Temperature Control by the Blood Temperature Monitor

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ABSTRACT

The rationale of temperature control during hemodialysis (HD) is to prevent heat accumulation, which increases body temperature and enhances hypotensive susceptibility. Treatments where thermal energy is neither delivered nor removed from the patient through the extracorporeal circulation (so-called extracorporeal thermoneutral treatments) lead to a marked increase in body temperature and to considerable heat accumulation during HD. Since this accumulation of heat cannot be explained by increased heat production, it must be related to reduced heat dissipation through the body surface. Peripheral vasoconstriction, and cutaneous vasoconstriction in particular, compensating for the ultrafiltration-induced decrease in blood volume is considered an important component in this setting. Therefore, to maintain temperature homeostasis, thermal energy has to be cleared from the patient by the extracorporeal system because cutaneous clearance of thermal energy is compromised intradialytically. The focus on dialysate temperature alone does not properly address the problem of controlled extracorporeal heat removal because dialysate temperature is only one of the variables involved in that process. These difficulties can be addressed by changing from the control of dialysate temperature to control of body temperature. Control of body temperature and temperature homeostasis is achievable by the physiologic feedback control system realized in the temperature control mode (T-mode) of the blood temperature monitor (BTM). The delivery of isothermic dialysis, that is, dialysis where body temperature is controlled to remain constant during the treatment, has impressively improved hemodynamic stability in hypotension prone patients.

The rationale of temperature control is to prevent heat accumulation, which increases body temperature in the patient during hemodialysis (HD). In general, an increase in body temperature is associated with an increase in blood flow to the compliant cutaneous circulation to provide cooling, an increase in cardiac output, a decrease in total peripheral resistance, and a reduction in blood pressure (1,2). This decrease in blood pressure should be prevented by temperature control.

Since the first reports in the early 1980s (3) many studies have confirmed that a low dialysate temperature in the range of 34–35.5°C improves intradialytic hemodynamic stability when compared to dialysate temperature set at 37°C or higher (4). Lower dialysate temperature improves cardiac contractility (5) and increases venous tone. For example, in a prospective study done in 11 patients, cool dialysis at 35.5°C significantly increased the lowest intradialytic as well as the postdialytic blood pressure and significantly reduced the number of nursing interventions as well as the volume of saline infused for intradialytic hypotension (6). However, there was no difference when compared to the effect of midodrine, an oral selective α_1-agonist, alone, nor did a combination of both midodrine and cool dialysate temperature provide any further benefit.

Components of Thermal Balance

Even though most studies have focused on dialysate temperature, a reduction in dialysate temperature alone does not properly address the problem of thermal balance during HD because dialysate temperature is only one of the variables involved in this issue.

Extracorporeal Heat Flow

The direct thermal effect of extracorporeal treatments depends on the amount of heat removed (negative sign) or delivered (positive sign) to the patient. Extracorporeal heat flow (J_{ex}, in watts [W]) is determined by the following relationship (7,8):

$$J_{ex} = c\rho(T_{art} - T_{ven})(Q_b - UFR), \qquad (1)$$

where the product $c\rho$ (3.81, in J/°C/cm^3) refers to material constants of blood (9), T_{art} and T_{ven} refer to the arterial and venous line temperatures at the fistula (10), Q_b is the extracorporeal blood flow (in ml/sec), and UFR is the ultrafiltration rate (in ml/sec).

Where is the effect of dialysate temperature (T_{dia}) in this relationship? In a first assumption one would think that the temperature of venous blood returning to the

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patient is determined by dialysate temperature and that T_{ven} can be substituted by T_{dia} in equation 1. This is only a crude assumption as explained in the following.

