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The thermal model of the rat under hemorrhagic shock hypothermia with microwave intervention

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ABSTRACT

The Thermal Model of the Rat Under Hemorrhagic Shock Hypothermia with Microwave Rewarming Intervention

by
Liu Zhe

A whole body thermal model simulating heat distribution and temperature regulation in rats during hemorrhagic shock and during post-shock microwave core rewarming period was developed. An electrical circuit was used to simulate the thermal system and a software named PSpice® was used to analyze the circuit. The temperature regulation as the result of the simulation is demonstrated to match the measured temperature histories of rats in hemorrhagic shock and the microwave rewarming experiment.

The blood pressure drop and cardiac output decrease were considered in the simulation and the so called "set point temperature" was investigated in the model. Linear decrease and increase of the set point temperature were assumed during the simulation of the shock period and the post-shock rewarming period, respectively. The agreement between the simulation result and the experimental data validates the general structure of the model and assumptions.

Sensitivity Analysis shows the blood pressure drop, set point temperature and the ambient temperature to be the most sensitive parameters in the simulation.

A small group(n=3) of rats were rewarmed with microwave energy in a chilled environment meant to cool and vasoconstrict the peripheral circulation while warming the core organs with the penetrating microwave energy. The the survival rate of the rats was compared with the previous

rewarming experiments. Even though the number of animals was statistically not adequate, the result of this work does suggest that further experiments along the same line, to increase the statistical data pool, are warranted. A larger number of experiments need to be performed to validate the suggestion.

A significant higher temperature gradient between the core and skin was observed during the chilled ambient rewarming which may be a contributory factor in the improvement of the survival statistics.

The data acquisition is very time consuming and labor intensive. It requires at least 2 days to gather the data from one animal; most of the animals die during the shock interval and these animals are lost to the data poll.

THE THERMAL MODEL OF THE RAT UNDER HEMORRHAGIC SHOCK HYPOTHERMIA WITH MICROWAVE INTERVENTION

by
Liu Zhe

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Under Hemorrhagic Shock Hypothermia
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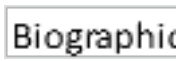

To my family for their love, encouragement and support.

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CHAPTER 1

INTRODUCTION

Hemorrhagic shock is one kind of hypovolemic shock caused by blood loss which leads to hypothermia, i.e., abnormally low body temperature. Physiologically, it can be described as a condition resembling that seen after frank hemorrhage in which the blood pressure falls, and in which the cardiac output decrease is ascribed not to cardiac weakness but to changes in the vessels or circulating blood volume. It is described as peripheral circulatory failure or, more loosely, shock.[1]

Hemorrhage causes blood volume loss and blood pressure drop. This will trigger the so called autoregulation system attempting to compensate blood supply to the vital core organs and to the brain and heart. This requires blood flow redistribution between the peripheral and the core zones. In order to do this, the hypothalamus has to elevate the peripheral resistance by increasing sympathetic outflow to the arterioles in peripheral vascular beds, thereby increasing peripheral vasoconstriction. This leads to a marked decrease of the peripheral blood flow. Meanwhile, since the core vascular beds remain unchanged, more blood flows to brain and heart, compensating the blood loss due to hemorrhage. That is why the skin and lips become pale and cold during hemorrhagic shock. At times, the skin will sweat, attempting to further decrease the skin temperature by evaporation. In addition, metabolic rate is reduced in order to lower the total body oxygen consumption and maintain enough oxygen supply to the brain and heart. This will cause the total body temperature decrease further.

Because of the autoregulation, the vital blood flow and total blood volume can be partially compensated by blood flow redistribution as well as extracellular fluid redistribution. Therefore at the early stages of shock, there is no significant cardiovascular disturbance. But if exsanguination is of such magnitude that the neural and the hormonal controls fail to compensate fully, the systemic arterial blood pressure will fall rapidly. Continuing the shock will cause specified diminution in cardiac output and core zone blood supply, partially disabling the function of the central nervous system as well as autoregulation. The loss of neural controls then causes the release of compensatory vasoconstriction. At this point, the peripheral resistance would begin to fall, drawing more blood from core area and deteriorating the nervous system. This vicious circle will lead to acute myocardial failure with a further drop in cardiac output and lower arterial pressure. If this is severe enough, the blood pressure would drop quickly to a very low level, even when the blood volume is completely restored. The shock symptoms will persist and the subject will expire.

Because temperature variation affects many physiological activities and parameters, the temperature effect on the hemorrhagic shock has drawn the attention of many researchers. It is hoped that proper control of the temperature at appropriate times could make it possible to control certain physiological activities and significantly improve the survival statistics from hemorrhagic shock. The investigations to-date do suggest that with the use of an optimized thermal intervention the survival rate from shock may be improved. This is the motivation for a better understanding of the body heat regulation and temperature variation during hemorrhagic shock as well as under thermal interventions. A whole body thermal model would be helpful in predicting hot or cold stress

locations during shock or the rewarming process.

The purposes of this project are:

1). Investigating a new method of post shock microwave rewarming which improves the survival statistics.

2). Simulating the systemic physiological response of rats to hypothermia caused by hemorrhagic shock, and to the microwave core rewarming treatment.

In this study, the healthy male rats were subjected to severe hemorrhagic shock. After the resuscitation, the rats were warmed by microwave in a cool environment. The temperature, blood pressure and other parameters were recorded and the mortality rate was compared with previous experiments.

Meanwhile, a mathematical model was developed to simulate two situations. The first situation is the shock period during which blood pressure and cardiac output decrease were the stimulating inputs, and the variations of temperature distribution, metabolic activities as well as peripheral resistance could be observed. A second situation is the microwave rewarming period during which calculated RF energy deposition within the body was the input to the model. During the simulation, the so called "set point temperatures" for both skin and the core layers of the rat model were assumed to change linearly with the time of shock or rewarming. The ambient temperature was adjustable to simulate the rewarming experiment in a chilled (6°C) environment which will be described in the following chapter.

Based on the mathematical thermal equations, an electrical model was developed to simulate the transfer of thermal energy under hypothermia.

A software package named "PSpice" was used in this work to analyze the electrical model. The result was then compared with the experimental data. During the simulation, some physiological parameters were manipulated in order to make the model fit the experimental data.

CHAPTER 2

PREVIOUS OBSERVATION

2.1 Overview

The study of hemorrhagic shock has a relatively short history. The term "shock" was first used in the English language in 1743 in an English translation of Henri François Le-Drans Treatise of Reflections Drawn from Experience with Gunshot Wound.[2]

Not until the middle of the 19th century did the descriptions of the symptoms of hemorrhagic shock begin to appear in the literature. The description written by John Collins Warren in 1895 was pretty close to the symptoms now accepted as diagnostic of shock.[3]

The experimental techniques were first applied to shock research in 1899, and Henderson, in 1908, gave an extremely accurate statement of the major factors in the initial etiology of hemorrhagic shock which is of accepted even in today's observations[2]. The development of the measuring techniques has greatly enriched the understanding of hemorrhagic as well as other types of shock. It is known that at some stages, they all have some common symptoms regardless of the different initial causes.

Treatment for shock can be traced back to World War I, when epinephrine was widely used to increase vasoconstriction and decrease the blood flow to skin as well as muscle. But some researchers reported by the end of World War I that epinephrine could shorten survival time of severely shocked patients and overusing it could even create shock[3]. In 1930, it was reported that ensuing shock could be remedied with the administration of plasma. Then it was further discovered that whole blood had better effect for resuscitation than plasma[2]. After it was noticed that the shift of

extracellular fluid occurred during the shock, salt solution began to be used along with blood in the resuscitation from hemorrhagic shock.

2.2 Thermal Intervention in the Treatment of Shock

An animal's response to hemorrhagic shock is complex and often fatal. Hypothermia induced during shock affects many physiological parameters and makes effective treatment difficult. Even though the effects of temperature on mortality from shock have been studied since World War I, its optimum treatment of shock is not very well established.

Partially due to the fact that more than half of the on-going research is concentrated on the septic aspect of hemorrhagic shock, even though it is widely accepted that shock will cause hypothermia, the effect of temperature intervention on the survival of shock, especially the severe shock, is still not very clear.

Recently some reports focusing on the temperature effect suggested the possibility of improving survival rate by using thermal intervention.

It was found[4] that externally heating hemorrhagic shocked rats during the shock period decreased their ability to withstand shock and increased the mortality.

H. M. Patel, P. E. Engler, et al [5] reported that microwave core-rewarming during the post shock period, when resuscitation was affected, could significantly increase the survival rate of hemorrhagic shocked rats. Microwave rewarming during shock, on the other hand, decreased the survival rate of shocked animals.

D. M. Meyer, et al[6] reported the effect of an opposite method: cooling the hemorrhagic shocked animals. According to his report, an increase in survival rate was observed after moderate hypothermia was applied to the

shocked rats during shock period.

The research described in Chapter 2 of this work suggests a further improvement of survival rate by core rewarming treatment in a cool environment. The rationale is to vasoconstrict the peripheral circulation, and to vasodilate the visceral circulation thereby funneling the compromised cardiac output to the vital organs.

2.3 Mathematical Model

Several mathematical thermal models describing body heat transfer in man as well as other animals have been reported[7]~[12]. Some of them were even developed especially in the application of hyperthermia, i.e., high temperature. The whole body thermal model of man reported by C. K. Charny, et al[13] considered the situation of hyperthermia treatment with the miniannular phased and annular phased array microwave applicators. The surface cooling with sprayed water and a circulating water bolus used in clinical case was also included in the model. But these models need to be modified in hemorrhagic shock because of the significant blood loss and the decrease in cardiac output.

CHAPTER 3

MATERIALS AND METHODS

The shock experiment model (not the mathematical model) used here was developed by the department of surgery of UMDNJ (University of Medicine and Dentistry of New Jersey). This model has been used in the department for several years and is believed to be able to resemble the clinical situation much more closely than previously used models because it is the only one simulating resuscitation which is used routinely in hospitals today as a major component of treatment to hemorrhagic shock.

3.1 Preparation

The animals used in this work were male Sprague-Dawley rats weighing 360~410g. In order to make them adjust to the lab environment, the rats were maintained in the lab at least 2 days prior to use. During this period of time, they were served with water and food (standard rat chow) until they were cannulated, which was 24 hrs prior to the shock.

24 hrs prior to shock, the rat was anesthetized with Ketamine (100 mg/kg). A polyethylene cannula (PE-50) was inserted into the common right femoral artery and the other end of the tube was routed subcutaneously to the dorsal region of the rat's neck. From there, the cannula was externalized and connected to a specially designed harness and swivel mechanism which fixes the cannula and, at the same time, allows the rat to move freely. After the cannulation, the rat was maintained by the parenterally administering Ringer's lactate solution containing 20% glucose at a rate of 100 cc/kg/day.

3.2 Shock and Resuscitation

Immediately prior to the bleeding, 500 unit of heparin was administered through the catheter to prevent blood clotting during bleeding. Through a **Y** connector, the catheter was then connected to a blood reservoir and a strain gauge transducer which was linked to a computer to monitor the mean arterial blood pressure (MABP) (Refer to Figure 1).

Hemorrhagic shock was induced by phlebotomy through the arterial catheter until the MABP of 30 mmHg was reached. Then this MABP was maintained by drawing or reinfusing the blood from or back to the animal until 80% of the maximum shed volume was returned to it, or 7 hrs of shock time has elapsed, whichever event occurred first. This moment marked the onset of the post shock period. All the remaining blood shed was then given back to the animal shortly. If MABP was below 80 mmHg after all blood was returned, a bolus of maintenance fluid was infused to simulate the resuscitation. But the amount of the fluid was not allowed to exceed the maximum shed. During the post shock period, the animal was maintained on twice the preshock volume of glucose and Ringer's lactate solution.

After shock, the rats were rewarmed with microwave energy in a cool room (6°C). This will maintain a low skin temperature during the whole core rewarming procedure. The microwave frequency was 2450 MHZ and the power was 92 w. The rate of energy absorption per unit mass of tissue was calculated as 1.6 w/kg. (See Section 4.2.4, eq.(26)). The average post shock core temperature before rewarming was 31°C. As soon as the core temperature was elevated to 35°C the rewarming was stopped, the microwave was turned off and the rat was maintained at normal room temperature (24°C). From then on both skin and core temperatures were monitored during shock and post shock rewarming periods. Skin

temperature was monitored by a thermal probe subcutaneously at the catheter exit point in the dorsal region while core temperature was measured by another thermal probe inserted into the rectum.

Other data like weight, maximum shed blood volume (MSV), initial arterial blood pressure (IMABP), post shock mean arterial blood pressure (PSMABP), and percent maximum shed volume of blood returned at the end of the shock (%MSVret) were recorded for each rat.

The blood volume of the animal was estimated by a equation(See Section 4.1, eq.(4)):

$$V(3)_{estimate}(ml) = Weight(g.) \times 0.08(ml/g.)$$

3.3 Instrument and Measurement

The equipment used in the measurement of shock experiment is shown in Figure 1.

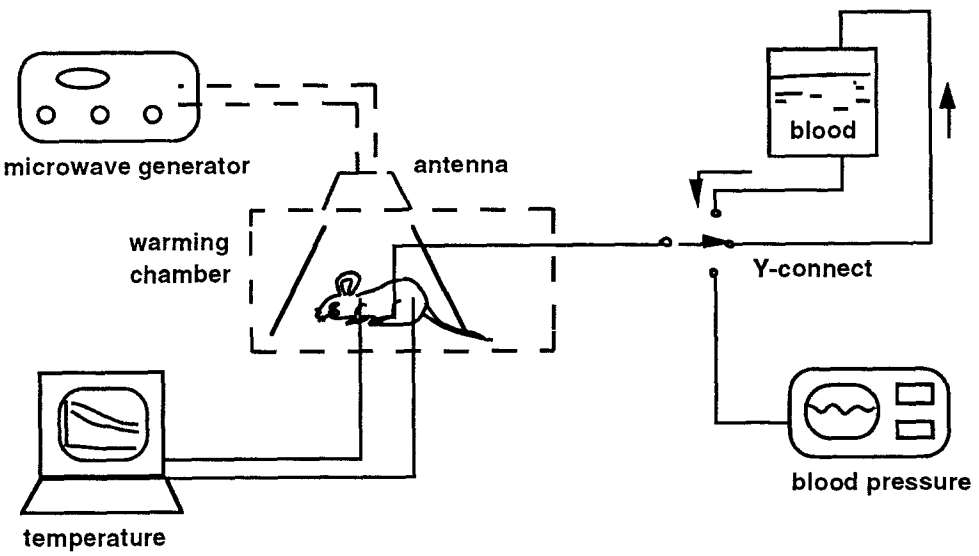

Figure 1 Instrument and Measurement

The temperature monitoring and recording system is the BSD-200 Precision Thermometry system, manufactured by BSD Medical Corporation. Its thermal probes are specially designed for use in electromagnetic fields. The microwave energy was created by a microwave generator MPS 2450~300cw made by Cheung Associates, Inc., at a frequency of 2450 MHZ. It can supply continuous power up to 300w. The microwave rewarming was performed in an anechoic chamber which was lined with microwave absorbing material. Inside the chamber, the experimental rats were placed under the antenna in such a way that the longitudinal axis of the animal was perpendicular to the incident magnetic field. The distance from the microwave antenna to the animal was approximately 38 cm.

In order to comply with the safety guidelines of OSHA (Occupational Safety and Health Administration) and ANSI (American National Standards Institute), microwave power leakage from the chamber was frequently monitored with a NARDA model 8121A electromagnetic radiation monitor. The leakage was not allowed to exceed 1 mw/cm^2 at any time during the experiment. The published safety standard stipulates maximum permissible exposure of 10 mw/cm^2 over any 6 minute interval for frequencies from 10 MHZ to 100 GHZ.

CHAPTER 4

SIMULATION MODEL

4.1 The Rat

The early mathematical thermal models introduced the concept of core and shell compartments, represented by the rectal and mean skin temperature.

Pennes, H. H.[14] developed a steady state thermal model of the forearm which was quite adequate in predicting the temperature gradient between core and skin under steady state conditions. Four characteristics of the model are: uniform cylindrical geometry, radial heat conduction, heat generation in tissues and heat convection by blood flow. The later models included mass balances of oxygen, carbon dioxide and lactic acid to estimate metabolic heat generation and perfusion[9]. Because of the rapid development of computer and measurement techniques, some of the thermal models today use computer simulation to obtain more accurate three-dimensional temperature distribution within the subject.

Charny's model[13] divided the human body into 15 cylindrical segments and the spherical head, each of which was subdivided into four layers: core, muscle, fat and skin. A separate central blood compartment was also included in his model to supply blood to the 16 segments.

