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Efficacy of Two Methods for Reducing Postbypass Afterdrop

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Background: ***Afterdrop,*** **defined as the precipitous reduction in core temperature after cardiopulmonary bypass, results from redistribution of body heat to inadequately warmed peripheral tissues. The authors tested two methods of ameliorating afterdrop: (1) forced-air warming of peripheral tissues and (2) nitroprusside-induced vasodilation.**

Methods: **Patients were cooled during cardiopulmonary bypass to approximately 32°C and subsequently rewarmed to a nasopharyngeal temperature near 37°C and a rectal temperature near 36°C. Patients in the forced-air protocol (n = 20) were assigned randomly to forced-air warming or passive insulation on the legs. Active heating started with rewarming while undergoing bypass and was continued for the remainder of surgery. Patients in the nitroprusside protocol (n = 30) were assigned randomly to either a control group or sodium nitroprusside administration. Pump flow during rewarming was maintained at 2.5 $l \cdot m^{-2} \cdot min^{-1}$ in the control patients and at 3.0 $l \cdot m^{-2} \cdot min^{-1}$ in those assigned to sodium nitroprusside. Sodium nitroprusside was titrated to maintain a mean arterial pressure near 60 mmHg. In all cases, a nasopharyngeal probe evaluated core (trunk and head) temperature and heat content. Peripheral compartment (arm and leg) temperature and heat content were estimated using fourth-order regressions and integration over volume from 18 intramuscular needle thermocouples, nine skin temperatures, and "deep" hand and foot temperature.**

Results: **In patients warmed with forced air, peripheral tissue temperature was higher at the end of warming and remained higher until the end of surgery. The core temperature afterdrop was reduced from 1.2 ± 0.2°C to 0.5 ± 0.2°C by forced-air warming. The duration of afterdrop also was reduced, from 50 ± 11 to 27 ± 14 min. In the nitroprusside group, a rectal temperature of 36°C was reached after 30 ± 7 min of rewarming. This was only slightly faster than the 40 ± 13 min necessary in the control group. The afterdrop was 0.8 ± 0.3°C with nitroprusside and lasted 34 ± 10 min which was similar to the 1.1 ± 0.3°C afterdrop that lasted 44 ± 13 min in the control group.**

Conclusions: **Cutaneous warming reduced the core temperature afterdrop by 60%. However, heat-balance data indicate that this reduction resulted primarily because forced-air heating prevented the typical decrease in body heat content after discontinuation of bypass, rather than by reducing redistribution. Nitroprusside administration slightly increased peripheral tissue temperature and heat content at the end of rewarming. However, the core-to-peripheral temperature gradient was low in both groups. Consequently, there was little redistribution in either case. (Key words: Anesthesia; heat; hypothermia; temperature; thermoregulation.)**

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HYPOTHERMIA often is deliberately induced in patients undergoing cardiac surgery because even mild hypother-

mia is thought to provide substantial protection against cerebral ischemia and provides myocardial protection.[1,2] Target core temperatures between 28 and 32°C are typical. Subsequent rewarming with the bypass pump rapidly increases core temperature to normal or even hyperthermic values. Discontinuation of bypass warming, however, frequently is associated with a decrease in core temperature ("afterdrop").[3–7] The resulting hypothermia may trigger shivering,[8,9] inhibit coagulation,[10] increase myocardial stress,[11,12] and reduce resistance to surgical wound infections.[13]

Core hypothermia after cardiopulmonary bypass results from redistribution of body heat to inadequately warmed peripheral tissue and from systemic heat loss.[14] Several methods of ameliorating afterdrop have been proposed, such as locally warming peripheral tissues while the core is rewarmed by the heat exchanger incorporated in the cardiopulmonary bypass machine. Although the amount of heat transferred by surface warming is small compared with that provided from the bypass machine, it can be applied directly to peripheral tissues that are otherwise warmed less effectively than the core. The result may be a reduced postbypass core-to-peripheral temperature gradient and therefore less afterdrop.

The potential effectiveness of peripheral tissue heating is supported by studies showing that forced-air warming before induction of general[15,16] or neuraxial[17] anesthesia significantly reduces postinduction redistribution of body heat. We therefore tested the hypothesis that forced-air heat applied to the legs during the rewarming period of cardiopulmonary bypass reduces afterdrop magnitude and duration.

A second approach reducing afterdrop magnitude is pharmacologic vasodilation to facilitate core-to-peripheral transfer of heat provided by the bypass machine. This method was first reported by Noback and Tinker in 1980.[18] They demonstrated that vasodilation with sodium nitroprusside during rewarming and high pump flow during cardiopulmonary bypass reduced core temperature afterdrop. Bypass temperature and pump flows were not reported in the Noback and Tinker article[18]; however, bypass probably was conducted near 28°C because that temperature was routine at the time of their study. More recently, Tugrul *et al.*[19] and Deakin *et al.*[20] reported reduced afterdrop magnitude when sodium nitroprusside was used to induce vasodilation during rewarming during cardiopulmonary bypass. In both cases, patients were cooled to core temperatures near 28°C using pump flows between 2.4 and 2.6 $l \cdot m^{-2} \cdot min^{-1}$, and bypass was discontinued at core temperatures exceeding 37.5°C.

