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# Understanding post-operative temperature drop in cardiac surgery: a mathematical model

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A mathematical model is presented to understand heat transfer processes during the cooling and re-warming of patients during cardiac surgery. Our compartmental model is able to account for many of the qualitative features observed in the cooling of various regions of the body including the central core containing the majority of organs, the rectal region containing the intestines and the outer peripheral region of skin and muscle. In particular, we focus on the issue of afterdrop: a drop in core temperature following patient re-warming, which can lead to serious post-operative complications. Model results for a typical cooling and re-warming procedure during surgery are in qualitative agreement with experimental data in producing the afterdrop effect and the observed dynamical variation in temperature between the core, rectal and peripheral regions. The influence of heat transfer processes and the volume of each compartmental region on the afterdrop effect is discussed. We find that excess fat on the peripheral and rectal regions leads to an increase in the afterdrop effect. Our model predicts that, by allowing constant re-warming after the core temperature has been raised, the afterdrop effect will be reduced.

*Keywords*: afterdrop; cardiac surgery; mathematical model.

## 1. Introduction

The cooling of patients during surgical procedures has been used for a number of years in a variety of operations (Curtis & Trezek, 1985) to reduce the metabolic rate of organs within the body and thus the

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amount of oxygen they consume. This has two purposes: (1) it is less likely that irreparable damage to vital organs will occur due to oxygen deficiency; and (2) it allows the surgeon more time should technical complications arise during the surgical procedure.

In the case of cardiac surgery, where cooling is most commonly used for cardiopulmonary bypass, cooling is performed by means of a heart lung machine (HLM). The process consists of five distinct phases as detailed below and shown in Fig. 1.

1. **Anaesthetization stage:** The patient is anaesthetized whereby the core temperature drops naturally by approximately 2°C (partly visible in Fig. 1 in the anaesthesia stage). This temperature drop is a result of redistribution of heat due to vasodilation caused by the anaesthetics (see Sessler, 2000, for further details).
2. The **cooling stage** of the surgery begins. This consists of the chest cavity being opened and the area around the heart (muscle and tissue) being prepared for the main surgical procedure. The body is then connected to an HLM whereby the blood is circulated through the machine and the temperature of the blood lowered at the instruction of the cardiac surgeon in agreement with the perfusionist. Blood from the HLM generally enters the body through a tube inserted in the aorta. A HLM contains a simple heat exchanger whereby the cooling or warming of fluid (most commonly blood) is achieved using water.
3. The main cardiac **surgical stage** takes place, during which the body is kept at a constant cooled temperature. The temperature during surgery depends on the surgical intervention, e.g. for aortic valve replacements and coronary artery bypass grafts 30°C is a common temperature, while during surgery on the aortic arch, the patient can be cooled to as low as 16–18°C.

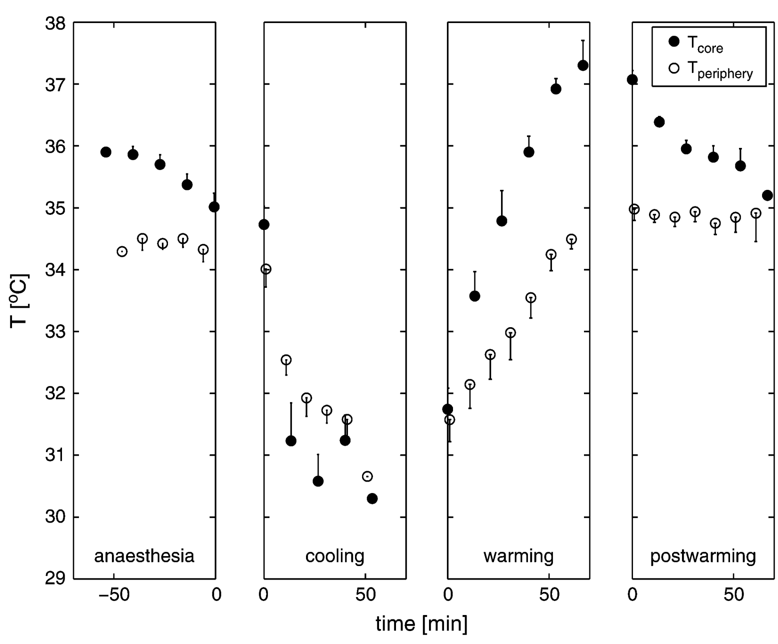


FIG. 1. A typical temperature curve for the cooling and re-warming process during cardiopulmonary bypass surgery (CPBS). Note that the surgical phase is not shown but during this time the temperature remains constant. Based on data from Severens *et al.* (2007b), where the vertical bars are error bars and denote the standard deviation of the mean.

4. **Warming stage:** Following completion of the surgical procedure the blood is warmed at a steady rate. Re-warming must not take place too quickly for large spatial or temporal differences in temperature can cause damage to cells and, on the larger scale, irreversible damage to organs. The maximum temperature to which any part of the tissue should be re-warmed is 37.5°C.
5. **Post-warming stage:** Once the core organs have reached a certain temperature, the patient is disconnected from the HLM and the temperature of the body is allowed to equilibrate.