The thermal insulation of the extracorporeal blood lines is not perfect. Assume a blood line of a given length (L) and a given thermal conductivity per length (α) which is perfused by a blood flow (Q_b) and exposed to the environmental temperature (T_{env}). The temperature of the blood entering the blood line is given as T_{in}. An approximation of the outflow temperature (T_{out}) in still air is obtained by the following relationship (10,11):

$$T_{out} = T_{env} + (T_{in} - T_{env})e^{-(\alpha L/Q_b)}. \quad (2)$$

For high blood flows which reduce the time of exposure of blood to the environment, the temperature drop at the outflow compared to the inflow becomes minimal ($T_{out} \approx T_{in}$). The same is true when reducing the thermal conductivity (i.e., increasing the insulation) and/or the length of the circuit or when increasing the environmental temperature to levels of the inflow temperature ($T_{env} \approx T_{in}$) (Fig. 1).

Venous Line Cooling

With HD the dialyzer serves as a perfect heat exchanger and the blood leaving the dialyzer and entering the venous blood line can be assumed to have the same temperature as the dialysate ($T_{in} = T_{dia}$), independent of arterial blood temperature feeding the extracorporeal circulation and of thermal energy losses in the arterial blood line. The venous fistula temperature at the outlet of the venous blood line can then be determined by inserting the proper variables into equation 2. With values for α in the range of 5–10 ml/min/m the drop in blood temperature in the venous line may be in the range of 0.5–1°C. The magnitude of the temperature drop is very sensitive to blood flow. The magnitude of the thermal energy flow, however, is largely insensitive to blood flow and primarily determined by the insulation characteristics of the venous blood line. Venous line cooling which occurs with any extracorporeal treatment is in the range between – 7 and – 15 W (12).

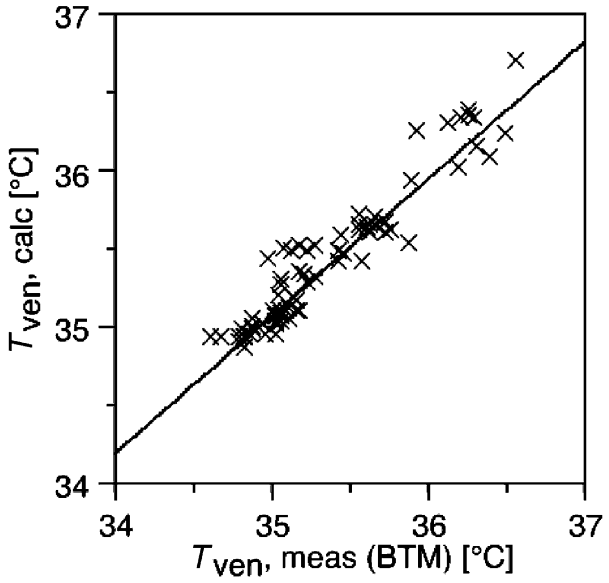

FIG. 1. Venous blood line temperatures. Venous blood line temperatures were measured (T_{meas}) by the BTM and compared to temperatures calculated (T_{calc}) from thermal conductivities, blood flows, dialysate, and environmental temperatures according to equation 2 ($T_{calc} = 0.87^{*}T_{meas} + 4.7$; $R^2 = 0.89$) (11).

Extracorporeal Line Cooling

Without HD and with convective treatment modes such as isolated ultrafiltration there is no heat exchange in the dialyzer and the entire length of the extracorporeal circulation is exposed to the lower temperature of the environment. With regard to the model presented in equation 2, these differences have two major implications. The length (L) of the extracorporeal system to be considered for heat exchange doubles and the inflow temperature to the extracorporeal circulation is given by T_{art} ($T_{in} = T_{art}$) instead of T_{dia}. With the same thermal conductivity of the blood line as above, but with doubling the effective length exposed to the environment, the decrease in blood temperature from the arterial sampling to the venous return site will be in the range of 1–2°C, depending on the blood flow. The magnitude of extracorporeal heat flow will be in the range of – 15 to – 30 W, depending on the insulation characteristics of the blood lines, and again, combined arterial and venous line cooling will be largely independent of blood flow.