We previously demonstrated that the core-to-peripheral tissue-temperature gradient is less after bypass at 31°C than at 27°C.[14] As might be expected, afterdrop magnitude also was reduced at the higher temperature. Nonetheless, pharmacologic vasodilation is likely to reduce afterdrop with relatively high bypass temperatures, just as it does before induction of general anesthesia.[21,22] We therefore tested the hypothesis that nitroprusside administration, in doses sufficient to increase pump flows by approximately 20%, decreases the magnitude and duration of postbypass afterdrop.

Methods

With approval from the Committee on Human Research at the University of Vienna and written informed consent, we enrolled 50 patients undergoing elective coronary artery bypass surgery in two protocols. Left ventricular ejection fractions for all patients exceeded 40% and all patients took vasoactive medications before surgery (*e.g.*, nitroglycerin, β-blocking drugs, or inhibitors of angiotensin converting enzyme).

We enrolled patients, aged 20 to 80 yr, for whom we did not anticipate requiring intra- or postoperative vasoactive medications. Patients undergoing reoperation, having diabetes or peripheral vascular disease, and with a body mass index more than 30 kg/m^2 or American Society of Anesthesiologists physical status IV were excluded.

Protocol

Room temperature was kept near 21°C throughout surgery. Patients were premedicated with oral diazepam (10 mg). Anesthesia was induced with intravenous etomidate (0.25 mg/kg), midazolam (0.1 mg/kg), fentanyl (5 μg/kg), and pancuronium (0.1 mg/kg). The tracheas were intubated and mechanical ventilation was adjusted to maintain end-tidal partial pressure of carbon dioxide (P_{CO_2}) near 35 mmHg. Anesthesia was maintained with fentanyl (0.3 mg/h) and midazolam (4 mg/h) in oxygen and air and with repeated doses of pancuronium. After induction of anesthesia, one catheter was inserted into the superior vena cava and another into a radial artery.

The arterial cannulation site was the ascending aorta. The bypass pump was primed with 1,500 ml lactated Ringer's solution and 100 ml mannitol, and pulsatile bypass flow was maintained at 2.5 $l \cdot m^{-2} \cdot min^{-1}$ during

cooling. A membrane oxygenator was used in all cases. The hematocrit was kept between 20 and 25%. Patients were cooled during cardiopulmonary bypass to a nasopharyngeal temperature near 32°C and a rectal temperature less than 33°C.

Patients were subsequently rewarmed by the heat exchanger on the cardiopulmonary bypass machine to a maximum nasopharyngeal temperature of 37°C and to a rectal temperature of near 36°C. The initial fluid–blood gradient was near 3°C, and arterial inflow temperature never exceeded 37.3°C. All fluids given during surgery were warmed to 37°C. A circulating water mattress was adjusted to 39°C during warming, and warming continued during the postbypass period. Cardiopulmonary bypass was subsequently discontinued, and patients were transferred to the intensive care unit or the postoperative recovery unit, intubated, and sedated. All temperature measurements were continued until the end of surgery.

Forced Air. Before rewarming, 20 patients were assigned randomly to either passive insulation (surgical drapes; n = 10) or forced-air cutaneous warming (Bair Hugger cardiac blanket; Augustine Medical, Inc., Eden Prairie, MN; n = 10). The sterile cover was positioned over the legs at completion of saphenous vein harvesting. Active cutaneous heating at the "high" setting (air temperature ≈ 43°C) was begun when bypass rewarming started; heating continued after bypass was discontinued, but was then stopped at the end of surgery. Cardiopulmonary bypass pump flow was maintained at 2.5 $l \cdot m^{-2} \cdot min^{-1}$ during rewarming. No vasoactive medication was administered during surgery.

Nitroprusside. Before rewarming, 30 patients were assigned randomly to either a control group (n = 15) or sodium nitroprusside administration (n = 15). Pump flow during rewarming was maintained at 2.5 $l \cdot m^{-2} \cdot min^{-1}$ in the control patients and at 3.0 $l \cdot m^{-2} \cdot min^{-1}$ in those assigned to nitroprusside. High resistance in the arterial line of the bypass machine prevented a further increase in pump flow. Sodium nitroprusside (Nipruss; Schwarz Pharma AG, Monheim, Germany) initially was administered as a continuous infusion (1.5 $\mu g \cdot kg^{-1}min^{-1}$). This dose was titrated to maintain a mean arterial pressure near 65 mmHg. Mean arterial pressure also was maintained near 65 mmHg in the control patients. Boluses of lactated Ringer's solution were administered in either group if deemed necessary by the attending anesthesiologist. No other vasoactive medications were administered to these patients during surgery.

