Electrical Heating Vest for Heart Failure and/or Hypertension Therapy

Submitted by:

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Abstract

Purpose:

To develop a lightweight, safe, and controllable electrical heating vest for heart failure and/or hypertension patients.

Methods:

a. A literature review related to the topic was conducted.

b. A model of a simplified human body thermoregulation system was developed and simulated. It was used to predict the power requirement of the battery to increase core body temperature up to 1 Celsius degree (°C).

c. A prototype with a smart controller was developed

d. In-vitro tests of the prototype were conducted to assess performance and safety.

e. The prototype was tested on 10 healthy human volunteers and the results were analyzed.

Results:

a. An average core body temperature increase of 0.3 °C ($P<0.05$) was observed in healthy human volunteer tests within 30 minutes.

b. The vest induced decreases in systolic blood pressure of 5.5 mmHg and diastolic blood pressure of 4.8 mmHg on average.

Conclusions:

A carbon-fiber vest can increase body core temperature by 0.3°C lowering systolic and diastolic blood pressure, which can be potentially used for helping heart failure and/or hypertension patients.

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List of Acronyms

EHV	Electrical heating Vest
SCM	Single-Chip Microcontroller
GLM	Generalized Linear Model
LED	Light-Emitting Diode
HSP	Heat Shock Protein
eNOS	Endothelial Nitric Oxide Synthase
BH4	Tetrahydrobiopterin
EHG	Electrical heating Garment
BMR	Basal Metabolic Rate
LIB	Lithium-ion Battery
DQ	Data Queue
ESD	Eight-Segment Display
INT	Interrupt
UI	User Interface
PSU	Power Supply Unit
LSD	Least Significant Difference
SD	Standard Deviation
WHV	Water Heating Vest

Chapter 1 Introduction

1.1 Clinical Needs and Issues

Heart failure is a condition in which the heart is unable to pump sufficient blood to meet the needs of the body. Despite major advances in pharmacology, medical devices and surgical treatments of heart failure, mortality and morbidity remain high [1]. Current therapeutic methods such as drugs, devices and transplants showed side effects, inherent high cost, poor quality of life, invasive properties, and/ or limited efficacy.

Hypertension (high blood pressure) is a condition in which the blood pressure in the arteries is persistently elevated [2]. It is one of the leading health problems in Canada [3] and all over the world [4]. Over time, chronic and untreated hypertension can cause heart disease, coronary artery disease, stroke, aortic aneurysm, peripheral artery disease, and chronic kidney disease [5]. Hypertension is mainly managed using lifestyle modification and antihypertensive medications.

The search of more effective, safer and affordable treatments for heart failure and hypertension continues.

1.2 Rationale

Thermal therapy (or hyperthermia) is the use of heat for therapeutic treatment. It has been used as a management method for chronic diseases such as rheumatic disease, endocrine dyscrasia and chronic cardiovascular diseases [6-8]. Current methods of thermal therapy include sauna/dry sauna and hot medium immersion. However, many hospitals do not have sauna or dry sauna devices due to the size and significant cost [1, 5]. In addition, some patients cannot receive sauna/dry sauna treatment at home, and they may not be applicable for hot medium immersion treatments.

1.3 Hypothesis

It is hypothesized that an electrical heating vest (EHV) can be used to increase the core body temperature slightly, and induce changes in physiological parameters such as heart rate, systolic and diastolic blood pressure.

1.4 Purpose

The purpose of this research is to develop and test a portable, lightweight, safe, and smart carbon-fiber electrical heating vest which can be a potential means of thermal therapy for heart failure and/or hypertension patients.

1.5 Method

a. A literature study of current thermal therapy mechanisms, heating methods, materials and devices was conducted. Published journal articles, books, patents, and thesis papers between 1971 and 2015 were selected for this study.

b. A simplified model of the human body thermoregulation system was built and simulated. This model was implemented on a numerical computing environment and matrix-based programming language, Matlab® (the MathWorks, Inc., United States).

c. The design of the EHV was divided into separate sub-systems, including heating, control, power supply, and the accessories. Hardware of the control system was designed based on a single-chip microcontroller (SCM). The control software was programed in specific C language for SCM.

d. In-vitro studies of a prototype of the EHV were conducted on a half-length manikin to assess the performance and the safety of the EHV.

e. Human tests on ten healthy volunteers were conducted in the laboratory of Cardiovascular Devices Division, University of Ottawa Heart Institute. Those tests were intended to see effectiveness of the prototype in core body temperature, heart rate, systolic and diastolic blood pressure. The results were analyzed with the two-way generalized linear model (GLM), and significant differences (P<0.05) in the tests were identified using Duncan's multiple range test.

1.6 Results

a. Theoretical mathematical model and simulation for heating the torso suggests that energy absorption rate of the body must be more than 145 Watt (W) to increase the core body temperature by 0.5°C. This value is achievable with current Lithium-ion battery technology and used to determine performance of the EHV power supply.

b. In healthy volunteer's tests, an average increase of 0.3°C (P<0.05) in core body temperature was observed. It induced a decrease in systolic blood pressure of 5.5 millimeters of mercury (mmHg) on average; and in the diastolic blood pressure of 3.3 mmHg.