Equation 1 can be used to predict expected thermal energy flows for different treatment conditions. For example, assuming a thermal conductivity $\alpha = 9.3$ ml/min/m (10) and a total length of 3 m for the extracorporeal circuit, the extracorporeal heat flow with isolated ultrafiltration when $T_{art} = 36.5$°C, $T_{env} = 22$°C, and $Q_b = 250$ ml/min is predicted with – 24 W. The actual average heat flow measured under these conditions was – 27 W (13). A similar effect on venous temperatures and extracorporeal cooling is to be expected with sham dialysis, which has been used to study the effects of blood exposure to the extracorporeal circulation without dialysis and/or ultrafiltration (14).

Online Hemodiafiltration

Since infusate can be produced online and filtered for ultrapure quality, the use of hemodiafiltration (HDF) is expanding. Whether online HDF provides the same hemodynamic benefit as standard HDF remains to be clarified (15). In terms of extracorporeal cooling, there should be no difference between HD and predilution HDF, because all blood passes the dialyzer so that all blood is under the control of dialysate temperature. The situation is different with postdilution HDF. It was recently shown that even when the infusion fluid is taken from dialysate with online HDF, the postdilution mode provides additional cooling. This can be explained by the additional infusion line increasing exposure surface and the reduced blood flow from the dialyzer to the infusion port. The exact amount of cooling provided by postdilution online HDF certainly depends on the ratio of blood flows to infusion flows.

Energy Expenditure

It is instructive to compare the magnitude of thermal energy flows in the extracorporeal system to the energy expenditure of the patient. Resting energy expenditure (REE, in W) in healthy adults can be estimated from anthropometric data using the Harris-Benedict equation (16):

$$REE_{\text{male}} = 3.2 + (0.668 \times \text{weight}) + (0.242 \times \text{height}) - (0.329 \times \text{age}) \quad (3)$$

$$REE_{\text{female}} = 31.7 + (0.470 \times \text{weight}) + (0.087 \times \text{height}) - (0.228 \times \text{age}),$$

where weight, height, and age are given in kilograms, centimeters, and years, respectively. REE for the average adult is in the range of 75 W. Since both kidneys account for approximately 10% of REE (17), the question arises whether the anthropometric formula is applicable to chronic renal failure (CRF) patients. However, specific energy expenditure (in W/kg) measured in 52 HD patients (1.14 ± 0.06 W/kg) was not different from that of healthy subjects (1.30 ± 0.15 W/kg) (18). It appears as if the expected reduction in REE by the loss in kidney function in HD patients was offset by a higher metabolic rate in other body tissues. It can be concluded that the Harris-Benedict equation remains applicable to estimate the energy expenditure in the average HD patient (19).

The amount of cooling observed with convective treatments covers 30–50% of estimated energy expenditure and cannot be without effect on physiologic temperature control. This insight has been helpful in clarifying some myths about the hemodynamic benefits of convective versus diffusive treatments which have been discussed elsewhere (20).

BTM Control

Body temperature and thermal balance during HD can be controlled by the blood temperature monitor (Fresenius Medical Care, Deutschland G.m.b.H., Bad Homburg, Germany) (21). The BTM can be operated in two control modes.

The T-control mode is used to control body temperature. Mixed venous blood temperature draining from all tissues can be considered a good representative of core temperature. However, the temperature of blood drawn from the patient's access does not necessarily reflect mixed venous blood temperature because of possible access and cardiopulmonary recirculation. The effects of recirculation on arterial line temperature are comparable to the effects of recirculation on arterial line urea concentration during dialysis and depend on the type and function of the access used. Thus, to determine mixed venous temperature as a surrogate for body temperature (T_b), arterial blood temperature (T_{art}) needs to be corrected for the combined effects of access and cardiopulmonary recirculation (R) and for the temperature of venous blood returning to the patient (T_{ven}) (22):