In our study, the rat was modeled as a cylinder that was compartmentalized into two concentric layers: core and skin. The skin layer in this model was somewhat thicker than the real skin, so it actually included some muscle tissue but most muscle was included in the core layer. In addition to these two layers, a separate central blood compartment was assumed to be located somewhere between them, supplying blood and transferring heat.

It is to be emphasized that this simple model is demonstrated to provide results that match measured temperature histories quite closely.

In the model, each layer is characterized by temperature T(i) in °C, specific heat c(i) in w•hr/g•°C, density ß(i) in g/cm^3, thermal conductivity k(i) in w/cm•°C, electrical conductivity μ(i) in s/m, volume V(i) surface area S(i) in cm^2, basal metabolic rate Q(i) in w/kg, and basal blood perfusion per unit mass of tissue §(i) in cm^3/hr•g. The blood compartment is characterized only by temperature, density and specific heat. All the values for these parameters are listed in Table 2[18].

The following dimensions are used in the simulation: the length of the rat is 16 cm, the outer radius R of the skin layer is 3 cm and the radius r of the core layer is 2.5 cm (Figure 2).

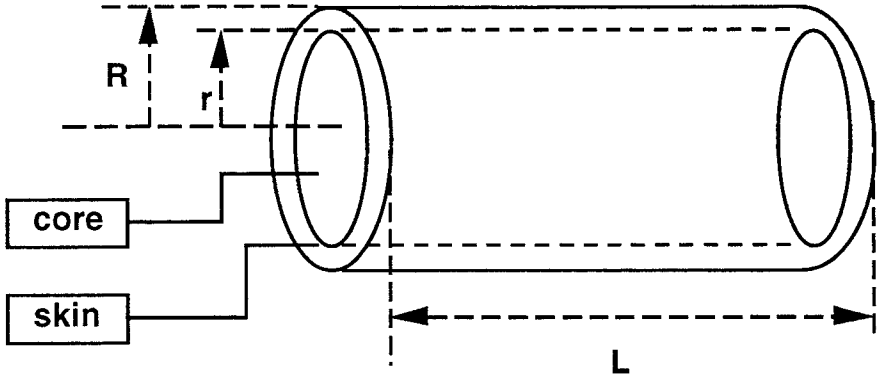

Figure 2 Geometry of Rat

The core volume of it can be calculated as:

$$V(1) = \pi \times r^2 \times L = 314 \ (cm^3) \qquad (1)$$

the volume of the skin layer:

$$V(2) = \pi \times (R^2 - r^2) \times L = 138\ (cm^3) \quad (2)$$

the skin surface area:

$$S(2) = 2\pi R \times L = 301\ (cm^2) \quad (3)$$

The weight of the rat is assumed to be 380g. and the blood volume is estimated by a formula used by the surgical department of UMDNJ:

$$V(3) = \text{Weight(g.)} \times 0.08(cm^3/g) \approx 30\ (cm^3) \quad (4)$$

4.2 Mathematical Heat Balance Equations

According to the compartmental block diagram of the heat transfer (Figure3), heat in the unit of thermal watts(w) is generated inside the tissue by metabolic activity Q_m, muscle activity Q_{act} and, only in the case of rewarming, Q_{rf}.

Heat is convectively transferred by perfusing blood $Q_{conv}(i)$ from core to blood and from blood to skin, and by conduction Q_{cond} from core to skin.

The loss of heat to the environment is through the convective exchange Q_{air} from skin and through the lost blood $Q_b(i)$.

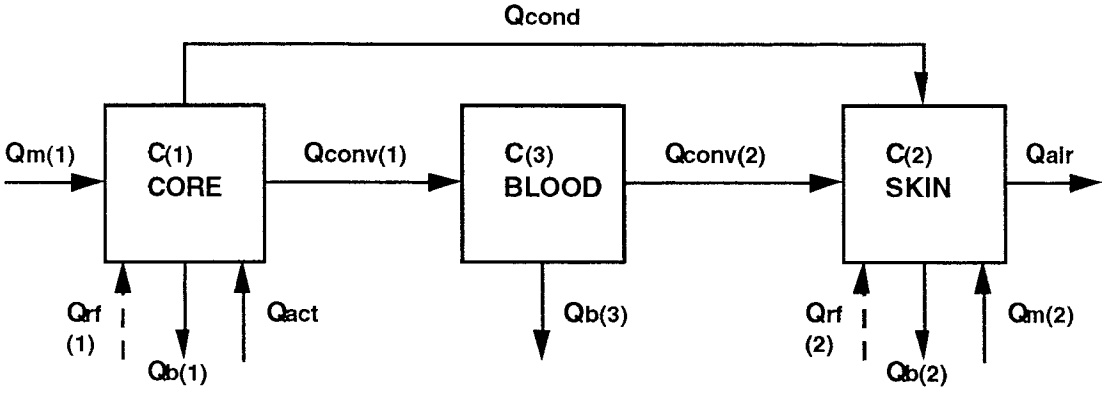

Figure 3 Block Diagram of Compartmental Model

From Figure 3, a set of differential equations are obtained describing the heat balance inside the rat:

1. Core Zone

(1). Hemorrhagic Shock:

$$C_1 \frac{\partial T(1)}{\partial t} = Q_m(1) + Q_{act}(1) - Q_{conv}(1) - Q_b(1) - Q_{cond} \quad (5)$$

(2). Postshock Rewarming:

$$C_1 \frac{\partial T(1)}{\partial t} = Q_m(1) + Q_{rf}(1) - Q_{conv}(1) - Q_b(1) - Q_{cond} \quad (6)$$

Because the rats are very weak and usually remain inactive during the post shock period, the muscle activity heat generation Q_{act} is neglected in this equation.

2. Skin layer:

(1). Hemorrhagic Shock:

$$C_2 \frac{\partial T(2)}{\partial t} = Q_m(2) + Q_{conv}(2) - Q_b(2) + Q_{cond} - Q_{air}(2) \quad (7)$$

(2). Postshock Rewarming:

$$C_2 \frac{\partial T(2)}{\partial t} = Q_m(2) + Q_{rf}(2) + Q_{conv}(2) + Q_{cond} - Q_b(2) - Q_{air}(2) \quad (8)$$

3. Blood Compartment:

$$C_3 \frac{\partial T(3)}{\partial t} = Q_{conv}(1) - Q_{conv}(2) - Q_b(3) \quad (9)$$

The temperature change is regulated by the heat capacitance:

$$C(i) = V(i) \times ß(i) \times c(i) \qquad (10)$$

Where C(i) is the heat capacitance in w•hr/°C of the compartment (i). In this equation and all the other equations used in this work, the unit (w) stands for the thermal watts when it is applied to the thermal energy related parameters. V(i) and ß(i) are the volume and density of the compartment,respectively, c(i) is the specific heat in w•hr/g•°C. All the values of these parameters used in this work are modified from literature[18], and can be found in Table (2) of Appendix I.

In this model the heat loss through exhalation[13] is ignored, and we did not consider the heat loss via urinating which might be one of the heat eliminating mechanisms analogous to sweating. Rats cannot sweat.

For each layer, a "set point temperature" $T_{set}(i)$ is determined, and assumed to change linearly with the shock or rewarming time (See Section 4.3.1).

4.2.1 Q_{cond}, Heat Transferred by Conduction

In this model, heat conduction along the axis of the cylinder is neglected. Heat conduction only occurred radially between the two adjacent layers and could be calculated as:

$$Q_{cond} = [\, T(1) - T(2) \,] \div R_{cond} \qquad (11)$$

where R_{cond} is the effective heat resistance in °C/w between core and skin layers and is determined by the equation:

$$R_{cond} = \frac{1}{G(1)} + \frac{1}{G(2)} \qquad (12)$$

and:

$$G(i) = \frac{2\pi \times k(i) \times L(i)}{\ln (r_2/r_1)} \tag{13}$$

where k(i) is the thermal conductivity for each layer in w/cm•°C, and L(i) is the length of the cylinder.

The heat resistance is actually the heat insulation, standing for the temperature increase(°C) divided by the heat flow(w) through the tissue.

In the equations, r_2 is the radius at boundary of each layer:

$$r_2(1) = r \tag{14}$$

$$r_2(2) = R \tag{15}$$

A layer's r_1 is the midvolume radius, i.e. the radius of a cylinder with a volume one half of the volume of the cylinder under consideration. The definition of r_1 for any compartment (core or skin) is defined, from Figure 4 and 5, as:

$$\pi r_1^2(i) \times L = V(i)/2 \tag{16}$$

where V(i)/2 is the half-volume of the compartment (i).

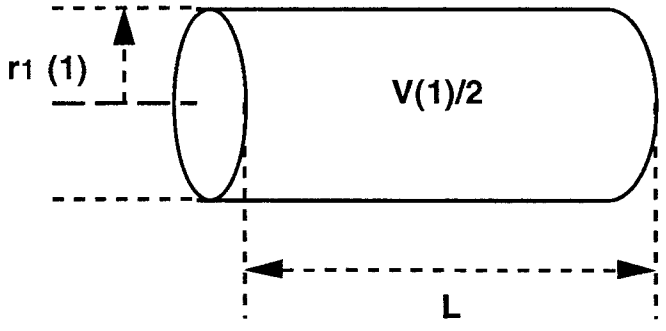

Figure 4 Midvolume Radius $r_1(1)$

From Figure 4, we have:

$$\pi r_1^2(1)xL = V(1)/2 = \pi r_1^2 xL/2 \tag{17a}$$

thus:

$$r_1^2(1) = r^2/2 \tag{17b}$$

Similarly, from Figure 5 it can be seen that:

$$\pi r_1^2(2)xL = V(2)/2 = \pi(R^2 - r^2)xL/2 \tag{18a}$$

therefore:

$$r_1^2(2) = (R^2 - r^2)/2 \tag{18b}$$

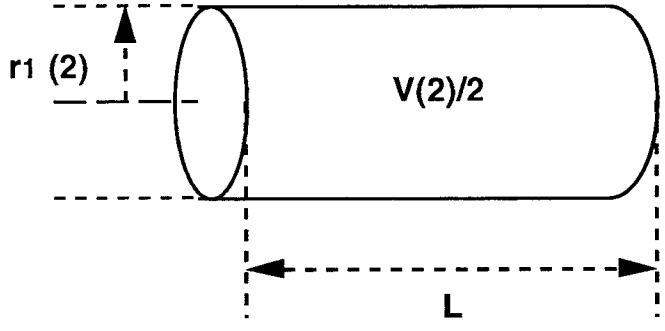

Figure 5 Midvolume Radius $r_2(1)$

4.2.2 Q_{conv}, Heat Transferred by Blood Perfusion

The blood flows between core and skin layers, transferring heat connectively:

$$Q_{conv}(i) = ß(i) \times V(i) \times [\, ß(3) \times c(3) \times §(i) \,] \times [\, T_{bin}(i) - T_{bout}(i) \,] \tag{19}$$

Where ß(i) is the density of compartment(i), c(i) is the specific heat in $w \bullet hr./g \bullet °C$, T_{bin} and T_{bout} are the temperatures of blood flowing into and out of the layer (i).

§(i) is the blood perfusion per unit mass of tissue in the unit of $cm^3/hr.\bullet g$, determined by thermoregulation and will be discussed in detail in Section 4.3.1. Actually, §(i) stands for the volumetric rate(cm^3/hr.) of blood flow per unit mass of the tissue. Then ß(3)•§(i) is the mass flow rate(g/hr.) of blood per unit mass of the tissue. Therefore ß(3)§(i)c(3) can be considered as the heat conductance(w/°C) per unit mass of the tissue due to the blood perfusion. Because ß(i)V(i) is the mass of the tissue, so ß(i)V(i)[ß(3)c(3)§(i)] is the thermal conductance in w/°C of the whole layer(i). When the temperature difference exists, the heat flow Q_{conv} in thermal watts(w) is produced.

It is assumed that blood is well mixed in the central blood compartment and there is no prearteriole heat transfer. Thus the blood temperature entering each layer, $T_{bin}(i)$, equals the central blood temperature T(3). It is also assumed that there is a complete thermal equilibration between each layer and the blood leaving it, so, $T_{bout}(i) = T(i)$. Thus the convective heat transfer by blood perfusion can now be determined by the equation:

$$Q_{conv}(i) = ß(i) \times V(i) \times [\, ß(3) \times c(3) \times §(i) \,] \times [\, T(3) - T(i) \,] \qquad (20)$$

4.2.3 Q_{air}, Heat Transferred to the Environment

Heat loss from the skin, Q_{air} can be calculated as:

$$Q_{air} = H(2) \times [\, T(2) - T_{air} \,] \qquad (21)$$

where T_{air} is the ambient temperature. It is 24°C during shock and 6°C during postshock warming because the animals were rewarmed in an environment chilled to 6°C. H(2), the effective heat conductance in w/°C, (again, w is the thermal watts), can be determined by the equation from the

literature [7]:

$$H(2) = [\, H_r + H_c \times 3.16 \times v^{0.5} \,] \times S(2) \qquad (22)$$

where v is the air velocity in m/s, H_r and H_c are the radiative(H_r) as well as convective(H_c) heat transfer coefficients in $w/m^2 \bullet °C$ respectively, their values are listed in Table (1). S(2) is the surface area of the skin layer.

4.2.4 Q_{rf}, Microwave Heat Source

Q_{rf} is the total microwave energy deposition in the body. It is divided into weighted averages of the volume-electrical conductivity product for each compartment:

$$Q_{rf} = Q_{dep} \times \frac{V(i) \times \mu(i)}{\Sigma} \qquad (23)$$

and:

$$\Sigma = \sum [\, V(i) \times \mu(i) \,] \qquad (24)$$

where $\mu(i)$, in s/m is the electrical conductivity of the layer (i), V(i) is its volume.

Q_{dep}, the total microwave energy absorption is calculated by the equation:

$$Q_{dep} = W \times SAR \qquad (25)$$

where W is the animal mass in kg, SAR(Specific Absorption Rate), in thermal watts(w)/kg, is the rate of energy absorption per unit mass of tissue from non-ionizing electromagnetic radiation[17]. The SAR value used in this work was determined from the Average SAR curves in "Radiofrequency Radiation Dosimetry Handbook". The copy of these curves from Patel's work can be found in Figure 6. Those curves demonstrate the amount of energy

absorbed per unit mass per density of incident wave (w/kg of biological tissue per mw/cm^2 of incident power), i.e., average SAR, versus the frequency of incident wave.

From the curves, the plane wave electromagnetic illumination and medium size rat suggests a value of 0.19 (w/kg)/(mw/cm^2) for average SAR, here w is the thermal watts. The incident power density in this work is estimated to be 9.5mw/cm^2.

Thus,

$$SAR \approx 0.19 \times 9.5 \approx 1.8 \text{ (thermal watts(w)/kg)} \quad (26)$$

4.3 Thermal Regulations

When the rat is in hemorrhagic shock, because of the decrease in blood volume and cardiac output, the autonomic nervous system strives to compensate for the blood loss to the vital organs to maintain a relative stable physiological state. To do so, the hypothalamus will signal the central nervous system to decrease the blood flow to peripheral arterioles. That causes the skin temperature to drop significantly. Furthermore, in order to maintain the oxygen supply to the brain and heart, the system tries to decrease the oxygen consumption in other parts of the body. This is accomplished by a reduction of the metabolic rate. Thus the temperature regulation is primarily determined by a redistribution of blood flow and the control of metabolic activity.

In this project, the core of the animal is rewarmed in a cool environment after resuscitation. The purpose is to help the rat increase the temperature gradient between core and skin in an attempt to further intensify the concentration of recovered blood flow to the vital core zone. It is

hypothesized that this can help the rat restore the hemostatic environment that was disturbed by the insufficient blood supply in severe shock.

4.3.1 Control of Blood Flow

Based on Stolwijk's work[7], the vasodilation and vasoconstriction of blood vessels in the skin layer is determined by the hypothalamic (head core) temperature. Since our model did not consider head as a separate compartment, the head temperature effect was neglected.

The concept "set point temperature" is used in this work, and is assumed to change linearly along with shock time. The significant agreement of the results between this model and the experiment suggests the validity of this assumption.

The control of skin blood flow and metabolic heat production in each layer are effected by the difference between its real temperature and set point temperature, which is represented as ERROR:

$$\text{ERROR} = T - T_{set} \tag{27}$$

where T_{set} is the set point temperature for each of the layers which can be determined at the thermoneutral condition: (T_{air} = 30°C, v = 0.1 m/s), with temperature regulation turned off and zero external energy input. Under this condition, the metabolic heat production and tissue blood perfusion are all at their basal levels. Applying this condition to heat balance equations, we can calculate the set point temperature for each layer. In this work, an electrical circuit(Figure 7) was used to simulate this condition to determine set point temperature. The software used for the electrical simulation circuit is PSpice. (See Appendix III.(A))

During shock, the set point temperature is assumed to decrease linearly with shock time:

$$T_{set} = T_{set0} - f \bullet t \tag{28a}$$

where T_{set0} is the preshock equilibrium set point temperature calculated under thermoneutral conditions. The coefficient f is related to the severity of shock. In this model, f is estimated according to the blood pressure drop.