It is the final stage of this procedure that can often lead to post-operative complications. Disconnection from the HLM and self-equilibration of temperature often lead to a sharp drop in core temperature, a phenomenon known as afterdrop. Afterdrop is assumed to be a result of the large temperature difference between the core and the peripheral regions (primarily the legs and arms). Patients who experience a large afterdrop in temperature often take longer to recover and may experience more post-operative complications than patients who are normothermic at the end of surgery (Sessler, 1995). Hence, the surgical procedure should seek to minimize this effect as much as possible.

In understanding why and how afterdrop occurs, some understanding is required of the heat transfer processes which occur within the body and the ways in which they do so. Since the cooling/heating process is driven by an HLM machine, which cools and warms the blood, respectively, heating of tissue can occur by two mechanisms: convective (perfusion) and conductive heat transfer. Perfusion relates to a volume of blood moving through a region of tissue in a given time. Conduction is the direct transfer of heat between various tissue regions of the body. The rate of perfusion varies over several orders of magnitude between strongly perfused regions, such as the head and chest regions, and weakly perfused regions, such as the limbs. In well-perfused regions of the body, the dominant heat transfer is that between the fluid and the tissue; in poorly perfused regions, conduction may dominate.

Current protocols for both cooling and re-warming patients rely on the expertise and experience of the surgeon, perfusionist and anaesthetist. For instance, in the course of recent years the target temperature for common cardiopulmonary bypass procedures has risen to a higher temperature (Cook, 1999). For example, target temperatures during aortic valve replacements and coronary artery bypass grafts have increased from 28 to 30°C.

A number of mathematical models currently exist in the literature which consider heat transfer within humans and the effect environmental conditions have on human thermoregulation. Early work in the area has been reviewed by Fan *et al.* (1971) and Hwang & Konz (1977). A consistent feature of many of these models is the segmentation or compartmentalization of various regions of the body and the consideration of heat transfer between them. Compartmentalization allows the models to vary in complexity from simple two-state ones to those which account for more complex issues such as metabolism and evaporation. Many of the models use systems of ordinary differential equations (ODEs) to describe the heat transfer between the various compartments. For instance, Stolwijk (1971) developed a six-segment model of the body (head, trunk, arms, hands, legs and feet), each segment consisting of four layers (representing the core tissue, muscle, fat and skin), all linked to a central blood supply. The motivation here was to consider how the body maintains a constant temperature in various cases, e.g. shivering, sweating and the control of vasodilation and vasoconstriction. It was assumed that the various regions of the body (core, muscle, fat and skin) consist of concentric cylinders, the temperature distribution between each region modelled by the heat equation (Pennes, 1948; Wyndham & Atkins, 1968). Huizenga *et al.* (2001) extended Stolwijk's model to consider a large number of body segments. The work of Fiala *et al.* (1999, 2001) has described the variation in temperature in a whole-body model consisting of 15 cylindrical and spherical segments. The model is used to consider the body's passive and active thermoregulatory response to various environmental conditions. An alternative approach is used by Curtis & Trezek

(1985). They formulated a five-compartment model which accounts for heat transfer between the core organs, muscle, fat, skin and the blood and considered the effect that cooling and re-warming have on these various parts of the body. More recent work by Havenith (2001), Zhang *et al.* (2001) and van Marken Lichtenbelt *et al.* (2004, 2007) has focused on adapting certain models so they are more patient subject specific.

In the work which follows, we consider a three-compartment ODE model to understand the heat transfer process which occurs during cooling and re-warming of patients during cardiopulmonary bypass surgery (CPBS). Only the work of Curtis & Trezek (1985) and Severens *et al.* (2007a) has to date focused on modelling heat transfer during CPBS. Our model differentiates between the three body regions of the core, rectum and periphery, and the effect of temperature-dependent and -independent perfusion rates is considered. Particular focus is given to understanding and reducing afterdrop. Increases in excess body fat and how changes in the size of certain body regions effect the re-warming protocol are also considered. Our simplified compartmental model allows the effects of parameter changes and compartmental size on afterdrop to be examined.

## 2. Model description

We consider a three-compartment model consisting of: (a) the core organs with the blood pool in the body core; (b) a rectal region (small and large intestines); and (c) the peripheral parts of the body. Inclusion of the rectal region in our model allows us to compare model outcomes with data on the change in temperature in this region and the effect it has on heat transfer between the core organs and peripheral regions. The peripheral region constitutes the legs and arms as well as the skin, fat and muscle covering other parts of the body.

The blood pool is assumed to be in continuous thermal equilibrium with the core region of the body, and we therefore assign a single temperature to these parts. We further assume that heat transfer is dominated by the effects of perfusion of the blood through the rectal and peripheral compartments, except for the heat transport between the rectum and the periphery, where conduction dominates as shown in Fig. 2. These assumptions are primarily a result of the observed differences in perfusion and conduction rates between different body regions as detailed in Table 1. In the work which follows, we neglect the initial precooling of the body following anaesthesia, Stage 1 of those detailed in Section 1.