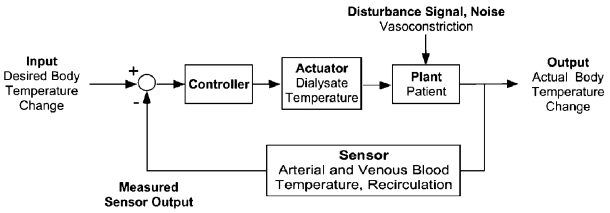

FIG. 2. Closed-loop temperature control system. Scheme of body temperature control as an example for the structure of a closed-loop feedback control system. The target change in body temperature is compared to the measured change in body temperature (sensor output) by the BTM (sensor). The error signal obtained from this comparison (negative feedback) is entered into the controller to determine the dialysate temperature to be set by the dialysis machine (actuator) and to change the temperature in the patient (plant). Even if the actual body temperature (output) is disturbed by external effects (disturbance signal or noise) not accounted for by the control system such as vasoconstriction or increased metabolic rate, the information provided by the actual output (negative feedback) allows to compensate for such effects, the degree of compensation depending on the type of control (proportional, integral, and differential control) (24).

$$T_b = (T_{art} - RT_{ven})/(1 - R). \quad (4)$$

A description of temperature and recirculation measurement by the BTM is found in a companion article in this issue (23).

The T-control mode requires the prescription of an hourly change in body temperature (in °C/hr) (Fig. 2). For example, to control for a constant body temperature throughout a dialysis treatment, that is, to deliver an isothermic dialysis, the temperature change rate has to be set to ±0.00°C/hr. The BTM controller uses the error signal between the desired and actual change in body temperature to actuate a bounded change in dialysate temperature which changes the temperature of the venous blood returning to the patient, thereby changing the extracorporeal heat flow (equations 1 and 2). Body temperature is a physiologic variable. The control of this variable by the BTM may therefore be called a physiologic feedback control system.

The BTM can also be operated in an E-control mode, which controls for the rate of thermal energy removal (in kJ/hr). To control for a treatment where thermal energy is neither removed from the patient nor delivered to the patient, that is, to deliver a so-called extracorporeal thermoneutral dialysis, the thermal energy flow rate has to be set to 0 kJ/hr. Even if this type of control has indirect effects on patient temperature, it actually controls thermal flow rate, which is not a physiologic variable. Therefore it is not a physiologic feedback control system.

While the BTM can be used to measure fistula temperatures and extracorporeal heat balance (J_{ex}) in almost any extracorporeal circulation where Q_b is greater than 120 ml/min, the measurement of recirculation (R), the calculation of body temperature, and the operation of the two control modes requires the presence of dialysis. A more detailed description of control problems in HD can be found elsewhere (24).

Heat Accumulation During HD

Contrary to uremic solutes, which accumulate between treatments, there is a potential for thermal energy to accumulate during HD. Essentially there are three possibilities for intradialytic heat accumulation:

- Delivery of thermal energy by the extracorporeal system. Unless patients with low body temperature are treated with warm dialysate, there is no direct transfer of thermal energy from the extracorporeal system to the patient (equation 7) (12).
- Increase in metabolic rate. The slight increase in metabolic rate of a few percent (25,26) does not explain the requirements to remove thermal energy in the range of 30–40% of estimated REE (13,15).
- Decreased dissipation of heat from the body surface during HD and ultrafiltration. The reduced transfer of metabolic heat from the body core to the body shell is essentially caused by cutaneous vasoconstriction as a compensation for ultrafiltration-induced hypovolemia. The interrelationship between blood pressure and temperature control is most impressively documented by the classic observation of a slow but steady increase in body temperature with a change from supine to upright body position (27). The physiologic control system apparently buys into a certain amount of heat accumulation and heat stress for the benefit of temporary blood pressure control. However, if the volume stress persists for a longer period of time, so that heat accumulation increases beyond a critical threshold, the increase in thermoregulatory drive will lead to an increase in cutaneous blood flow and blood volume which will reduce peripheral resistance and lead to a decrease in blood pressure and an increased risk for intradialytic morbid events. The increase in body temperature with quiet standing is assumed to contribute to orthostatic hypotension.

