Advanced Course and Workshop on Blood Flow
BF 2005 – (pp.439–449) – Warsaw, 2005.

Patient Temperature in Cardiac Surgery—Model Development and Experiments

N.M.W. Severens [1,2], W.D. Van Marken Lichtenbelt [3]
G.M.J. Van Leeuwen [1], A.A. Van Steenhoven [1]
and B.A.J.M. De Mol [2]

[1] *Technische Universiteit Eindhoven*
PO Box 513, 5600 MB Eindhoven, The Netherlands
n.m.w.severens@tue.nl

[2] *Academic Medical Center*
PO BOX 22660, 1100 DD Amsterdam, The Netherlands

[3] *Maastricht University*
PO BOX 616, 6200 MD Maastricht, The Netherlands

During cardiac surgery the body is cooled by means of the heart lung machine in order to protect vital organs like heart and brain. Afterwards the body is rewarmed followed by decoupling of the heart lung machine. However, due to unnatural distribution of body heat (relatively cold periphery) often an undesirable drop of core temperature occurs. This 'afterdrop' adversely affects recovery.
This article details about the development of a mathematical model to understand the heat transfer processes in the body during surgery. With the numerical model we can mimic the temperature distribution in a human body during and after cardiac surgery. Measurement data is being collected that can be used as input data in the model and for validation of the model. In this way we get more insight into the occurrence and prevention of afterdrop.

1. Introduction

For over four decades, whole body hypothermia has been widely used to reduce metabolic demand and protect vital organs during open heart surgery. During cardiac surgery with cardiopulmonary bypass—the majority of car-

diac surgical interventions—cooling is performed by means of the heart lung machine (HLM). The procedure consists of six distinct phases as detailed below and shown in Fig.1.

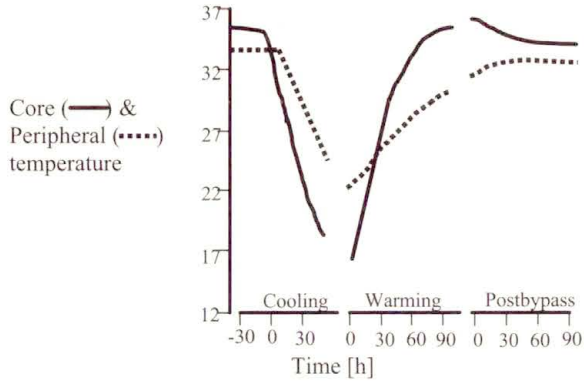

FIGURE 1. Core and peripheral temperatures during and after deep cardiopulmonary bypass. Adapted from Rajek [9].

1. The patient is anaesthetized. Due to anaesthetics the patient's metabolic rate is lowered and the threshold for vasoconstriction shifts to lower core temperatures. Furthermore the anaesthetics often contain vasodilatators. This leads to a lowering of the core temperature of approximately 2°C (not shown in Fig.1) [6].

2. The first stage of the actual surgery: the thorax is opened.

3. The body is connected to a HLM whereby the blood is circulated through the machine. Blood from the HLM enters the body through a tube inserted in the aorta. The oxygenator of the HLM contains a simple heat-exchanger in which the heat exchanging fluid is water. In this stage the patient is cooled further by adjusting the temperature in the heat exchanger.

4. The main cardiac surgical procedure takes place during which the body is kept at a constant low temperature. The temperature during surgery depends on the surgical intervention e.g. for aorta valve replacements and coronary artery bypass grafts 30°C is a common temperature, whilst during surgery on the aortic arch the patient is cooled to 16–18°C.

5. On nearing completion of the surgical procedure the body is warmed at a steady rate by adjusting the water temperature of the heat exchanger. Rewarming must not take place too rapidly in order to prevent cell damage. Core body parts (thorax and brain) react faster on rewarming than peripheral parts (arms and legs).

6. Once the core organs have reached the target temperature the patient is disconnected from the HLM and the temperature of the body is allowed to self equilibrate. This often results in a phenomenon known as afterdrop: a decrease in the temperature of the core organs. The afterdrop effect is considered to be a result of the large temperature difference between the core and peripheral regions at the moment of decoupling [11].

Patients who experience a large afterdrop need longer to recover and may experience more post-operative complications [8] than patients who are not hypothermic after surgery. Clinicians try to prevent or at least minimize the afterdrop effect as much as possible. Often forced-air heating blankets that are draped over the patients legs are used in the rewarming phase. In this way the temperature gradient between the core and the periphery decreases.

For the prevention of the afterdrop effect more knowledge about heat transfer in the anaesthetized human body during cardiac surgery is needed. We are building a numerical thermal model of the patient that can be used by a clinician to determine the optimal warming protocol in order to avoid afterdrop.

