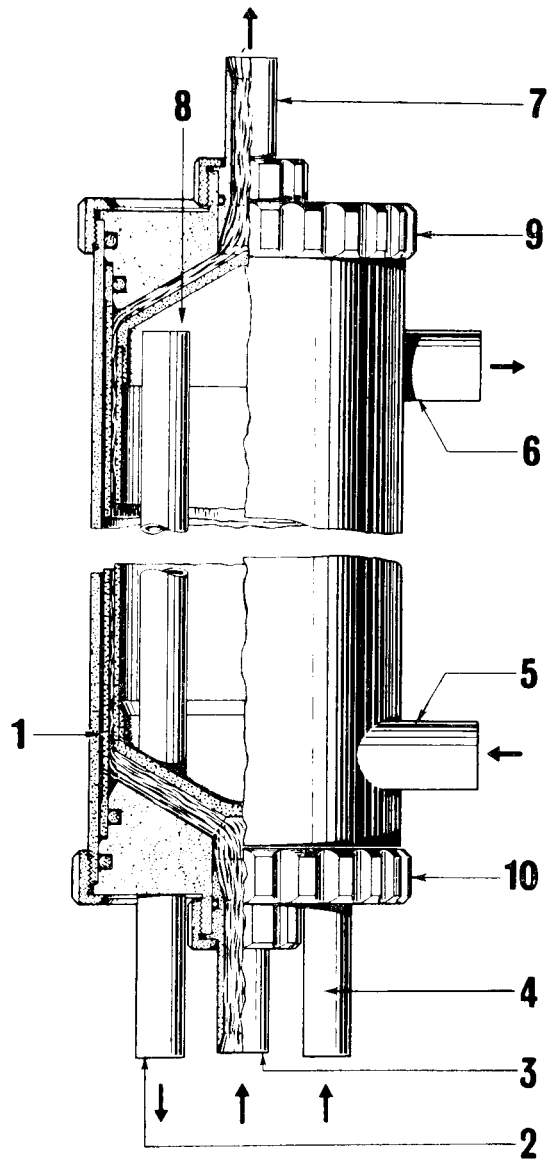


FIGURE 2.—Honeywell stainless steel heat exchanger. Blood enters at (3) and passes as a blood film (1) between an inner (8) and outer water jacket. After warming, the blood flows out at the top of the exchanger (7). Each water jacket is supplied separately with water; the inner jacket from below (2) and (4) and the outer jacket from the side (5) and (6). The apparatus can be dismantled for cleaning by unscrewing both ends (9) and (10).

to the patient (see Figures 10, 18 and 23). This cooling is most apparent at the lower flows, but the patient is usually little affected because, in spite of the large temperature discrepancy of the blood, the low flow means there is only a small deficit of heat.

### NON-DISPOSABLE BLOOD WARMERS

Because metal conducts heat well, non-disposable blood warmers are usually made of stainless steel. They are highly efficient and can warm blood from 4° C to 38° C at flows of over 3 l/min. It is this efficiency which makes these the devices of choice for cardiopulmonary bypass circuits. Heat is supplied by circulating water at 40° C through the outer and inner chambers. The blood flows through the middle chamber. One such device is shown in Figure 2. As well as having good warming efficiency, these warmers have very low resistance to flow. It must be remembered that although the heated bath for the circulating water may be in the next room, it is still an electrical device and the water, the stainless steel warmer and the blood provide a direct electrical connection to the patient's heart. A small leak of current from an electrical fault could cause sudden ventricular fibrillation. The Honeywell warmer is now manufactured by Medisco Equipment Limited under licence.

### DISPOSABLE BLOOD WARMERS

The word disposable refers to the part of the warmer through which the blood flows. In most devices this part is a coiled tube and the heating is done by an electrically heated water bath. One device differs from this common type. This is a flat PVC (polyvinylchloride) bag similar to that described by Russell (1969*a*). In this commercial design heat is produced by metal plates on either side of the bag. This "dry heat" warmer is discussed separately. Many of the coils and water bath warmers are interchangeable, so the coils and the baths are each considered as a group.

### DRY HEAT WARMING

*Fenwal Blood Warmer (4R4304)*

The Fenwal blood warmer is the only commercially available unit which warms during infusion, but is not a water bath warmer. It is rectangular (Figure 3) with a door which is opened to insert the blood warming bag (Fenwal 4C2416). The unit is available in 110 and 240 volts and the heating elements are rated at 750 watts.

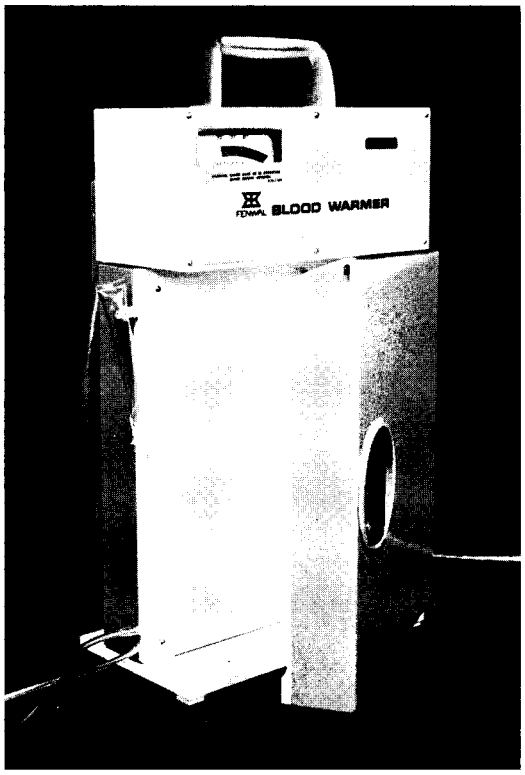


FIGURE 3.—Fenwal dry heat blood warmer. The plastic heat exchange bag is hung on the warming plate on the main body of the warmer. The door is closed and locked by rotating the handle, which extends the locking catch on the top and bottom of the door. The bag is filled with blood while the air trap on the side is squeezed. This air trap should be two-thirds filled with blood.

The bag is heated by warming elements on both sides. However, the door is not separately earthed and could cause a serious shock if it becomes live while open. When closed, the door is effectively earthed into the case by locking catches. The unit weighs 8·7 kg and takes about two minutes to reach its operating temperature. The warmer will stand on a table or can be mounted on a drip stand approximately $\frac{1}{2}$ in to $1\frac{1}{2}$ in diameter. The heating circuit is controlled by two sets of thermostats in the door; one set maintains the heating pad between 37° and 38° C, the second set are safety thermostats which operate at above 41° C. The safety thermostats turn off the heaters and trigger the alarm, which is a loud steady tone. The unit has an amber light to indicate when the power is on.

The main set of thermostats can be overridden by a micro-switch which is accessible

through a hole in the back of the unit. If the micro-switch is held with an insulated rod, the warmer can exceed 40° C and then the audible alarm is triggered. This is a recommended test procedure before use. The alarm tone ceases as soon as the temperature falls below 40° C. The warmer has been modified since these tests, and on warmers of serial number 830 onwards the door is correctly earthed. An additional thermal safety cut-out, which is designed to operate if the safety alarm fails, is fitted from serial number 1015 onwards. The thermometer

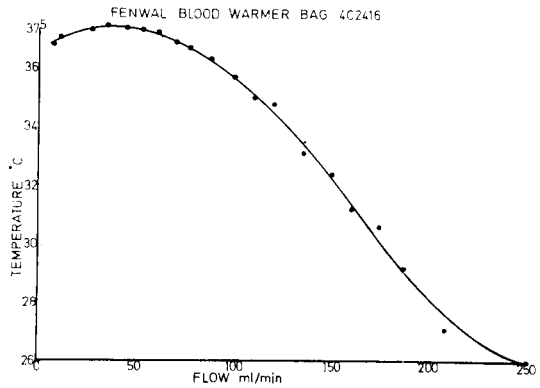


FIGURE 4.—Performance of the Fenwal blood warmer and bag. Output temperature of the warmer against flow rate in ml/min. Performance for iced water (0° C) with heater set at 37·5° C. Output temperature at 150 ml/min is 32·4° C. Each dot represents one observation.

on the warmer is electric and is calibrated in 1° C steps from 32° C to 41° C. This region is green. Below 32° C the thermometer dial is white and above 41° C it is red. On the test unit the thermometer appeared to over-read slightly, but this did not exceed 0·5° C. The manufacturer indicates that the unit should not be used in the presence of inflammable anaesthetics.

The warming bag is made of two sheets of 0·15 mm thickness PVC and measures about 20×22 cm. The two walls are welded in inter-digitating ridges to form a continuous channel about 3·5 m long. A small chamber of about 5 ml is inserted on the patient side of the warmer as a bubble trap. The priming volume is about 55 ml.

When the warmer is being used, the door should not be opened. If it is opened while blood is being infused under pressure, the bag will swell and the door cannot be closed again. However, the bag is reasonably strong and will not rupture until a pressure of 1,500 mm of Hg (30 lb/sq in) or more has been reached. At this stage the priming volume of the bag is about 250 ml. As the pressures found during a forced infusion do not generally exceed 300 mm of Hg, the present bag seems very adequately constructed.

Performance of the unit was very satisfactory (Figure 4): a flow of 150 ml/min resulted in an output temperature of 32·4° C; at 200 ml/min the plate temperature fell slightly to 36° C. The free flow through this unit with iced water was 175 ml/min, so that by gravity alone a flow of 60 ml/min with blood could be expected.