During post shock rewarming, T_{set} is assumed to increase linearly:

$$T_{set} = T_{setn} + g \bullet t \tag{28b}$$

where T_{setn} is the set point temperature before rewarming is initiated.

It needs to be pointed out that the result of this study suggests that both f and g have different values for the core and skin layers. All the values are listed in Table (1).

In addition, two central signals were defined:

$$\text{STRIC} = \begin{cases} -5.0 \times \text{ERROR} & \text{, if ERROR} < 0 \\ 0 & \text{, if ERROR} > 0 \end{cases} \tag{29}$$

$$\text{DILAT} = \begin{cases} 7.5 \times \text{ERROR} & \text{, if ERROR} > 0 \\ 0 & \text{, if ERROR} < 0 \end{cases} \tag{30}$$

These two signals control the skin-blood perfusion rate §(2) by the equations:

$$\S(2) = \frac{\S_b'(2) + D_d \times \text{DILAT} \div [\, ß(2) \times V(2) \,]}{1 + D_s \times \text{STRIC}} \tag{31}$$

where

$$\S_b'(2) = \S_b 2) \times BF^{\text{ERROR}/ø} \tag{32}$$

where $$\S_b'(2) = \S_b2) \times BF^{ERROR/\phi} \quad (32)$$

where D_d and D_s are weighting coefficients proportional to the density of vasodilation and vasoconstriction effecters on the skin layer, respectively. In this work, they are both assumed to be 7.8.[18]

$\S'_b(2)$ is the basal blood perfusion rate which changes with ERROR in an exponential way. The values of the BF and ϕ are based from Charny's work and modified to improve the result here (See Table 1).

Since muscle is not considered an independent layer in this model, the control of muscle blood flow in previous works[7], [13] is not applicable here. Instead, core blood flow was represented as a function of skin blood flow and total cardiac output.

In the shock model used here, shock is maintained by keeping the rat at very low blood pressure (30mmHg), so it is simply assumed in this work that cardiac output CO is determined only by blood pressure BP:

$$CO = CO_b \times \left[1 - b_1 \times \left(\frac{BP_0 - BP}{BP_0}\right) - b_2 \times \left(\frac{BP_0 - BP}{BP_0}\right)^2\right] \quad (33)$$

where CO_b is the basal cardiac output, b_1 and b_2 are two experimental coefficients. BP_0 is the preshock blood pressure.

Actually, after the sudden drop at the beginning of the hemorrhage, the cardiac output will temporally increase and then, because of the severe shock model used in this project, the CO will decline with the significant blood pressure drop.

In this study, the temporary increase of the CO is ignored; instead CO is approximated to gradually decrease from some lower level immediately

after the bleeding begins.

Therefore core blood perfusion rate is determined by:

$$\S(1) = \frac{[\,CO - \S(2) \times ß(2) \times V(2)]}{ß(1) \times V(1)} \qquad (34)$$

Actually, the thermal regulation within the rat is a feed back control procedure: the variation of the set point temperature Tset(eq.(28)) and the compartment temperature T(i) will determine the parameter ERROR (eq.(27)), which controls the parameter DILAT and STRIC(eq.(29,30)), as well as $\S_b'(2)$(eq.(32)). These three parameters determine the blood perfusion rate in the skin compartment §(2)(eq.(31)) and in the core compartment §(1)(eq.34)) which in turn control the convective heat flow $Q_{conv}(i)$(eq,(18)). On the other hand, the parameter ERROR, which depends on T_{set} and T(i)(eq.(27)), controls the metabolic heating $Q_m(i)$(eq.(35)).

In this work, the expression *ERROR/ø* in eq.(32) and *ERROR/Δ* in eq.(35) are called the controlling variables for Q_{conv} and Q_m, respectively. They will be represented by the voltages of the controlling nodes in the electrical simulation circuit(Figure 8) which will be discussed in detail in Section 4.4.

4.3.2 Control of Metabolic Heat Production

The control of metabolic heating $Q_m(i)$ expressed here for the compartment(i) is based on Charny's work:

$$Q_m(i) = Q_b(i) \times MT^{ERROR/\Delta} \qquad (35)$$

Again, the values of MT and Δ are modified from Charny's work(Refer to Table 1).

In this model, the heat production of muscle activity was included because,

unlike human objects, rats keep moving around in the cage until the late stage of shock. This effect was simply expressed as an additional variation on metabolic heat production because it will decline along with metabolism:

$$Q_{act} = 0.12 \times Q_m(1) \quad (36)$$

Muscle activity can only affect the heat production in muscle which, in our model, is mostly included in the core layer. Since the rats are usually inactive due to the weakness during the post shock rewarming period, Qact is ignored in the equation of rewarming (eq. (6))

4.4 Electrical Simulation Circuit

Since electrical circuit analysis is well developed and has many convenient tools, it is convenient to model a thermal network with an electrical network. Figure 8 shows a electrical circuit simulating the heat flow described in Section 4.2.

In the circuit, current sources are used to express the heat flow Q within the tissues, and voltage sources are used for the temperatures at different layers. Nodes (1), (2) and (3) in the circuit stand for the three compartments of core, skin and blood, respectively.

Almost all of the current and voltage sources connected to the nodes (1), (2) and (3) are the controlled sources which are symbolized with the diamond shape to distinguish them from the constant sources. The nodes from (4) to (11) are the controlling variables for the controlled sources.

The constant voltage source E_4 expresses the ambient temperature, so the node voltage V(4) is T_{air}. The linearly varying voltage sources V_5 and V_{50} are the set point temperatures of skin and core, so the node voltages V(5) and V(50) are $T_{set}(2)$ and $T_{set}(1)$, respectively. The node voltages V(7) and V(70) are exponential controlling variables $ERROR/\Delta$ for $Q_m(2)$(eq.(35))

when ERROR(2) is positive and negative, respectively. V(6) is the controlling variable *ERROR/Δ* for $Q_m(1)$(eq.(35)). The voltage sources V_{10} is BP_0, the preshock blood pressure, and BP is the varying blood pressure during the shock or rewarming. V_9 is their difference, i.e., blood pressure drop(eq.(33)). The node (12) is a subcircuit for a voltage divider used to manipulate the dividing operation. The node voltage V(8) is the controlling variable *ERROR/ø* for the $Q_{conv}(2)$(eq.(19)).

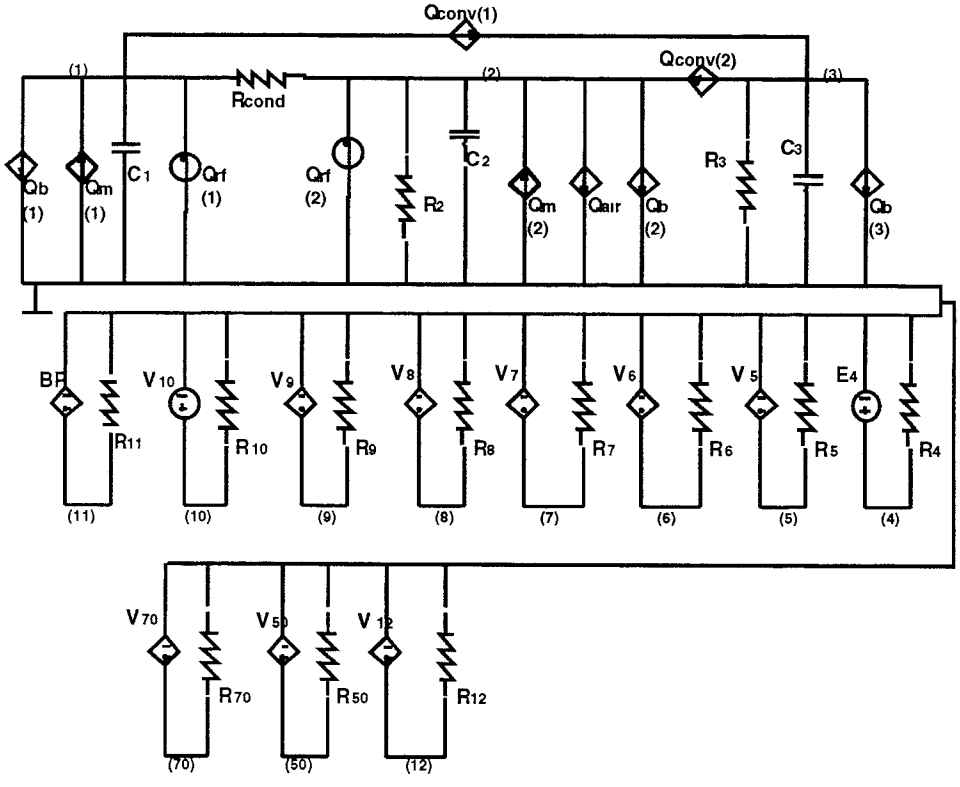

Figure 8 Electrical simulating Circuit

In this circuit, because we assume that $T_{set}(1)$ is always below T(1) during the shock and can be higher than T(1) only during the rewarming period, we consider the possibility that ERROR(1) is negative only in the rewarming situation. We used node voltages V(i) as all the controlling

variables, not all of them express the temperature as node (1) ~ (3) do. For example, V(7), V(70), V(6) and V(8) have no unit, V(9) ~ V(11) have the unit of blood pressure(mmHg).

In order to be analyzed by PSpice, linear polynomials are used to approximate the exponential functions in this circuit.

Thermal parameters such as temperature, heat flow, heat resistance and capacitance were represented by electrical voltage, current, resistance and capacitance respectively as shown in Table(3).

4.5 PSpice Program

The electrical circuit presented in Figure 8 was solved on the VAX computer using the software PSpice® from MicroSim Corporation. The program is listed in Appendix III, with (B) related to shock hypothermia and (C) to post shock rewarming. The PSpice program for the special circuit calculating set point temperatures under thermoneutral conditions is listed in Appendix III, (A).

Table 3. Equivalence Between Thermal and Electrical Parameters

THERMAL SYSTEM	ELECTRICAL SYSTEM
Q, Heat Flow (w = joul/s.)	I, Current (amp = col./s.)
T, Temperature (°c)	V, Voltage (volts)
C, Heat Capacitance (w•hr/°c)	C, Electrical Capacitance (F)
R, Heat Insulation (°c/w)	R, Electrical Resistance (Ω)

CHAPTER 5

RESULT

5.1 Survival Rate and the Post Shock Rewarming

The shock model used in this project was very severe: 60%~80% blood loss. Only 3 rats were still alive at the end of shock out of 28 rats used. Of the 25 rats died, 4 died before shock and 21 died during shock. The 3 surviving rats at the end of the shock were then rewarmed by the method developed in this work and survived 24, 40 and 72+ hrs, respectively. All the others died during or even before shock, not affording an opportunity to apply the post shock rewarming.

Of the 21 animals that died during shock, most of the deaths occurred after about 30%~40% of the maximum blood shed had been returned. From the shock model used here, that means that the rats died at 30%~40% blood loss. Since the purpose of this work was to observe the effect of post shock core rewarming in a chilled environment on the survival rate of the shocked animals, the conclusions are based on only three animals. Consequently the results are suggestive only. To draw statistically valid conclusion would require a significantly larger number of animals that survive this severe shock. Nevertheless, some conclusions could still be reached even from these limited data.

In this work, the three rats being rewarmed after resuscitation by microwave energy in a cool ambient was considered as group A: the microwave rewarming process was initiated at the onset of the post shock period in a cool room (6°C). These three data points are compared with the experimental results of Patel's work[5] identified as group B, where the rats were rewarmed with the microwave energy during the post-shock period in

a normal environmental temperature (25°C). From Figure 10 it can be seen that the survival rate of group B was 30% at 24, 48 and 72 hrs. (n=10). The survival rate of group A is shown in Figure 9. Although the data are not statistically valid, it nevertheless suggested that the survival rate is improved for group A in which the animals are rewarmed in a chilled environment.

The typical measured body temperature-time curves for the rats during shock in group A is shown in Figure 11. The temperature histories during post shock rewarming are shown in Figure 12.

During the post shock microwave rewarming, the animals in group A maintained a larger temperature gradient between the core and the skin than the rats in group B. Because this larger gradient might help the animal to concentrate the blood flow to the more vital core organs, it is hypothesized to be a contributing factor in the improvement to the survival statistics.

After the rewarming protocol, the animals were kept at normal room temperature (26°C). During that period of time, the skin and core temperature were autoregulated by the animals. Comparing the temperature histories for group A and group B in Figure 12, it can be observed that the core temperature of group A remains at a higher level after the rewarming is ended.

The normal ambient core rewarming group (group B) required an average of 91 minutes of active microwave reheating to raise their core temperature by 4°C, from 30°C to 34°C, at a rate of 0.044°C/min. In comparison, it only required group A, which was rewarmed in a chilled environment, about 72 minutes to raise their core temperature from 31°C to 35°C at a faster rate of 0.057°C/min.

It needs to be pointed out that during the time these experiments were conducted, an unusually large number of deaths among rats in severe hemorrhagic shock were also reported by other research groups in the surgical lab of UMDNJ. An investigation was initiated concerning the possible virus, but no reason was found for the death.

5.2 Simulation of Hemorrhagic Shock Hypothermia

During hemorrhagic shock the blood pressure, cardiac output and metabolic rate described in the model are decreased, along with the heat production by muscle activity. Figure 13 shows the variation of simulated core and skin temperatures represented by the voltage v(1) and v(2) in the electrical circuit drawn in Figure 8, respectively. Typical experimental temperature history curve was compared with the simulating result in Figure 14, while experimental data averaged for the 3 animals, and the result of simulation were shown in Figure 15. The general agreement with minor deviation between the simulation and the experiment could be seen. The deviation in Figure 14 could possibly be explained as the effect of blood reinfusion during shock; details will be discussed in Section 6.2.

5.3 Simulation of Post Shock Core Rewarming

For the microwave core intervention, the RF energy deposit is the major heat input to the simulating circuit. The partial recovery of blood pressure as well as it's effect on metabolic heat production are also included. The simulated temperature history is shown in Figure 16 and the comparison with experimental data in Figure 17(typical) and 18(average(n=3)). It is seen that the simulation results also match with the experimental data during post shock rewarming.

It has to be pointed out that in order to get the best simulation result, some parameters in this model have different values during the simulations of shock and rewarming. For example, the thermal conductive resistance R_{cond} is assumed to be 4.3Ω during the shock and 4.1Ω during the rewarming period because of the loss of blood during the shock will decrease the thermal conductivity, thereby increase the thermal resistance R_{cond}. During the shock, the air velocity v(eq.(22)) is assumed to be 0.1m/s, but since the rewarming is performed in an anechoic chamber, the air velocity is then assumed to be 0.07m/s. During the rewarming, the skin temperature T(1) is occasionally less than the skin temperature set point $T_{set}(1)$, i.e., $T(1)<T_{set}(1)$, which is assumed impossible during the shock. So another node voltage V(60) is set up to represent the exponential controlling variable *ERROR*/Δ for the metabolic heating $Q_m(1)$ under this situation which is similar to V(70) for $Q_m(2)$(See Section 4.4). Another parameter is the thermal capacitor of the blood C(3), for which we assumed a value of 350Farads during the post-shock rewarming and 250Farads during the shock because the blood volume decrease during shock causes the thermal capacitance to decline.

It also needs to be pointed out that the ambient temperature in both the simulation and the experiment in group A was about 6°C. This is the key feature of the rewarming method discussed in Chapter2. Figure 19 shows the experimental body temperature of the rats during post shock rewarming with the ambient temperature set at 26°C. In comparison with Figure 18 it is evident that temperature gradient between the core and skin are greater in a lower ambient temperature. This greater gradient is hypothesized to be a factor in the improvement of survival rate. To test this hypothesis will require comparing the survival rate of a statistically

significant number of animals who were rewarmed in a chilled environment after resuscitation, with the survival rate of a control group in which no temperature intervention was attempted.

CHAPTER 6

DISCUSSION

6.1 The Survival Rate

Today's hemorrhagic treatment includes a combination of modern techniques such as biochemistry, hematology, immunology, etc. Some reports have demonstrated the temperature effect on the shock treatment. Hemorrhagic shock causes hypothermia and the body temperature, especially skin temperature, drops to an abnormally low level. It appeared to be logical to keep the patient warm during shock. But detailed studies showed that not all rewarming methods produced the desired effect on the survival, and some methods could even increase the mortality. A. J. Sori, et al[4] found that peripherally heating hemorrhagic shocked rats during the shock period decreased their ability to withstand shock and increased the mortality.