As the thermoregulatory responses of the body (the active system) are to a large extent impaired during cardiac surgery, we will only consider passive heat processes (Sessler, 1995). Finally, the effect of heat loss to the environment and any heat generated by metabolic processes is small compared to the redistribution of heat due to anaesthesia and the cooling and re-warming by the HLM (Sessler, 2000). These processes are thus neglected in the work which follows.

While model data are available elsewhere in the literature for temperature recordings taken in other regions of the body, our focus here is on developing a model which accounts for temperatures recorded

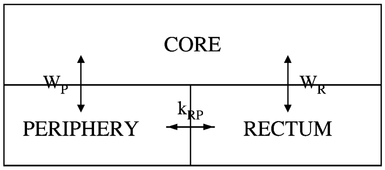


FIG. 2. A schematic representation of the three-compartment model indicating that perfusion ($W_P$ and $W_R$) is the dominant method of heat transfer between the core and rectal and the core and peripheral regions while conduction ($k_{RP}$) dominates between the rectal and the peripheral areas.

TABLE 1 *Model parameters. Values for the density, heat capacity, perfusion and conduction rates are taken from Table* 2 *of Fiala et al.* (1999)

| Parameter | Dimensions | Value | Remarks |
|---|---|---|---|
| $\rho$ | $\mathrm{kg\,m^{-3}}$ | $\sim 1 \times 10^3$ | Volume average of the density for each body segment provided in Table 2 of Fiala *et al.* (1999). |
| $c$ | $\mathrm{J\,kg^{-1}\,K^{-1}}$ | $\sim 2.9 \times 10^3$ | Volume average of the heat capacity for each body segment provided in Table 2 of Fiala *et al.* (1999). |
| $T_0$ | $^\circ\mathrm{C}$ | 37 | Body temperature at start of cooling process. |
| $W_\mathrm{R}$ | $\mathrm{s^{-1}}$ | 0.08 | Average of the perfusion rates for the ‘viscera’, ‘bone’ and ‘muscle’ parts of the ‘abdomen’ segments provided in Table 2 of Fiala *et al.* (1999). |
| $W_\mathrm{P}$ | $\mathrm{s^{-1}}$ | 0.01 | Average of the perfusion rates for all parts of the ‘arms’, ‘legs’, ‘hands’ and ‘feet’ segments excluding the skin. |
| $k_\mathrm{RP}$ | $\mathrm{W\,K^{-1}}$ | $1.10 \times 10^{-5}$ | Conduction estimate based on geometry of abdomen, arms and legs excluding skin. |
| $\alpha$ | $\mathrm{K^{-1}}$ | $6.93 \times 10^{-2}$ | Rate of non-linear perfusion. |
| $a$ | $\mathrm{m^3\,K\,s^{-1}}$ | $4.64 \times 10^4$ | Rate of cooling and re-warming. |
| $V_\mathrm{C}$ (normal) | $\mathrm{m^3}$ | $25 \times 10^{-3}$ | Control parameter. |
| $V_\mathrm{C}$ (obese) | $\mathrm{m^3}$ | $28 \times 10^{-5}$ | Control parameter. |
| $V_\mathrm{R}$ (normal) | $\mathrm{m^3}$ | $7 \times 10^{-5}$ | Control parameter. |
| $V_\mathrm{R}$ (obese) | $\mathrm{m^3}$ | $10 \times 10^{-5}$ | Control parameter. |
| $V_\mathrm{P}$ (normal) | $\mathrm{m^3}$ | $35 \times 10^{-5}$ | Control parameter. |
| $V_\mathrm{P}$ (obese) | $\mathrm{m^3}$ | $55 \times 10^{-5}$ | Control parameter. |

in both the nasal cavity, which we have taken to be part of the core, and the rectum. Given the low perfusion rate of the periphery, in particular fat, and its relatively high conductivity, the periphery may act as a heat source during the cooling procedure and a heat sink during re-warming of the body. Hence, we include it here to see what effect it will have on the overall blood (core) temperature.

The equations governing the heat transfer process are given by

$$V_\mathrm{C}\rho_\mathrm{C}c_\mathrm{C}\frac{\mathrm{d}T_\mathrm{B}}{\mathrm{d}t} = \begin{cases} -a, & 0 \leqslant t < t_1, \\ 0, & t_1 \leqslant t < t_2, \\ a, & t_2 \leqslant t < t_3, \\ -\rho_\mathrm{B}c_\mathrm{B}V_\mathrm{R}W_\mathrm{R}(T_\mathrm{R})(T_\mathrm{B}-T_\mathrm{R}) & \\ \qquad -\rho_\mathrm{B}c_\mathrm{B}V_\mathrm{P}W_\mathrm{P}(T_\mathrm{P})(T_\mathrm{B}-T_\mathrm{P}), & t_3 \leqslant t \leqslant t_4, \end{cases} \tag{1}$$