This warmer cannot be used with any of the warming coils; only the Fenwal warming bag is suitable. However, the Fenwal warming bag could be used in the Grant and Tuta warming baths. Its performance would then be degraded probably several centigrade degrees.

## WATER BATH BLOOD WARMERS

### *Disposable Coils*

These are made of either PVC (polyvinyl-chloride) or high-density polyethylene (polythene). The PVC does not have the ability to conduct heat as well as the poly-ethylene but is more flexible and so is easier to wind on a former. The PVC can also be welded into pre-formed coils. The usual length of tube for PVC is from 5 m to 8 m. Coils made of high-density polyethylene are more efficient at transferring heat and can be of shorter length. Shorter coils decrease the resistance to flow. All coils are in sterile packaging ready for immediate use. All coils examined had Luer fittings; female fittings for input and male for output, unless otherwise stated.

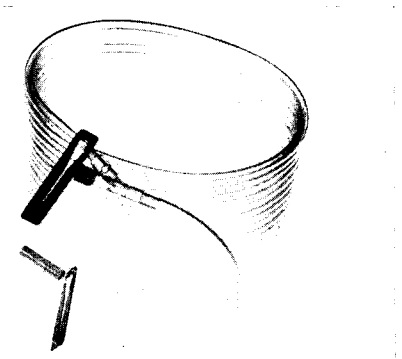

FIGURE 5.—Abbott blood warming coil.

*Abbott Coil.* The Abbott coil is shown in Figure 5. It is 7·4 m of 4·4 mm outside diameter PVC tube with 0·5 mm wall thickness. The tubing is formed into a coil approximately 10 cm in diameter. Priming volume is 50 ml. Performance in an agitated bath (37° C) is shown in Figure 6. At 150 ml/min the output temperature is 28·4° C. Free flow with iced water is 154 ml/min, corresponding to a blood flow of about 50 ml/min. An injection site is provided and flow can be controlled with metal wedges both on the patient side and the input side of the coil.

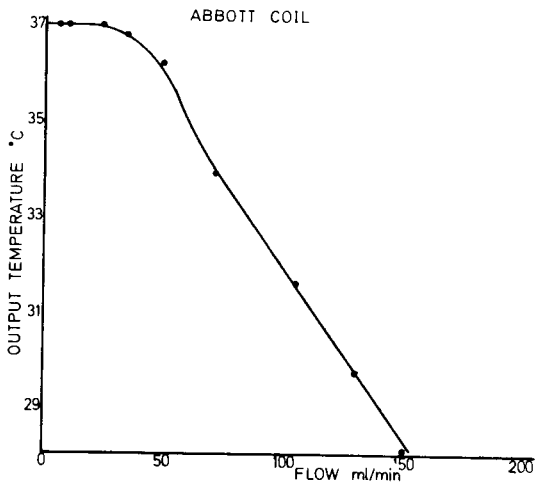


FIGURE 6.—Performance of the Abbott blood warming coil in an agitated bath at 37° C. Performance curve for iced water (0° C). Output temperature at 150 ml/min is 28·4° C. Each dot represents one observation.

*Avon Medical.* The Avon Medical coil is 6 m of free PVC tubing approximately 5·5 mm outside diameter with 0·7 mm wall thickness. This tube can be easily wound on a former. A pre-formed coil (A80) of 5·1 m is also available with short, 40 cm, input and output leads (Figure 7). The coil has a good free flow characteristic and an average flow of blood was 68 ml/min over eight infusions into patients, using a 14 gauge cannula under free flow. This corresponds with the maximum observed flow of 184 ml/min with iced water. The heat transfer at a flow of 150 ml/min is poor, however, and the output temperature is 26·5° C at this flow (Figure 8). Priming volume is approximately 65 ml. No flow control or injection site is provided.

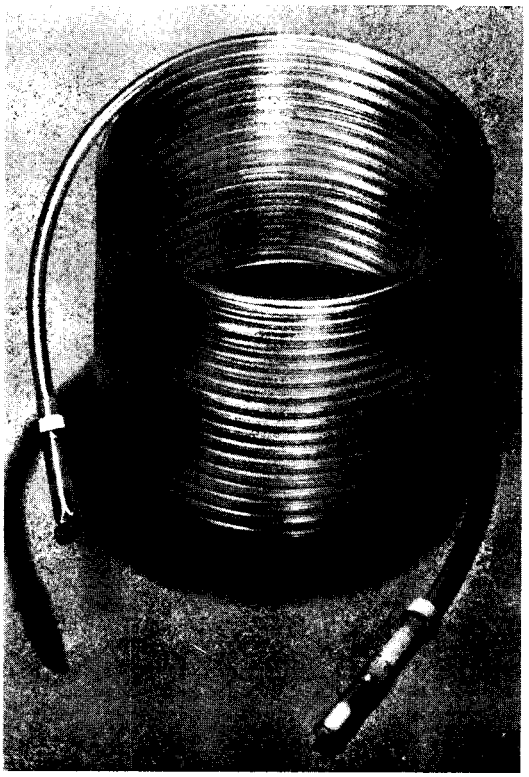

FIGURE 7.—Avon medical blood warming coil (A80).

*Baxter Plexitron.* The Baxter Plexitron coil (Figure 9) is made of high-density polythene; the coil is 3·1 m long with outside diameter 5 mm and 0·4 mm wall thickness. The polythene is rigid and formed into a coil about 9 cm in diameter. There is a 45 cm PVC tube at the inlet and a 150 cm PVC tube at the outlet. Both PVC tubes are of smaller bore than the polythene. The overall priming volume is approximately 50 ml. The output temperature at 150 ml/min is 32·4° C, which is very satis factory. However, the long output lead gives appreciable heat loss below 60 ml/min (Figure 10).

The free flow with blood is only 60 ml/min and is restricted mainly by the input and output leads. The coil with the input and output leads had a free flow of 90 ml/min with dextran 70 in dextrose at 20° C; the flow rose to 240 ml/min when both leads were removed. An injection site and a wedge roller flow control are provided on the output lead.

Because of confusion on the trade name of "Baxter", the company is now manufacturing

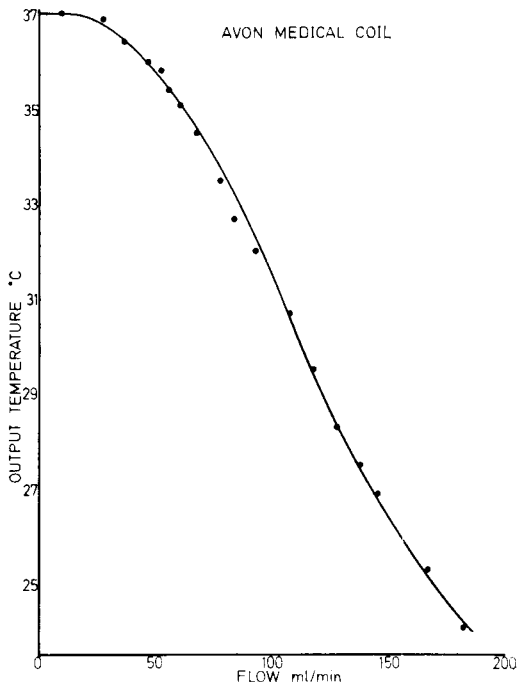


FIGURE 8.—Performance of 6 m of Avon medical tubing in an agitated bath at 37° C. Performance curve for iced water (0° C). Output temperature at 150 ml/min is 26·5° C. Each dot represents one observation.

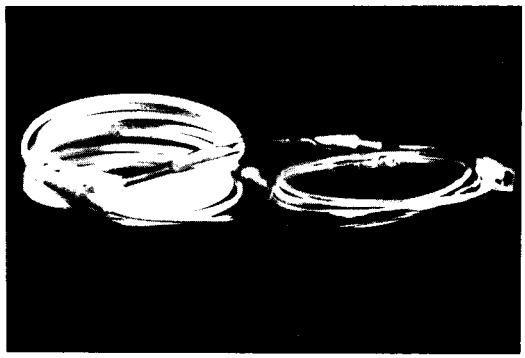

FIGURE 9.—Baxter Plexitron blood warming coil made of polythene.

only under the name of "Travenol". The coil is now known as Travenol Plexitron.

*Hemogard.* The Hemogard coil is shown in Figure 11; it is a double PVC coil, one coil being wound tightly inside the other. There is 5·6 m of tubing with outside diameter 5·5 mm

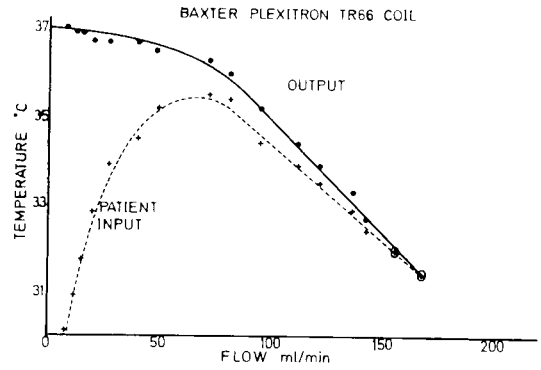


FIGURE 10.—Performance of the Baxter Plexitron blood warming coil in an agitated bath at 37° C. Performance curves for iced water (0° C). Output temperature is shown as a solid line; each dot represents one observation. Temperature at the patient end of the output lead is shown as the dashed line labelled "patient input"; each cross represents one observation (ambient temperature 20° C). At the two highest flows it can be seen that the output and patient input observations were the same value. The output temperature at 150 ml/min is 32·4° C.