2. Whole Body Model

2.1. General Model

The computational model that is being developed is based on descriptions of Fiala [2, 3] who developed a thermal model for predicting human thermal and regulatory responses. We extended the model in such a way that it is also applicable to cardiac surgery.

The numerical model approximates the geometry of the human body with a sphere (head) and cylindrical elements, see Fig. 2. Each element consists of different tissue layers (bone, muscle, fat, skin). The tissue layers consist of one or more nodes. The temperature at the tissue nodes are calculated by

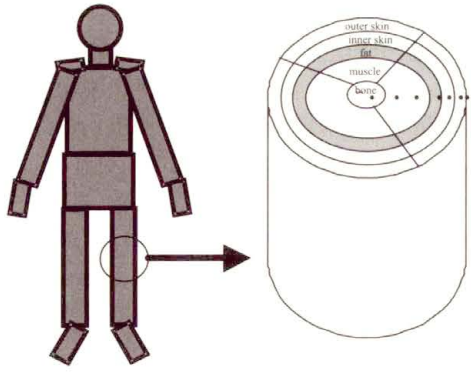

FIGURE 2. Schematic drawing of the human body model. On the right side a detail picture is given of the tissue layers in the leg.

solving the Pennes bioheat [7] equation for each time step:

$$\begin{aligned} \rho c \frac{\partial T}{\partial t} &= \nabla k \cdot \nabla T + \rho_b c_b w_b (T_a - T) + q_m \\ \text{storage} &= \text{conduction} + \text{convection} + \text{heat production} \end{aligned} \tag{2.1}$$

with ρ tissue density, c specific heat, T_a local arterial blood temperature, T tissue temperature, t time, k thermal conductivity, w volumetric blood perfusion rate $[\frac{\mathrm{m^3 blood}}{\mathrm{m^3 \cdot s}}]$, q_m metabolic heat production and subscript b denoting blood properties. The partial derivatives with respect to radius were approximated by using a central difference method. On the interface between two adjoining tissue layers, boundary conditions are used that impose continuity of temperature and heat flux across the interface.

The arterial blood temperature in the human model is calculated by assuming that the returning venous blood is mixed in a virtual mixing vessel. The temperature of the mixed venous blood is the new arterial temperature. For some elements counter current heat exchange (CCX) between arteries and veins takes place. Local temperature T_a is in that case the arterial temperature after CCX.

The heart lung machine is implemented in the model in such a way that the temperature of the arterial blood that enters the body can be prescribed. This temperature is used instead of the mixing vessel temperature of the venous blood.

Autonomous thermoregulation by the body occurs in four ways: vasodilatation, vasoconstriction, shivering and sweating. Thermoregulation is described in the model by implementing control equations based on regression analysis of Fiala [3]. Fiala derived equations that give a description how the human body adapts to changes in the environment so as to maintain its normal temperature. These thermoregulatory responses are determined by the deviation of core temperature and average skin temperature from their neutral values: $\Delta T_i = T_i - T_{i,\text{neutral}}$. The control equation for e.g. vasoconstriction (Cs [-]) reads:

$$\text{Cs} = 35[\tanh(0.3\Delta T_{sk,m} + 1) - 1]\Delta T_{sk,m} + 3.9\Delta T_{sk,m}\frac{dT_{sk,m}}{dt}$$

where $T_{sk,m}$ is the mean skin temperature. Cs has a minimum value of 0. A similar type of equation can be used to describe vasodilatation (Dl [W/K]). Because of the hypothermic situation in cardiac surgery vasodilatation will not occur (Dl = 0). Vasodilatation and vasoconstriction affect the volumetric perfusion of the inner skin layer, but not the blood flow in the other tissue types. Defining $\beta_i = \rho_b c_b w_b$ the expression for tissue blood flow is of the following form:

$$\beta_i = f \times 2^{\frac{T_i - T_{i,0}}{10^{\circ}\text{C}}} \tag{2.2}$$

with

$$\begin{aligned} f &= \frac{\beta_{0,i} + a_{dl,i}\text{Dl}/V_i}{1 + a_{cs,i}\text{Cs}\, e^{-\text{Dl}/50}} && \text{for inner skin layer} \\ f &= 1 && \text{for other tissue} \end{aligned} \tag{2.3}$$

in which $a_{dl,i}$ and $a_{cs,i}$ are the distribution factor of vasodilatation and vasoconstriction respectively and V_i is the volume [m^3] of segment i. Equation (2.2) is based on the Q10-criterium as first mentioned by Stolwijk [12]: a 10 °C temperature decrease will halve the blood flow.