Measurements

Radial arterial blood pressures and heart rates were recorded at 5-min intervals (Hellige, Inc., Freiburg, Germany), along with arterial saturation and end-tidal P_{CO_2} (Dräger, Lübeck, Germany). Vasomotor status was evaluated using forearm-minus-fingertip and calf-minus-toe skin temperature gradients.[23] Gradients exceeding 0°C were considered to be evidence of significant vasoconstriction because this value correlates with clinically important isolation of the core and peripheral thermal compartments.[24] Core temperatures were recorded from the nasopharynx. Rectal temperature was recorded from a probe inserted 10 cm past the anus.

Arm and leg tissue temperatures were determined as previously described.[25] Briefly, the length of the thigh (groin to mid-patella) and lower leg (mid patella to ankle) were measured in centimeters. Circumference was measured at the mid upper thigh, mid lower thigh, mid upper calf, and mid lower calf. At each circumference, right leg muscle temperatures were recorded using 8-, 18-, and 38-mm-long, 21-gauge needle thermocouples (Mallinckrodt Anesthesiology Products, Inc., St. Louis, MO) inserted perpendicular to the skin surface. Skin surface temperatures were recorded immediately adjacent to each set of needles and directly posterior to each set. Subcutaneous temperature was measured on the ball of the foot using a Coretemp (Terumo Medical Corp., Tokyo, Japan) "deep tissue" thermometer.[26] This device estimates tissue temperature approximately 1 cm below the skin surface and was used instead of inserting needles into the foot.

The lengths of the right arm (axilla to elbow) and forearm (elbow to wrist) were measured in centimeters. The circumference was measured at the midpoint of each segment. As in the right leg, 8-, 18-, and 38-mm-long needle thermocouples were inserted into each segment. Skin surface temperatures were recorded immediately adjacent to each set of needles. Core, skin surface, and muscle temperatures were recorded from thermocouples connected to two calibrated Iso-Thermex 16-channel electronic thermometers (Columbus Instruments International, Corp., Columbus, OH) and Mon-a-Therm 6510 two-channel thermometers (Mallinckrodt Anesthesiology Products, Inc.). Palm temperature was measured using a second channel of the Coretemp deep tissue thermometer.

Data Analysis

The leg was divided into five segments: upper thigh, lower thigh, upper calf, lower calf, and foot. Each thigh

and calf segment was further divided into an anterior and posterior section, with one third of the estimated mass considered to be posterior.

Anterior segment tissue temperatures, as a function of radial distance from the center of the leg segment, were calculated using skin surface and muscle temperatures using fourth-order regressions. Temperature at the center of the thigh was set to core temperature. In contrast, temperature at the center of the lower leg segments was estimated from the regression equation with no similar assumption. Anterior limb heat content was estimated from these temperatures, as previously described,[27] using the formula

$$Q_{(0\rightarrow r)} = 2(\pi r^2 L)\rho s\left[a_0 + \frac{a_2 r^2}{2} + \frac{a_4 r^4}{3}\right], \qquad (1)$$

where $Q_{(0\rightarrow r)}$ (cal) is heat content of the leg segment from the center to radius r, L (cm) is the length of the leg segment (*i.e.*, groin to mid thigh, mid calf to ankle), ρ (g/cm^3) is tissue density, s (cal · °C^{-1} · g^{-1}) is the specific heat of leg tissues, a_0 (°C) is the temperature at the center of the leg segment, and a_2 (°C/cm^2) and a_4 (°C/cm^4) are the fourth-order regression constants. The specific heat of muscle was taken as 0.89 cal · °C^{-1} · g^{-1} and density as 1.06 g/cm^3.

Rather than assume full radial symmetry, we assumed only that radial temperature distribution in the posterior leg segments would also be parabolic. Accordingly, we calculated the regression constant a_2 in the posterior leg segments from a_0 determined from the adjacent anterior segment and the posterior segment skin temperature. Posterior segment tissue heat contents were then determined from equation 1. Average segment tissue temperatures were determined by the equation

$$T_{Ave} = a_0 + \frac{a_2 r^2}{2}. \qquad (2)$$

The derivation of these equations, and their limitations have been previously described.[27]

Deep temperature measured on the ball of the foot was assumed to represent the entire foot. Thus, foot heat content was calculated by multiplying foot temperature by the mass of the foot and the specific heat of muscle. Average temperatures of the thigh and lower leg (calf and foot) were calculated by weighting values from each of the nine segments in proportion to their estimated masses. The right and left leg were treated comparably throughout this study, so we assumed that average tissue temperatures in the two limbs were similar.

Deep temperature measured on the palm was assumed to represent the entire hand. Thus, hand heat content was calculated by multiplying hand temperature by the mass of the hand and the specific heat of muscle. Arm tissue temperature and heat content were calculated from parabolic tissue temperature regressions and the aforementioned equations. In the arms, we assumed full radial symmetry and therefore did not separately calculate posterior segment values. As in the leg, average temperatures of the arm and forearm (forearm and hand) were calculated by weighting values from each of the three segments in proportion to their estimated masses.