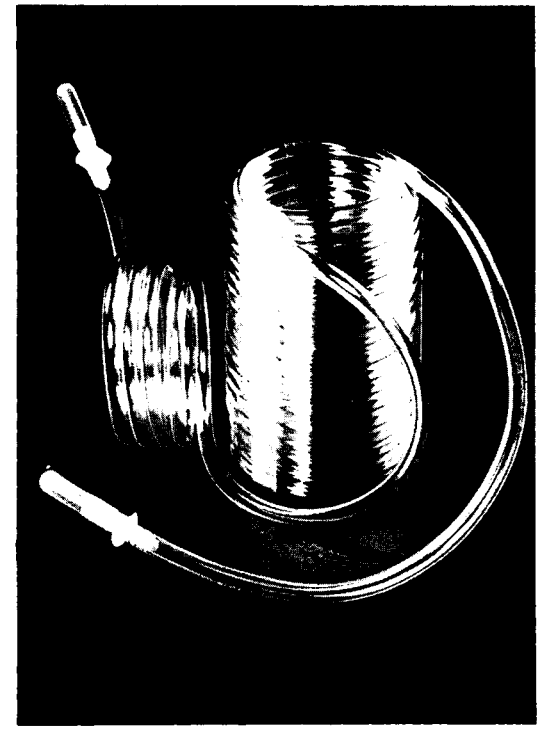

FIGURE 11.—Hemogard blood warming coil. The tubing is wound as a double coil which is held by three tapes.

and wall thickness 0·6 mm. The whole double coil has a priming volume of 75 ml. The corrected output temperature/flow relationship is shown in Figure 12. At a flow of 150 ml/min the corrected output temperature was 21·2° C.

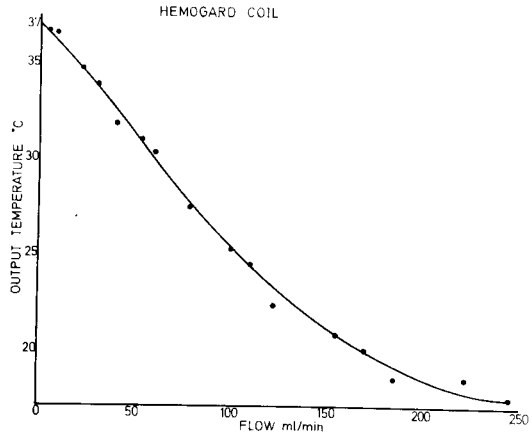


FIGURE 12.—Performance of Hemogard blood warming coil in an agitated bath at 37° C. Performance curve for iced water (0° C). Output temperature at 150 ml/min is 21·2° C. Each dot represents one observation.

The estimated free flow of 225 ml/min was achieved with iced water. Neither an injection site nor flow control is provided. Although the coil is specifically constructed for use with the Hemogard blood warmer, it would be possible to use it with the Grant or Tuta blood warming baths.

*Hemocoils.* The Hemocoil (Figure 13) is pre-formed PVC and is designed to fit the Hemokinetitherm blood warmer. The coil has a diameter of approximately 10 cm. It has 7·7 m of tubing with internal diameter 3·1 mm and approximately 0·6 mm wall thickness. The priming volume is 55 ml. The heat transfer characteristics are illustrated in Figure 14;

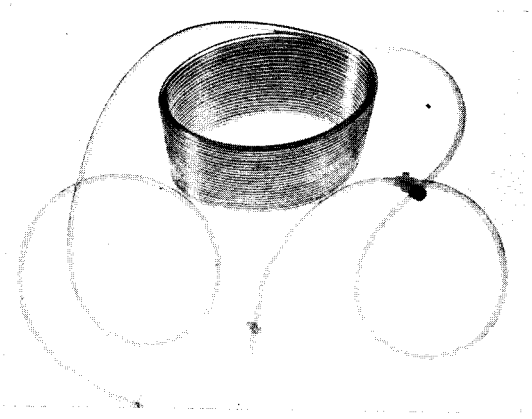

FIGURE 13.—Hemocoil, designed for use with the Hemokinetitherm blood warmer.

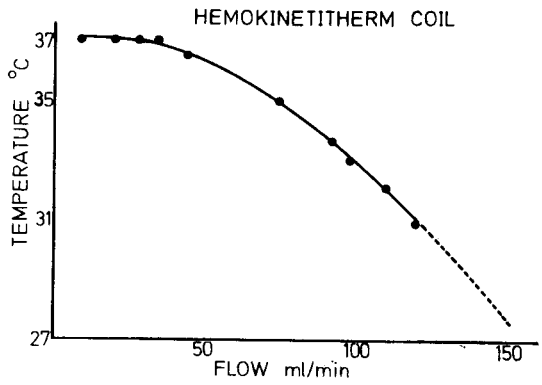


FIGURE 14.—Performance of Hemocoil (Hemokinetitherm) in an agitated bath at 37° C. Performance curve for iced water (0° C). Output temperature at 150 ml/min could only be estimated by extrapolation as about 27° C.

at 150 ml/min the output temperature is 27° C. Free flow with blood is estimated as 30 ml/min, but Manners and Mills (1968) could only achieve a free flow through a 15 gauge cannula of 15 ml/min, which suggests that a forced infusion would be frequently necessary. An injection site is provided on the more recent coils, but there is no flow control.

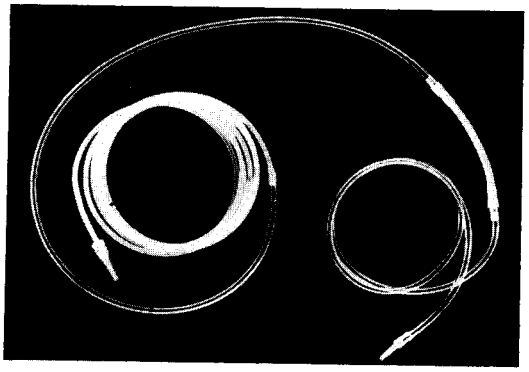

FIGURE 15.—Portex infusion coil. The heat exchange coil of high density polythene is whiter and more opaque than the PVC output lead.

*Portex Infusion Coil (200/700/000).* The Portex Infusion coil is a pre-formed coil of high-density polythene (Figure 15). It is 9 cm in diameter. The tubing is 2·7 m long with

wall thickness 0·4 mm and outside diameter 5 mm. The input is a fitting which accepts a Luer male connection and is joined directly to the polythene coil. The output lead is 2 m of PVC tubing with external diameter 6 mm and 0·6 mm wall thickness. The priming volume is 50 ml. The high-density polythene achieves a good heat exchange (Figure 16); at 150 ml/min the output temperature was very acceptable at 34·7° C. A free flow with blood of over 90 ml/min can be expected. The output lead has an injection site but no flow control is provided.

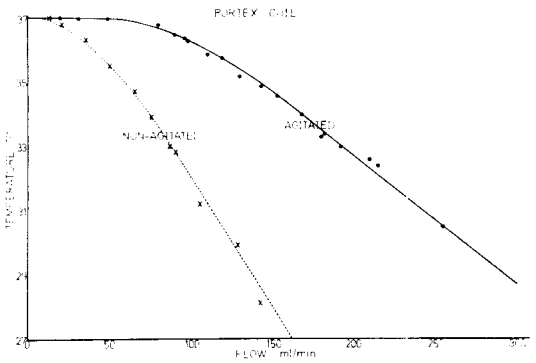


FIGURE 16.—Performance of Portex coil in baths at 37° C. The solid line and dots show the performance in an agitated bath. The dashed line and crosses show the performance in an unagitated bath (Bristol Blood Warmer Mk 11). Each dot or cross represents one observation of the output temperatures. The output temperature at 150 ml/min in an agitated bath was 34·7° C. However, in the Bristol bath the output temperature was only 28° C. Both performance curves are for iced water (0° C).

*Steritex (5T–26HL, 5T–26L).* The Steritex coil (Figure 17) is 7 m of PVC tubing with 5 mm outside diameter and approximately 1 mm wall thickness. It is available as free tubing (5T–26L) and pre-formed coils (5T–26HL). This set is designed for use with the Hetotherm blood warmer. The tubing is fitted with Luer screw fittings, which are compatible only with the Steritex drip set. However, the push-on fittings of other manufacturers should fit. The tubing is also available with Record fittings (5T–26HR, 5T–26R). An injection site and flow control are provided on the output line. The output temperature/flow relationship is shown in Figure 18; at 150 ml/min flow the output temperature is 26° C. Free flow with blood is 55 ml/min.

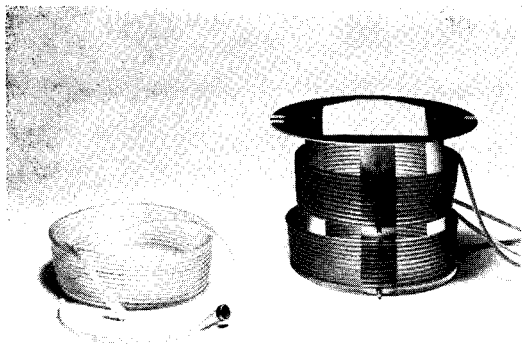

FIGURE 17.—Steritex formed coil and two coils fitted to Hetotherm former.