Volume Hypothesis

The hemodynamic hypothesis of intradialytic heat accumulation is supported by the observation that the amount of thermal energy to be removed for isothermic HD correlates with ultrafiltration requirements and with relative blood volume changes, two measures of hemodynamic perturbation (7,8). The relative heat accumulation of 30% measured in these studies shows that only 70% of the metabolic rate were dissipated through the body surface, whereas 30% of the metabolic rate had to be removed through the extracorporeal circulation, otherwise the body temperature would have increased.

These results prompted further investigations. If heat accumulation were caused by hemodynamic effects, it would be expected that extracorporeal cooling required to maintain a constant body temperature during isothermic HD would be largely different between treatments combined with ultrafiltration and without ultrafiltration. As expected, extracorporeal cooling requirements to maintain a constant body temperature increased with increasing ultrafiltration, however, marked heat accumulation was also found in treatments without ultrafiltration (28). The result that body temperature tends to increase without ultrafiltration cannot be explained by the so-called volume hypothesis, and more studies need to be done to resolve these discrepancies.

Heat accumulation could be related to the circadian rhythm of body temperature. A patient starting isothermic dialysis in the morning would be "clamped" to the temperature measured at the beginning of dialysis and all metabolic heat intended to elevate body temperature because of the circadian rhythm would be removed through the extracorporeal circulation. Indeed, most studies are done during morning and day shifts. In this regard, it would be interesting to study patients during night shifts.

Bioincompatibility and Temperature

Heat accumulation without ultrafiltration could also be related to effects caused by the exposure of blood to the extracorporeal circulation. Exposure to the extracorporeal circulation and to hemophane dialyzers, which excluded the effects of HD and/or ultrafiltration (sham dialysis), decreased white blood cell count, decreased granulocyte oxidative metabolism, and decreased oxygen uptake (14). However, without dialysis it is difficult to control the thermal effects that occur together with blood line exposure. Extracorporeal cooling delivered by sham dialysis was in the range of -25 W, comparable to the cooling provided with isolated ultrafiltration, and comparable to the cooling predicted by equations 1 and 2. Two hours of sham dialysis were also associated with a decrease in body temperature by approximately 0.3°C.

Therefore, to analyze the effect of blood exposure to the extracorporeal circulation and to prevent the cooling of blood which may have masked an increase in body temperature caused by this exposure, the whole extracorporeal circulation would have to be maintained at the temperature of arterial blood entering the circuit. As discussed above (equation 2) the thermal losses to the environment can be minimized when the environmental temperature (T_{env}) is increased to levels of the arterial temperature.[1]

The heat loss to the environment could also be prevented by controlling the temperature of venous blood returning to the patient. In this case, and without preventing heat losses in the arterial line, the temperature of blood exposed to the dialyzer will be 0.5–1°C lower than arterial blood. This temperature drop may be large

[1]Such a setup could be realized by placing the whole extracorporeal circulation into an air-filled bag with the air in this container warmed to 37°C. Air is a good insulator so that heat losses or heat gains in the extracorporeal circulation will be much smaller, even if the temperature of the air is not exactly equal to arterial blood temperature. A water bath would have to be adjusted to follow the changes in arterial blood temperature. In addition to placing the lines into a bag or case, one could place the blood lines (in countercurrent arrangement, for kidney physiologists) into foamed tubes in order to minimize convection. An air bath (insulation) would be easier to place around all parts of the extracorporeal circulation than a water bath. Leaks would not be such a problem. The air could be warmed and blown through this bag or container by an adjustable hair dryer.

enough to modulate the inflammatory response in the dialyzer and could be one of the reasons why convective treatments are better tolerated than diffusive treatments. (With thermoneutral dialysis, i.e., dialysis where thermal energy is neither removed nor delivered to the patient, and without additional insulation of the extracorporeal blood line, the temperature in the dialyzer has to be 0.5–1°C higher than the arterial blood temperature. This temperature difference may be large enough to modulate the inflammatory response in the dialyzer.) Because of the temperature drop that occurs in the arterial line and in the dialyzer, a control of venous line temperature alone appears insufficient when studying the temperature dependence of interactions between the blood and the extracorporeal circulation. Therefore, when investigating effects of temperature on cellular activation in the extracorporeal system, temperature control of the whole extracorporeal system is required.