Changes in trunk and head heat content were modeled simply by multiplying the weight of the trunk and head by the change in core temperature and the average specific heat of human tissues. Trunk and head weight was estimated by subtracting the calculated weight of the extremities (from the radial integration) from the total weight of each subject.

Afterdrop was defined as the decrease in core temperature after discontinuation of bypass. Similarly, the *afterdrop time* was defined by the period from the end of bypass until the minimum postbypass core temperature was observed. Statistical analysis was performed separately for each study because these were sequential protocols. Differences between the control and treatment groups were evaluated using chi-square or two-tailed, unpaired t tests, as appropriate. Results are expressed as the mean ± SD; differences were considered to be statistically significant when $P < 0.05$.

Results

Forced-air Protocol

Demographic and morphometric characteristics of the patients assigned to passive insulation (n = 10) and forced-air warming (n = 10) were similar (table 1). Core temperature at the onset of bypass, approximately 1 h after induction of anesthesia, was similar in both groups and decreased at the end of cooling to a minimum of approximately 31.8 in both groups. Cardiopulmonary bypass was discontinued in both groups at a core temperature near 37°C and a rectal temperature near 36.5°C.

Changes in core heat content and peripheral tissue heat content were similar in both groups at the onset of bypass and during cooling. Rewarming during bypass increased core heat content similarly in each group. In patients warmed with forced air, core heat content de-

creased only slightly after discontinuation of bypass (17 ± 9 kcal), whereas the decrease was significantly greater in the control group (39 ± 10 kcal). Peripheral tissue heat content after discontinuation of bypass increased twice as much in the forced-air group compared with the passive insulated patients (12 ± 12 kcal *vs.* 6 ± 8 kcal). Consequently, total body heat content at the end of surgery exceeded precooling values by 139 ± 55 kcal in the forced-air patients, but only by 94 ± 37 kcal in the passively insulated patients (fig. 1).

Peripheral tissue temperature at the onset of bypass was near 33.5°C in both groups and decreased to a minimum of 32.1°C. At the end of rewarming, peripheral tissue temperature in the forced-air group was higher than in the control group and continued to increase during the postbypass period. In contrast, peripheral tissue temperature in the control group remained essentially stable after discontinuation of bypass. Consequently, peripheral tissue temperatures in the two groups differed by nearly 1°C at the end of surgery (fig. 2). The core-to-periphery temperature gradient at the end of warming was significantly less in the forced-air (1.4 ± 0.5°C) than in the control (2.2 ± 0.6°C) group.

The core temperature afterdrop in the forced-air group was 0.5 ± 0.2°C and lasted 27 ± 14 min. In contrast, afterdrop in the passively insulated patients was 1.2 ± 0.2°C and lasted twice as long: 50 ± 11 min (table 2).

Table 1. Morphometric and Demographic Characteristics in the Forced-air Protocol

	Passive Insulation	Forced-air	*P*
Sex (M/F)	8/2	8/2	—
Weight (kg)	78 ± 9	77 ± 11	0.88
Height (cm)	171 ± 7	171 ± 8	0.96
Age (yr)	62 ± 12	62 ± 9	0.99
Preoperative ejection fraction (%)	55 ± 6	53 ± 8	0.53
Grafted veins/arteries	16/16	13/17	—
Arm weight (kg)	10 ± 2	10 ± 2	0.77
Leg weight (kg)	27 ± 4	26 ± 4	0.6
Peripheral fraction of body mass (%)	47 ± 4	46 ± 3	0.44
Core weight (kg)	41 ± 6	42 ± 6	0.83
Cooling time (min)	50 ± 12	59 ± 14	0.14
Total rewarming time (min)	50 ± 9	58 ± 21	0.31
Total bypass time (min)	100 ± 9	117 ± 25	0.06
Time from separation of bypass until the end of surgery (min)	60 ± 8	58 ± 9	0.52

Data presented as the mean ± SD. There were no statistically significant differences between the groups.