$$V_\mathrm{R}\rho_\mathrm{R}c_\mathrm{R}\frac{\mathrm{d}T_\mathrm{R}}{\mathrm{d}t} = \rho_\mathrm{B}c_\mathrm{B}V_\mathrm{R}W_\mathrm{R}(T_\mathrm{R})(T_\mathrm{B}-T_\mathrm{R}) - k_\mathrm{RP}(T_\mathrm{R}-T_\mathrm{P}), \quad 0 \leqslant t \leqslant t_4, \tag{2}$$

$$V_\mathrm{P}\rho_\mathrm{P}c_\mathrm{P}\frac{\mathrm{d}T_\mathrm{P}}{\mathrm{d}t} = k_\mathrm{RP}(T_\mathrm{R}-T_\mathrm{P}) + \rho_\mathrm{B}c_\mathrm{B}V_\mathrm{P}W_\mathrm{P}(T_\mathrm{P})(T_\mathrm{B}-T_\mathrm{P}), \quad 0 \leqslant t \leqslant t_4, \tag{3}$$

where

- $T_{\mathrm{B}}$, $T_{\mathrm{R}}$ and $T_{\mathrm{P}}$ [K] are the temperatures of the blood, rectum and periphery, respectively;
- $a$ [W] is the rate of cooling and re-warming of the blood;
- $W_{\mathrm{R}}$ and $W_{\mathrm{P}}$ [$\mathrm{s}^{-1}$] are the blood perfusion rates of the rectum and periphery;
- $k_{\mathrm{RP}}$ [$\mathrm{WK}^{-1}$] is the heat transport coefficient between the rectum and the periphery;
- $\rho_i$ [$\mathrm{kg\,m}^{-3}$] and $c_i$ [$\mathrm{J\,kg}^{-1}\mathrm{K}^{-1}$] ($i = B, C, R, P$) represent the density and heat capacity of the blood, the core organs, the rectum and the periphery;
- $V_i$ [$\mathrm{m}^3$] ($i = C, R, P$) represent the volume of the core, rectum and periphery; and
- $t_1$, $t_2$, $t_3$ and $t_4$ [min] are the times at the end of the cooling stage, the start of re-warming, the end of re-warming and the end of surgery, respectively. The period $t_1 - t_2$ is referred to as the 'surgical time' in the following sections.

Our model equations assume that during cooling and re-warming, the only factor which determines the blood temperature is the rate of cooling/re-warming by the HLM. During surgery, we assume a constant blood temperature. In the final stage of the procedure, after the HLM has been turned off, passive heat processes between the model compartments are assumed to be the main contribution to temperature changes.

It was noted by Stolwijk (1971) that perfusion rates are temperature dependent such that

$$W_i(T_i) \sim \mathrm{e}^{\alpha(T - T_{\mathrm{ref}})}, \tag{4}$$

a relationship (a reformulation of the $Q_{10}$ effect) derived from experimental data on vasculature constriction and dilation in male humans. Here, $i = C, R, P$, $\alpha = 6.93 \times 10^{-2}\,\mathrm{K}^{-1}$ and $T_{\mathrm{ref}}$ is a reference temperature (which we will take equal to 37°C). In the work which follows, we wish to access the importance of temperature-dependent perfusion upon the description of heat distribution.

In the final period, when the body is disconnected from the HLM, the model confirms that the total heat content of the body

$$E_{\mathrm{total}} = V_{\mathrm{C}}\rho_{\mathrm{C}}c_{\mathrm{C}}T_{\mathrm{C}} + V_{\mathrm{R}}\rho_{\mathrm{R}}c_{\mathrm{R}}T_{\mathrm{R}} + V_{\mathrm{P}}\rho_{\mathrm{P}}c_{\mathrm{P}}T_{\mathrm{P}} \tag{5}$$

is conserved.

We assume that all parts of the body are approximately at the same temperature at the start of the cooling procedure such that

$$T_{\mathrm{B}}(0) = T_{\mathrm{R}}(0) = T_{\mathrm{P}}(0) = T_0. \tag{6}$$

This assumption also implicitly assumes that there is no subsequent heat loss or gain to and from the surrounding environment. Cooling of the periphery before the start of the HLM procedure is taken to be negligible.