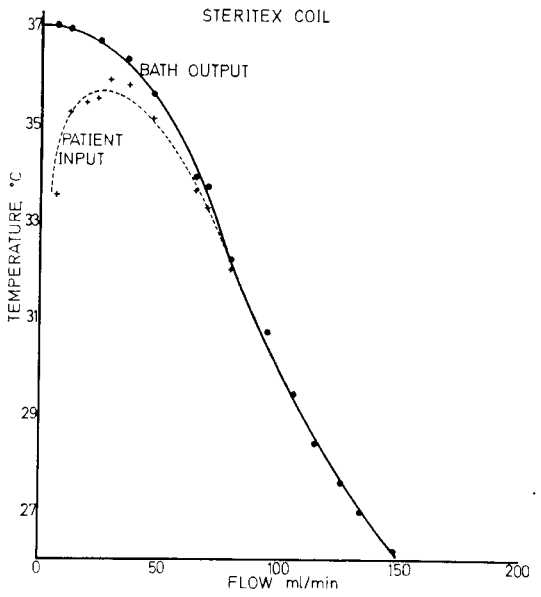


FIGURE 18.—Performance of Steritex coil (5T–26L) tubing in an agitated bath at 37° C. The solid line and dots show the output temperatures. The dashed line and crosses show the temperature at the patient input with an ambient temperature of 25° C. Each dot or cross represents one observation. The performance curve is for iced water (0° C). Output temperature for 150 ml/min is 26° C.

*Tuta Twin Coil (836–50).* The Tuta Twin coil (Figure 19) is identical to the Cutter high capacity heat exchange twin coil. The coil is 9 m of PVC tubing with 5·5 mm external diameter and 0·4 mm wall thickness. The twin coil is arranged as two pre-formed coils; the outer coil is about 10 cm diameter, while

the second coil is about 7 cm, and fits loosely inside the first. Priming volume is 65 ml. The free flow with blood is 65 ml/min. At 150 ml/min heat transfer is better than any other PVC coil and an output temperature of 29·8° C is achieved with an agitated water bath at 37° C (Figure 20). There is an injection site on the output lead but no flow control is provided. This coil is intended for use with the Tuta temperature controlled water bath. This bath is not agitated, and so deteriorates the performance of the coil.

FIGURE 19.—Tuta twin coil (836–50). This is a single tube formed into successive coils. One coil is sited inside the other with a gap of approximately 1 cm all round.

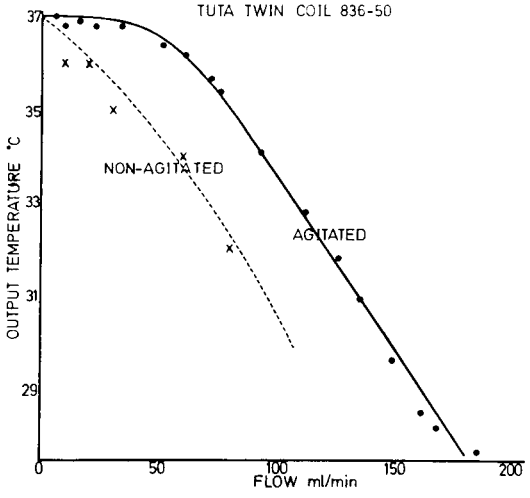


FIGURE 20.—Performance of Tuta twin coil (836–50) in an agitated bath at 37° C is shown by the dots and solid line. The performance in a non-agitated Tuta bath (corrected to a bath temperature of 37° C) is shown by the crosses and dashed line (data from manufacturer).

*Tuta Single (Paediatric) Coil (836–00).* The Tuta Single coil (Figure 21) is identical to the Cutter HX unicoil. It is 5 m of PVC tubing apparently the same as the Tuta twin coil tubing. The tubing is formed into a single coil 9 cm in diameter. Priming volume is 25 ml.

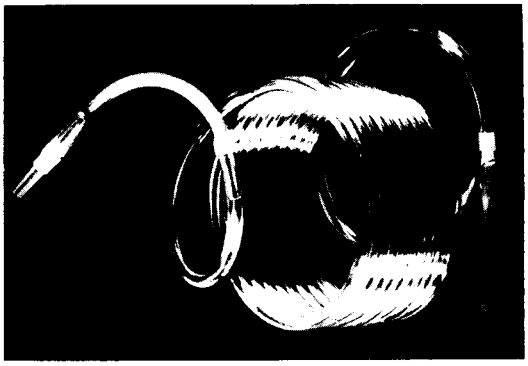

FIGURE 21.—Tuta single coil (836–00) for paediatric use.

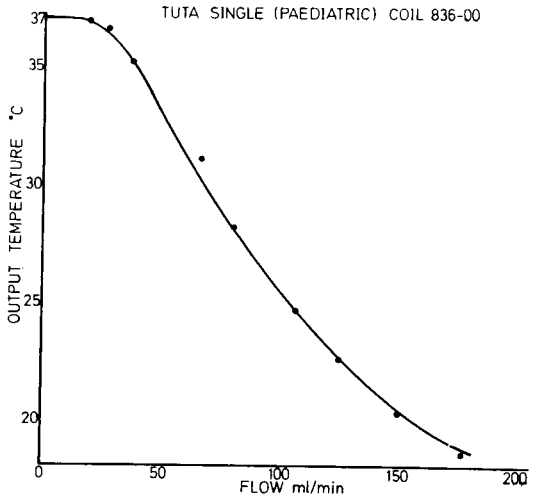


FIGURE 22.—Performance of Tuta single (paediatric) coil (836–00) in an agitated bath at 37° C. Performance curve is for iced water (0° C). Each dot represents one observation. Output temperature at 150 ml/min is 20° C. This coil is intended only for low flows such as would be expected in paediatrics.

Free flow with blood is 70 ml/min. The output temperature at 150 ml/min is 20° C. This coil is suitable only when low flows, say less than 40 ml/min, are appropriate (Figure 22). For

example, it would be reasonable to use this coil during exchange transfusion of a new-born baby. No flow control is provided but there is an injection site on the output lead.

*Viggo Sangofixdf.* This design is integrated with an infusion set and made of PVC. The tubing is slightly smaller than that used in most coils, and has external diameter 3·2 mm and wall thickness 0·8 mm. The overall length of tubing is 9·8 m, of which 7 m conveniently fits into the blood warmer. A roller wedge flow control is provided on the output lead. Priming volume is 55 ml. The expected output temperature at a flow of 150 ml/min is 31° C (extrapolated) (Figure 23). The estimated free flow with blood is 35 ml/min. This was estimated from a free flow of 110 ml/min with iced water. No injection site is provided. This integrated design is most suitable for a warmer such as the Hetotherm, which has a former for free tubing. Viggo also make 9 m PVC coils to be plugged into the infusion line. The heat exchange ability of these coils appears to be similar to the tubing tested.

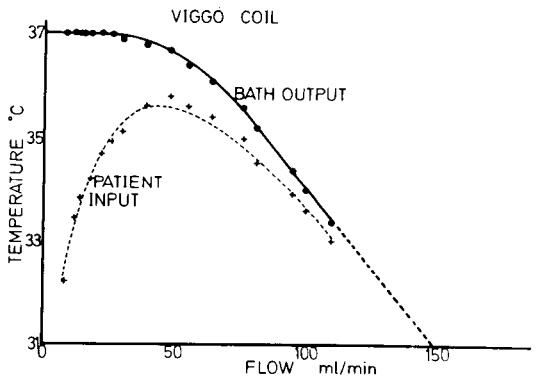


FIGURE 23.—Performance with iced water (0° C) of Viggo Sangofixdf coil in an agitated bath at 37° C is shown by the dots and solid line. The output temperature has been extrapolated to obtain an output temperature of 31° C at 150 ml/min. The temperature at the patient input is shown by a dashed line and crosses (ambient temperature 23° C). Each dot or cross represents one observation.

## COMPARISON OF DISPOSABLE UNITS

The 11 units tested are all which could be found in use (Table 1). Eight units tested were PVC tubing. One unit was a thin PVC bag. Two units were polythene tubing. The PVC tubing units gave the lowest output temperatures because the ability of PVC to transfer heat is poor. The only satisfactory PVC unit was the Fenwal bag, which is made of PVC sheet much thinner than any PVC tubing. Both the polythene coils gave good output temperatures. However, these coils are rigid and so are not suitable for winding on a former. This means they cannot be used in some warmers.

Of the three units which gave output temperatures over 32° C, only the Portex coil had a satisfactorily low resistance to flow. At present, one disposable unit on the market, the Portex coil, has a good heat transfer and does not impede flow. Only two other disposable units, the Fenwal flat bag and the Baxter Plexitron, achieve a satisfactory output temperature.

TABLE 1

*Comparison of the Output Temperature and Free Flow of Various Disposable Blood Warming Devices*

The output temperature is given for a flow of 150 ml/min and, in all units except the Fenwal warming bag, this output temperature has been derived with an agitated bath at a temperature of 37° C. Free flow is given for A.C.D. blood (haematocrit approximately 35 per cent) without needle or cannula at a 150 cm head of pressure
E = estimated

| Disposable units | Output temperature (at 150 ml/min) | Free flow (ml/min) |
|---|---|---|
| 1. Abbott .. .. | 28·4 | 50 (E) |
| 2. Avon .. .. | 26·5 | 68 |
| 3. Baxter .. .. | 32·4 | 60 |
| 4. Fenwal .. .. | 32·4 | 60 (E) |
| 5. Hemocoil .. .. | 27·0 (E) | 30 (E) |
| 6. Hemogard .. .. | 21·0 | 75 (E) |
| 7. Portex .. .. | 34·7 | 90 (E) |
| 8. Steritex .. .. | 26 | 55 |
| 9. Tuta single .. .. | 20 | 70 |
| 10. Tuta twin .. .. | 29·8 | 65 |
| 11. Viggo .. .. | 31 (E) | 35 (E) |

## WARMING BATHS

The warming baths differ widely in detail but have some common features. One is that heating is achieved by a thermostatically controlled electric element. With electrical heating it is important that the apparatus is well earthed. The water in the bath must also be earthed. Although plastic coils electrically insulate the infused fluid from the water bath, any fault or fracture in the coil would allow an electric current to flow from the bath down the infusion line. Poor earthing would also mean a hazard to staff.