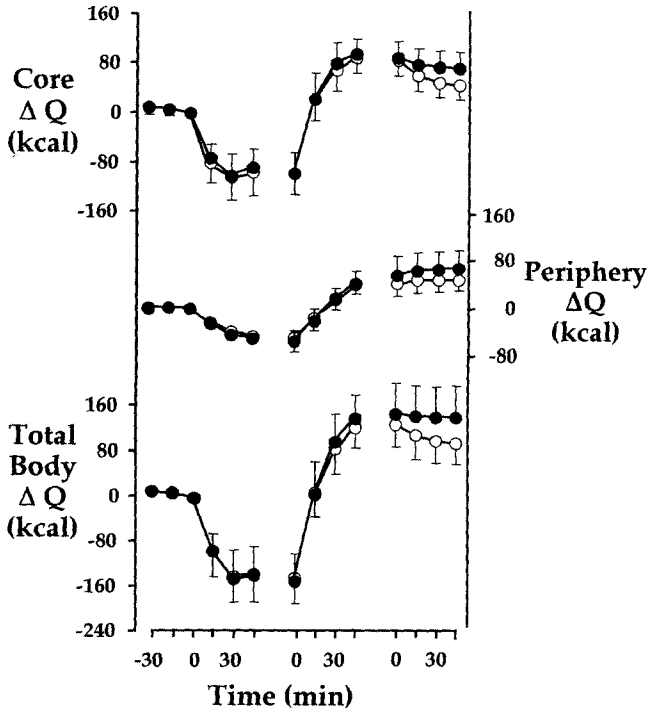

Fig. 1. Change in core and peripheral heat contents during cooling and rewarming while undergoing bypass in the patients assigned to forced-air heating or passive insulation during rewarming. The beginning of bypass cooling was designated time zero for cooling. Because the duration of cooling differed among patients, a second zero time was defined as the beginning of rewarming. Similarly, the end of rewarming identified time zero for the postbypass period. (Filled circles) Patients warmed with forced air. (Open circles) Control patients. Data are presented as the mean ± SD; see table 2 for statistical analysis.

Nitroprusside Protocol

Demographic and morphometric characteristics of the patients assigned to control (n = 15) and sodium nitroprusside (n = 15) were similar (table 3). One patient assigned randomly to the control group was excluded because of surgical problems after weaning from bypass. The mean dose of administrated sodium nitroprusside during rewarming was 1.6 ± 0.6 $\mu g \cdot kg^{-1} \cdot min^{-1}$. Mean individual doses ranged from 0.7 to 3.1 $\mu g \cdot kg^{-1} \cdot min^{-1}$. Nitroprusside administration increased pump flow during the rewarming period from 4.8. ± 0.3 l/min in the control group to 5.7 ± 0.5 l/min. Nonetheless, mean arterial pressure and heart rate were comparable in the two groups.

Changes in core heat content and peripheral tissue heat content were similar during cooling in both groups. However, core and peripheral tissue heat contents were slightly higher in the nitroprusside group during re-

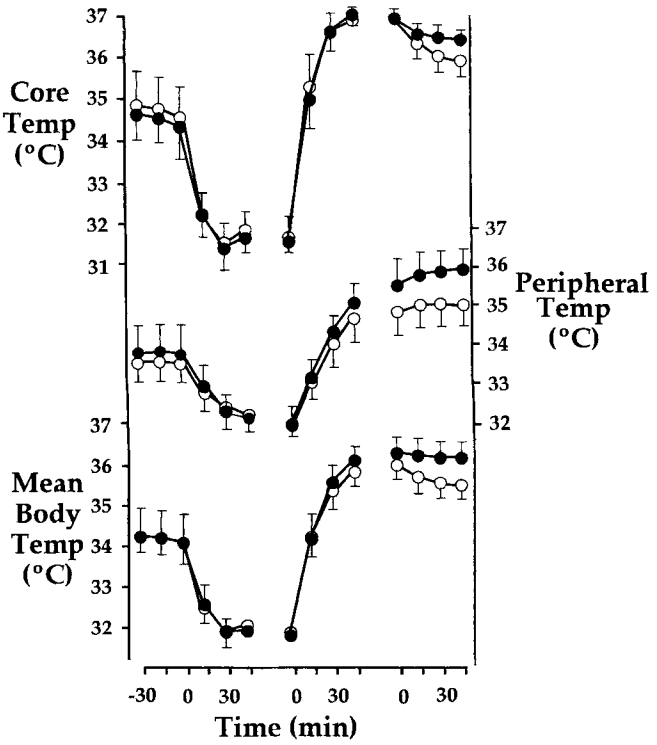

Fig. 2. Core temperatures during and after cardiopulmonary bypass in patients assigned to forced-air heating or passive insulation during rewarming. The beginning of bypass cooling was designated time zero for cooling. Because the duration of cooling differed among patients, a second zero time was defined as the beginning of rewarming. Similarly, the end of rewarming identified time zero for the postbypass period. (Filled circles) Patients warmed with forced air. (Open circles) Control patients. Data are presented as the mean ± SD; see table 2 for statistical analysis.

warming. After discontinuation of bypass, peripheral heat content increased twice as much in the nitroprusside group than in the control patients (12 ± 10 kcal *vs.* 6 ± 8 kcal). Core heat content decreased similarly in both groups. Consequently, total body heat content at the end of surgery was 102 kcal higher than precooling values in the nitroprusside group, but only 65 kcal greater in the control patients, a difference that was statistically significant (fig. 3).