Data from Fiala *et al.* (1999) give that the ratios of densities and heat capacities between the different regions are approximately unity, i.e. $\frac{\rho_i c_i}{\rho_j c_j} \sim 1$ $(i, j = C, R, P)$. Hence, we can simplify the above model by dividing each equation by the common value $\rho_i c_i$ to yield

$$V_{\mathrm{C}} \frac{\mathrm{d}T_{\mathrm{B}}}{\mathrm{d}t} = \begin{cases} -a^*, & 0 \leqslant t < t_1, \\ 0, & t_1 \leqslant t < t_2, \\ a^*, & t_2 \leqslant t < t_3, \\ -W_{\mathrm{R}}{}^*(T_{\mathrm{R}})(T_{\mathrm{B}} - T_{\mathrm{R}}) - W_{\mathrm{P}}{}^*(T_{\mathrm{P}})(T_{\mathrm{B}} - T_{\mathrm{P}}), & t_3 \leqslant t \leqslant t_4, \end{cases} \tag{7}$$

$$V_{\mathrm{R}} \frac{\mathrm{d}T_{\mathrm{R}}}{\mathrm{d}t} = W_{\mathrm{R}}{}^*(T_{\mathrm{R}})(T_{\mathrm{B}} - T_{\mathrm{R}}) - k_{\mathrm{RP}}{}^*(T_{\mathrm{R}} - T_{\mathrm{P}}), \quad 0 \leqslant t \leqslant t_4, \tag{8}$$

$$V_{\mathrm{P}} \frac{\mathrm{d}T_{\mathrm{P}}}{\mathrm{d}t} = k_{\mathrm{RP}}{}^*(T_{\mathrm{R}} - T_{\mathrm{P}}) + W_{\mathrm{P}}{}^*(T_{\mathrm{P}})(T_{\mathrm{B}} - T_{\mathrm{P}}), \quad 0 \leqslant t \leqslant t_4, \tag{9}$$

where $W_i^*$, $k_{\mathrm{RP}}{}^*$ and $a^*$ are rescaled perfusion, transport and cooling rates given by

$$W_{\mathrm{R}}{}^* = V_{\mathrm{R}} W_{\mathrm{R}}, \quad W_{\mathrm{P}}{}^* = V_{\mathrm{P}} W_{\mathrm{P}}, \quad k_{\mathrm{RP}}{}^* = k_{\mathrm{RP}}/(\rho c) \quad \text{and} \quad a^* = a/(\rho c).$$

The presence of the prefactor of the different volumes for each region allows us to see what effect each may have, in particular the periphery, on the core (blood) and rectal temperatures.

## 3. Parameter values and estimation

Given the detail of the model developed by Fiala *et al.* (1999, 2001), their papers provide a good source of data on rates of heat transfer (via both perfusion and conduction) and the capacitance of specific body parts and organs as shown in Table 1. The rate of cooling and re-warming $a^*$ has been chosen to ensure that heating and cooling of the core take place over a period of 20 min.

Our model will be solved for estimated values of the volume of the core, peripheral and rectal regions and the change in blood temperature as dictated by the HLM. In order to compare the differences in the effect of excess peripheral tissue, we have considered comparing the case of a normal man (weight of 70 kg) with that of an obese individual of the same height, noting that a body mass index of 30 or greater is considered an indicator of large amounts of excess body tissue. The excess body mass has been distributed throughout the three regions, with the majority being added to the periphery.

## 4. Model analysis and results

Equations (7–9) were solved numerically with the respective initial conditions (6) using the ODE solver ode45 in Matlab.

Figure 3 shows solutions of the model for a typical surgical time of one hour, where the perfusion rates are described by (4). We note that this result shows good qualitative agreement with Fig. 1, in particular the afterdrop effect in the core region at the end of the re-warming process is clearly observed. The difference in temperature distribution between the core, rectum and periphery in time is as expected, where the temperature of the periphery takes a longer period of time to decrease given that conduction between the rectum and the periphery is the most dominant form of heat transport in comparison to perfusion.

### 4.1 *The effect of temperature-dependent perfusion*

In order to assess the contribution of temperature-dependent perfusion to the rate of heat transfer between the core and peripheral and rectal regions, we consider solutions to the governing equations for

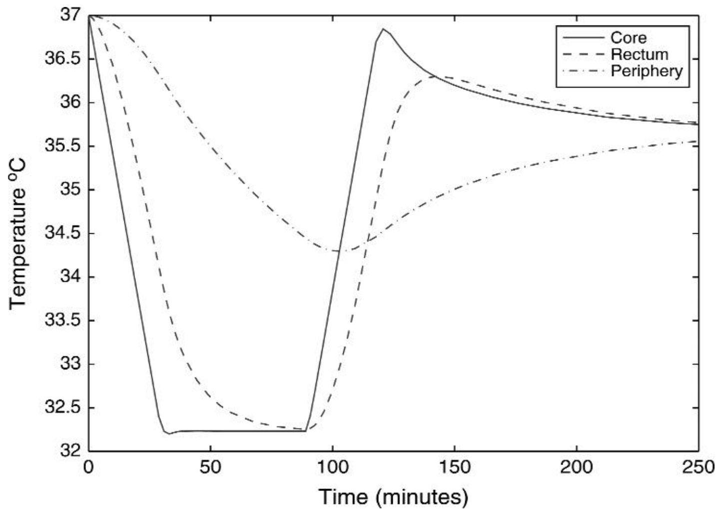


FIG. 3. Model results for a cooling and re-warming procedure. The simulation is for a healthy individual with a body cooling time of 30 min, surgery lasting 60 min and re-warming of 30 min. Parameter values used are those detailed in Table 1.