Optimal Control

Based on the concept of minimally perturbing the physiologic system, it appears straightforward neither to remove nor to add thermal energy through the extracorporeal circulation ($J_{ex} = 0$ W). Such a treatment is called "extracorporeally thermoneutral" (see above). Since blood temperatures tend to decrease in the venous line because blood leaving the dialyzer is exposed to the cool environment, extracorporeally thermoneutral treatments usually require dialysate temperatures in the range of 37–37.5°C. This approach has been followed in a few studies with the result that patient temperatures increased by approximately 0.5°C throughout dialysis (10,29,30). Since an increase in body temperature is expected to increase cutaneous blood flow and to decrease total peripheral resistance (1), thermoneutral HD may indeed favor hypotensive episodes and do more harm than good.

The other major approach would be to adjust the removal of thermal energy so that there is no heat accumulation in the patient (31). This goal can be achieved by controlling for a constant body temperature (T_b = constant). Such a treatment is called "isothermic" ($\Delta T_b = 0$°C) (see above).

The clear hemodynamic benefits of isothermic compared to thermoneutral dialysis have been documented in a multicenter study done in 95 hypotension-prone dialysis patients (32). In this field the study stands out for the number of patients studied and for the approach which eliminated the influence of confounding individual variables, such as absolute body temperatures, blood flows, and dialysate temperatures.

As expected, body temperatures increased by 0.47 ± 0.24°C with thermoneutral treatments, and the 50% incidence of intradialytic morbid events was not affected when compared to the control period. However, using isothermic treatment modes ($\Delta T_{art} = 0.01 \pm 0.16$°C), thermal energy was removed from the patients at a mean rate of -0.90 ± 0.35 kJ/(kg*hr), amounting to 24% of estimated energy expenditure. In order for this to occur, the incidence of intradialytic morbid events fell to 25%.

Isothermic treatments involved considerable cooling but did not affect the dose of delivered dialysis measured by Kt/V_{urea} as might be expected from the alterations in regional blood flow distribution (33). This is in accordance with results from previous studies and can be explained by the reduction in hypotensive episodes, which are themselves known to augment compartment effects and reduce Kt/V_{urea} (29,34,35).

One aspect deserves special attention. Isothermic treatments required a decrease in dialysate temperatures, but the decrease developed gradually throughout dialysis and the minimum dialysate temperature of 35.7°C never reached the lower levels used in many previous studies. This probably explains the good tolerance of the treatment. Is this good tolerance an indicator of optimal care in this aspect of dialysis? One can think of treatment modes where extracorporeal cooling exceeds the requirements for an isothermic treatment so that body temperature eventually decreases. The BTM used in this study can indeed be set to prescribe an hourly change in body temperature. We do not know whether there are any benefits to be expected from such a prescription. However, a control to merely lower body temperature abandons the concept of physiologic feedback control, as under these circumstances the extracorporeal control system is working against physiologic temperature control. Unless there is a resetting in the hypothalamic thermostat during HD, which might be linked to the removal of uremic toxins or to other aspects of the dialysis procedure, the attempt to lower body temperature by the extracorporeal device can be expected to be counterregulated by the much more powerful internal temperature control mechanisms. Patients can be expected to start shivering and feel uncomfortable, which is likely to defeat one of the objectives of an optimal dialysis to minimize the perturbation of the dialysis patient.