Many different rewarming methods have been tried in the treatment of hemorrhagic shock: extracorporeal blood rewarming using hemodialysis, hyperthermia blanket, heated operating suites, infusion of intravenous solutions, warm gastric, colon and bladder irrigation, cardiopulmonary bypass, peritoneal lavage and direct mediastinal irrigation[20]~[27].

Some of these methods are moderately effective, but most are considered highly invasive, inconvenient in an emergency room setting and may not be effective for the severely traumatized patient.

Although some core rewarming techniques, such as peritoneal lavage, are used today because of their practical advantage, they require surgical intervention and are of limited use[28],[29].

Microwave energy as a practical noninvasive core rewarming technique has been studied recently in the treatment of hemorrhagic hypothermia. Microwave is converted to thermal energy inside the biological tissue. This effect, plus the metabolic heat generation, will help the animal regulate it's temperature. It has been observed that the application of moderate microwave energy can affect the survival rate of hemorrhagic shocked rats.

When hemorrhage occurs, cardiac output (CO) and mean arterial pressure (MAP) decrease immediately, while the heart rate and peripheral resistance remain stable for a while. Then all these four variables will become elevated. CO and MAP will increase toward, but still remain below, the normal level, the heart rate and peripheral resistance will rise above normal level. The system obviously is trying to compensate for the effect of blood loss: increased high heart rate overcomes the reduce of CO, elevated peripheral resistance lowers the peripheral blood flow and compensates for the decreased blood supply to the brain. The peripheral resistance elevation is primarily affected by peripheral arteriolar vasoconstriction. Therefore the skin becomes pale and cold, and kidney as well as intestinal blood flow also is largely decreased, sometimes even to zero. The compensation in shock also includes the movement of interstitial fluid into capillaries, namely, the redistribution of the extracellular fluid[30].

Moderate shock can be compensated by the subjects themselves as soon as bleeding is stopped and blood volume is restored. But severe shock will cause autoregulation and compensation failure, leading to death even if the blood volume is fully restored.

Severe shock can reduce cerebral blood flow which adversely affects the central nervous system, which controls the compensatory mechanism. This will diminish the ability of autoregulation which, in turn, further

decreases the cerebral blood flow. This inadequate cerebral blood flow furthermore produces failure of the respiratory control centers. All these will lead to peripheral vasodilation which accelerates cerebral blood decrease, leading to further deterioration of physiological status. At this time, even if blood volume is completely restored, because of the failure of the central control system, the blood flow will not be directed to the vital core zone where the brain and heart are. Thus the insufficiency of cerebral blood supply, the functional disability of the central nervous system as well as autoregulatory or compensatory failure will be persist. This will delay the recovery from shock. That is why in severe shock, the complete restoration of the blood volume can not salvage the victims and the symptoms of shock will remain.

There are still many other mechanisms in circulation collapse. But it is generally agreed that the disabling of the central nervous system may be the major reason for death in severe shock. Therefore, by helping the shocked animals to restore their core (cerebral and coronary) blood supply their compensation function may be restored. Thus the whole resuscitation procedure would be faster, and the irreversible damage caused by shock could be reduced. This may be one of the key factors to improve the survival rate.

The hypothesis of this study is that if the shocked animal is helped to elevate its core temperature, the blood vessels in the vital core zones will be dilated. At same time, if the skin temperature is lowered, the peripheral vasoconstriction may maintain an adequate blood supply to the vital organs. Even if the autoregulation can not function well, the large temperature gradient between core and skin will divert blood flow to the cerebral vasculartur and may restore the central nervous system and its

autoregulatory ability to normal.

The result of the experiments, even though statistically not adequate, suggests that further experiments along the same line to increase the statistical data pool are warranted. But a larger number of experiments need to be performed to validate the hypothesis. The data acquisition is very time consuming and labor intensive. It requires at least 2 days to gather the data from one animal; most of the animals die during the shock interval and these animals are lost to the data poll.

6.2 The Simulation

This work is an attempt at modeling the whole body thermal system under hemorrhagic shock. With this simple model it is possible to predict temperature distribution as well as its variation, metabolic heat generation, cardiac output and peripheral resistance change. The general agreement between the result obtained from the model and the experimental data validates the general structure of the model.

In order to obtain the best result, some simulating parameters had to be manipulated. The effect of hemorrhage on the decrease of metabolic heat production was expressed by equations:

$$Q_b(1) = 4.5 \times 10^{-4} \times (BP_0 - BP) \tag{37}$$

$$Q_b(2) = 1.2 \times 10^{-4} \times (BP_0 - BP) \tag{38}$$

$$Q_b(3) = 1.1 \times 10^{-4} \times (BP_0 - BP) - 0.65 \tag{39}$$

where Q_b, in w, is the heat reduction rate due to the blood pressure drop, in mmHg. This suggests, for instance, that for each mmHg drop in BP, there is assumed to be 4.5×10^{-4} w of heat production decrease in the core compartment.

In this model, the so called "set point temperature" is assumed to decrease linearly with the time during the shock and increase linearly with the time during the post-shock rewarming(eq.(28a,b)). In order to get the best result, it has to be assumed that the set point temperature T_{set} has different rates of change for the skin and the core compartment, and each of them has the different values during the shock and the rewarming period. The four values for the increase rate g (eq.28b)) or decrease rate f (eq.(28a)) of $T_{set}(1)$ as well as $T_{set}(2)$ are listed in Table(1) of APPENDIX I.

A sensitivity analysis suggests that during the shock and post shock period, the most sensitive parameters affecting the core and skin temperature as well as metabolic rate, are set point temperature T_{set}, blood pressure drop ΔBP and effective heat conduction resistance between core and skin R_{cond} (See Table.(4) and (5)). (sensitivity analysis result)

Other sensitive parameters affecting the core temperature, the core metabolic rate and the skin temperature are the blood perfusion rate in the core layer §(1), and ambient temperature T_{air}.

A minor deviation of the temperature variation during shock between the simulated and the experimental temperature histories was observed(Figure 14). This might due to the fact that we did not consider the effect of blood reinfusion during shock. According to the shock model used in this work, which was described in detail in Chapter2, the animal was bled until the blood pressure dropped to 30 mmHg, and was then maintained at this value by either withdrawing or reinfusing the animal's blood until the end of the shock. The intermittent blood reinfusion would cause the cardiac output fluctuate and slightly increase, which might explain the slower decreasing rate of the experimental core as well as skin temperature at the middle of the shock period when the reinfusion was

started.

This model, demonstrates the effect of peripheral rewarming reported in Patel's work[5]. It is known that the critical function of the animal in severe shock is to maintain blood and oxygen supply to the brain and vital organs. Peripheral rewarming during shock will elevate the peripheral temperature and draw more blood from vital core zone, accelerating the deteriorating feedback cycle and increasing the mortality.

Core rewarming during shock, although it does not increase peripheral blood flow, does increase the metabolic rate during shock and increases the oxygen consumption. This will decrease the oxygen supply to vital brain and heart, thereby also decreasing the survival statistics.

Moderate cooling during shock can lower skin temperature and core temperature, decreasing peripheral blood flow and metabolic rate as well as oxygen consumption. Therefore an improvement of survival can be expected. But hypothermia intervention during shock should be performed with great care so as not to lower the temperature and metabolic rate beyond physiological limits. Otherwise the mortality would be elevated.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

From the results discussed above, it is suggested that this model can provide a general prediction of the rat's whole body thermal response during shock. More accurate prediction such as thermal variation in some specific area at certain depth of shock would require a modification of this simple model.

Further modification of the simulation model might be expected to include the consideration of the head as a separate compartment and a muscle layer distinct from a core layer. Because the hypothalamus is located in brain, the head temperature might be more critical in the thermal adjustment of the animal. Subdivision of the muscle layer could make it possible to simulate the blood redistribution between muscle and core layers.

Further modification of the warming technique might also include an environment of temperature which is feed-back controlled to maintain a fixed skin temperature. This control system may reduce or control the heat loss from the skin.

Another possibility might be the use of microwave shielding in order to selectively heat parts of the body. For example, warming or cooling only the head would be interesting because the hypothalamus and other central nervous control systems are concentrated in the brain. The selective warming or cooling may cause the central nervous system to receive different feedback signals and to react independently. In this way it might be possible to intervene thermally with the activity of the central nervous system and manipulate it to favor the recovery from shock.

Furthermore, selective warming of the head could help in understanding the thermal response function of the hypothalamus.

APPENDIX I

TABLES

Table 1 Parameters Used in the Simulation

H_r	Radiative Heat Transfer Coefficient	0.095	($w/m^{2o}C$)
H_c	Convective Heat Transfer Coefficient	0.09	($w/m^{2o}C$)
D_d	Weighting Coefficient of blood perfusion	7.8	–
D_s	Weighting Coefficient of blood perfusion	7.8	–
$T_{set0}(s)$	Skin Preshock Setpoint Temperature	31	(°C)
$T_{set0}(c)$	Core Preshock Setpoint Temperature	37.2	(°C)
$T_{setn}(s)$	Skin End Shock Setpoint Temperature	29	(°C)
$T_{setn}(c)$	Core End Shock Setpoint Temperature	31.5	(°C)
f(s)	Setpoint Temperature Decreasing Rate During Shock (Skin)	0.0199	(°C/min.)
f(c)	Setpoint Temperature Decreasing Rate During Shock (Core)	0.0276	(°C/min.)
g(s)	Setpoint Temperature Increasing Rate During Rewarming (Skin)	0.0199	(°C/min.)
g(c)	Setpoint Temperature Increasing Rate During Rewarming (Core)	0.0276	(°C/min.)
BF	–	2.0	–
ø	–	4.5	(°C)
MT	–	1.07	–
Δ	–	0.2	(°C)
$b_1(1)$	Experimental Coefficient in CO ~ ΔBP Relationship	$1.1x10^{-6}$	–
$b_2(1)$	"	$5.3x10^{-4}$	–
$b_1(2)$	"	$0.4x10^{-6}$	–
$b_2(2)$	"	$3.5x10^{-4}$	–

Table 2 Thermophysical Characteristics of Rat

PARAMETER	UNIT	CORE	SKIN	BLOOD
Density	(g/cm^3)	1.25	0.78	0.76
Specific	Heat(w•hr./g•°C)	$8.8x10^{-4}$	$7.8x10^{-4}$	$8x10^{-4}$
Thermal Conductivity	(w/cm•°C)	0.0083	0.0041	–
Electrical Conductivity	(1/Ω)	0.75	0.4	–
Basal Metabolism	(w/kg)	1.2	0.1	–
Basal Perfusion	(cm^3/hr.•g)	20CO	6	–

Table 4. Sensitivity Analysis of the Mode(in Shock)

___ (A). DC SENSITIVITIES OF OUTPUT V(1) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (VOLTS/UNIT)	NORMALIZED SENSITIVITY (VOLTS/PERCENT)
R_{COND}	4.000E+00	2.126E-04	8.504E-06
R_{C1}	4.000E+00	1.132E-04	4.530E-06
R500	1.000E+00	0.000E+00	0.000E+00
R2	1.000E+12	0.671E-29	3.671E-19
R3	1.000E+12	0.748E-29	3.748E-19
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+01	0.127E-07	4.127E-08
R60	1.000E+01	0.000E+00	0.000E+00
R7	1.000E+01	0.319E-10	1.319E-11
R70	1.000E+01	-3.057E-17	-3.057E-18
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
R110	1.000E+00	-2.185E-21	-2.185E-20
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	1.485E-18	1.485E-14
R13	1.000E+06	8.573E-19	8.573E-15
R_{TOP}	1.000E+00	0.000E+00	0.000E+00
R_{BOT}	1.000E+00	0.000E+00	0.000E+00
R_{fwd}	1.000E+00	0.000E+00	0.000E+00
R_{rev}	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
R15	1.000E+12	0.000E+00	0.000E+00
V100	0.000E+00	0.000E+00	0.000E+00
V501	0.000E+00	0.000E+00	0.000E+00
V200	0.000E+00	0.000E+00	0.000E+00
V4	2.380E+01	0.701E-08	2.309E-08
V5	3.100E+01	4.004E-07	-1.241E-07
V50	3.720E+01	-9.573E-04	-3.561E-04
V10	1.050E+02	2.153E-21	2.260E-21
V11	1.200E+02	1.044E-04	1.253E-04

___ (B). DC SENSITIVITIES OF OUTPUT V(2) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (VOLTS/UNIT)	NORMALIZED SENSITIVITY (VOLTS/PERCENT)
R_{COND}	4.000E+00	-2.120E-04	-8.481E-06
R_{C1}	4.000E+00	0.000E+00	0.000E+00
R2	1.000E+12	0.320E-26	7.320E-16
R3	1.000E+12	0.649E-28	2.649E-18
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+01	0.065E-10	2.065E-11
R60	1.000E+01	0.000E+00	0.000E+00
R7	1.000E+01	0.630E-07	2.630E-08
R70	1.000E+01	-6.097E-14	-6.097E-15
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
R110	1.000E+0	-1.441E-21	-1.441E-20
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	4.900E-12	4.900E-08
R13	1.000E+06	2.829E-12	2.829E-08
R_{top}	1.000E+00	0.000E+00	0.000E+00
R_{bot}	1.000E+00	0.000E+00	0.000E+00
R_{fwd}	1.000E+00	0.000E+00	0.000E+00
R_{rev}	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
R15	1.000E+12	0.000E+00	0.000E+00
V100	0.000E+00	0.000E+00	0.000E+00
V501	0.000E+00	0.000E+00	0.000E+00
V200	0.000E+00	0.000E+00	0.000E+00
V4	2.380E+01	0.935E-04	4.604E-05
V5	3.100E+01	1.470E-03	-4.556E-04
V50	3.720E+01	-4.790E-07	-1.782E-07
V10	1.050E+02	1.420E-21	1.491E-21
V11	1.200E+02	5.224E-08	6.269E-08
V140	0.000E+00	0.000E+00	0.000E+00
I500	0.000E+00	0.000E+00	0.000E+00

___ (C). DC SENSITIVITIES OF OUTPUT V(3) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (VOLTS/UNIT)	NORMALIZED SENSITIVITY (VOLTS/PERCENT)
R_{COND}	4.000E+00	-5.024E-07	-2.010E-08
R_{C1}	4.000E+00	-1.128E-04	-4.512E-06
R500	1.000E+00	0.000E+00	0.000E+00
R2	1.000E+12	0.100E-28	2.100E-18
R3	1.000E+12	0.469E-26	7.469E-16
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+01	0.061E-10	2.061E-11
R60	1.000E+01	0.000E+00	0.000E+00
R7	1.000E+01	0.545E-10	7.545E-11
R70	1.000E+01	-1.749E-16	-1.749E-17
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
R110	1.000E+00	-4.567E-22	-4.567E-21
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	-4.897E-12	-4.897E-08
R13	1.000E+06	-2.828E-12	-2.828E-08
R_{top}	1.000E+00	0.000E+00	0.000E+00
R_{bot}	1.000E+000	0.000E+00	0.000E+00
R_{fwd}	1.000E+00	0.000E+00	0.000E+00
R_{rev}	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
R15	1.000E+12	0.000E+00	0.000E+00
V100	0.000E+00	0.000E+00	0.000E+00
V501	0.000E+00	0.000E+00	0.000E+00
V4	2.380E+01	.551E-07	1.321E-07
V5	3.100E+01	.688E-04	2.073E-04
V50	3.720E+01	-4.781E-07	-1.779E-07
V10	1.050E+02	4.499E-22	4.724E-22
V11	1.200E+02	5.214E-08	6.256E-08
V140	0.000E+0	0.000E+00	0.000E+00
I500	0.000E+0	0.000E+00	0.000E+00

Table 5. Sensitivity Analysis of the Model (During Postshock Rewarming)