1.7 Contribution

An electrical heating vest was developed and tested to increase core body temperature by 0.3°C, which can be potentially used as a means for reduction of blood pressure of hypertension patients and may be also potentially tested for heart failure patients.

1.8 Organization of Thesis

The thesis is organized as followed:

Chapter 1: Introduction of the research and the layout of this thesis.

Chapter 2: A summary of the literature research.

Chapter 3: The theoretical modeling and simulation study.

Chapter 4: The design of the electrical heating vest.

Chapter 5: The in-vitro studies including functional and safety tests.

Chapter 6: The healthy human volunteer study on 10 individuals.

Chapter 7: A summary of the key results.

Chapter 8: The conclusion of the research and future study directions.

Chapter 2 Literature Search

Thermal therapy (or hyperthermia) has been used as a management method for chronic diseases such as rheumatic disease, endocrine dyscrasia and chronic cardiovascular diseases, and in rehabilitation medicine around the world [6-8,12]. It transfers heat to the body to increase local or whole body temperature. The organism's response to heat load for avoiding potential harm is one of the body's protective mechanisms. By this response, certain diseases, particularly chronic diseases, can be prevented, improved or even cured.

It has been reported that increasing core body temperature up to 1°C would result in a noticeable improvement in the quality-of-life for patients with heart failure and/or hypertension [1,6-8,11].

In this literature search, possible thermal therapy mechanisms, heating methods, materials and devices have been reviewed. Published journal articles, books, patents, and thesis papers between 1971 and 2015 have been selected for this study.

2.1 Potential Thermal Therapy Mechanisms for Heart Failure and Hypertension

2.1.1 Sympathetic Nervous Activity

It has been shown that decreased sympathetic activation is one of the characteristics of metabolic syndromes such as high blood glucose level, hypertension, and some heart diseases [12]. Decreased sympathetic activation leads to decreased blood vessel distensibility and increased stiffness grade that occur in most metabolic syndrome patients [13]. A temporary inhibition of sympathetic nerve activity has been observed during thermal therapy, suggesting the potential of thermal therapy for improving the elasticity of blood vessels and enhancing the cardiovascular function by modulating the activity level of sympathetic nerve [14,15].

2.1.2 Heat Shock Protein

Heat shock proteins (HSP) are a family of proteins produced by cells in response to heat load [16]. Over-expression of HSP can impede cardiac myocyte apoptosis, particularly HSP90 which protects cardiomyocytes from interacting with other protein substrates including the glucocorticoid receptor, the estrogen receptor, the androgen receptor, and the progesterone receptor [17,18]. HSP90 activation may result in increased production of endothelial nitric oxide synthase (eNOS) which would proliferate the bioavailability of nitric oxide (NO) [1]. And NO, an important vasodilator substance, can helps prevent atherosclerosis by maintaining vasodilation and inhibiting platelet aggregation [19]. The research of Bellmann has indicated that the expression of HSP70 links to the NO system through modulating the cellular response to cytokines with enhanced activation of the p38 (one activated protein kinase) pathway [20]. This was also proved by Genth-Zotz who has developed a study for the relationship between HSP70, and the disease severity and survival of patients with chronic heart failure [21]. Staib has conducted an in-vivo test on exercised rat and found that cardiac HSP72 mRNA translation may be promoted by elevated body temperature [22], which was also observed in McCormick’s study on animals [23]. In conclusion, the activity and expression of eNOS can be accentuated by heat production, and thermal therapy can possibly strengthen vascular endothelial functionality through over-expressing HSP [24].

2.1.3 Shear Stress

Shear stress is a result of tangential force applied to a surface due to fluids motion [25]. Blood flow inside vessels gives rise to shear stress that acts in the direction of the flow along the blood vessel walls. Thermal therapy can reduce both the pre- and after-loads on the heart by improving friction, and increasing shear stress in blood vessels by regulating vascular diameter

[26]. As heat energy increases, higher blood flow rate raises the shear stress which promotes biochemical reactions responsible for vasodilation and anti-coagulation (increased NO production) in order to improve endothelial function [27]. Hence, thermal therapy could increase shear stress and improve vascular performance.

2.1.4 Tetrahydrobiopterin

Tetrahydrobiopterin (BH4), also known as sapropterin, is one of the cofactors for NO production by nitric oxide synthases [28]. Increasing in BH4 leads to a drop in the uncoupling rate of nitric oxide synthase which can boost the production of NO and enhance cardiovascular functions [29]. Thermal therapy has been used to treat certain BH4 deficiency diseases, and BH4 can potentially improve cardiovascular functionality [30].

2.2 Physiological Parameters Impacted by Thermal Therapy

Physiological changes induced by thermal therapy manifest in several parameters including core body temperature, cardiac and vascular functionality, blood pressure, blood glucose level and insulin sensitivity. A review paper published by Mussivand et al. summarized the various clinical improvements potentially induced by thermal therapy. Those parameters were classified as endothelial functions, hemodynamics and cardiac structure and functions (Table 2-1) [1].