For shivering (Sh [W]) a similar type of control equation as for vasoconstriction has been developed. Shivering leads to extra metabolism in muscle tissue according to:

$$q_{i,\text{Sh}} = a_{sh,i}\text{Sh}/V_i \tag{2.4}$$

which must be included in q_m in Eq. (2.1). In Eq. (2.4) $a_{sh,i}$ is the distribution factor for shivering. The shivering induced perfusion in muscle tissue is given by [5]:

$$\beta_{\text{i,Sh}} = 0.932 q_{i,\text{Sh}}. \tag{2.5}$$

The coefficient 0.932 in Eq. (2.5) is estimated on the basis of the amount of oxygen that blood needs to supply for extra work in muscle tissue [1].

2.2. Adaptation for Anesthesia

Additionally adaptations are made that modify the thermoregulation equations for a situation where the patient is anaesthetized. Sessler [10] showed that thermoregulatory thresholds in anaesthetized subjects differ from unaesthetized subjects. During general anaesthesia the thresholds for vasoconstriction and nonshivering thermogenesis change from $\approx 36.7°C$ to $\approx 34.5°C$. Similarly, the thresholds for active vasodilatation and sweating increase $\approx 1°C$. Shivering rarely occurs during anesthesia and even if it is triggered it is most time prohibited by muscle relaxants.

Van Leeuwen [5] implemented anesthesia parameters that take into account the lowering of the vasoconstriction and shivering thresholds. Temperature shift parameters are introduced to describe the threshold change for thermoregulatory responses during anaesthesia e.g.: $\Delta T_{cs,\mathrm{ca}} = \Delta T_{cs}\mathrm{ca}$, where ca is a measure for the level of anaesthesia and $\Delta T_{cs,\mathrm{ca}}$ is the shift in vasoconstriction threshold at the specific anaesthesia level. The parameters ΔT_{cs} and ΔT_{sh} are fixed input parameters. The values that are used for these parameters in the preliminary simulation given in paragraph 2.3 are $-4°C$ and $-5°C$ respectively.

Some phases during surgery may exist in which the effects of anaesthetics wear off. This is taken into account by adjusting the magnitude of ca where the normalized value of ca is between 0 and 1. The washout of the anaesthetic parameter ca is modelled as follows:

$$\frac{d\mathrm{ca}}{dt} = \frac{\mathrm{ca}_{in} - \mathrm{ca}(t)}{\tau_1} - \frac{\mathrm{ca}(t)}{\tau_2} \tag{2.6}$$

in which ca_{in} is the supply of anaesthetics, and τ_1 and τ_2 time constants describing the average diffusion and decay.

The control equation for vasoconstriction under anesthesia has become:

$$\mathrm{Cs} = 35[\tanh(0.3(\Delta T_{sk,m} - \Delta T_{cs,\mathrm{ca}}) + 1) - 1](\Delta T_{sk,m} - \Delta T_{cs,\mathrm{ca}}) + 3.9(\Delta T_{sk,m} - \Delta T_{cs,\mathrm{ca}})\frac{dT_{sk,m}}{dt} - \mathrm{ca} \times Av.$$

In practice administration of anaesthetics is accompanied by a loss of vascular tone and an increase in peripheral blood flow. This is modelled by adding

the negative term ca $\times$ Av in the control equation for vasoconstriction. The vasotone paramater Av was set to 80 [5].

During cardiac surgery muscle relaxants are administered to the patient that prohibit shivering. Towards the end of the intervention the administered dose muscle relaxants can decline. The control equation for shivering then reads:

$$\mathrm{Sh} = 10[\tanh(0.5(\Delta T_{sk,m} - \Delta T_{sh,\mathrm{ca}}) + 3.6) - 1](\Delta T_{sk,m} - \Delta T_{sh,\mathrm{ca}}) - 28(\Delta T_{hy} - \Delta T_{sh,\mathrm{ca}}) + 1.7(\Delta T_{sk,m} - \Delta T_{sh,\mathrm{ca}})\frac{dT_{sk,m}}{dt} - 30 \quad (2.7)$$

where T_{hy} the hypothalamus/core temperature. Furthermore administration of anaesthetics lowers the metabolic rate. This effect was modelled by adjusting the heat production term in (2.1) in the following way:

$$q_m = q_m(1 - \mathrm{ca} \times q_{\mathrm{ca}}) + q_{Sh}$$

where q_{ca} is set to 0.15 Wm^{-3} for the standard anatomy.