Peripheral tissue temperature was comparable in the two study groups at the onset of bypass and during cooling. Rewarming during bypass increased peripheral tissue temperature 0.5°C more in the nitroprusside group than in the control patients. The core-to-peripheral tissue temperature gradient at the end of warming was significantly less in the nitroprusside (2.0 ± 0.7°C) than in the control (2.6 ± 0.5°C) group. Peripheral tissue temperature continued to increase in the nitroprusside group after discontinuation of bypass, whereas it remained nearly unchanged in the control group. Consequently, peripheral tissue temperature was 0.7°C greater in the nitroprusside than in the control group at the end of surgery.

Core temperature at the onset of bypass, approximately 1 h after induction of anesthesia, did not differ between groups and decreased to a minimum value near 31.9°C in both groups. Bypass was discontinued at a core temperature of 37°C in both groups. In the nitroprusside group, a rectal temperature of 36°C was reached after 30 ± 7 min of rewarming, and the maximum rectal temperature was 36.8 ± 0.4°C at the end of rewarming. In contrast, it required 40 ± 13 min to reach a rectal temperature of 36°C in the control group, and even at the end of rewarming, rectal temperature remained at 36.4 ± 0.4°C, which was significantly lower than in the nitroprusside patients (fig. 4).

The core temperature afterdrop in the nitroprusside group was 0.8 ± 0.3°C and lasted 34 ± 10 min after bypass, whereas the core temperature afterdrop in the control group was 1.1 ± 0.3°C and lasted 44 ± 13 min after bypass. This difference was significantly significant, but is not clinically important (table 4).

Table 2. Temperatures, Afterdrop, Pump Flow, and Hemodynamic Responses During the Forced-air Protocol

	Passive Insulation	Forced-air	*P*
Nasopharyngeal temperature at the end of rewarming (°C)	37.1 ± 0.2	37.0 ± 0.2	0.240
Rectal temperature at the end of rewarming (°C)	36.3 ± 0.6	36.5 ± 0.6	0.440
Peripheral tissue temperature at the end of rewarming (°C)	34.8 ± 0.6	35.5 ± 0.7	0.028
Core-to-peripheral temperature gradient (°C)	2.2 ± 0.6	1.4 ± 0.5	0.004
Afterdrop (°C)	1.2 ± 0.2	0.5 ± 0.2	<0.001
Afterdrop duration (min)	50 ± 11	27 ± 14	<0.001
Pump flow during rewarming (l/min)	5.1 ± 0.2	5.2 ± 0.1	0.590
Mean arterial pressure during rewarming (mmHg)	66 ± 11	68 ± 8	0.870
Systemic vascular resistance during rewarming (dyn · s · cm^{-5})	966 ± 47	951 ± 37	0.840
Heart rate after bypass (beats/min)	78 ± 2	82 ± 2	0.470
Ambient temperature (°C)	21.2 ± 0.2	21.3 ± 0.1	0.290
Total fluid (l)	4.7 ± 0.7	4.7 ± 0.9	0.950

Data presented as the mean ± SD.

Table 3. Morphometric and Demographic Characteristics in the Nitroprusside Protocol

	Control	Nitroprusside	*P*
Sex (M/F)	13/1	11/4	—
Weight (kg)	79 ± 8	78 ± 11	0.89
Height (cm)	173 ± 5	172 ± 7	0.62
Age (yr)	64 ± 9	62 ± 11	0.64
Preoperative ejection fraction (%)	51 ± 11	54 ± 14	0.50
Grafted veins/arteries	24/17	27/18	—
Arm weight (kg)	10 ± 1	9 ± 2	0.30
Leg weight (kg)	27 ± 4	27 ± 5	0.94
Peripheral fraction of body mass (%)	47 ± 3	46 ± 3	0.45
Core weight (kg)	42 ± 4	42 ± 6	0.86
Cooling time (min)	50 ± 12	49 ± 14	0.78
Total rewarming time (min)	51 ± 12	50 ± 12	0.81
Total bypass time (min)	101 ± 21	99 ± 19	0.75
Time from separation of bypass until the end of surgery (min)	57 ± 12	59 ± 9	0.70

Data presented as the mean ± SD. There were no statistically significant differences between the groups.

Discussion

Afterdrop, the precipitous reduction in core temperature after cardiopulmonary bypass, results from core-to-peripheral redistribution of body heat and systemic heat loss from surgical incisions to the environment.[14,28] The primary factors influencing afterdrop magnitude are the core-to-peripheral tissue temperature gradient, the core temperature during cooling while undergoing bypass, the duration of rewarming during bypass, and blood-borne convection of heat. This study evaluated two factors likely to alter the temperature gradient between core and peripheral tissues. The key element in both cases is relative isolation of peripheral tissues from the rapid changes in core temperature resulting from cardiopulmonary bypass.

The first factor we tested was peripheral skin surface warming using forced air. Our theory was that the relatively small amount of heat provided by forced air would prevent afterdrop by warming peripheral tissue during the final phase of bypass, thus reducing the core-to-peripheral tissue temperature gradient. Forced-air heating indeed reduced the postbypass decrease in core temperature by more than a factor of two. This finding confirms a recent report.[29] However, the mechanism differed significantly from what we and others assumed.