Due to measurement difficulties, core body temperature, heart rate, systolic and diastolic blood pressure were selected for this research. The review of the parameters below considered different methods for thermal therapy, which can give dissimilar results.

Table 2-1 Clinical improvements trends resulting from thermal therapy [1]

Physiological Parameters		Trends
Endothelial Function	Vascular Resistance	Decreased
Hemodynamics	Systolic Blood Pressure	Decreased
	Diastolic Blood Pressure	Decreased
Cardiac Structure and Function	Ejection Fraction	Decreased
	Stroke Index	Increased
	Cardiac Remodeling	N/A

2.2.1 Core Body Temperature

Generally, the core body temperature is managed by thermoregulation system of the body within a narrow range for optimal metabolic activity. Despite influencing factors such as age, exertion, infection, sex and time of the day, typical values are well established: 36.8±0.4°C (under the tongue) and 37.0±0.5°C (rectal or vaginal) [31]. However, thermal therapy is intended to break the thermal balance state and increase the core body temperature up to 1°C.

C. Tei compared a 10-minute warm-water bath at 41°C and a 15-minute sauna bath at 60°C. The results showed that both methods can raise the pulmonary arterial blood temperature by 1.2°C, but only the sauna method can achieve an increase of 1°C in core body temperature [26]. These results have been mentioned in several articles [1,30].

Despite the benefits of thermal therapy established through various studies, minimal research has been conducted regarding thermal therapy using wearable devices. A water-flow heating vest which can potentially be used for thermal therapy was developed by Robert, A. The healthy human volunteer's study with the vest showed that the core body temperature can reach an average of approximately 0.2°C higher than the results of control groups with a 40-minute session at 65°C [32].

2.2.2 Heart Rate

Heart rate is the number of contractions of the heart per minute and for the normal resting adult human heart rate ranges from 60 to 100 beats per minute (bpm) [31].

According to C. Tei's research, the heart rate of patients with chronic heart failure increased by 20 to 25 bpm when they received a continuous warm-water bath or sauna. The result may be associated with vasodilation-related reflex and the direct cardiac effect of warming or stimulation of the sympathetic nervous system [26]. It has been also reported that a 15-minute warm-water bath would increase the cardiac output of healthy college students, resulting in an increased heart rate and drop of systemic vascular resistance [33]. Keast's research suggested that sauna can increase heart rate to a range of 100-160 bpm, which depends on individual heat tolerance and exposure. Besides, the heart rate changes during sauna resembles those observed during moderate to vigorous walking [6]. Robert's water heating vest can induce an average increase in heart rate of 40 bpm on healthy volunteers, which resembles the results observed in traditional thermal therapy sessions such as sauna and warm-water bath [32].

Increased heart rate may be a potential danger for patients with ischemic cardiomyopathy during thermal exposure. Whereas, separated studies conducted by Vuori and Libert indicate that habituation to thermal therapy blunts the heart rate response, and acclimation of heat can improve thermal tolerance, accompanied by a fall in heart rate at rest and during work [34,35].

2.2.3 Blood Pressure

Blood pressure is the force exerted by circulating blood on the walls of blood vessels. Without further specification, "blood pressure" usually refers to the arterial pressure in the systemic circulation. Blood pressure is usually expressed in terms of the systolic (maximum during one heart beat) pressure over diastolic (minimum in between two heart beats) pressure and is measured in millimeters of mercury (mmHg) [31].

Several researchers have verified that thermal therapy can decrease the systolic and/or diastolic blood pressure of patients with cardiovascular diseases [26, 36]. Giannetti showed that a sauna bath decreases the systolic blood pressure of coronary disease patients from 142 ±14 mmHg to 123 ±15 mmHg, a 13% drop [37]. A continuous 10-minute hot-water bath at 40°C can help hypertension patients reduce the systolic blood pressure significantly, and the improvement can last up to 10 minutes after the bath [38]. For chronic heart failure patients, although the systolic blood pressure did not change, the pulmonary and diastolic arterial pressure decreased noticeably within a 15-minute sauna bath at 60°C [14]. Similar results were observed with thermal therapy on congestive heart failure patients [36].

Thermal therapy may also affect the blood pressure of healthy adults. Various studies indicated a notable drop in the blood pressure of healthy volunteers treated with similar warm-water bath at 40°C for 10 minutes. Decrease in systolic and/or diastolic blood pressure were observed in Shin's, Sugiyama's, and Miwa's tests [38-40]. Boone reported that a warm-water bath at 37°C can reduce mean values of arterial blood pressure and systolic pressure for college students [33]. Kawabe found that the systolic and diastolic pressure of middle-age individuals (age: 41.6 ±11.7) decreased significantly if they took a bath before bed, and the effect sustained for 60 minutes after the bath [41]. In the test of Robert's water heating vest, there was a noticeable decrease in systolic blood pressure, but no change in diastolic blood pressure observed on five healthy human subjects [32].