___ (A). DC SENSITIVITIES OF OUTPUT V(1) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (VOLTS/UNIT)	NORMALIZED SENSITIVITY (VOLTS/PERCENT)
RCOND	4.500E+00	3.746E-04	1.686E-05
RC1	4.500E+00	2.266E-04	1.020E-05
R2	1.000E+12	0.465E-29	2.465E-19
R1000	1.000E+03	0.000E+00	0.000E+00
R3	1.000E+12	0.600E-29	2.600E-19
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+12	0.422E-21	2.422E-11
R60	1.000E+12	-3.906E-21	-3.906E-11
R7	1.000E+12	3.147E-24	-3.147E-14
R70	1.000E+12	1.644E-23	1.644E-13
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
R110	1.000E+00	-8.574E-16	-8.574E-09
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	-1.166E-20	-1.166E-16
R13	1.000E+06	2.091E-19	2.091E-15
Rtop	1.000E+00	0.000E+00	0.000E+00
Rbot	1.000E+00	0.000E+00	0.000E+00
Rfwd	1.000E+00	0.000E+00	0.000E+00
Rrev	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
V100	0.000E+00	0.000E+00	0.000E+00
V200	0.000E+00	0.000E+00	0.000E+00
V1000	0.000E+00	-6.994E-20	0.000E+00
V4	7.000E+00	0.207E-08	4.345E-09
V5	3.100E+01	0.666E-07	5.165E-08
V50	3.150E+01	5.721E-04	1.802E-04
v10	1.070E+02	-3.511E-05	-3.757E-05
V11	9.000E+01	3.511E-05	3.160E-05
V140	0.000E+00	0.000E+00	0.000E+00
I1	0.000E+00	0.997E-03	0.000E+00
I2	0.000E+00	0.867E-07	0.000E+00
I1000	0.000E+00	6.994E-08	0.000E+00

___ (B). DC SENSITIVITIES OF OUTPUT V(2) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (VOLTS/UNIT)	NORMALIZED SENSITIVITY (VOLTS/PERCENT)
RCOND	4.500E+00	-3.747E-04	-1.686E-05
RC1	4.500E+00	7.909E-08	3.559E-09
R2	1.000E+12	0.555E-26	5.555E-16
R1000	1.000E+03	0.000E+00	0.000E+00
R3	1.000E+12	0.566E-30	5.566E-20
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+12	0.075E-24	1.075E-14
R60	1.000E+12	-1.734E-24	-1.734E-14
R7	1.000E+12	7.092E-21	-7.092E-11
R70	1.000E+12	3.705E-20	3.705E-10
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
r110	1.000E+00	-2.148E-16	-2.148E-09
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	5.095E-14	5.095E-10
R13	1.000E+06	-9.139E-13	-9.139E-09
rTOP	1.000E+00	0.000E+00	0.000E+00
RBOT	1.000E+00	0.000E+00	0.000E+00
rfwd	1.000E+00	0.000E+00	0.000E+00
rrev	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
v100	0.000E+00	0.000E+00	0.000E+00
v200	0.000E+00	0.000E+00	0.000E+00
v1000	0.000E+00	-1.576E-16	0.000E+00
v4	7.000E+00	0.399E-04	9.790E-06
v5	3.100E+01	0.044E-04	9.435E-05
V50	3.150E+01	2.540E-07	8.002E-08
v10	1.070E+02	-8.796E-06	-9.412E-06
V11	9.000E+01	8.796E-06	7.917E-06
V140	0.000E+00	0.000E+00	0.000E+00
I1	0.000E+00	0.868E-07	0.000E+00
I2	0.000E+00	0.998E-03	0.000E+00
I1000	0.000E+00	1.576E-04	0.000E+00

___ (C). DC SENSITIVITIES OF OUTPUT V(3) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (VOLTS/UNIT)	NORMALIZED SENSITIVITY (VOLTS/PERCENT)
RCOND	4.500E+00	1.575E-07	7.085E-09
RC1	4.500E+00	-2.268E-04	-1.021E-05
R2	1.000E+12	1.334E-30	1.334E-20
R1000	1.000E+03	0.000E+00	0.000E+00
R3	1.000E+12	5.857E-26	5.857E-16
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+12	1.076E-24	1.076E-14
R60	1.000E+12	-1.735E-24	-1.735E-14
R7	1.000E+12	-1.704E-25	-1.704E-15
R70	1.000E+12	8.900E-25	8.900E-15
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
r110	1.000E+09	-1.819E-16	-1.819E-09
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	-5.098E-14	-5.098E-10
R13	1.000E+06	9.144E-13	9.144E-09

___ (D). DC SENSITIVITIES OF OUTPUT I(v100) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (AMPS/UNIT)	NORMALIZED SENSITIVITY (AMPS/PERCENT)
RCOND	4.500E+00	-6.320E-05	-2.800E-06
RC1	4.500E+00	-3.880E-05	-1.780E-06
R2	1.000E+12	4.140E-30	-4.140E-20
R1000	1.000E+03	0.000E+00	0.000E+00
R3	1.000E+12	4.381E-30	-4.381E-20
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+12	0.130E-19	7.130E-09
R60	1.000E+12	-1.150E-18	-1.150E-08
R7	1.000E+12	0.303E-25	5.303E-15
R70	1.000E+12	-2.771E-24	-2.771E-14
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
R110	1.000E+00	1.445E-16	1.445E-09
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	1.964E-21	1.964E-17
R13	1.000E+06	-3.523E-20	-3.523E-16
Rtop	1.000E+00	0.000E+00	0.000E+00
Rbot	1.000E+00	0.000E+00	0.000E+00
Rfwd	1.000E+00	0.000E+00	0.000E+00
Rrev	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
V100	0.000E+00	0.000E+00	0.000E+00
V200	0.000E+00	0.000E+00	0.000E+00
V1000	0.000E+00	1.179E-20	0.000E+00
V4	7.000E+00	1.046E-08	-7.322E-10
V5	3.100E+01	2.808E-08	-8.703E-09
V50	3.150E+01	1.684E-01	5.305E-02
v10	1.070E+02	5.916E-06	6.331E-06
V11	9.000E+01	-5.916E-06	-5.325E-06
V140	0.000E+00	0.000E+00	0.000E+00
I1	0.000E+00	3.365E-04	0.000E+00
I2	0.000E+00	1.494E-07	0.000E+00
I1000	0.000E+00	-1.179E-08	0.000E+00

___ (E). DC SENSITIVITIES OF OUTPUT I(v200) ___

ELEMENT NAME	ELEMENT VALUE	ELEMENT SENSITIVITY (AMPS/UNIT)	NORMALIZED SENSITIVITY (AMPS/PERCENT)
RCOND	4.500E+00	7.040E-05	3.168E-06
RC1	4.500E+00	-1.486E-08	-6.687E-10
R2	1.000E+12	1.044E-26	-1.044E-16
R1000	1.000E+03	0.000E+00	0.000E+00
R3	1.000E+12	1.046E-30	-1.046E-20
R4	1.000E+12	0.000E+00	0.000E+00
R5	1.000E+12	0.000E+00	0.000E+00
R50	1.000E+12	0.000E+00	0.000E+00
R6	1.000E+12	2.021E-25	-2.021E-15
R60	1.000E+12	3.258E-25	3.258E-15
R7	1.000E+12	3.548E-18	-3.548E-08
R70	1.000E+12	1.853E-17	1.853E-07
R8	1.000E+12	0.000E+00	0.000E+00
R9	1.000E+12	0.000E+00	0.000E+00
R10	1.000E+12	0.000E+00	0.000E+00
R110	1.000E+00	4.036E-17	4.036E-10
R11	1.000E+12	0.000E+00	0.000E+00
R12	1.000E+06	-9.573E-15	-9.573E-11
R13	1.000E+06	1.717E-13	1.717E-09
Rtop	1.000E+00	0.000E+00	0.000E+00
Rbot	1.000E+00	0.000E+00	0.000E+00
Rfwd	1.000E+00	0.000E+00	0.000E+00
Rrev	1.000E+00	0.000E+00	0.000E+00
R14	1.000E+01	0.000E+00	0.000E+00
V100	0.000E+00	0.000E+00	0.000E+00
V200	0.000E+00	0.000E+00	0.000E+00
V1000	0.000E+00	2.961E-17	0.000E+00
V4	7.000E+00	2.628E-05	-1.839E-06
V5	3.100E+01	0.878E-01	5.822E-02
V50	3.150E+01	-4.773E-08	-1.503E-08
V10	1.070E+02	1.653E-06	1.768E-06
V11	9.000E+01	-1.653E-06	-1.487E-06
V140	0.000E+00	0.000E+00	0.000E+00
I1	0.000E+00	1.666E-07	0.000E+00
I2	0.000E+00	3.754E-04	0.000E+00
I1000	0.000E+00	-2.961E-05	0.000E+00