The amount of heat available is important, as inadequate heat means the temperature of the bath falls during a rapid infusion. A heating power of 400 watts or more is desirable (see Appendix 4). Some heat is lost maintaining

the bath temperature even without load, but most of the heat should be available for warming the blood.

The temperature control during transfusion is also important. There should be one control which is set to maintain the selected water temperature; usually this is between 37° C and 39° C. A second safety thermostat should operate at two or three centigrade degrees higher if the first control fails. When the second safety thermostat operates, some form of warning should occur, preferably both visible and audible alarms. This safety thermostat must be easily or automatically re-set once the temperature returns to the operating level. If the safety thermostat can be re-set only in the factory, it means a warmer which is accidentally filled with hot water before use will be useless for the imminent operation.

There are two types of water bath, agitated and non-agitated. Those baths which are not agitated have the merit of simplicity. The heat transfer through the water to the coil from the electric element depends on adequate convection in the water. As flow increases, convection becomes less and less adequate as a means of heat transfer. Unaided convection is a slow process and a difference of several degrees centigrade may occur between the water close to the tube and that in the bottom of the bath near the thermostat and heater. For this reason, non-agitated warmers show a pronounced fall in the bath temperature during rapid infusion. Agitation speeds the convection and ensures the heat transfer is rapid. If the performance of a coil is poor in an agitated bath, it is worse in a non-agitated bath. At higher flows the output temperature is at least 3° C lower than if the bath is agitated (see Figures 16, 20 and 27).

Agitation is done by an electric motor driving an impeller or a water pump. Unfortunately, designs of electric motor which have brush commutators spark when running and therefore any blood warmer so agitated is a hazard if potentially explosive anaesthetic mixtures are used. Induction motors are inherently free from sparking and so are preferable. Contact thermostats, such as liquid or bimetallic expansion devices, may also spark when turning off. They too are unsuitable for use in a potentially explosive environment. They must be sealed in an air-tight case, or some other method of temperature control must be used. One method which does not require thermostats uses thermistors which electronically control the duration for which the heating element is used during each cycle of the power (see Appendix 3).

All electrical parts must be suitable for use in the theatre. The cost and extra weight entailed may make it undesirable to flame-proof the apparatus, but if this is not done it should be stated clearly on the container in the appropriate language. It is important that they should be clearly marked with words such as "DO NOT USE WITH INFLAMMABLE ANAESTHETICS". Current thinking may cause this to be modified so that an apparatus which could spark is kept a certain distance away from the dangerous area (Vickers 1972). The life of the thermostats and heater should be very long with modern designs, and some assurance should be sought that the probable life will be five or more years if used at the rate expected for the hospital.

*Bristol Blood Warmer Mk II (Portex).* The Bristol Blood Warmer Mk II bath is made of metal and fibre glass (Figure 24). It weighs 7 kg when full of water. It is not agitated and heating depends on convection from the heating element in the bottom. It can be used on a table or clamped to a drip stand of 19–32 mm diameter. It holds approximately 3·4 l of water, which is heated by a 1,500 watt element. Heating is controlled by a triac circuit and the final temperature of 37·5° C ± 1° C is achieved in about $6\frac{1}{2}$ minutes. The power required to maintain the bath temperature without load was 3 per cent of the heater power. Portex were not prepared to reveal the full circuit of the heater/control system, but inspection and information which they provided show that there are two thermistors which sense the temperature in the lower bath. One thermistor controls the heating element to maintain the temperature at about 37° C by a zero switching burst control of the power. The second thermistor is set to operate at 40° C and in addition there is a cut-out which turns off the heating element. The cut-out cannot be re-set by the user. This has been modified on the Mk III model, and the cut-out can be re-set by the user. Interference with ECG and similar equipment when the heater is switching on and off is unlikely with this design. If the bath temperature exceeds 40° C, the only alarm is a steady red light on the top of the bath. No thermometer is provided. Other coils could be fitted into this bath. The present design is such that the coil is in a region where convection currents are slight. This means a large gradient occurs between the heater and the coil at high

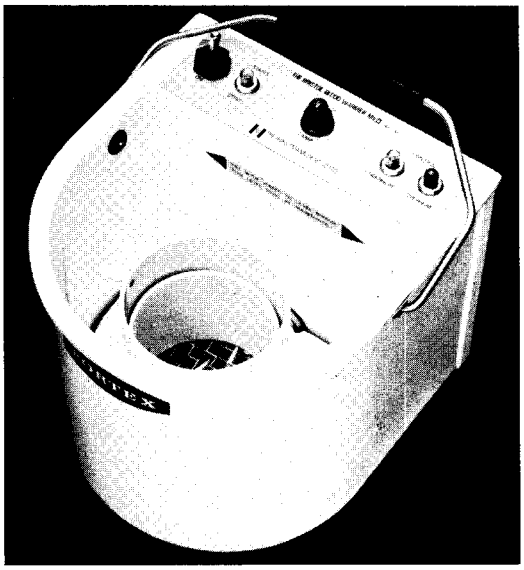

FIGURE 24.—Bristol Blood Warmer Mk II. The panel on top at the back has, from left to right, mains power switch, mains indicator, fuse socket, indicator light for heating, indicator light for overheating. In front is the "D"-shaped warming bath. The heating element is in the bottom of the bath and is protected by a wire grill and a platform. The coil clips on the cylinder in the centre of the bath.

flows and the performance of the coil is seriously impaired (Figure 16). There is a difference of 6·7° C at a flow of 150 ml/min between the performance of a Portex coil in this bath and in an agitated bath.

The only instruction on the warmer is the level for filling with water inside the bath. Although this warmer should be safe with inflammable anaesthetics, no information about this is present on the warmer or in the manufacturer's literature.

*Hetotherm Type 02C640Q.* The prototype for the Hetotherm was described by Dybkjaer and Elkjaer in 1964. This warmer is constructed in three parts: a 4·5 l polycarbonate tank, a stainless steel former for the coil, and a combined heater-stirrer-thermostat unit which is inserted on top of the tank (Figure 25). Earlier models were smaller and had a Perspex former and circular combined unit. The total weight is about 8·5 kg. A heavy stand with a tripod base is available for the warmer. The warmer is attached to the stand by a stainless steel ring and clamp, which are inseparable from the stand. The water is agitated by a stirrer with four blades. The stirrer is driven by a small induction motor mounted above in the combined unit. This produces enough noise to be obtrusive in a quiet theatre. The heater is rated at 600 watts and can be supplied for either 240 or 110 volts. The power required to maintain the bath temperature without load was 1·5 per cent of the heated power. Temperature is controlled with two thermostats, both of which are mercury thermometer switches. These are very accurate, but failure may occur after prolonged use. The first thermostat controls a triac circuit. The second thermostat is set at 39° C and controls the alarms as well as the heater. Above 39° C an audible alarm operates. The alarm is a moderately loud continuous tone, with a penetrating pitch. The alarm ceases when the water temperature falls below 39° C and the warmer again functions.

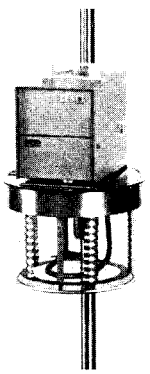

FIGURE 25.—Hetotherm blood heater type 02C 640Q. The aluminium box on the top of the warmer is the temperature control unit and contains the stirring motor, alarm and thermostats. The broad metal band below the unit holds the warmer on its special drip stand. Within the transparent polycarbonate bath is the coil former, a mercury thermometer (centre front) and the heating element.

Two other safety controls are present; both operate magnetically switched reed relays. One turns on the alarm if there is insufficient water in the tank to cover the heater. The other turns off both stirrer and heater if the combined unit is removed from the tank. A mercury thermometer is placed on the side of the tank as an independent check on the temperature. Unfortunately, this thermometer can rotate in its case and unless carefully set it may turn until the opaque side is nearest to the tank wall. The current model has the thermometer held by rubber grommets. Heto do not claim in their literature that this warmer is suitable for use with inflammable anaesthetics, but its construction appears to avoid any possibility

of sparks from the motor or switches, and they have confirmed that it should be safe under such conditions. No instructions are printed on the warmer.

The warmer can be used with any PVC tubing which is not pre-coiled; for example, Avon, Steritex or Viggo. Most pre-formed coils have too small a diameter to be used. although the Steritex pre-formed coil will fit on the smooth former (Figure 17). They can, however, be uncoiled and re-coiled on the former. The two polythene coils are awkward to use on the stainless steel former because they do not fit well; they do, however, give the best performance.

This warmer was the most efficient of those examined, and it also had the best safety features, in particular an independent mercury thermometer and a loud audible alarm.

*Grant BW2.* This is a stainless steel water bath (Figure 26) which was developed from the Grant laboratory water bath (Philpott and Slee 1967). The bath takes 5·3 l of water and the total weight with water is 10·6 kg. It can be used on a table or mounted on a drip stand 12–30 mm in diameter. The heating element is 240 or 110 volts, 300 watts. The power required to maintain the bath temperature without load was 10 per cent of the heater power. A green light on the front panel indicates mains power, and an adjacent orange light indicates when the heater is on.