A few studies did not clearly show an improvement in blood pressure for thermal therapy. Nagasawa performed a warm-water bath test with elderly hypertension patients (mean age: 75). It was found that both the systolic and diastolic blood pressure increased slightly but there were no significant differences compared to the basal levels [42]. Besides, lower water temperature (34.5°C) did not cause any notable changes in blood pressure [39,40]. Yet, when elderly subjects were treated with a warm-water bath at 34.5°C, the blood pressure increased. This probably has more to do with the effects of hydrostatic pressure than thermal therapy [26].

2.3 Methods for Thermal Therapy

The objective of thermal therapy is to increase the core body temperature up to 1°C. The various means for thermal therapy are classified according to heat transfer methods for the body.

Invasive Heat Transfer: This method uses catheters to collect blood from the body. The blood is heated in a heat exchanger and then returned to the circulation system to heat the whole organism [43]. Although the heat transfer efficiency is clearly higher than with non-invasive methods, invasiveness poses unacceptable risk and inconvenience for common use. Therefore, this approach is not considered in this research.

Non-invasive Heat Transfer: Most methods for thermal therapy are non-invasive, and focus on heating the environment to increase skin temperature and raise the core temperature. These methods are sorted by different sizes of the heated space as discussed below.

2.3.1 Room Heating

In human history, heating a room is one of the most common ways to get thermal comfort, particularly in cold weather. The usual methods, including heat pumps, fireplaces, and radiators, are not practical ways to significantly increase core body temperature. However, there are two other methods that can be applied: steam sauna and dry sauna.

Steam Sauna: Steam Sauna takes place in a closed chamber filled with high temperature steam. The recommended temperature at the face level of the user is approximately 80 to

100°C, and the relative humidity inside is from 15% to 30% [44].

Dry Sauna (Figure 2-1): Similar to steam sauna, a closed room is heated, but the heat source is infrared heaters placed on the wall. The generated infrared rays heat the skin and other exposed surfaces but have no effect on the surrounding air. The room temperature is maintained at approximately 60°C, and the humidity is low and not controlled.

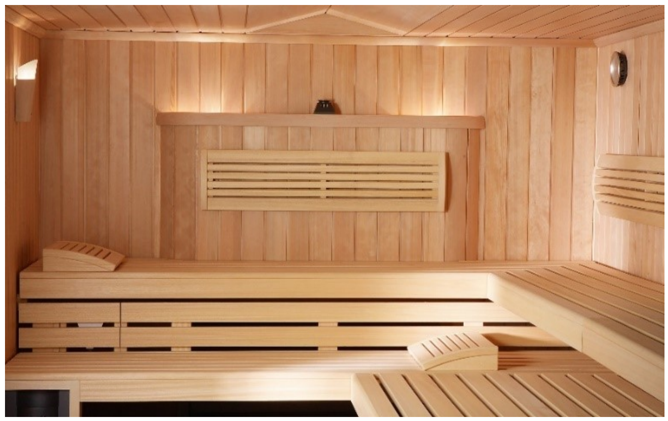


Figure 2-1 A dry sauna room by KLAFS GmbH & Co. KG (Germany) [47]

Advantages

The core body temperature can be increased quickly with high environmental temperatures during steam sauna or dry sauna session. For steam sauna, the core temperature can rise by 1°C in 30 minutes [45], while dry sauna can take only 15 minutes to achieve the same increment [46]. Since both methods change the environmental temperature, the whole body is exposed to the uniform high temperature, and the induced effects take less time to manifest than with other local-heating methods.

Disadvantages

The price of a sauna or dry-sauna room and equipment is not affordable for individual patients and most institutions. Furthermore, it is inefficient to heat a whole room compared to a local environment or an individual. In addition, sauna equipment cannot be easily moved, and ancillary requirements such as a strong power supply, specific building materials, and ventilation must also be considered. All these factors limit wider application of steam sauna and dry sauna for thermal therapy.

2.3.2 Local Environment Heating

Unlike the room heating approaches, local heating methods increase the environment temperature of a space that is only a little larger than the human body. Three examples are described below.

IRATHERM® Systems (Figure 2-2): These devices (Germany) use heat radiation to warm the patient. The generated (infrared) radiation resembles solar radiation filtered through water. Since the radiation is absorbed into the well perfused skin layer (corium), blood circulation rapidly distributes the warmth while the patient's epidermis is only slightly affected. The principle of this technology resembles dry sauna, but it limits the heating only to the patient [48].

Figure 2-2 IRATHERM® 1000 by Ardenne Institute for Applied Medical Research Ltd. (Germany) [49]

Warm-Water Shower/Immersion: This is a traditional but effective method of thermal therapy. The water temperature is 40 to 44°C, and the duration is 10 to 20 minutes [38,40,41].

Hot Wax Immersion: Thermal therapy by hot wax or paraffin has been used for rheumatic arthritis (RA) and joint pain. A thick layer of pre-heated wax is spread on a local area, or over the entire body. The wax is approximately 50°C and can raise skin temperature by 3 to 10°C, depending on the duration [50,51].

Advantages

Despite the reduced heating area, the whole body still benefits from relatively uniform heating, which leads to a quick response to heat. For the IRATHERM® system, this can increase the core body temperature by 1°C in 41 minutes on average [46]. To achieve the same increment takes 10 to 30 minutes for warm-water shower or immersion [52,53].