2.3. Example: Cardiac Surgery

With the current model we simulated a complete cardiac surgical procedure with characteristics as in Table 1. In the simulation shivering is impaired during the first two phases. During the second last and last phase (t = 160–270 min.) we assume that shivering is re-establishing according to (2.6) and (2.7). Also vasomotion is returning to a normal level.

TABLE 1. Characteristics of simulation of the surgical procedure.

Time [min]	Simulation
0–70	Supply anaesthetics: ca = 1, T_∞ = 18°C, shivering prohibited
70–160	Cooling patient till 30°C, ca = 1, shivering prohibited
160–210	Rewarming till 37°C, using heating blanket, ca = 0
210	Decoupling from heart lung machine, using heating blanket, ca = 0

In Fig. 3 preliminary results of core and peripheral temperatures are shown during cardiac surgery. This result shows the main temperature characteristics as also observed in Fig. 1, such as the slower reaction of the periphery compared to the core to the arterial blood temperature changes prescribed by the HLM and the characteristic afterdrop after decoupling the

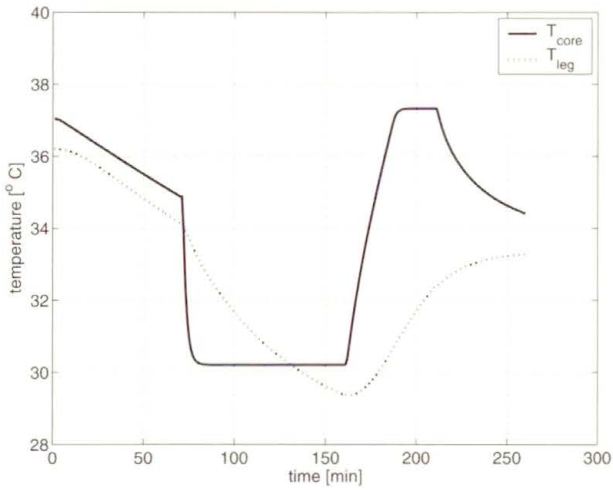

FIGURE 3. Core and peripheral temperature simulations of a cardiac surgery. The solid line gives the core (brain) temperature and the dashed line gives the temperature of the periphery *viz.* muscle layer in the leg.

HLM. Uncertainties in the model exist about the moment shivering actually starts and the chosen values in the vasomotion relations during surgery. Clinical data is now being collected to validate and refine the control equations—vasodilatation, vasoconstriction and shivering—of patients that undergo open heart surgery.

3. Experimental Methods

With approval from the Medical Ethical Committee of the Academic Medical Center of Amsterdam we are studying 16 patients undergoing aorta valve replacement. The aim of the study is to find a relation between different cooling/rewarming procedures and the core-periphery gradient with corresponding changes in perfusion. The study results will be used to deduct relations of thermoregulation—changes in perfusion by vasomotion—of cardiac patients during anesthesia that can be used in the numerical model.

3.1. Protocol

We enroll only patients aged 60–80 years. Patients are cooled during cardiopulmonary bypass to a minimum nasopharyngeal temperature of 30°C. They are rewarmed on completion of surgery to a nasopharyngeal tempera-

ture of 37–37.5°C and a rectal temperature of minimally 36.3°C. The ingoing blood temperature is maximum 4°C warmer than the temperature that leaves the patient's body. The flow rate of the heart lung machine is set to approximately 2.4 L/min per m^2 body surface.

A schematic overview of the experimental setup at the operating theater is depicted in Fig. 4. The same setup is used at the intensive care unit, with the exception of the heart lung machine. Eight patients will be covered with forced-air warming blankets during the rewarming phase and the other eight patients are rewarmed without using heating blankets. After disconnecting the HLM, patients are transferred to the intensive care unit where they are covered by standard draping.

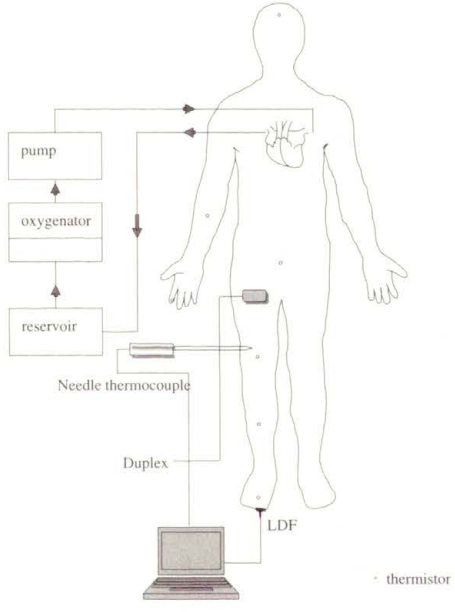

FIGURE 4. Setup in operating theater. The patient is connected to a heart lung machine that consists of: a reservoir, an oxygenator with heat exchanger and a pump. All used measurement techniques are shown at the measurement position: wireless thermistors (iButtons) depicted by ○, needle thermocouple in the upper thigh, Laser Doppler Flowmetry on the big toe, Duplex measurements in the femoral artery.