Adjustable control and safety thermostats are on the front panel, and are covered by screw caps which must be undone with a rod for adjustment. Both thermostats are liquid expansion devices, adjustable through a hole in the case with a fine screwdriver. The control thermostat should be set at 37° C and the safety thermostat at 39° C, although when received the safety thermostat was set at 45° C. The adjustment is coarse and neither thermostat is easy to set more accurately than about one centigrade degree. If the safety thermostat operates, the red " Fault " light on the front panel comes on.

The warmer is safe in explosive atmospheres because the housing below the bath is sealed and gas-tight so anaesthetic vapours cannot enter. A dial thermometer is inserted through the front panel into the lower bath. It reads from 0° C to 60° C and in the warmer tested consistently read about two centigrade degrees low. The dial thermometer can be adjusted by a screw which is accessible when the thermometer is removed from the bath. No instructions are provided to do this, however. When filled with water at 20° C, the bath took 25 minutes to reach 37° C. The final temperature without an infusion was 38·1° C. The operating


FIGURE 26.—Grant BW2 blood warmer. The warmer has a slotted lid to reduce heat loss. Operating instructions are printed clearly on the front. The dial thermometer is on the left of the bath. The lower compartment is gas-tight; note the heavy fitting for the power lead. From left to right in the lower compartment is the safety thermostat adjustment, red " fault " light, control thermostat adjustment, indicator light for heater, indicator light for mains power.

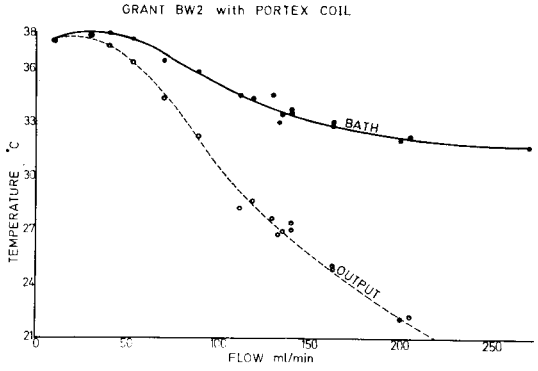


FIGURE 27.—Performance of Grant blood warmer with iced water through a Portex coil. As flow increases, the water temperature within the bath declines, as shown by the dots and the continuous line; at 150 ml/min the bath temperature has fallen 5° C. The output temperature from the Portex coil is correspondingly deteriorated as shown by the circles and dashed line; at 150 ml/min the output is 25·6° C compared to 34·7° C in an agitated bath (Figure 16).

instructions are clearly printed on the front of the bath. Unfortunately, the lettering can be scratched and might become so badly abraded with frequent rough use as to be illegible. The low power and lack of agitation mean the bath temperature falls with a rapid infusion (Figure 27).

*Hemotherm.* The Hemotherm (Figure 28) was not available for examination and testing and all information has been supplied by the manufacturer. This warmer is constructed of aluminium with a stainless steel water bath.

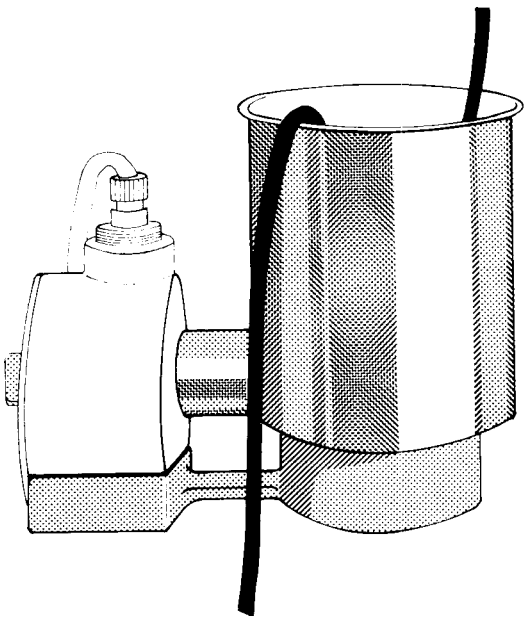

FIGURE 28.—Hemotherm blood warmer. The stainless steel bath is shown with tubing in the bath. The heater housing is on the left with the power lead entering from the top. The electrical parts are isolated in a gas-tight compartment to render the warmer safe in the presence of inflammable anaesthetics.

Its total weight is about 10 kg. It is designed to be set on a table and no option of stand mounting is provided. The heating element is 110 volts rated at 400 watts. Heating time is probably about 10 minutes. Heat control is by a single adjustable thermostat and it appears no overriding safety thermostat is provided. The warmer has the electrical parts enclosed in a sealed housing which is rated safe for use with inflammable anaesthetic agents. No alarm devices are provided and no thermometer is incorporated in the design. The water bath would appear suitable for most of the pre-formed coils which are available.

The Hemotherm appears to be a robust, simple warmer which lacks some of the highly desirable safety features which would avoid overheating.

*Hemogard.* The prototype for the Hemogard blood warmer was described by Bennett and Alladine (1967). The warmer (Figure 29) is a metal housing with a clear Perspex bath. The total weight is 5 kg. The warmer can stand on a table or clamp onto a drip stand up to 25 mm in diameter. The water capacity of the bath is 800 ml. The water is agitated by a small water pump in the housing which takes water from and returns it to the bottom of the bath. The circulatory pump makes little noise when running. The whole warmer is rated 240 volts, 720 watts, and the heating element is 500 watts of this. The heating efficiency of the heater could not be assessed as there is nothing to indicate when the heater is operating. The heater element forms a central core in the water bath and the Hemogard double coil is mounted

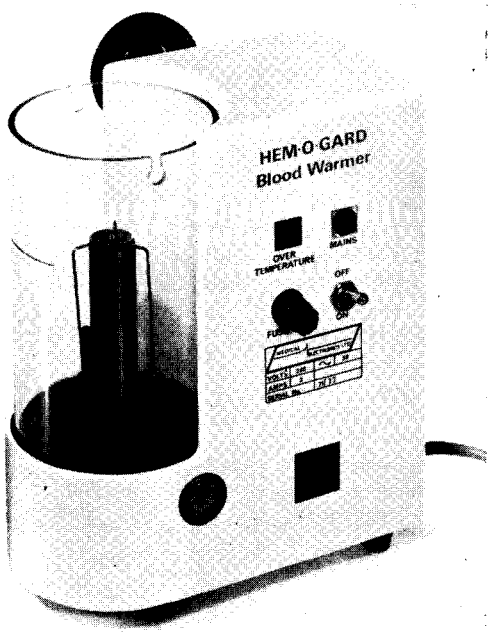


FIGURE 29.—Hemogard blood warmer. The clear water bath contains a central heater and thermostat. The notches in the top edges of the bath are to hold the tubing entering and leaving the bath. The socket for the drip stand is just visible on the far side of the warmer. On the near side, from below upwards, are the dial thermometer (10–120° C), fuse, power switch, over-temperature and mains indicator lights.

around this on a light three-rail frame. A mains power light indicates when the warmer is on.

The normal operating temperature of the bath is 38·5–39° C. When first switched on, the warmer was at an ambient temperature of 23·5° C and took 4½ minutes to reach 37·4° C and another 3½ minutes to reach 38·8° C. There is an independent check on the bath temperature by a small 25 mm diameter dial expansion thermometer which has a range of 10–120° C and which is inserted into the case just below the water bath. This thermometer was difficult to read and on the warmer which was tested it consistently read one or two centigrade degrees lower than the true temperature of the bath.

The bath temperature is controlled at about 38·5° C by a thermostat adjacent to the heater in the bath. However, with flows above 50 ml/min the bath temperature falls significantly (Figure 30). A second safety

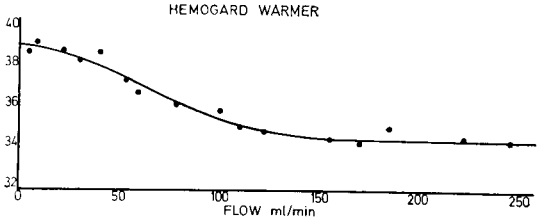


FIGURE 30.—Performance of Hemogard warmer with iced water. Bath temperature is shown against flow. As flow increases to 150 ml/min the bath temperature falls from 38·5° C to 34° C.

thermostat will operate if the bath temperature exceeds 40° C; when this operates, the red light comes on. The light is the only indication of excessive temperature; the circulatory water pump continues to function. When the temperature falls below 40° C the red light goes off. The manufacturers do not claim the warmer is suitable for use with inflammable anaesthetic agents, and from the information available this would seem unlikely. No warning is given, however, that it should not be used in these circumstances.

Only the Hemogard coil fits this unit, although free PVC tubing could be fitted into the bath with some difficulty. The performance of this bath with its own coil is less efficient than would be expected normally of an agitated bath, possibly because the double coil construction prevents a good circulation of water.

*Hemokinetitherm.* The Hemokinetitherm was first described by Koons in 1964. The warmer (Figure 31) is a cast aluminium block weighing 9·1 kg with water. It is designed to stand on a table and there is no provision for screwing it onto a drip stand. It has a deep slot in the top where the heat exchange coil is inserted. The slot takes 600 ml of water and the coil. The heating elements are in the block around the slot and are rated at 600 watts. The warmer can be supplied for 110 or 240 volts. When the warmer is switched on a red light comes on.