Disadvantages

Although warm-water shower or immersion methods are more energy-friendly, the large amount of used water is wasted. More importantly, during the treatment medical instruments such as electrocardiograms or other devices could be dangerous or not function correctly, so the application of these methods is limited.

The major disadvantages of the IRATHERM® system are the high cost of the device and stringent requirements of the power supply [53], and the relatively high surface temperature that could also affect physiological monitoring devices.

2.3.3 Personal Heating

As opposed to the methods that adjust the environmental temperature, personal heating methods change only the microclimate near the skin and around the body. Personal heating can be achieved with heating blankets and garments.

Heated Blankets: The whole body or a certain area is covered by a blanket and receives heat. Hot water and resistive heating material are the most common heat media of blankets. For those using hot water circulation, water is heated to a temperature of 40 to 50°C with an external electrically powered heater [54]. In the research of Lima, M.V., an Aesthetics (Bio Term Manufacture and Commerce of Thermal Products LTD, Japan) infrared thermal blanket with resistive materials (Figure 2-3) was used for thermal therapy with decompensated heart failure patients. The surface temperature of the blanket was maintained at 50°C [55]

Personal Heating Garments: The heat source can be liquid, air, electrical, chemical or phase changing heating materials [56]. Currently, the most practical heating media for these garments are water and electrically resistive materials.

Figure 2-3 Patient at rest on a bed using of heat through an infrared thermal blanket [55]

a) Water Heating Garments

These devices have circulation tubes to allow heated water to circulate. Since water is available almost everywhere and has relatively higher specific heat capacity, it is the one of most popular materials for fluid-flowing heating garments [32,57].

b) Electrical Heating Garments (EHGs)

For this type of garments, heat is produced by resistive materials that are powered by batteries or the electricity system. The heating materials can be metals, alloys, or polymers. EHGs are commonly used in high altitude, deep water, and other relatively cold environments. However, there is minimal literature regarding using an EHG for thermal therapy.

Advantages

Since personal heating methods focus on the body itself, the energy consumption is far less than methods that heat larger environments. As there is no immersion in water or other media, little limitation is required for physiological parameter monitors during treatments. More importantly, patients do not have to travel to or stay at specific institutes and can receive thermal therapy at flexible times and various locations. In addition, the therapist can easily adjust the material surface temperature for a target value of core body temperature, which means that treatment is reliable and safe, and can be customized to specific patients.

Disadvantages

The wearable feature and safety concern of personal heating devices limit the output thermal power. Core body temperature can be elevated by around 0.5°C with a water blanket in one hour [58], and no significant change of core body temperature was observed with an electrical infrared thermal blanket in Lima's study [55]. Similar result was observed on the water heating vest developed by Robert, whose study showed the core body temperature only increased by 0.2°C on average [32]. However, even if the change of core body temperature was minimal, some changes were observed in physiological parameters, such as blood pressure and cardiac output, which are related to cardiovascular performance [32, 55, 58].

The heating power of Robert's water heating garment is obtained directly from the electricity system [32], which makes impossible to move freely wearing this type of garment. The weight of the garment filled with water reduces the comfortability as well.

For electrical heating garment, the current must be under the safety level, to avoid any hazard of electrical shocks. Besides, correct insulation should be applied when using a high-voltage (higher than 20 volts, V) power supply.

2.3.4 Summary of Heating Methods

The advantages and disadvantages of the different non-invasive heating methods are summarized in Table 2-2, and the personal heating garments are compared, including personal heating blankets, water heating garments, and electrical heating garments. Each method can be selected according to the requirements and conditions for institutions and/or patients. With respect to daily and individual treatments outside hospitals, though the range of temperature increase of personal heating garments is less than with other methods, it is still the primary option for thermal therapy.

Table 2-2 Summary of the current non-invasive heating methods

Methods	Advantages	Disadvantages
Room Heating	1. Uniform temperature level for the whole body; 2. Simple principle with a long history; 3. Much existing clinical data for reference.	1. Large consumption of energy due to low efficiency; 2. Equipment cost and large space requirement must be considered; 3. The temperature cannot be accurately controlled.
Local Environment Heating	1. Relatively higher efficiency; 2. Uniform heat distributed over the entire body; 3. existing clinical data for reference.	1. Specific medium (water, wax) is required, and used only once; 2. Instruments and measurements are limited; 3. Not portable.
Personal Heating Blankets	1. Low energy waste; 2. Easy to use, even at home; 3. Accurate temperature control.	1. Only a few researches about using this method for thermal therapy [54,55]; 2. Not portable.
Water Heating Garments	1. Low energy waste; 2. Partially portable; 3. Accurate temperature control.	1. Relatively heavy; 2. Must be connected to the electrical system; 3. Only one study using this method for thermal therapy [32].
Electrical Heating Garments	1. Washable and Fully portable; 2. Use and forget; 3. Automatic temperature and time control; 4. Low device cost.	1. Limited output power due to the lithium-ion battery and safety considerations; 2. No clinical research about this method for thermal therapy.