APPENDIX II

FIGURES

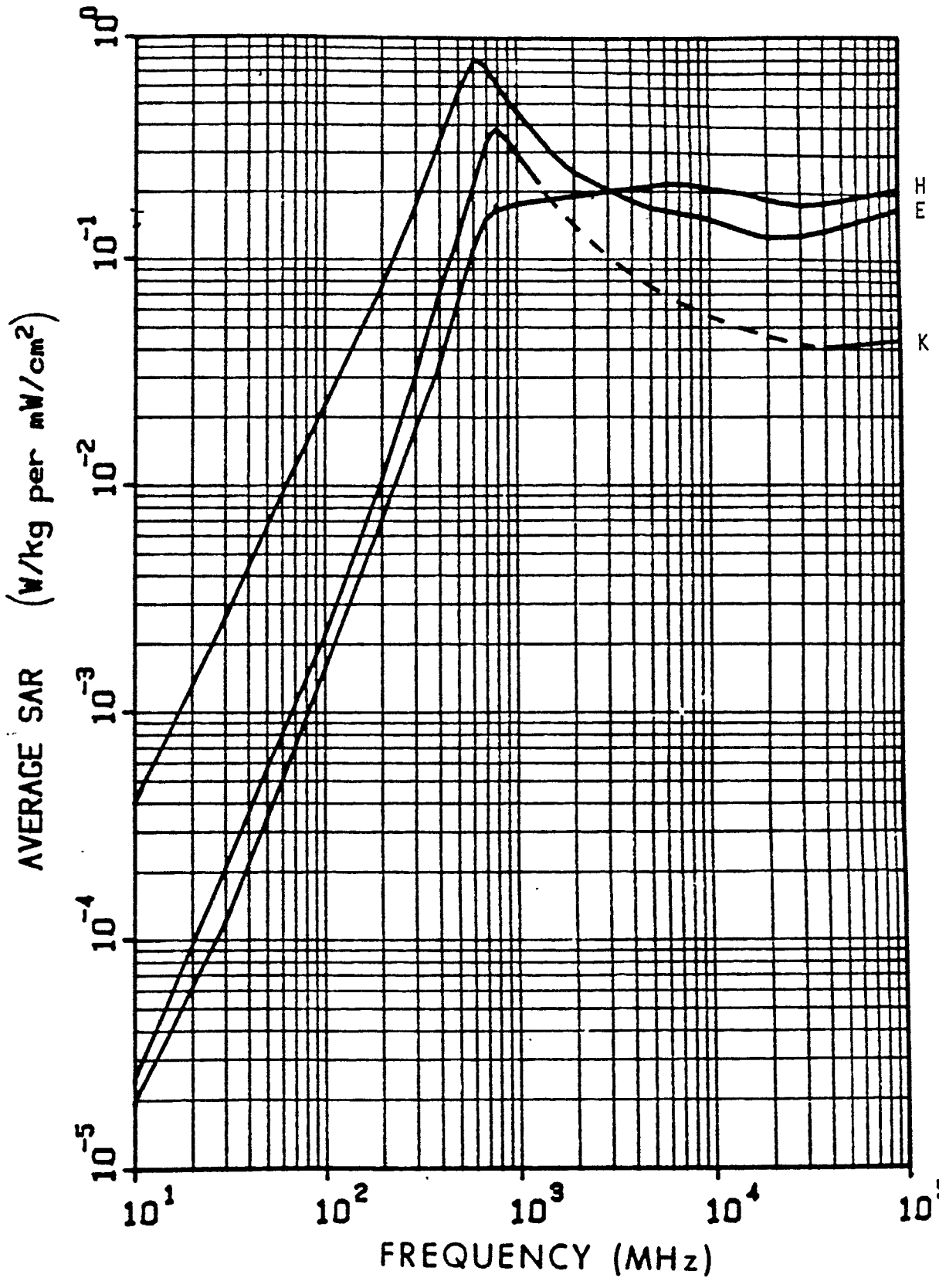

Figure 6 Average SAR

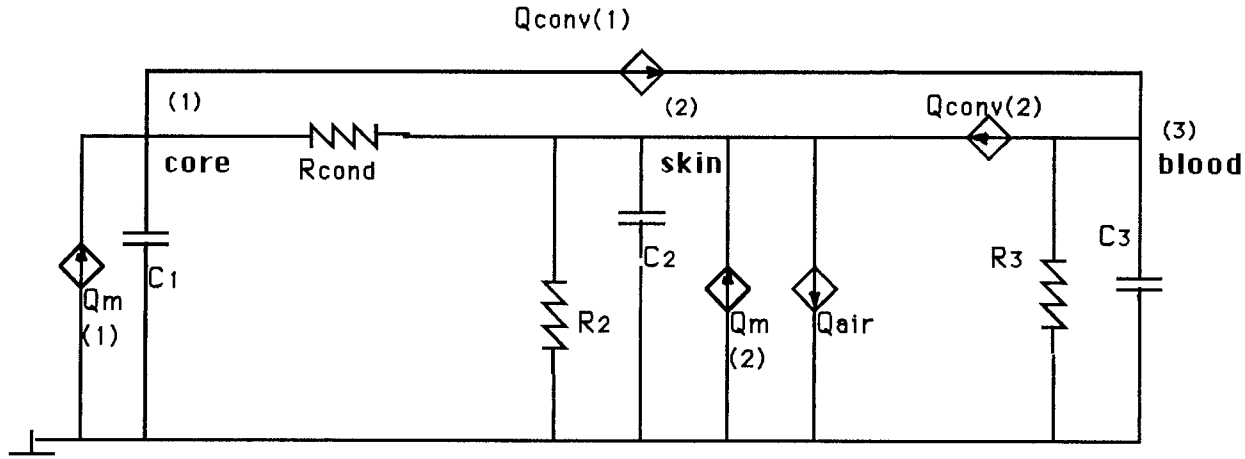

Figure 7 Set Point Temperature Simulation Circuit

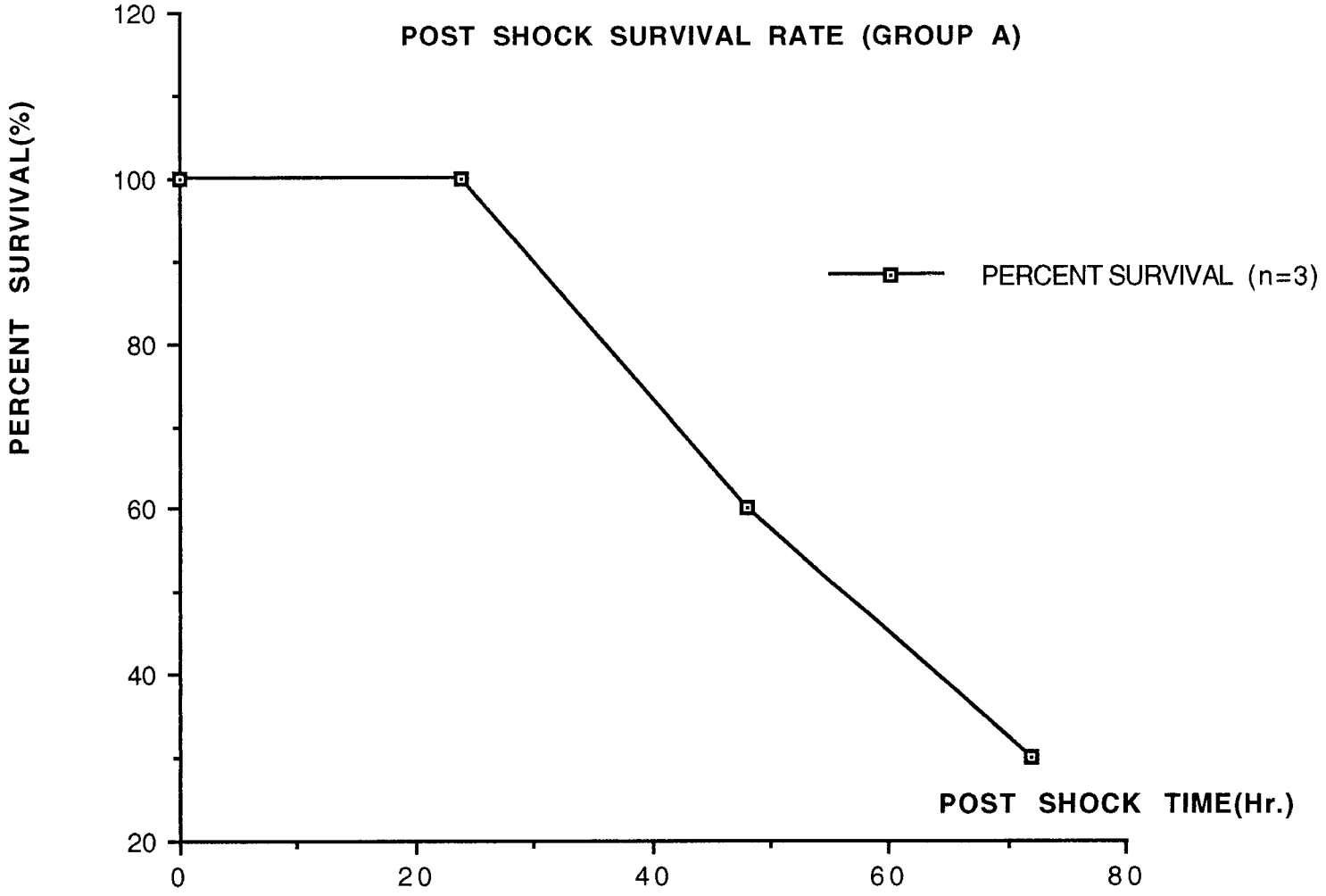

Figure 9 Survival Statistics of Group A

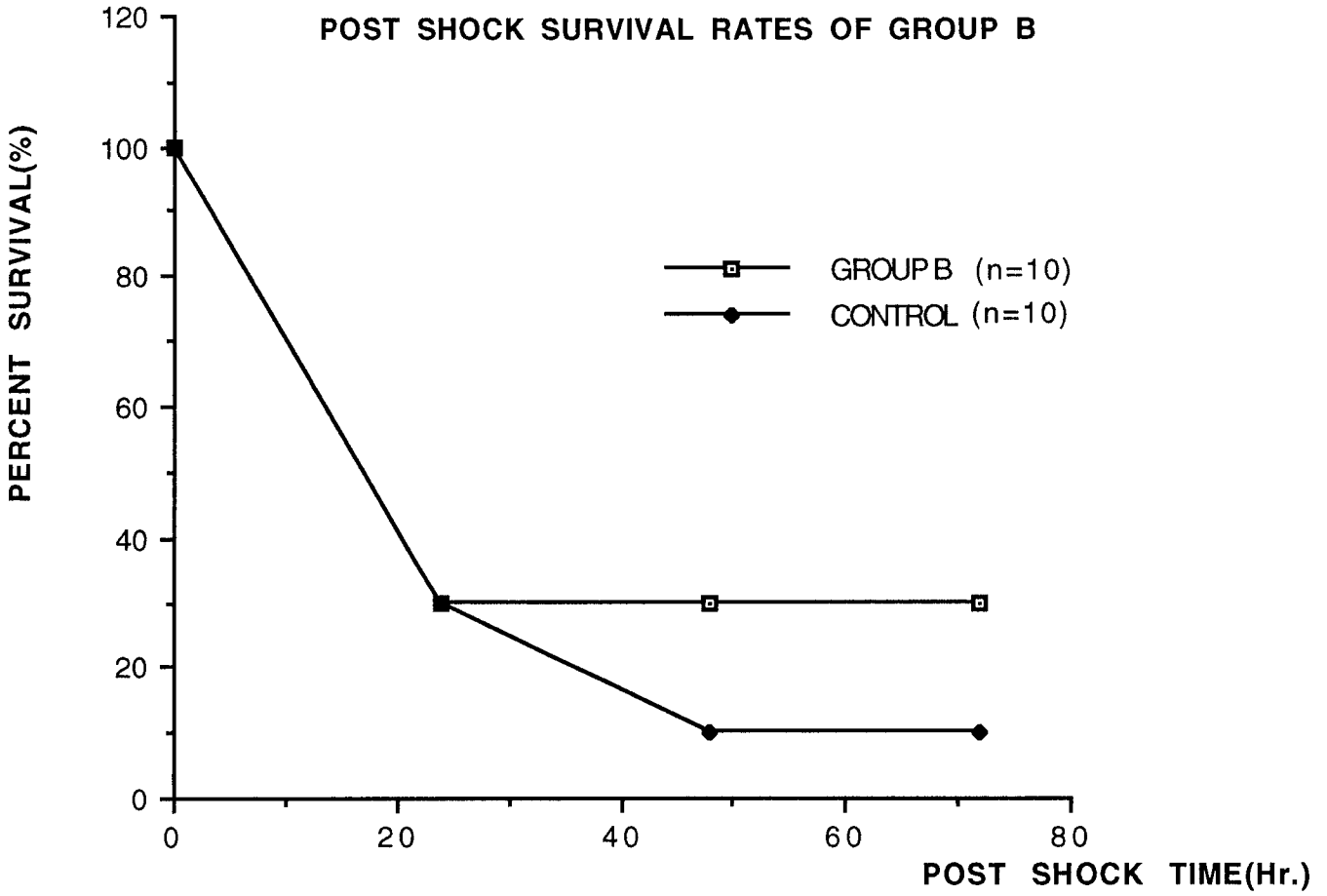

Figure 10 Survival Statistics of Group B

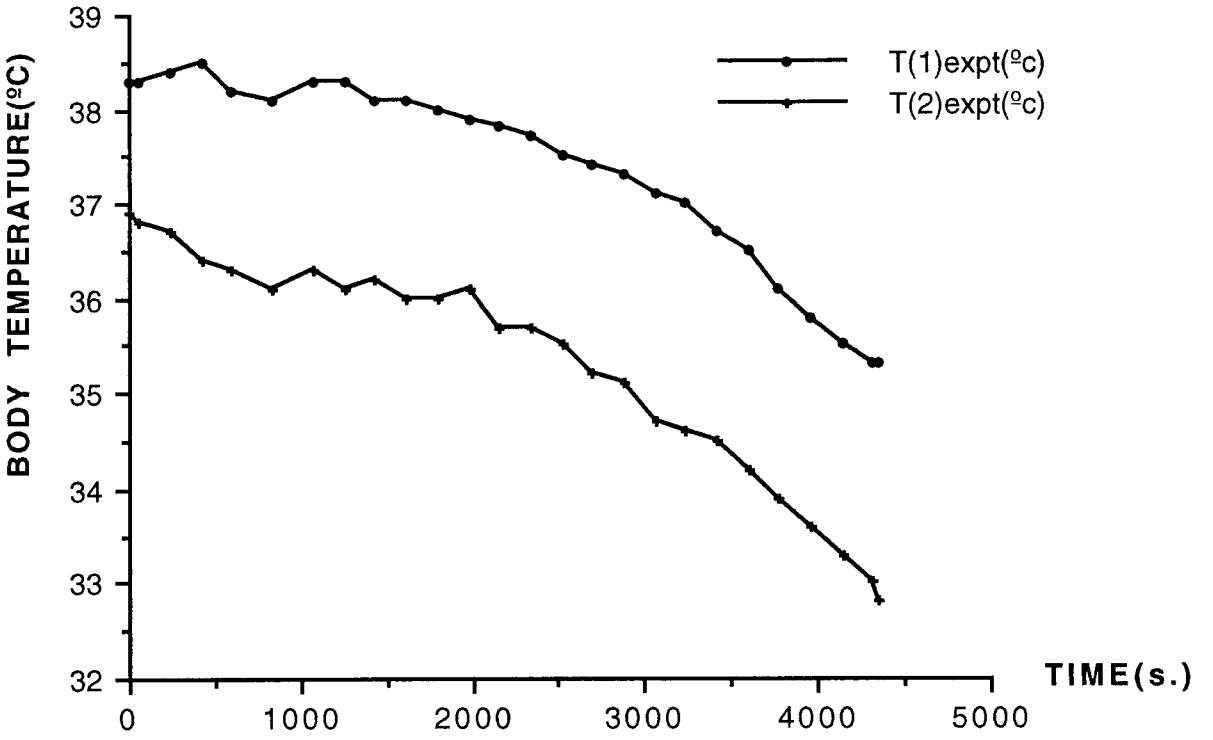

Figure 11 Typical Body Temperature Histories During Shock (Group A)

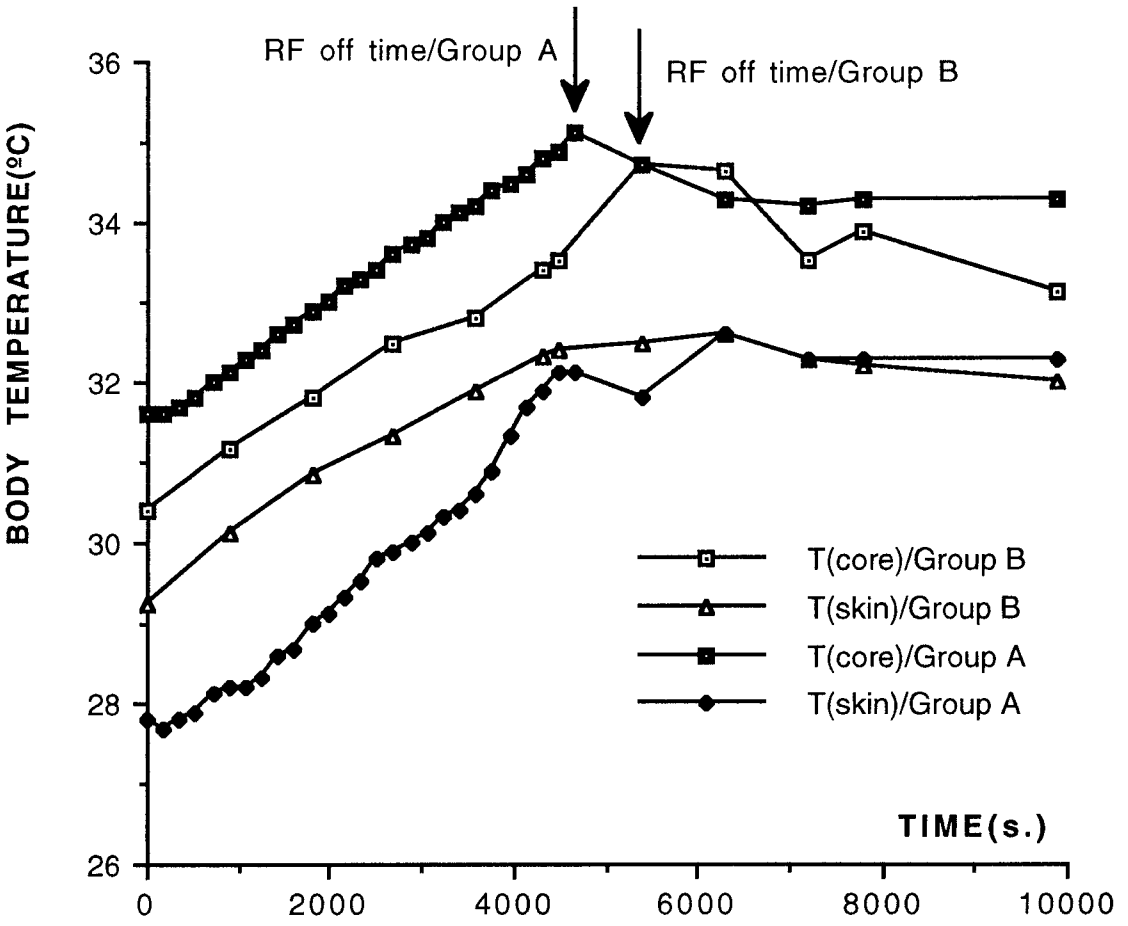

Figure 12 Body Temperature Histories During Rewarming

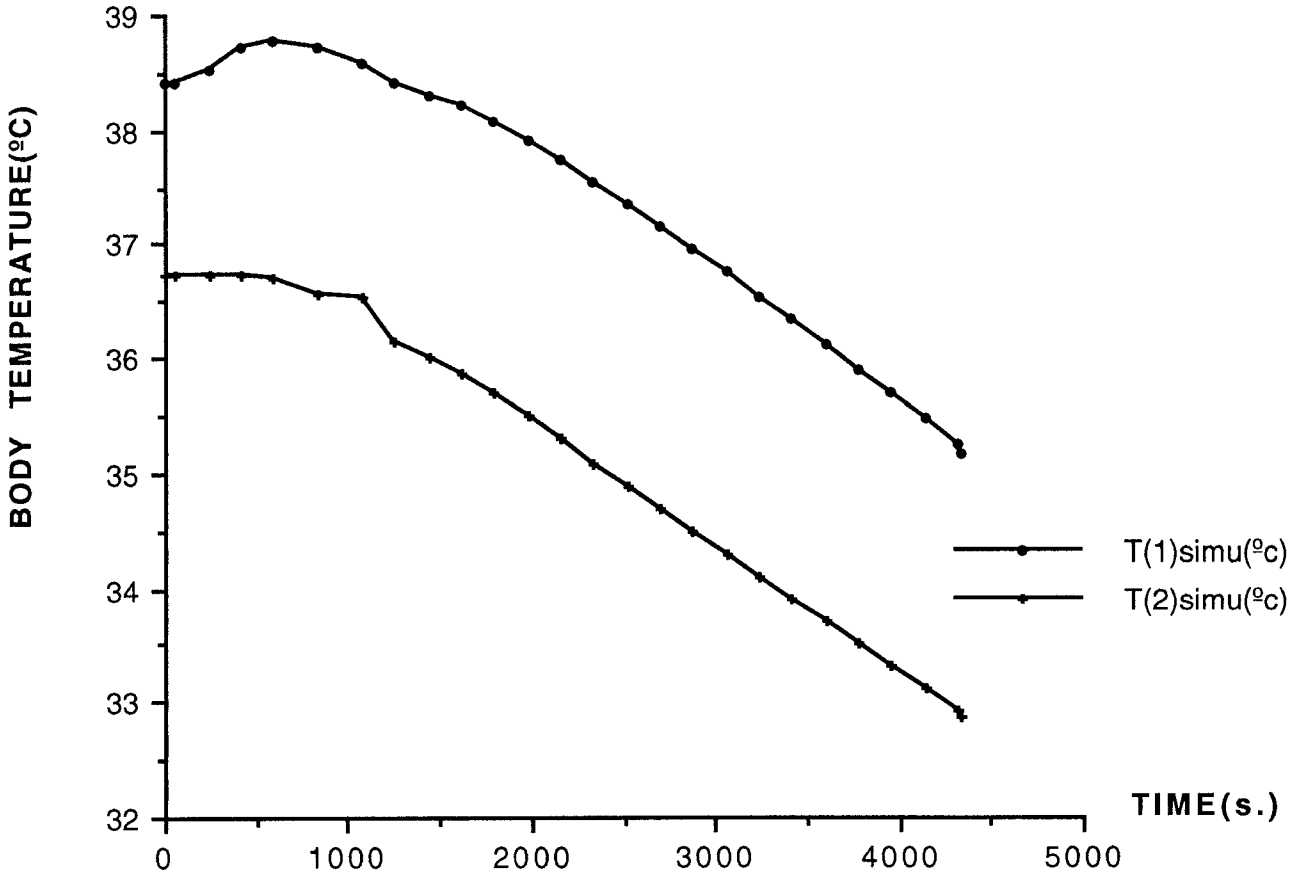

Figure 13 Simulated Body Temperature During Shock

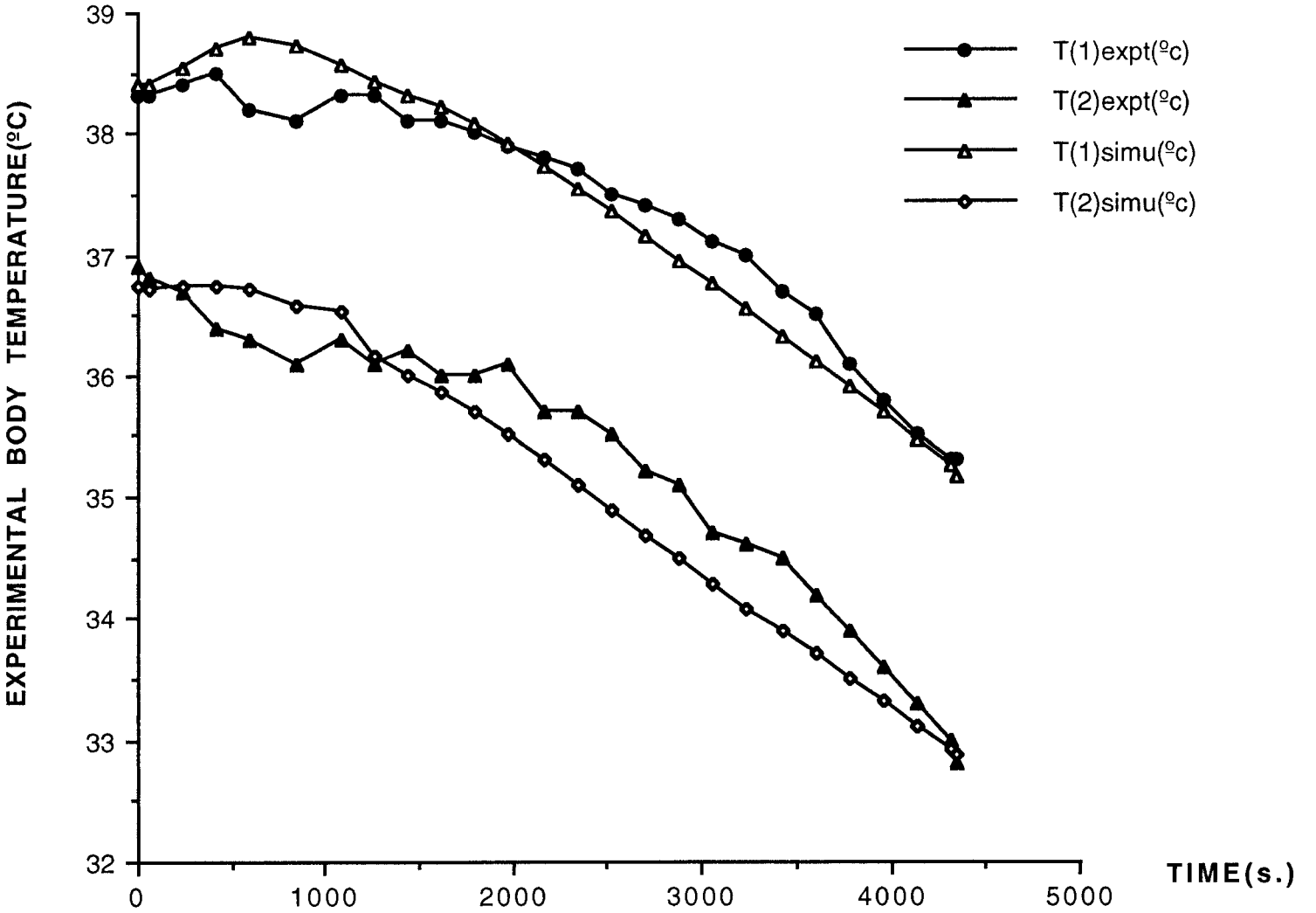

Figure 14 Body Temperature During Shock (Simulated and Typical Experimental)