During the hour of bypass rewarming, lower body, forced-air warming probably increased net transfer of heat across the skin surface by 50 kcal.[30,31] Peripheral tissue temperature and heat content at the end of rewarming were thus greater than in the control group. As a result, the core-to-peripheral tissue temperature gradient was slightly reduced in the forced-air patients: 2.2 *versus* 1.4°C. However, core temperature was identical in the two groups at the end of rewarming.

Peripheral tissue temperature increased during the postbypass period in both groups and was consistent with some core-to-peripheral redistribution of body heat. However, total body heat content decreased in the control patients, whereas it remained nearly constant in the actively warmed patients. This suggests that the major benefit of forced-air warming was systemic warming sufficient to prevent postbypass heat loss from the surgical incision. Forced-air heating therefore significantly ameliorated the postbypass decrease in core temperature, but not by preventing redistribution; instead, surface warming better maintained body heat content.

The second factor we tested was nitroprusside admin-

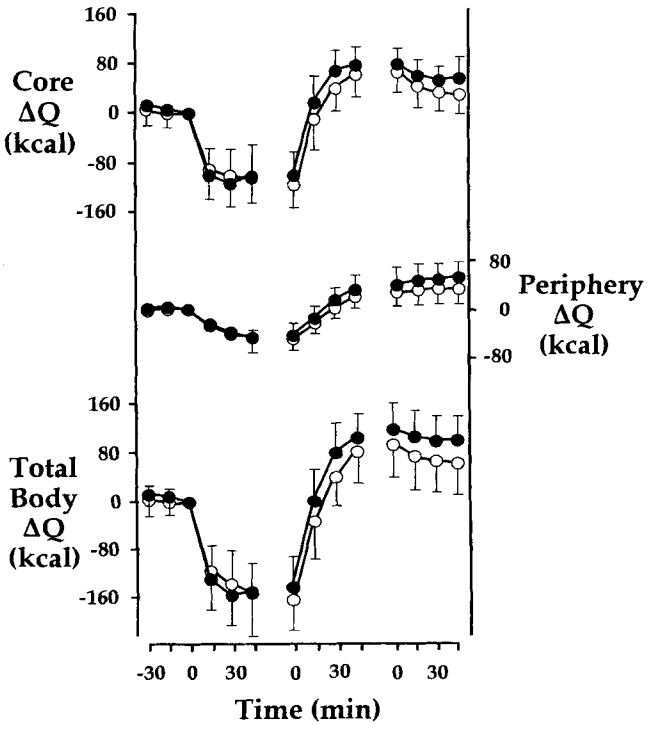

Fig. 3. Change in core and peripheral heat contents during cooling and rewarming while undergoing bypass for patients participating in the nitroprusside protocol. The beginning of bypass cooling was designated time zero for cooling. Because the duration of cooling differed among patients, a second zero time was defined as the beginning of rewarming. Similarly, the end of rewarming identified time zero for the postbypass period. (Filled circles) Patients undergoing vasodilation with sodium nitroprusside. (Open circles) Control patients. Data are presented as the mean ± SD; see table 4 for statistical analysis.

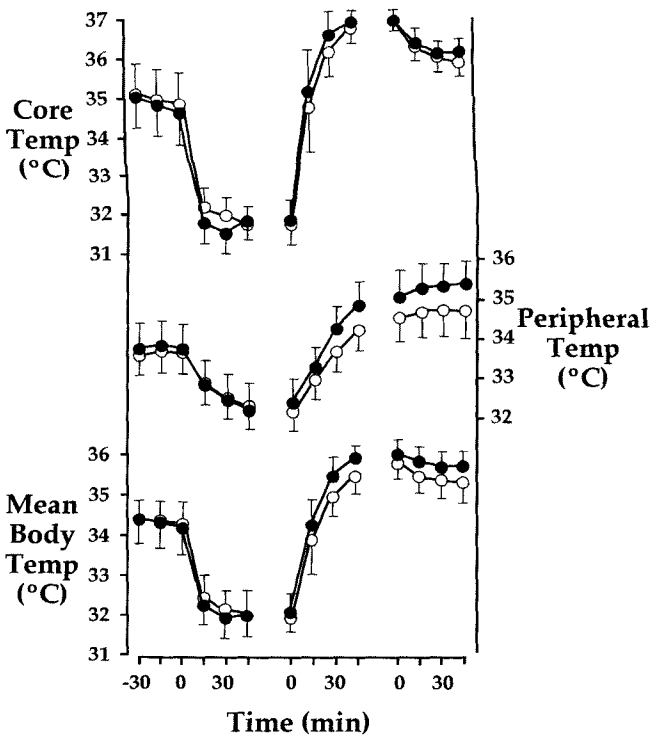

Fig. 4. Core temperatures during and after cardiopulmonary bypass for patients participating in the nitroprusside protocol. The beginning of bypass cooling was designated time zero for cooling. Because the duration of cooling differed among patients, a second zero time was defined as the beginning of rewarming. Similarly, the end of rewarming identified time zero for the postbypass period. (Filled circles) Patients undergoing vasodilation with sodium nitroprusside. (Open circles) Control patients. Data are presented as the mean ± SD; see table 4 for statistical analysis.