2.4 Human Body Thermal Homeostasis Theoretical Principles

Human beings are homo-thermal animals, and the core body temperature always remains relatively stable regardless of changes in the ambient temperature. A general survival condition of the organism is to maintain the core body temperature at approximately 37°C, which is the homeostasis between heat production, absorption and dissipation managed by the body's temperature regulating mechanism. The principles of human body thermal homeostasis are fundamental for developing a mathematic model of the thermoregulation system when heating the human body.

2.4.1 Heat Production

Body heat is produced by the metabolism of tissue and organs, including muscles, internal organs and the brain [59]. At rest, organs produce most of the heat, especially the liver, while muscles are the main heat-producers in motion [60]. The secretion of adrenaline and norepinephrine can raise the metabolic rate of the body and increase heat production, and the shivering of muscles also produces heat. Table 2-3 indicates the approximate proportion of heat produced by the major organs.

Table 2-3 Proportion of heat produced by the major organs [61]

Organ System	Rest State	Motion State
Heart and respiratory organs	16%	9%
Liver, spleen, and digestive organs	30%	9%
Skeletal muscles	25%	76%
Myelencephalon	18.4%	6%
Kidney	5.6%	N/A
Others	5%	N/A
Total	100%	100%

The basal metabolic rate (BMR) is the measure used to describe the heat energy produced by the body. Normally, the BMR of a male adult is approximate 168 kilojoules per square meter per hour ($kJ/m^2 \cdot h$). Age, sex, stature, and other physiological conditions can affect the BMR as well as the surface area of the body [62].

Heat production at rest is approximately 210 $kJ/m^2 \cdot h$, slightly more than the BMR [62]. When the body is under physical exertion, the heat production is higher as the workload and duration increases.

2.4.2 Heat Dissipation

The thermal energy of the body is dissipated by radiation, convection, conduction, and evaporation [63]. These heat exchange processes are affected by physical parameters of the environment such as temperature, humidity, air velocity, garment, and air pressure. Additionally, sweating, controlled by temperature regulation may regulate skin temperature. Humidity may also influence heat dissipation [64]. Besides, respiration, urination and excretion also dissipate heat outside the body [47].

When only heating part of the body, the negative temperature gradient limits the heat convection of the heated part due to higher ambient temperature. However, the unheated portions of the body are exposed to the normal room temperature. It is required to consider the effect of heat convection of these parts when modeling thermoregulation of the organism [65].

Heat can be dissipated through evaporation as water on the surface of the body changing from liquid to gaseous state, transferring internal heat outside the body. At a core body temperature of 37°C, one gram of water can dissipate 2,448 joules (J) of energy. Skin temperature, water vapor pressure, air-vapor differential pressure, air velocity, surface area and the volume of vaporized water all influence the evaporation capacity. The amount of heat dissipated by evaporation depends largely on the capacity of evaporation and the ambient air to absorb water vapor [47].

2.4.3 Heat Absorption

When the ambient temperature is higher than the skin temperature, heat transfers from the surrounding to the body. The means of heat absorption by the body are still radiation, convection, and conduction [59].

When there is a heat source surrounding the body, it can generate electromagnetic radiations (mainly infrared and/or red radiation) which can increase skin temperature significantly [29,47,55]. Sauna, IRATHERM® systems, and carbon-fiber heating methods transfer heat mainly by radiation.

Heat can also be absorbed by convection from outside. When the temperature of the air layer on the skin is higher than the skin temperature, the skin will be heated, while the air layer loses heat and must replace it from the outer warmer air. This forms an air flow, which can be natural or artificially forced. The steam sauna transfers heat mainly by convection [29,33].

If a heat source is attached or close to the skin, because of its higher temperature than the skin itself, the heat energy flows from the surface of the heat source to the skin by heat conduction.

Most body-heating methods use a combination of several mechanisms to heat the body. For example, the carbon-fiber heating garment conducts heat to the underwear, and the warmed underwear conducts the heat to the skin [10]. Meantime, the air layer between the underwear and the skin is also heated, and transfers heat by convection to the skin. Besides, the skin also receives far infrared radiation generated by carbon fibers directly. These principles aim to increase the skin temperature, and heat the blood and tissues nearby. The heated blood delivers heat energy to other locations or organs inside the body through internal body heat conduction [28,66].

2.5 Thermoregulation Modeling When Heating the Human Body

When the body is exposed to a hot environment (air temperature higher than 35°C), it can acclimate itself by physiologic adjustment and behaviors [67]. However, if the duration is too long, high ambient temperature will lead to the unbalance among heat producing, absorbing and dissipating, which may cause core body temperature increasing, profuse sweating, and even heat stress [47].

To determine the required energy to increase core body temperature by certain amount, for example, 1°C, a model of human thermoregulation with heating should be developed. Detailed model which considers every aspect of thermal physiology is too complex and it is also extremely difficult to make an accurate mathematical description of biological control systems. Hence, practical modeling of body thermoregulation is abstracted and properly simplified from the physiological responses and the main methods employed are grouping and layering.