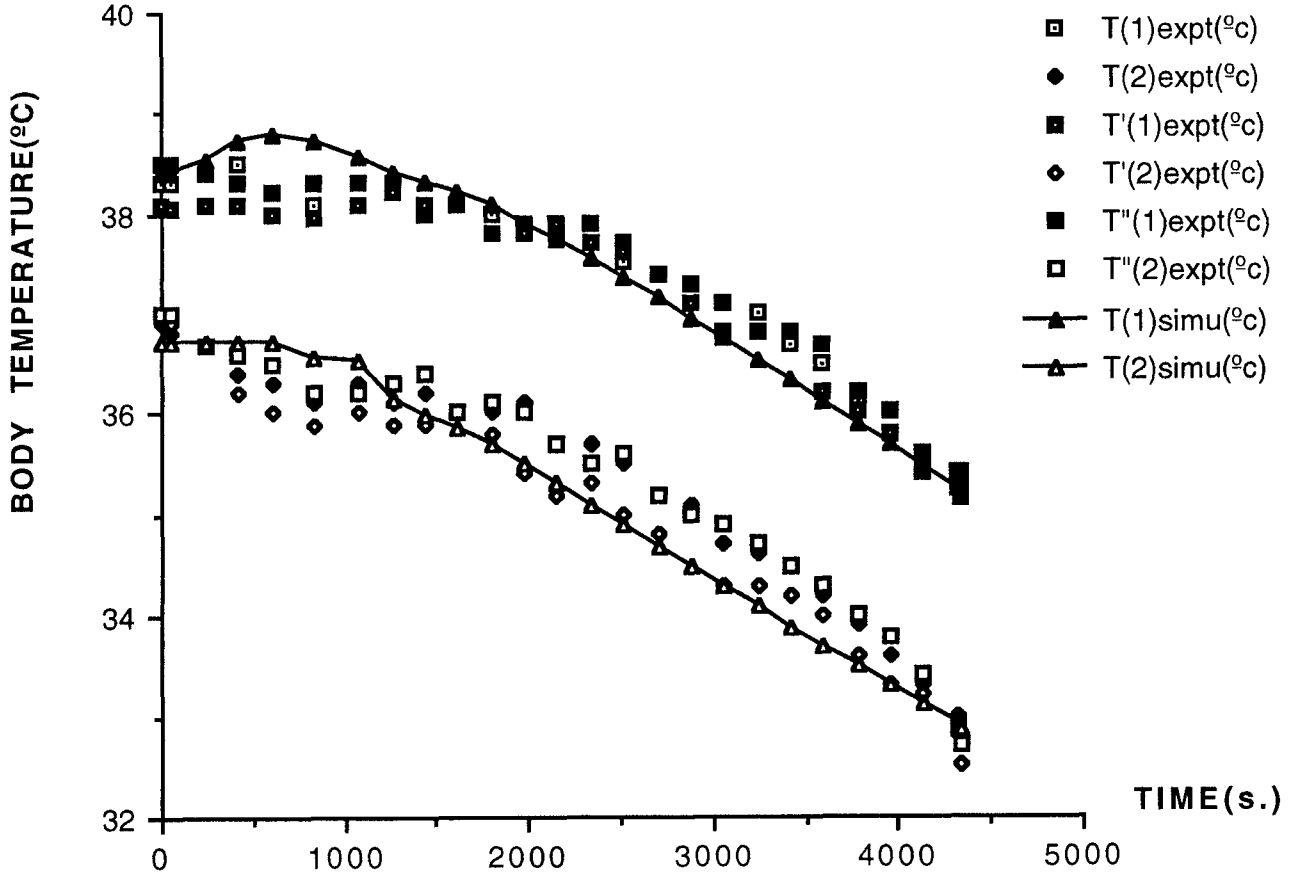

Figure 15 Body Temperature During Shock(2) (Simulated and Averaged(n=3) Experimental)

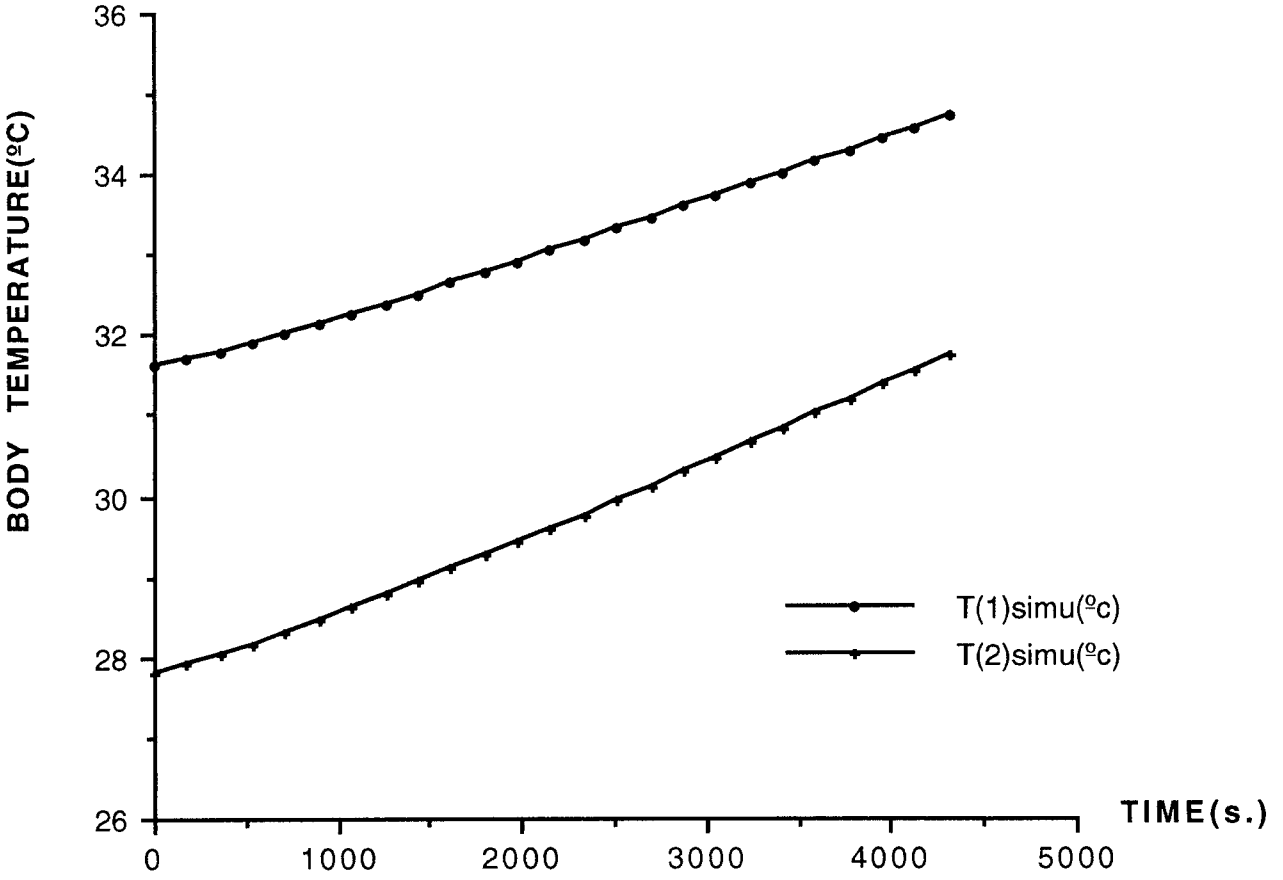

Figure 16 Simulated Body Temperature During Post Shock Rewarming

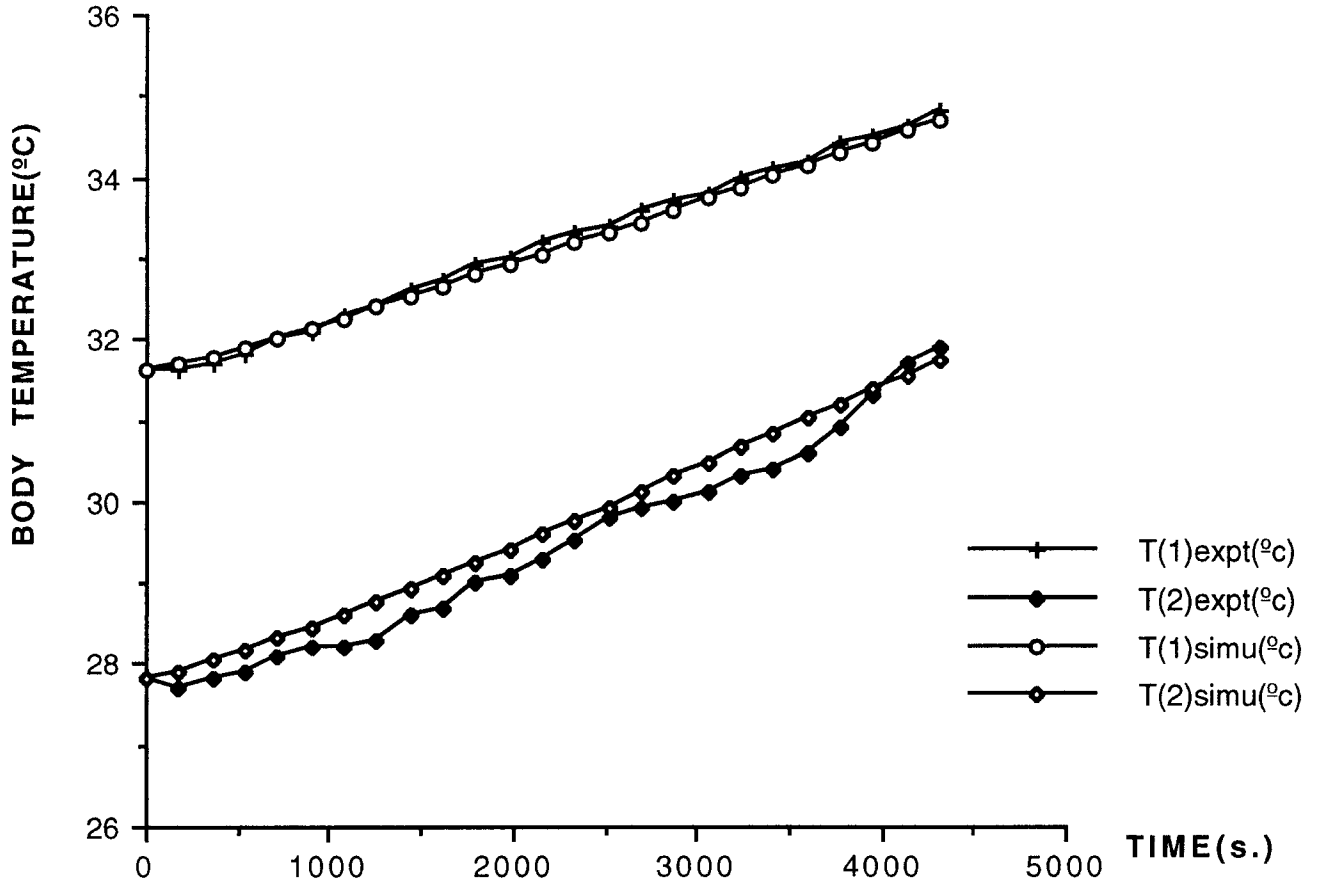

Figure 17 Body Temperature During Post Shock Rewarming (Simulated and Typical Experimental)

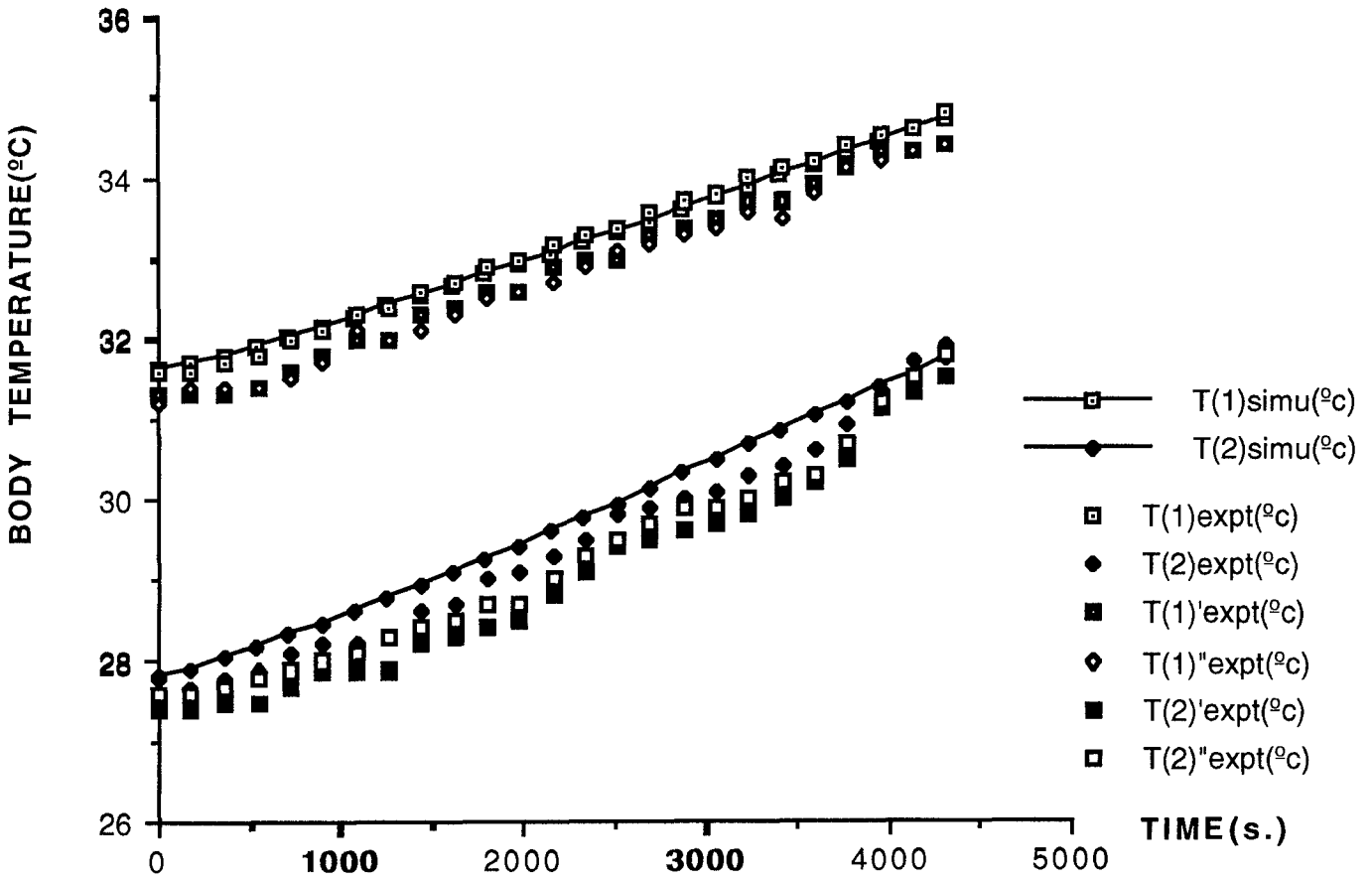

Figure 18 Body Temperature During Post Shock Rewarming (Simulated and Averaged Experimental)