istration, the theory being that active vasodilation would improve distribution of heat from core tissues to the periphery. Nitroprusside infusion during rewarming slightly increased peripheral tissue temperature and heat content and the rate at which core temperature increased. However, the core-to-peripheral temperature gradient was similar and low in each group (2.0 and 2.6°C). Consequently, there was little redistribution in either group, and the difference in afterdrop between the groups was only 0.3°C.

In 1980, Noback and Tinker[18] first reported a reduction in core temperature afterdrop by nearly 1°C when sodium nitroprusside and high pump flow was used during rewarming. Recent studies by Deakin *et al.*[20] and Tugrul *et al.*[19] reported 0.5 and 1.0°C decreases in afterdrop in patients who underwent vasodilation with nitroprusside during warming. However, in both studies, patients were cooled to 28°C or less during bypass. An additional important difference is that rewarming was rapid because large temperature differences were maintained between the arterial inflow and water in the heat exchanger. Finally, bypass appears to have been discontinued at relatively high core temperatures (*i.e.*, 38°C).

All of these factors contribute to a high core-to-peripheral temperature gradient, which is the major factor determining afterdrop magnitude. Therefore, there are many reasons to expect that nitroprusside would be more effective at lower bypass temperatures than at the approximate 32°C we maintained. An additional difference is that we included only patients undergoing coronary artery bypass grafting with a left ventricular ejection fraction that exceeded 40% who did not require intra- or postoperative vasoactive medications. Furthermore, none had known peripheral vascular disease or diabetes mellitus. Therefore, our results apply to bypass near 32°C in relatively healthy patients who are slowly

Table 4. Temperatures, Afterdrop, Pump Flow, and Hemodynamic Responses during the Nitroprusside Protocol

	Control	Nitroprusside	*P*
Nasopharyngeal temperature at the end of rewarming (°C)	37.0 ± 0.2	37.0 ± 0.2	0.510
Rectal temperature at the end of rewarming (°C)	36.4 ± 0.4	36.8 ± 0.4	0.012
Peripheral tissue temperature at the end of rewarming (°C)	34.5 ± 0.6	35.0 ± 0.7	0.036
Core-to-peripheral temperature gradient (°C)	2.6 ± 0.5	2.0 ± 0.7	0.018
Afterdrop (°C)	1.1 ± 0.3	0.8 ± 0.3	0.047
Afterdrop duration (min)	44 ± 13	34 ± 10	0.030
Pump flow during rewarming (l/min)	4.8 ± 0.3	5.7 ± 0.5	<0.001
Mean arterial pressure during rewarming (mmHg)	67 ± 10	65 ± 9	0.520
Systemic vascular resistance during rewarming ($dyn \cdot s \cdot cm^{-5}$)	1002 ± 54	869 ± 42	0.040
Heart rate after bypass (beats/min)	78 ± 3	80 ± 3	0.740
Ambient temperature (°C)	21.2 ± 0.1	21.1 ± 0.1	0.250
Total fluid (l)	4.7 ± 1.0	5.7 ± 1.4	0.04

Data presented as the mean ± SD.

rewarmed to a normal (as opposed to a supranormal) core temperature.

The core-to-peripheral temperature gradient in these patients at the end of bypass (1.4–2.6°C) was less than that we reported previously (3.5 ± 1.8°C).[14] Although the protocols are superficial similar, there are some important differences. For example, bypass flow was nonpulsatile.[32] Furthermore, patients in the previous study were cooled to a lower core temperature during bypass and rewarmed to higher core temperatures before discontinuation of bypass. It is likely that these factors combined to reduce the core-to-peripheral gradient in the current patients and, thus, the potential benefits of nitroprusside.

In summary, cutaneous warming reduced the core temperature afterdrop from 1.2 ± 0.2°C to 0.5 ± 0.2°C. However, heat-balance data indicate that this reduction resulted primarily because forced-air heating prevented the typical decrease in body heat content after discontinuation of bypass, rather than by reducing redistribution. Nitroprusside administration slightly increased peripheral tissue temperature and heat content at the end of rewarming. However, the core-to-peripheral temperature gradient was low in both groups. Consequently, there was little redistribution in either case. We conclude that forced-air heating during and after rewarming decreases afterdrop magnitude. In contrast, nitroprusside administration does not produce a clinically important reduction in afterdrop magnitude in patients cooled to approximately 32°C and slowly rewarmed to 37°C.

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