the two cases of $\alpha = 6.93 \times 10^{-2}\,\mathrm{K}^{-1}$ and $\alpha = 0\,\mathrm{K}^{-1}$ (constant perfusion), for different surgical times. Model solutions for the two cases are shown in Fig. 4(a,b). We note that there are slight deviations in the peripheral and rectal temperatures towards the end of the cooling process, when perfusion is taken to be temperature dependent or constant. This is a result of the effects of temperature-dependent perfusion requiring more time to obtain a larger temperature differential, given the smallness of $\alpha$. In the case where $\alpha(T - T_{\mathrm{ref}}) \sim \mathrm{O}(1)$, i.e. when the temperature differential is larger, the effect of the non-linear relationship of (4) is more pronounced, leading to a larger difference in the rectal and peripheral temperatures (results not shown). For completeness and the remainder of the work presented here, we take $\alpha = 6.93 \times 10^{-2}\,\mathrm{K}^{-1}$.

## 4.2 *Afterdrop*

Figures 3 and 4(a) show model results for a surgical time of 60 min, for constant and non-linear perfusion rates, and Fig. 4(b) shows results for a surgical time of 120 min (non-linear perfusion rate). Both results show a considerable drop in core temperature (afterdrop) at the end of the re-warming process. We note that although the surgical time varies in each case, the magnitude of the afterdrop remains relatively constant at approximately 1.3–1.5°C, the slightly larger difference being for the longer surgical time. This is because there is little variation in temperature for the rectal and peripheral regions for the two different cases, hence leading to a little change in the final temperature difference at the end of re-warming and the final equilibrium temperature.

In order to reduce afterdrop, we have considered what effect re-warming at a constant temperature following surgery has on the overall afterdrop effect. Figure 5(a,b) shows constant re-warming for 30 and 60 min, respectively, following a surgical time of 120 min. We note that even re-warming for a period of 30 min reduces the afterdrop effect from around 1.5 to 0.8 °C, comparing Figs 4(b) and 5(a). Longer re-warming, for a period of 60 min, reduces this difference to less than half a degree. This reduction in afterdrop can be explained by considering the effect that re-warming has on the

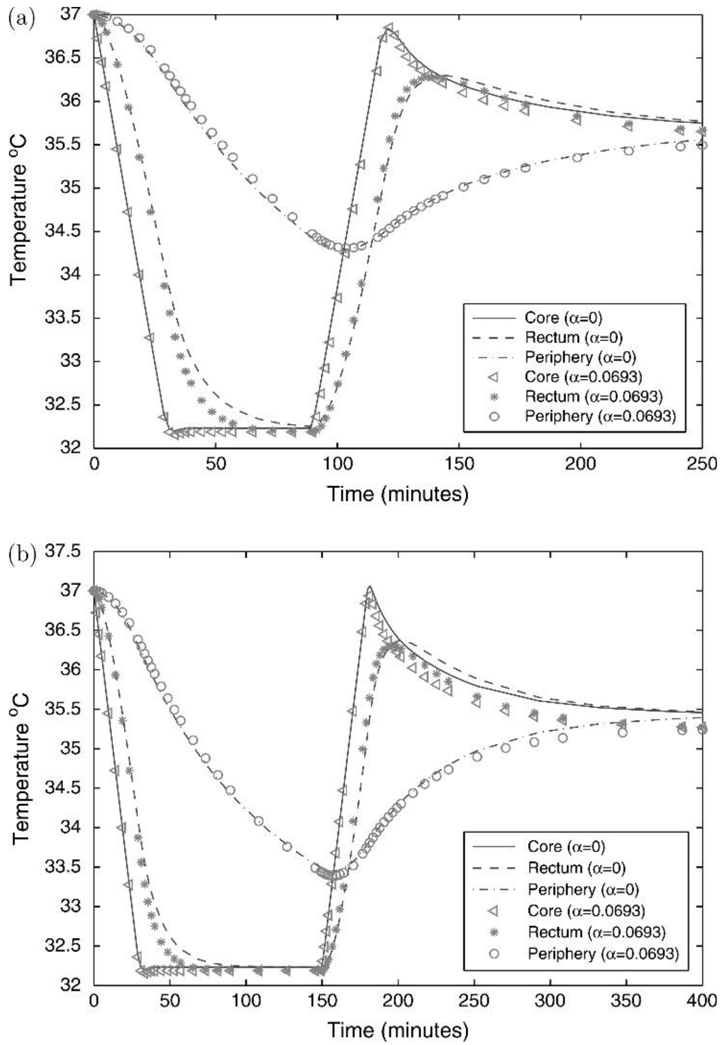


FIG. 4. The effect of temperature-dependent perfusion on predicted temperature distribution in the core, rectum and periphery for surgical times of (a) 60 and (b) 120 min. (a) Only a marginal difference between the predicted temperature for each region for constant ($\alpha = 0$) and non-linear perfusion ($\alpha = 6.93 \times 10^{-2}$) in (4). Here, the temperature variation between the regions is small. However, marginally greater differences in the final temperature are seen as shown in (b), when the temperature variation between regions is largest (due to prolonged surgical time and further peripheral cooling) and perfusion is the dominant warming mechanism between the regions.

redistribution of heat throughout the system. In implementing re-warming, one allows the temperature of the rectal and peripheral regions to slowly rise such that the difference between these and the core region is reduced. In keeping the core at a constant warm temperature, while these regions are re-warmed, the temperature difference between the regions is reduced to a point where the afterdrop effect is negligible.