In conclusion, when concerned about hemodynamic stability, it is probably best to prevent an increase in body temperature during HD. Since a decrease in body temperature is likely to elicit powerful compensatory mechanisms, such as an increase in metabolic rate, maintaining body temperature at a constant level is probably a good choice.

References

1. Gotch FA, Keen ML, Yarian SR: An analysis of thermal regulation in hemodialysis with one and three compartment models. *ASAIO Trans* 35:622–624, 1989
2. Daugirdas JT: Pathophysiology of dialysis hypotension: an update. *Am J Kidney Dis* 38:S11–S17, 2001
3. Maggiore Q, Pizzarelli F, Zoccali C, Sisca S, Nicolo F, Parlongo S: Effect of extracorporeal blood cooling on dialytic arterial hypotension. *Proc Eur Dial Transplant Assoc* 18:597–602, 1981
4. Sherman RA, Rubin MP, Cody RP, Eisinger RP: Amelioration of hemodialysis-associated hypotension by the use of cool dialysate. *Am J Kidney Dis* 5:124–127, 1985
5. Levy FL, Grayburn PA, Foulks CJ, Brickner ME, Henrich WL: Improved left ventricular contractility with cool temperature hemodialysis. *Kidney Int* 41:961–965, 1992

6. Cruz DN, Mahnensmith RL, Brickel HM, Perazella MA: Midodrine and cool dialysate are effective therapies for symptomatic intradialytic hypotension. *Am J Kidney Dis* 33:920–926, 1999
7. Rosales LM, Schneditz D, Morris AT, Rahmati S, Levin NW: Isothermic hemodialysis and ultrafiltration. *Am J Kidney Dis* 36:353–361, 2000
8. Schneditz D, Rosales L, Kaufman AM, Kaysen G, Levin NW: Heat accumulation with relative blood volume decrease. *Am J Kidney Dis* 40:777–782, 2002
9. Polaschegg HD: Pressure and flow in the extracorporeal circuit. *Clin Nephrol* 53:S50–S55, 2000
10. Schneditz D, Martin K, Krämer M, Kenner T, Skrabal F: Effect of controlled extracorporeal blood cooling on ultrafiltration induced blood volume changes during hemodialysis. *J Am Soc Nephrol* 8:956–964, 1997
11. Morris AT, Schneditz D, Fan Z, Kaufman AM, Levin NW: Dialysate temperature is not the sole determinant of extracorporeal blood cooling during hemodialysis (HD) [abstract]. *J Am Soc Nephrol* 7:1414, 1996
12. Schneditz D: Temperature and thermal balance in hemodialysis. *Semin Dial* 14:357–364, 2001
13. van der Sande FM, Gladziwa U, Kooman JP, Bocker G, Leunissen KM: Energy transfer is the single most important factor for the difference in vascular response between isolated ultrafiltration and hemodialysis. *J Am Soc Nephrol* 11:1512–1517, 2000
14. Kuhlmann U, Sternberg JF, Lange H: Bioincompatibility of the extracorporeal circuit in hemodialysis [abstract]. *Nephrol Dial Transplant* 15:A165, 2000
15. van der Sande FM, Kooman JP, Konings CJ, Leunissen KML: Thermal effects and blood pressure response during post-dilution hemodiafiltration and hemodialysis: the effect of volume of replacement fluid and dialysate temperature. *J Am Soc Nephrol* 12:1916–1920, 2001
16. Harris A, Benedict FG: *A Biometric Study of Human Basal Metabolism in Man*. Publication 279. Washington, DC: Carnegie Institute, 1919
17. Gallagher D, Belmonte D, Deurenberg P, Wang Z, Krasnow N, Pi-Sunyer FX, Heymsfield SB: Organ-tissue mass measurement allows modeling of REE and metabolically active tissue mass. *Am J Physiol* 275:E249–E258, 1998