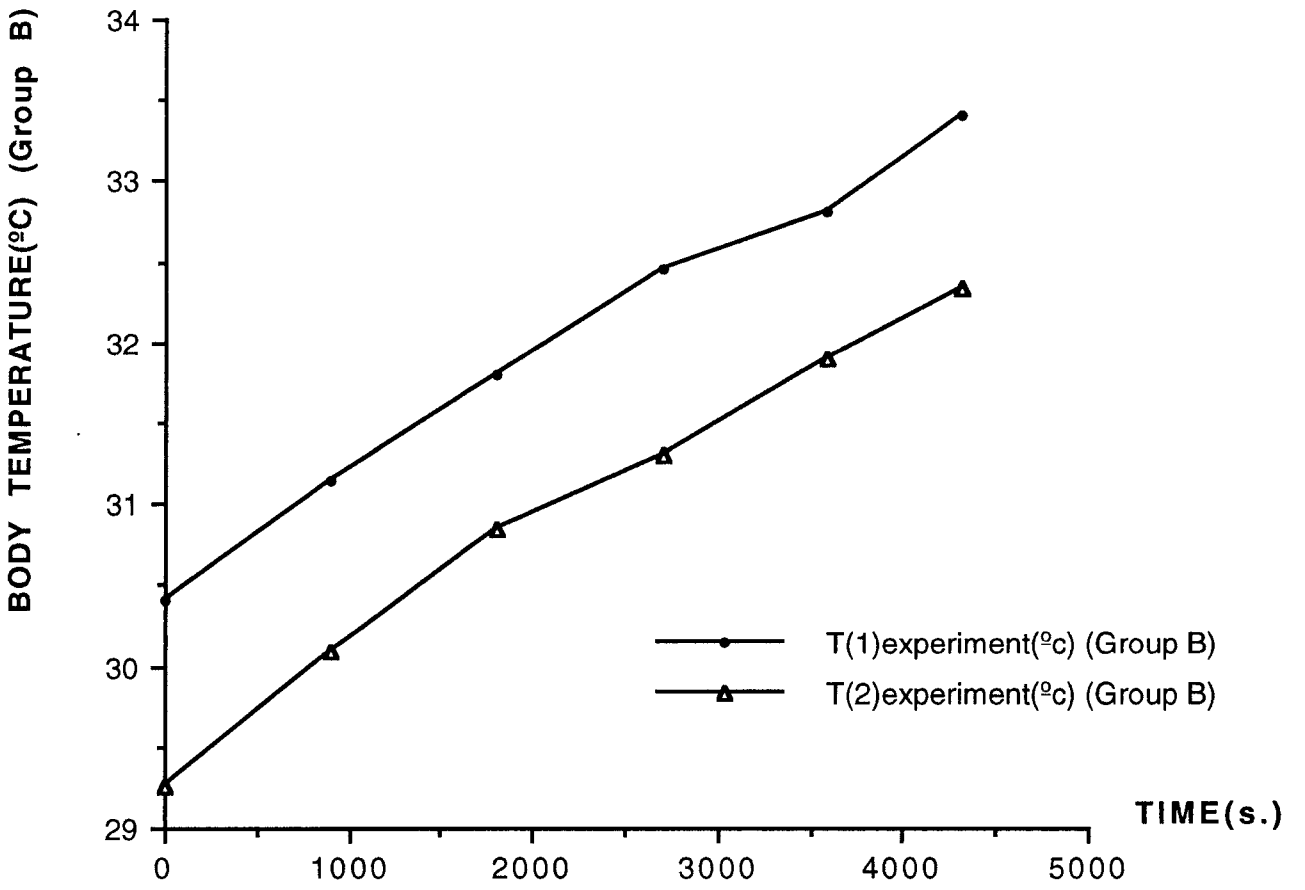

Figure 19 Body Temperature In Rewarming (Group B)

APPENDIX III

PSPICE SIMULATION PROGRAMS

(A). PSpice Program For the Set Point Temperature Calculation

```
******* 12/04/92 ******* PSpice 4.03 - January, 1990 ******* 16:41:24 *******
*SETPOINT TEMPERATURE CALCULATION*
****     CIRCUIT DESCRIPTION     ***********************************

RCOND 1 2 4.1 ;
IM1 0 1 0.45 ; Qmet(1)
RC1 1 3  5.338; Qconv(1)
R1 1 0 1E20k
*
GA2 2 0 (2,4) 3.71e-1; Qair(2)
IC2 2 3 .394 ; Qconv(2)
IM2 0 2 3.8E-2; Qm(2)
R2 2 0 1E9k
*
R3 3 0 1E20k
*
V4 4 0 30; Tair
R4 4 0 1E20k
*
.OP
.END

******* 12/04/92 ******* PSpice 4.03 - January, 1990 ******* 16:41:24 *******
```

(B). PSpice Program For the Hemorrhagic Shock

```
******* 12/04/92 ******* PSpice 4.03 - January, 1990 ******* 16:41:24 *******
* BODY HEATFLOW MODEL (HEMORRHEGIC SHOCK SIMULATION)

****     CIRCUIT DESCRIPTION
******************************************************************************

C1 1 0 2600; COMPARTMENT #1 IS CORE.
RCOND 1 2 4.3; Qconduct from (2) to (1).
GM1 0 100 POLY(1) (6,0) 0.456 4.346E-2 2.07E-3 6.58E-5 ; Qmet(1)
GM-1 1 0 POLY(1) (9,0) 0 0 0.00053;
GMactive 0 100 poly(1) (15,0) 0 0 3E-4
V100 100 1 0
RC1 3 1  4;Qconv(1)
*
C2 2 0  652.8; 311.22 ; COMPARTMENT#2 IS SKIN
GA2 2 0 (2,4) 97E-3; Qair(2)
GC2 3 2 POLY(2) (3,2) (103,0) 0 0 0 0 1
GM2 0 200 POLY(1) (7,0) 3.8E-2 3.62E-3 1.726E-4 5.483E-6; Qm(2) when
T(2)>Tset(2)
GM2cold 0 200 poly(1) (70,0) 3.724e-2 2.926e-2; Qm(2) when T(2)<Tset(2)
V200 200 2 0
GM-2 2 0 POLY(1) (9,0) 0 0 0.00035
R2 2 0 1E9K
*
C3 3 0 250;COMPARTMENT #3 IS BLOOD
R3 3 0 1E9k
G3 0 3 POLY(1) (9,0) .45 0 -0.00011
*
V4 4 0 23.8 ; REFFERENCE TEMPERATURE T/AIR
R4 4 0 1E9k
*
V5 5 0 pwl(60 31 7000 28.7)
R5 5 0 1E9k
*
V50 50 0 pwl(60 37.2 120 37 7000 34); Tset(1)
R50 50 0 1E9K
*
D6 66 6 Dmod
E6 66 0 (1,50) 6 ; EXPONENCIAL CONTROLLING VARIABLE X1 when
T(1)>Tset
R6 6 0 10
*
D60 61 60 Dmod
E60 61 0 (50,1) 7.8; exp controlling variable X1 when T(1)<Tset
R60 60 0 10
*
D7 77 7 Dmod
```

```
E7 77 0 (2,5) 7.85;EXPONENCIAL CONTROLLING VARIABLE X2
R7 7 0 10
*
D70 71 70 Dmod
E70 71 0 (5,2) 7.85; exp controlling variable X2 when T(2)<Tset(2)
R70 70 0 10
*
E8 8 0 (2,5) 0.322 ; CONTROLLING VARIABLE FOR Qconv(2)
R8 8 0 1E9k
*
*E9 9 0 (10,11) 1 ; B.P. DROP
E9 9 0 (110,11) 1
R9 9 0 1E9K
*
*V10 10 0 120
V10 10 0 105
R10 10 0 1E9K
*
D10 10 110 Dmod
R110 110 11 1K
*
V11 11 0 PWL(0 120  300 110 420 80 480 60 1000 33 1360 50 1800 33 18000 33)
*V11 11 0 PWL(60 120 120 120 500 33 1100 50 1700 33 6000 33)
R11 11 0 1E9K
*
Ddilat 120 12 Dmod
Edilat 120 0 (2,5) 0.6562; Qdilat=7.5*WARMS(2)
R12 12 0 1E6
*
Dstric 130 13 Dmod
Estric 130  0 (5,2) 1; COLTS(STRIC)
R13 13 0 1E6
*
Htop 101 0 V140 1; POLY(1) (8,0) .3941 .273 9.47E-2 2.187E-2; Qconv(2)
Rtop 101 0 1e6
Ebot 102 0 poly(1) (13,0) 1 1
Rbot 102 0 1E6
Efwd 103 0 POLY(2) (101,0) (104,0) 0 1E6 -1E6
Rfwd 103 0 1e6
Erev 104 0 poly(2) (103,0) (102,0) 0 0 0 0 1
Rrev 104 0 1e6
*
GC2bas 0 14 POLY(1) (8,0) .3941 .273 9.47E-2 2.187E-2; local cntrol of Qconv(2)

GC2dilat 0 14 POLY(2) (8,0) (12,0) 0 0 0 0 6.57e-2; central 'dilating'
*+control of Qconv(2)
R14 14 140 10
V140 140 0  0
*
```

```
E15 15 0 POLY(1) (11,0) -33 1
R15 15 0 1E9K
*
.IC V(1)=38.4 V(2)=36.7 V(3)=37.5
.TRAN/OP 60 11000 [UIC]
.MODEL Dmod D (is=1e-9 IBV=1E-80)
.print tran v(1) v(2) v(3) v(5) v(6) V(9) I(v501) I(V200) I(v100) I(gm2cold)
I(gm2); v(7) v(12) v(13)
.PROBE v(1) v(2) v(3) V(15)
.SENS V(1) V(2) V(3) I(v100) I(v200)
.END

******* 12/04/92 ******* PSpice 4.03 - January, 1990 ******* 16:41:24 *******
```

(C). PSpice Program For the Post Shock Rewarming

```
******* 12/04/92 ******* PSpice 4.03 - January, 1990 ******* 16:53:55 *******
* BODY HEATFLOW MODEL (POSTSHOCK MICROWAVE
HEATINGSIMULATION)

****     CIRCUIT DESCRIPTION
******************************************************************************

C1 1 0 2600;;3454; 2200 ; COMPARTMENT #1 IS CORE.
I1 0 1 PULSE(0 1.41 0 0 0 10000 12000); Qrf(1), step pulse.
RCOND 1 2 4.1;;--5;;6.933 Qconduct from (2) to (1).
GM1 0 100 POLY(1) (6,0) 0.456 4.346E-2 2.07E-3 6.58E-5 ; Qmet(1)
GM1cold 0 100 poly(1) (60,0) 0.438 0.057
V100 100 1 0
FM1cardiac 0 1 V100 .7;;--0.5
gm-1 1 0 poly(1) (9,0) 0 0 0.00052
RC1 1 3  4.5;;--5;;5.338; Qconv(1)
*  w(1)+w(2) should =C.O.,so Rc1=0.2669[C.O.-w(2)]
*
C2 2 0  652.8;;--772.8; 311.22 ; COMPARTMENT#2 IS SKIN
I2 0 2 pulse(0 0.25 0 0 0 10000 12000)
GA2 2 0 (2,4) 70e-3;;100e-3;;***301.55e-3;;--371.55E-3; Qair(2)
GC2 3 2 POLY(2) (3,2) (103,0) 0 0 0 0 1
GM2 0 200 POLY(1) (7,0) 3.8E-2 3.62E-3 1.726E-4 5.483E-6; Qm(2) when
T(2)>Tset(2)
GM2cold 0 200 POLY(1) (70,0) 3.724e-2 2.926e-2 ;Qm(2) When T(2)<Tset(2)
V200 200 2 0
FM2cardiac 0 2 poly(2) v100 v1000 0 0 0 0 0.09
Gm-2 2 0 poly(1) (9,0) 0 0 0.00013
R2 2 0 1E9k
*
R1000 1000 0 1E3
I1000 0 1001 PWL(0 0 1500 0 7000 15)
V1000 1001 1000 0
*
C3 3 0 350;250;;--188; 139.23 ;COMPARTMENT #3 IS BLOOD
R3 3 0 1E9k
G3 0 3 poly(1) (9,0) .35 0 -0.00011
*
v4 4 0 pwl(0 7 420 8 1200 10 7000 10);
R4 4 0 1E9k ; HUGE R TO CLOSE THE LOOP
*
V5 5 0 pwl(0 31 3000 33 7000 34);
R5 5 0 1E9k
*
*V50 50 0 30;pulse(28 30 0 0 4800 0 6000); Tset(1)
*V50 50 0 pwl(60 37 120 37 5000 34 7000 33); Tset(1)
V50 50 0 PWL(0 31.5 7000 36)
```

```
R50 50 0 1E9K
*
D6 66 6 Dmod
E6 66 0 (1,50) 6;;--POLY(2) (1,0) (50,0) 0 8 -8 ; EXP CONTROLLING
VARIABLE X1 When T(1)<Tset
R6 6 0 1E9k
*
D60 61 60 Dmod
E60 61 0 (50,1) 7.8 ; E controlling variable X1 when T(1)<Tset(1)
R60 60 0 1E9K
*
D7 77 7 Dmod
E7 77 0 (2,5) 7.85;;--6 ;EXP CONTROLLING VARIABLE X2 when
T(2)>Tset(2)
R7 7 0 1E9k
*
D70 71 70 Dmod
E70 71 0 (5,2) 7.85; exp controlling variable X2 when T(2)<Tset(2)
R70 70 0 1e9k
*
E8 8 0 POLY(2) (2,0) (5,0) 0 .322 -.322; CONTROLLING VARIABLE FOR
Qconv(2)
R8 8 0 1E9k
*
*E9 9 0 (10,11) 1 ; B.P. DROP
E9 9 0 (110,11) 1
R9 9 0 1E9K
*
*V10 10 0 120
V10 10 0 107
R10 10 0 1E9K
*
D10 10 110 dmod
R110 110 11 1e6k
*
*V11 11 0 PWL(60 120 120 120 500 33 1100 50 1700 33 6000 33)
V11 11 0 PWL(0 90 1500 100 7000 119.8)
R11 11 0 1E9K
*
Ddilat 120 12 Dmod
Edilat 120 0 (2,5) .6562;; 0.0781 ; Qdilat=7.5*WARMS(2)
*R120 120 0 1E9K
R12 12 0 1E6
*
Dstric 130 13 Dmod
*R130 130 0 1E9K
Estric 130  0 (5,2) 1;; 0.5 ; COLTS(STRIC)
R13 13 0 1E6
*
```

```
Htop 101 0 V140 1; POLY(1) (8,0) .3941 .273 9.47E-2 2.187E-2; Qconv(2)
Rtop 101 0 1e6
Ebot 102 0 poly(1) (13,0) 1 1
Rbot 102 0 1E6
Efwd 103 0 POLY(2) (101,0) (104,0) 0 1E6 -1E6
Rfwd 103 0 1e6
Erev 104 0 poly(2) (103,0) (102,0) 0 0 0 0 1
Rrev 104 0 1e6
*
GC2bas 0 14 POLY(1) (8,0) .3941 .273 9.47E-2 2.187E-2; local cntrol of Qconv(2)
GC2dilat 0 14 POLY(2) (8,0) (12,0) 0 0 0 0 6.57e-2; central 'dilating'
*+control of Qconv(2)
R14 14 140 10
V140 140 0  0
*
.IC V(1)=31.6 V(2)=27.8 V(3)=29.3
.TRAN/OP 60 18000 [UIC]
.MODEL Dmod D (is=1e-9 IBV=1E-80)
.print tran v(1) v(2) v(3) ;v(5) v(6) v(7) v(12) v(13) I(GC2) I(Rc1)
.PROBE v(1) v(2) v(3) ;v(20000);V(12) V(13) I(gc2) I(Rc1) i(g3)
.SENS V(1) V(2) V(3) i(v100) I(v200)
.END

******* 12/04/92 ******* PSpice 4.03 - January, 1990 ******* 16:53:55 *******
```

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