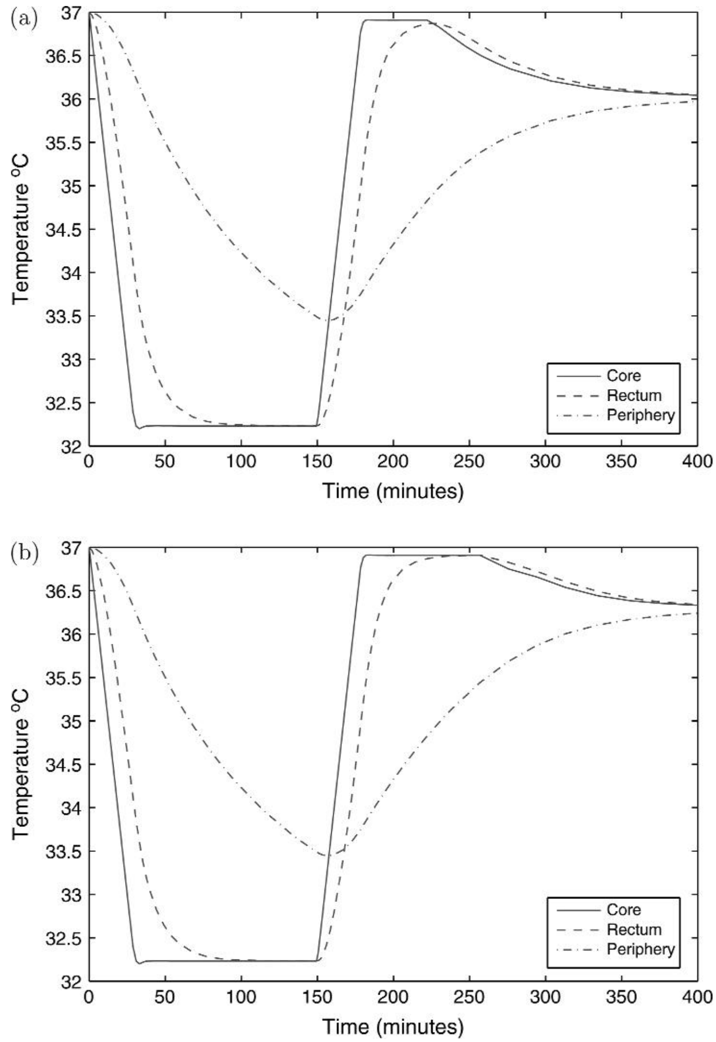


FIG. 5. The effect of constant warming at the end of the re-warming procedure for a surgical time of 120 min. A constant warming time of 45 min is shown in (a) and that of 90 min in (b). Note the reduction in afterdrop.

### 4.3 *Excess peripheral tissue*

Our model formulation allows us to assess the effect that variation in the size of each of the three compartments may have on the cooling and re-warming process. This is particularly pertinent in cases where patients may carry excess body fat. While the core region of patients with excess body fat is likely to remain of similar size to the case of a healthy person, excess fat will be deposited primarily in the peripheral and to some degree rectal regions. Our model allows us to compare the effect that variation in volume of these two regions has on the observed afterdrop.

Figure 6(a,b) demonstrates the effect that variation in the size of the rectal and peripheral regions has on the magnitude of the afterdrop effect. In the case of Fig. 6(a), we have considered the case of a standard cooling and re-warming procedure with a surgical time of 120 min. This figure demonstrates