18. Kuhlmann U, Schwickardi M, Lange H: Energy expenditure in patients with renal failure [abstract]. *Nephrol Dial Transplant* 15:A50, 2000
19. Rosales L, Schneditz D, Ronco C, Levin NW: Prediction of energy expenditure (E) from anthropometric data, heart rate and urea kinetic variables in hemodialysis (HD) patients [abstract]. *J Am Soc Nephrol* 11:295A, 2000
20. Maggiore Q, Pizzarelli F, Dattolo P, Maggiore U, Cerrai T: Cardiovascular stability during haemodialysis, haemofiltration and haemodiafiltration. *Nephrol Dial Transplant* 15:S68–S73, 2000
21. Krämer M, Polaschegg HD: Control of blood temperature and thermal energy balance during hemodialysis. *Proc IEEE EMBS* 14:2299–2300, 1992
22. Krämer M, Polaschegg HD: The relevance of thermal effects during hemodialysis. In: Friedman EA, Beyer MM eds). American Society for Artificial Internal Organs, 39th Annual Meeting. M84. Philadelphia: JB Lippincott, 1993
23. Schneditz D, Kaufmann AM, Levin NW: Surveillance of access function by the blood temperature monitor. *Semin Dial* 16:483–487, 2003
24. Lindsay RM, Schneditz D: In: Winchester JF: ed. Online monitoring and biofeedback. In: *Replacement of Renal Function by Dialysis*. Dordrecht, The Netherlands: Kluwer Academic, 2002
25. Lange H, Krautwald E, Krautwald G, Ebel H: The effect of extracorporeal haemodialysis on energy turnover. *Proc EDTA-ERCA* 22:106–110, 1985
26. Ikizler TA, Wingard RL, Sun M, Harvell J, Parker RA, Hakim RM: Increased energy expenditure in hemodialysis patients. *J Am Soc Nephrol* 7:2646–2653, 1996
27. Amberson WR: Physiologic adjustments to the standing posture. *Univ Md Sch Med Bull* 27:127–145, 1943
28. van der Sande FM, Rosales LM, Brenner Z, Beerenhout CH, Kooman JP, Levin NW, Greenwood RN, Schneditz D, Leunissen KML: Effect of hemodialysis combined with ultrafiltration on thermal parameters, skin blood flow, and energy expenditure [abstract]. Blood Purif 21:368(abst), 2003
29. Kaufman AM, Morris AT, Lavarias VA, Wang Y, Leung JF, Glabman MB, Yosuf SA, LeVoci AL, Polaschegg HD, Levin NW: Effects of controlled blood cooling on hemodynamic stability and urea kinetics during high-efficiency hemodialysis. *J Am Soc Nephrol* 9:877–883, 1998
30. van der Sande FM, Kooman JP, Burema JH, Hameleers P, Kerkhofs AM, Barendregt JM, Leunissen KM: Effect of dialysate temperature on energy balance during hemodialysis: quantification of extracorporeal energy transfer. *Am J Kidney Dis* 33:1115–1121, 1999
31. Maggiore Q: Isothermic dialysis for hypotension-prone patients. *Semin Dial* 15:187–190, 2002
32. Maggiore Q, Pizzarelli F, Santoro A, Panzetta G, Bonforte G, Hannedouche T, Aluarez de Lara MA, Tsouras I, Loureiro A, Ponce P, Sulkova S, Van Roost G, Brink H, Kwan JT: The effects of control of thermal balance on vascular stability in hemodialysis patients: results of the European randomized clinical trial. *Am J Kidney Dis* 40:280–290, 2002
33. Schneditz D, Van Stone JC, Daugirdas JT: A regional blood circulation alternative to in-series two compartment urea kinetic modeling. *ASAIO J* 39:M573–M577, 1993
34. Yu AW, Ing TS, Zabaneh RI, Daugirdas JT: Effect of dialysate temperature on central hemodynamics and urea kinetics. *Kidney Int* 48:237–243, 1995
35. Ronco C, Brendolan A, Crepaldi C, La Greca G: Ultrafiltrations-Rate und Dialyse-Hypotension. *Dialyse J* 40:8–15, 1992