2.5.1 Models Reviewing

In earlier researches, the anatomy of the body was abstracted to one simple-shape object, or several segments such as a sphere for the head and cylinders for the torso, legs, arms, and feet. And the entire object or each single segment contains several layers. The surface area of each segment is modeled by the thermal effect, rather than by geometrical equivalence.

Gagge divided the body into two concentric circles, in which the internal layer includes organs, muscle and tissues, and outer layer is the skin [63]. On this basis, each layer was modeled separately to derive the internal heat transfer, heat exchange with the environment, core temperature and skin temperature. Stolwijk considered the body in six segments: head, trunk, arms, hands, legs, and feet, and each segment with four layers: skin, fat, muscle, and core [64]. Every layer of all segments was modeled with the control theory and a feedback regulation, to derive the temperature and diaphoretic volume. Yigit built a steady-state model of body thermoregulation, and calculated the effect of garment on the thermal exchange of the body with the environment, per thermal and humid resistance [69]. Salloum modified the Stolwijk's model by dividing each of arms, legs, and trunk into upper and lower segments. And the developed heat transfer model was based on four nodes: core, skin, artery, and vein [70].

Recent researches have treated the body as a complexly shaped object divided into a large number of segments and layers according to physiology and surface shapes. The highly-detailed models lead to more accurate calculations and simulations.

Tanabe and his team built a combined *65-multi-node* (65MN) model to calculate and simulate thermoregulation, radiation, and computational fluid dynamics [71]. The 65MN model represents the anthropometric data of a man who weighs 74.430 kg and has a body surface area of 1.870 m^2. Cropper conducted a research to build a nude computational thermal manikin by calculating computational fluid dynamics. There are 56,000 surface elements in this model, which were divided into 59 regions to match 59 defined body parts [65]. Kobayashi developed a *Jointed Circulation System No.2* human thermoregulation model with only 17 segments. However, all body segments have artery and vein blood pools and the limb segments have a detailed vascular system consisting of superficial veins and arteriovenous anastomoses [66]. Zhang H and team built a model of human physiology and comfort that increased number of segments to infinite, instead of the six in the Stolwijk model [72].

2.5.2 Modeling Heat Production and Transfer of the Body

The rate of heat production is related to metabolism, work, and shivering. Heat production by metabolism is distributed to each layer of each segment, while heat production by work or shivering is only distributed to the muscle layers. However, in resting state with a normal or higher room temperature, the body is not working or shivering, so heat production is approximately equivalent to the metabolic rate. [62,64]

Heat is transferred between each layer by conduction, which only occurs between neighboring layers in the same segment. Heat transfer in different segments is modeled as heat exchange by blood flow, with a virtual central blood layer [71].

Specifically, the skin layer of every segment transfers heat by radiation, convection, and evaporation, while the heat loss by respiration is modeled in the core layer [64,71,72].

2.5.3 Model Improvement for Hot Environment

When the body is in a hot environment (with air temperature higher than the body temperature) for a long period, the rate of chemical reactions in the body can increase, which leads to higher metabolic heat production. So, another heat component of effects for the hot environment is added to the heat production [73].

Similarly, the rate of blood flow increases as the temperature rises, which causes increased heat dissipation. This effect is expressed by adding an increment to heat exchange by blood flow [74,75].

In hot conditions, neural central regulation makes important contributions to the physiological responses of the body. The body regulating function manages the difference between the current body temperature and the set optimal temperature through sweating and vasodilatation [63,66].

2.5.4 Model Comparison

The body's thermoregulation models are used to predict the thermal condition of the body, which means there is always a difference between values of the core body temperature obtained by simulations and measurements. A summary of several existing models is shown in Table 2-4.

Table 2-4 Thermoregulation models with the accuracy and applications

Researcher	Number of Segments	Number of Layers	Accuracy	Applications	Reference Number
Gagge, A. P. 1971	1	2	<1°C	Thermal Effects of different Exercise and Clothes	[63]
Stolwijk, J. 1971	6	4	N/A	Exercise	[64]
Yigit, A. 1998	16	N/A	N/A	Garment Comfort	[69]
Zhang, H. 2001	16 -Unlimited	4	<0.5°C	Garment Comfort	[72]
Tanabe, S. I. 2002	16	4	<0.4°C	Effects of Environment Change	[71]
Salloum, M 2005	9	4	<0.5°C	Garment Comfort	[70]
Xiang, S. 2008	12	4	N/A	Body Heating	[59]
Cropper, P 2010	59	N/A	N/A	Garment Comfort	[65]
Kobayashi, Y 2013	17	4	<0.5°C	Thermal Physiological Response	[66]

2.6 Heating Materials for Electrical Heating Garments

The heating element is the effector of electrical heating garments (EHGs). Current EHG products generate heat by electrically resistive heating wires, filaments or fibers connected to the controller with a power supply. Those elements are typically placed in parallel on, or wound around the whole or part of the garment.

The heating materials can be metal wires [73-74], neutralized textile fabrics [75-78], graphite [79], electrically conductive rubber [80], positive temperature coefficient polymers [81] or carbon polymer heating fabrics [82-93]; they are classified into metallic materials and carbon-based materials for EHGs.