3.2. Methods

Before surgery the patients's body characteristics are measured: length, weight, length of the thigh and lower leg, circumference of the mid-upper thigh, mid-lower thigh, mid-upper calf and mid-lower calf.

Data is collected during surgery and the first six hours at the intensive care unit. Blood pressure and heart rate are recorded every minute. Core temperatures are measured from the nasopharynx. Temperatures in the rectum and in the pulmonary artery are measured once per minute. Leg tissue temperature is determined using needle thermocouples (Physitemp Instruments Inc.) with three sensors at 8-, 18-, and 38-mm. The needles are inserted perpendicular to the skin surface slightly lateral from the anterior midupper right thigh. Mean skin temperature according to the seven-point system of Hardy/Dubois [4] is determined by performing measurements with wireless thermistors (iButton) at the forehead, lower arm, finger tip, foot dorsum, lower leg, upper leg and abdomen. In order to measure thermoregulatory changes skin perfusion is measured by Laser Doppler Flowmetry (Perimed) on the right big toe. The many arteriovenous shunts under the toe show very strong responses to temperature. The calf-minus-toe skin-surface gradient is also used as an indicator for vasoconstriction and vasodilation [6]. Blood supply to the leg is measured by Duplex-measurements in the right femoral artery. Diameter and centerline velocity in the artery are measured at four defined points in time.

4. Outlook

Measurements have started in the surgery room and intensive care unit. The resulting data will be used for further development of the model. Furthermore the heat loss from the opened thorax during cardiac surgery will be studied what must eventually lead to adjustment of the thorax cylinder in the whole body model.

Acknowledgement

We are fortunate that in building our own model we could build on the model developed by dr. Fiala, now at De Montfort University (UK).

References

1. R.F. BURTON, *Physiology by Numbers; an encouragement to quantitative thinking*, 2nd ed. Cambridge UK: Cambridge University Press, 2000.

2. D. FIALA, K.J. LOMAS, and M. STOHRER, *A computer model of human thermoregulation for a wide range of environmental conditions: the passive system*, J. Appl. Physiol., **87**(5) : 1957–1972, 1999.

3. D. FIALA, K.J. LOMAS, and M. STOHRER, *Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions*, Int. J. Biometeorol., **45** : 143–159, 2001.

4. J.D. HARDY and E.F. DUBOIS , *The technic of measuring radiation and convection*, J. Nutr., **15** : 461–475, 1938.

5. G.M.J. VAN LEEUWEN, F.E.M. JANSSEN, W.D. VAN MARKEN-LICHTENBELT, B.A.J.M. DE MOL, and A.A. VAN STEENHOVEN , *Modelling patient temperature for improved thermal management during surgery*, Proceedings of The ASME-ZSIS International Thermal Science Seminar II, Bled, Slovenia, pp.362–368, 2004.

6. T. MATSUKAWA, D.I. SESSLER, A.M. SESSLER, M.B.A. SCHROEDER, M. OZAKI, A. KURZ, and C. CHENG, *Heat flow and distribution during induction of general anesthesia*, Anesthesiology, **82** : 662–673, 1995.

7. H.H. PENNES, *Analysis of tissue and arterial blood temperatures in the resting human forearm*, J. Appl. Phys., **1**(2) : 93–122, 1948.

8. K.H. POLDERMAN, *Application of therapeutic hypothermia in the intesive care unit: oppurtunities and pitfalls of a promising treatment modality-Part 2: Practical aspects and side affects*, Intensive Care Med, **30** : 757–769, 2004.

9. A. RAJEK, R. LENHARDT, D.I. SESSLER, M. GRABENWÖGER, J. KASTNER, P. MARES, U. JANTSCH, and E. GRUBER, *Tissue heat content and distribution during and after cardiopulmonary bypass at 17°C*, Anesth. Analg., **88** : 1220–1225, 1999.

10. D.I. SESSLER, *Deliberate mild hypothermia*, Neurosur. Anesthesiology, **7**(1) : 38–46, 1995.

11. D.I. SESSLER, *Perioperative heat balance*, Anesthesiology, **92** : 587–596, 2000.

12. J.A.J. STOLWIJK, *A mathematical model of physiological temperature regulation in man*, NASA CR-1855, 1971.