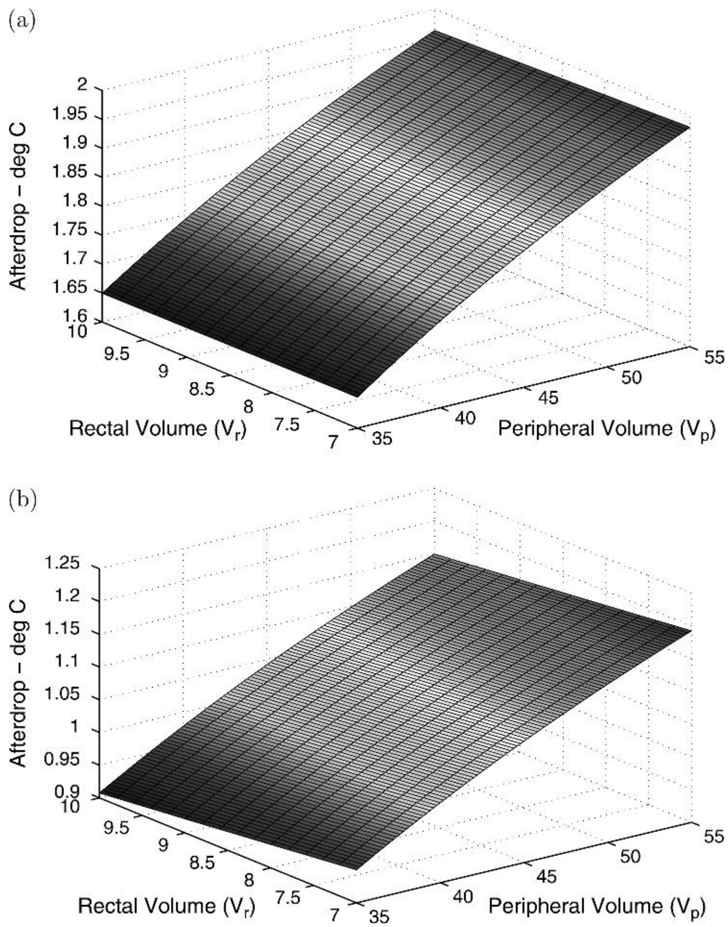


FIG. 6. The effect that the size of the rectal and peripheral regions has on the overall afterdrop effect. A common cooling and re-warming procedure with a surgery time of 120 min results in a volume versus temperature variation in afterdrop as shown in (a). In (b), we have considered the effect of a post-surgical constant re-warming time of 45 min.

that as the size of the regions increases, so does the effect of afterdrop. This is not unexpected given an increase in tissue for the other compartments, comparative to the core region which remains fixed, means a larger heat sink exists leading to a larger difference in temporal temperature gradients. The effect of constant post-surgical re-warming, for a period of 45 min, is demonstrated in Fig. 6(b). We note that the qualitative nature of the result is the same as that without additional re-warming—the afterdrop increases with increasing size of the rectal and peripheral regions. However, we note that the average afterdrop temperature across the varying size of the rectal and peripheral regions is $0.79 \pm 0.06^{\circ}$C compared to $1.83 \pm 0.1^{\circ}$C for non-constant post-surgical re-warming.

## 5. Summary and discussion

A simple compartmental model has been formulated to describe the heat transfer processes between bulk tissue regions during cooling and re-warming of bodies during surgical procedures. In particular, our model formulation has allowed us to focus on understanding the effect of a large temperature drop in the core organs at the end of the re-warming process (afterdrop), the effect that an increase in excess tissue on the rectal and peripheral regions has on the size of the afterdrop effect and whether temperature-dependent perfusion effects any of these outcomes.

The afterdrop effect was found to increase with longer surgical periods if the re-warming period remained the same. This is due to increased surgical time leading to an increase in the temperature difference between the rectal and peripheral regions and that of the core. Constant re-warming at the end of the post-surgical re-warming period helped to redistribute heat over the compartments thus decreasing the afterdrop effect. Unless the timescale of interest for surgery was particularly long or the change in temperature is particularly large, neither of which is present here, temperature-dependent perfusion was not found to greatly affect the model outcomes.

Increasing the size of the rectal and peripheral regions increased the afterdrop effect. While the trend in increasing afterdrop with increasing size of the rectal and peripheral regions remained the same with and without constant post-surgical re-warming, the average afterdrop temperature was reduced by more than 60% when constant re-warming was introduced. We note that we have not accounted for the effect that any changes in excess body fat may have on the tissue properties. Such effects require knowledge of how perfusion and conduction change as the tissue size varies.

Our model and its conclusions have allowed us to understand how heat is dynamically distributed during the cooling and re-warming procedures employed in a number of surgical procedures. This has allowed us to suggest a simple remedy for decreasing the effects of afterdrop, i.e. to simply re-warm patients for extended periods of time following the surgical procedure. This result shows the advantage of keeping patients connected to the HLM a little longer and the related physiological benefits of doing this, e.g. improved vasodilation. However, this result competes with findings between CPBS duration and morbidity; increasing the duration of the total surgical time can have adverse physiological effects (Sotaniemi, 1980; Wesselink *et al.*, 1997). Wahba *et al.* (2001) found a significant correlation between the duration of CPBS and increased blood coagulation as well as a decrease in platelet count and function during CPBS. Longer surgery can also lead to an increased need for transfusion of red blood cells.

We note that our model has not included other effects which could act as further heat sinks such as heat loss through the thorax and chest cavity to the surrounding surgical theatre (heat loss to the environment) and the fact that patients are unclothed during surgery. Such surgical procedures often now employ the use of thermal forced air heating blankets to prevent heat loss from the peripheral regions to the outside environment. Furthermore, the dilation of vessels, while occurring on a smaller length scale than that of the overall body, may play important roles in the redistribution of heat to such regions. Although small compared to heat redistribution during the surgical procedure, heat generated from any metabolic processes could be included as an extension of the current model. It is our aim to assess the effects of such issues in future work.

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