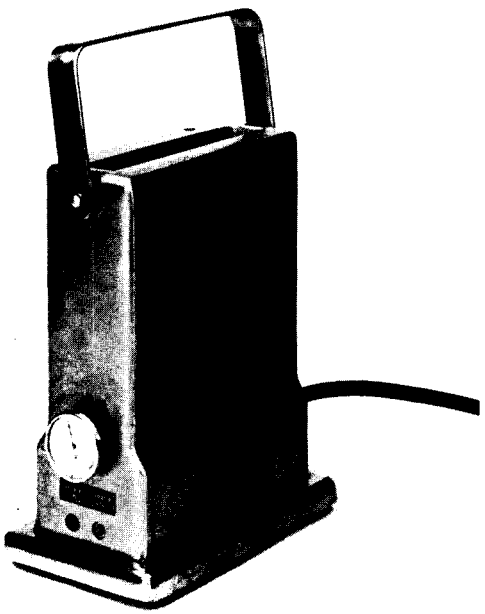

FIGURE 31.—Hemokinetitherm blood warmer. The warmer has a metal carrying handle, immediately below which is the slot for the coil and water. The power cord enters at one end. At the other end is the dial thermometer. Below this, on the left, is the red light indicating power on and, on the right, is the yellow heater light.

Adjacent to this is a yellow light which indicates when the heater is operating. The blood is warmed by conduction of heat from the metal where the coil touches the block and by convection of the water in the bath. The major part of the heat transfer would appear to be by convection. Approximately 2 per cent of the heater power is required to maintain the bath temperature. The warmer takes about 10 minutes to reach its operating temperature of 39·5° C from an ambient temperature of 25° C. The bath temperature is regulated by a thermostat in the case set to 39° C. A safety thermostat is provided which operates at about

41° C. If the normal thermostat fails and the safety thermostat is controlling the bath temperature, the red power light and the yellow heater light turn on and off together as the heating elements operate. No audible or other

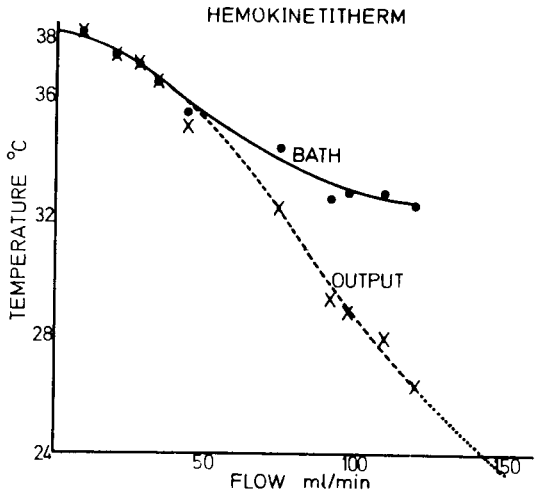


FIGURE 32.—Performance of the Hemokinetitherm warmer and coil with iced water. As flow increases, the bath temperature falls. Flow only reached 120 ml/min and by then the bath temperature had fallen from 39·5° C to 32·4° C. The output temperature from the Hemocoil in the Hemokinetitherm is shown as a dashed line with crosses. The dots and continuous line show the bath temperature. Each dot or cross represents one observation. The fine dotted line extrapolated from the cross at 120 ml/min gives an estimated output temperature at 150 ml/min of 23·5° C.

visual warning of overheating is provided. The thermostats appear to be bimetallic strips which can spark when switching, but the warmer has been carefully designed so that the thermostats and heater elements are enclosed in a gas-tight case. The thermostats and heaters can be exposed by undoing screws in the base of the warmer. No instructions are provided on the warmer but clear instructions are given in the manufacturer's literature.

A rotary dial thermometer approximately 4 cm diameter is provided. It is fixed through the case of the warmer and projects into the base of the bath. The temperature range is 0–50° C and the scale is marked in red above 41° C. On the warmer tested, the thermometer consistently read about five centigrade degrees below the bath temperature as measured by a mercury thermometer.

This is a simple non-agitated water bath and the heat transfer suffers because of it (Figure 32). The recommended coil made for the Hemokinetitherm is of PVC and thus the output temperature at high flows is poor. The warmer, however, can accommodate either the Baxter (Travenol) or the Portex polythene coil, both of which conduct heat better than the recommended coil and give superior output temperatures.

*Tuta.* The Tuta water bath (Figure 33) was not available for examination so all information is from the manufacturer. The warmer is constructed of chromed copper and weighs 3 kg. It is a simple water bath with no agitation. The warmer is designed to stand on a table or be mounted on a drip stand of 12–32 mm diameter. The bath capacity is 2 l.

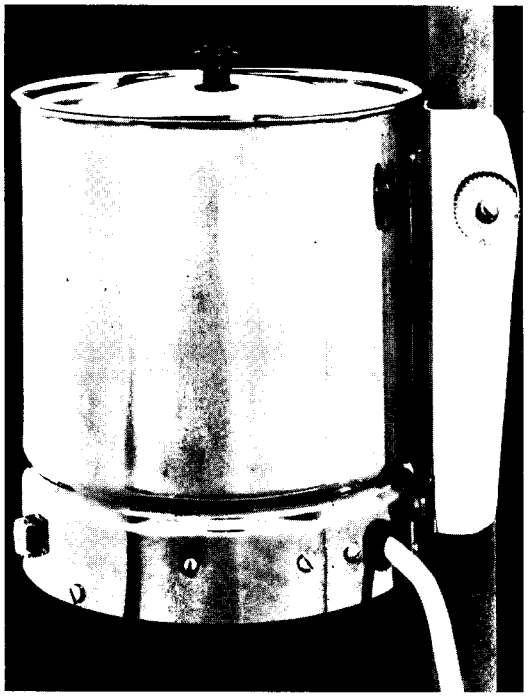

FIGURE 33.—Tuta water bath. The warmer is shown screwed on to a stand. The power cord enters the base. The power light is visible on the left. The warmer is provided with a lid over the water bath. In the current model a glass thermometer projects above the lid, and an over-heat light is provided.

The heater rating is 240 volts, 200 watts, and the bath reaches its operating temperature in about 13 minutes when filled with cold water (20° C). Operation of the heating element is indicated by an amber light on the side of the

base. The light is only on when power is being supplied to the heating element. The heating is controlled by a bimetallic thermostat which is set at 39° C±1° C. This thermostat can be adjusted through a hole in the base with a screwdriver. A safety thermostat is an electrothermal device which renders the whole warmer inoperative. A red button on the case must be pressed in to re-set the thermostat and allow the warmer to function again. The red button does not move out very far when the safety thermostat is triggered. A red over-heat alarm light is provided. This light operates at 42° C. A 0–50° C glass thermometer is built into the bath and projects above the lid. A 30–50° C metal encased thermometer is also available and would seem preferable. Because of the thermostat design, this warmer is probably not flame-proof and may be hazardous with inflammable anaesthetic agents. No warning about this is given by the manufacturer.

In the current model the electrothermal cut-out has been replaced by a thermostat. At 42° C the red overheat light comes on and the safety thermostat switches off the heater.

### GENERAL DISCUSSION

Disposable blood warmers seem to be the most suitable for warming blood in most situations where massive transfusions are required. Unfortunately, all the warmers tested were unsatisfactory either because they were potentially unsafe or because they could not deliver blood at 150 ml/min above a temperature of 32° C. The Fenwal blood warming unit, now that it has been properly earthed, with its blood warming bag, is the only currently available warming system which is completely satisfactory. The Hetotherm is an excellent warming bath which is capable of meeting the requirements, and it has some excellent features such as a good audible alarm, and an independent

TABLE 2
*Comparison of Disposable Blood Warmers*

| Blood warmers | Weight (kg) | Agitated | Heater power (watts) | Safety thermo-stat | Thermo-meter | Heating time (min) | Insert | Stand | Alarm |
|---|---|---|---|---|---|---|---|---|---|
| Grant .. .. | 10·6 | No | 300 | C | D | 25 | All | Yes | V |
| Hemogard .. | 5·5 | Yes | 500 | C | D | 4½ | 6 | Yes | V |
| Hemokinetitherm .. | 9·1 | No | 600 | C | D | 10 | 1, 3, 5, 7 | No | — |
| Hemotherm .. | 10 | No | 400 | NA | — | NA | All | No | — |
| Hetotherm .. | 8·5 | Yes | 600 | C | M | 6½ | 2, 8, 11 | Yes | A |
| Bristol (Portex) .. | 7 | No | 1500 | R | — | 6½ | 1, 2, 3, 5, 7, 11 | Yes | V |
| Tuta .. .. | 3 | No | 200 | RC | M | 13 | 1, 3, 6, 7, 9, 10 | Yes | V |
| Fenwal .. .. | 8·7 | — | 750 | CR | E | 2 | 4 | Yes | A |

Safety thermostat: C=automatic reset, R=must be reset, C and R=design has changed recently—see text.
Type of thermometer: E=electric, M=mercury, D=dial expansion (e.g. Rotatherm).
Heating time=time to reach the working temperature from ambient (about 20° C).
Insert: All=all coils; numbers refer to coils in Table 1.
Stand=warmer can be attached to drip stand.
Alarm: V=light operates if overheating, A=warning tone operates if overheating.
—=does not apply.
NA=information not available.

The size of the water bath makes it suitable for use with most pre-formed coils. Tuta coils, when used in this bath, have a worse performance than when used in an agitated bath (see Figure 19). This warmer is simple and robust. It is the lightest warmer available and has some safety provisions against overheating. However, its heating capacity is below that necessary for adequate heating at a flow of 150 ml/min. No instructions are given on the warmer but clear instructions are provided in the manufacturer's literature.

mercury thermometer for checking the bath temperature. Unfortunately, the Travenol Plexitron and Portex coils which would give the desired performance are not suitable for the large former in the bath. Thus the Hetotherm must use PVC coils which degrade the warming seriously, as no PVC coil can give an output temperature of 32° C at a flow of 150 ml/min. The performance of the disposable units are compared in Table 1.

The minimum requirement for a satisfactory warming bath is a heating capacity of 400 watts

with a control and a safety thermostat. At least two of the baths examined are seriously underpowered (see Table 2). Ideally, a bath should give both a visible and audible alarm if overheating occurs. Two baths have no independent alarm at all. The bath should be provided with a mercury or alcohol glass thermometer for an independent check on the temperature. Dial thermometers are not reliable; those on the three warmers tested all read lower than the bath temperature. The experience with similar thermometers in the intensive care unit at Hammersmith Hospital suggests that dial thermometers can be expected to fail after several years of clinical use.

The ideal disposable warming unit should be safe and should provide an output temperature of better than 32° C at a flow of 150 ml/min. This review has not attempted to assess the safety of the plastic sets available. However, only the polythene coils and the Fenwal blood-warming bag have a satisfactory output temperature. The Portex coil has the lowest resistance as shown by a good free flow of 90 ml/min. However, it is not suitable for use in the Hetotherm, which is the best bath. If the Portex coil is used in other non-agitated baths its performance is significantly worse. All the non-agitated water baths except the Bristol failed in that they were either underpowered or lacked overheating alarms. The design of the Bristol (Portex) warming bath is such that adequate convection is impossible and the excellent properties of the Portex coil are so degraded that a better overall performance could be had from rewinding a Tuta twin coil into the Hetotherm.

The lack of instructions on the warmers is disturbing; only the Grant warmer provided full clear instructions. The absence of any warning about the warmer being hazardous with inflammable anaesthetics is a particularly important omission. Although some manufacturers provide clear instructions in their literature, the information is easily mislaid.

It would appear that 10 of the 11 manufacturers of blood warming devices are producing products which are seriously deficient. It is hoped that this review may stimulate interest so that the current technical expertise can be used appropriately to produce fully effective blood warming systems.

## APPENDIX 1

An approximate value for the blood flow through a moderate bore apparatus can be found if the flow rate with water is found at 150 cm head of pressure and divided by 3.

The viscosity of blood at 0° C is approximately 2½ times greater than blood at 37° C (Burton 1965). Water alters its viscosity by approximately the same proportion as blood over the same temperature range.

Viscosity of water at 37° C = 0·007 centipoise

Viscosity of blood at 37° C = 0·026 centipoise (Coulter and Pappenheimer 1949).

A normal unit of stored blood is diluted approximately 15 per cent with aqueous solution, thus expected viscosity at 37° C = 0·023 centipoise.

The improvement in flow through a blood warming apparatus as the blood viscosity declined would occur similarly with water. The expected flow is inversely related to viscosity. The viscosity of stored blood is about three times greater than water (0·023/0·007). Therefore, stored blood should flow about one-third as fast as water through the same apparatus.

## APPENDIX 2

Comparison of dextran 70 in dextrose 5 per cent (Macrodex) and stored blood, both at 4° C.

| Warming coil | Macrodex flow (ml/min) | Blood | Percentage |
|---|---|---|---|
| Abbott, free end | 58 | 45 | 78 |
| Baxter plexitron, 14 g cannula .. | 75 | 53 | 76 |
| Baxter plexitron, free end .. | 136 | 100 | 74 |
| Steritex, 14 g. cannula .. .. | 52 | 39 | 75 |
| Tuta twin coil, 14 g cannula .. | 75 | 60 | 80 |
| Viggo, 14 g cannula .. .. | 43 | 31 | 72 |
| Mean flow Macrodex *v.* blood | — | — | 77 |

*The anticipated flow with blood is the flow with dextran 70 reduced by one-quarter.*

## APPENDIX 3

Semi-conductor power control can be achieved by means of a device called a triac. Like most transistor devices, it uses a very small current to control the full current that passes through the triac and powers the heater or other device.

The method of switching is electronic and does not use mechanical contacts, so that it is particularly suitable where sparking would be hazardous.

By electronically switching the triac on for only a part of the time, the amount of power delivered to the heater can be controlled from continuously on, i.e. full power, to as little as 10 per cent. Two methods of triac control are used (Figure 34). One technique is to

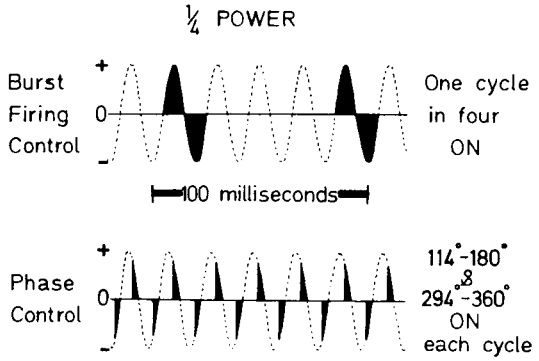


FIGURE 34.—Diagram showing the two methods of triac control; burst firing (upper) and phase control (lower). Each sine wave (dashed line) represents the voltage in an a.c. power line; the abscissa is time, the ordinate is voltage. Positive voltage is indicated above the zero line, negative is below. The shaded regions indicate that current is flowing. Both methods are shown supplying 25 per cent power. In burst firing control, the current is turned on during one cycle in every four. The triac is turned on when the voltage and current are zero and automatically turns off again at zero. This is called "zero switching". In phase control, the current is turned on during approximately the last one-third of each voltage surge. The triac automatically turns off when the voltage, and hence the current, reaches zero.

control the power in bursts. In this method the triac limits the power by switching on for a number of cycles and then off for a number of cycles. Burst firing thus controls the power in steps but can be almost as flexible as phase control. Burst firing has the major advantage that it can control much greater amounts of power without generating interference because the triac is switched on and off at the moments when the alternating current in the power line is zero. This is called "zero switching".

The other and simpler method is to switch on the power for limited times during each cycle (Reed 1969). This is called "phase control". A serious disadvantage of this method is that at about 50 per cent power the triac is suddenly switching on a heavy current during each mains cycle. This produces interference both in the main supply and by radiofrequency radiation. Thus delicate equipment such as ECG or EEG machines can be upset even if they are battery operated. Interference becomes important with power greater than 100 watts and circuits must be designed to minimize it. Above 500 watts it becomes increasingly difficult to suppress interference (Budek 1970) and therefore phase control is not suitable for controlling the heater power in a medical blood warmer.

## APPENDIX 4

Calculation of the minimum heating power required.

Assume:

1. Bank blood at 4° C.
2. Blood infused not below 32° C.
3. Specific heat of A.C.D. blood about 0·95.
4. Infusion rate 150 ml/min.

Heat required/ml = specific heat × temperature rise.

Heat required/min = flow × heat required/ml.

$$= 150 \times 0 \cdot 95 \times 28 \text{ calories/min.}$$

$$1 \text{ watt} = 14 \cdot 3 \text{ cal/min.}$$

Therefore minimum power required at 100 cent efficiency $= \dfrac{150 \times 0 \cdot 95 \times 28}{14 \cdot 3}$.

$$= 280 \text{ watts.}$$

Allow for heat loss by convection and evaporation at maximum 10 per cent. Minimum rating 310 watts.

(1 watt = 0·23892 cal/sec = 14·3352 cal/min.)

## ACKNOWLEDGEMENTS

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## MANUFACTURERS

Abbott coil
Abbott Laboratories Ltd., Queensborough, Kent, ME11 5EL, England.

Avon medical coil
Avon Medicals Ltd., 1649 Pershore Road, Birmingham, B30 3DR, England.

Baxter Plexitron
Travenol Laboratories Ltd., Caxton Way, Thetford, Norfolk, 1P24 3SE, England.

Bristol blood warmers and Portex infusion coil
Portex Ltd., Hythe, Kent, CT21 6JL, England.

Fenwal dry heat blood warmer
Travenol Laboratories Ltd., Caxton Way, Thetford, Norfolk, 1P24 3SE, England.

Grant BW2
Grant Instruments (Cambridge) Ltd., Barrington, Cambridge, CB2 5QZ, England.

Hemocoils and Hemokinetitherm
Dupaco Incorporated, P.O. Box 98, San Marcos, California, 92069, U.S.A.

Hemogard
The Medical Supply Association Ltd., Bourne Road, Benley, Kent, DA5 1NX, England.

Honeywell heat exchanger, Type 2132
Medisco Equipment Ltd., 52/54 Peascod Street, Windsor, Berkshire, SL4 1DE, England.

Hetotherm blood warmer
Heto, Klinthojvaenge 3, 3460 Birkerod, Denmark.

Ohio Model 987
Ohio Medical Products, 1400 East Washington Avenue, Madison, Wisconsin, U.S.A.

Steritex coil
Steritex Trading A/S, 6 Hojvangen, DK 3060 Espergaerde, Denmark.

Taurus 300 (Plessey)
Tellurometer (U.K.) Ltd., Oakcroft Road, Chessington, Surrey, KT9 1RG, England.

Tuta coils and blood warmer
Tuta Laboratories (Australia) Pty. Ltd., 332 Burns Bay Road, Lane Cove, N.S.W., 2066, Australia.

Viggo coil
Viggo AB, Gasebäcksvägen 36, 252 27 Helsingborg, Sweden.