2.6.1 Metallic materials

The concept of heating the body with electrical power by placing resistive materials in clothing is not new. In World War II, inventors developed a jacket for bomber air crews which was fitted with metal cables connected to low-voltage power supplies [73]. In the 1970s, Deloire and his team demonstrated a heating garment, with resistive alloy wires covered by a layer of polyvinyl chloride, can tolerate heat and withstand high temperatures [76]. The high stretch property of the garment make the wearer move easily and distributed the heat uniformly.

The critical drawback of metallic cables or wires is that metal can be oxidized in high temperatures. When the metal accumulates an oxide layer on the surface, the effective sectional area for current flowing can be reduced and the current load is higher, which may cause the wire losing strength and becoming brittle. Besides, because heated metallic materials generate more visible and near-infrared light than far-infrared radiation, most metallic materials have a lower electricity-to-heat transfer efficiency than carbon materials [82]. And the metal cables and wires are usually too thick for comfort.

Recent researches have been focusing on using metal-plated fibers or fabrics as heating materials for EHGs. Li, C developed an EHG with silver-plated resistance heating filaments knitted into the fabric. At low-voltage (12V), it was only 2% of the resistance change for an 8°C increase of surface temperature with 3-minute heating, which indicated a good thermal stability [78]. However, the output power of this fabric was only 40-110 W/m^2 which was insufficient to increase core body temperature around 1°C. Meanwhile, the fabrics had to be specially manufactured, which makes application difficult.

2.6.2 Carbon-based materials

1) Rubber-loaded Composites

A polymer matrix composite can be filled with conductive polymers or other suitable particles. This method has been applied in many fields, including light-emitting devices, electromagnetic shielding, batteries, and self-heating elements. Meng, D., and his team investigated the electrical heating properties of a butyl rubber-loaded boron carbide composite. With a power supply of 12 V, the composite can increase the surface temperature from 20°C to 45°C in two minutes [80]. However, currently there are no products that use similar materials for an electrical heating garment.

2) Carbon fibers

Carbon-fiber filaments with over 99% carbon content were used as heating materials of some EHGs. The infrared emitting rate of the carbon fiber is up to 0.95, while the rate of normal carbon or graphite materials is approximately 0.85, which implies a better heating performance [82]. Compared to metallic heating elements, carbon-fiber filaments are lighter, safer, and more easily produced, which makes a portable carbon-fiber heating garment achievable. With respect to control accuracy, the thermal response of carbon fibers is rapid, while there is always a control delay for heating with metallic materials.

Carbon-fiber elements have been becoming popular in recent EHG research. Rantanen, J. has developed a heated shirt with carbon fabric heating panels. It was powered by a battery, and controlled by an integrated system with nine temperature sensors and three humidity sensors [83]. The prototype was tested in cold conditions from -14 to -20°C. Though the selected power could maintain the body comfortable, it is not sufficient to increase the core temperature significantly. There are similar products on the market, such as heating clothes produced by Gerbing® (Netherlands) [84] and electrical heating gloves created by Harley-Davidson® (Canada) [85] (Figure 2-4). These products with a 12V power supply are able to protect people in cold environments but cannot be used for thermal therapy.

(a) (b)

Figure 2-4 Products of carbon-fiber electrical heating garments
(a) heated clothes produced by Gerbing® [84]
(b) Heated gloves by Harley-Davidson® [85]

Some researchers have focused on the potential physiological improvement of wearing carbon-fiber heating garments that can generate far-infrared radiation with wavelengths of 8 to 15 micro-meters (μm). It has been found that those garments can make some improvement for the body, such as higher sleep quality, better vascular circulation, and relief of pains when applied frequently. Far-infrared can also enhance the body's metabolism and immunity [88,89].

Lima, M. V. proposed achieving thermal vasodilation by using a portable infrared thermal blanket which generated heat via 44 infrared heating pads with carbon fibers. They reported that the cardiac index increased and the systemic vascular resistance was reduced [55].

Hasegawa, K compared the core temperatures of patients undergoing major abdominal surgery, warmed by a circulating-water garment, forced-air, and a carbon fiber heating blanket [9]. The tests showed that though the heating performance of the carbon-fiber blanket was lower than the other two methods, it was more efficient with less energy consumed. Hasegawa also suggested that the carbon-fiber heating material with lower surface temperature was safer and lighter than with water or air flow heating methods [9]. Several patents in the United States Patents database can be found using carbon fibers as the heating materials to develop EHGs [91-95].

As the carbon fiber has excellent thermal performance and the ability to generate far-infrared radiation, it can be the heating material of an electrical heating vest potentially for thermal therapy.

Chapter 3 Theoretical Study

3.1 Rationale

Electrical heating garments on the market are mainly used for protection from cold environments. The heating power required for thermal therapy to increase core body temperature up to 1°C is much higher than what is needed for cold environment protection.

There is little evidence in the literature about the heat requirements of an electrical heating vest (EHV) potentially for thermal therapy and there are no clear guidelines to follow. So, a study to investigate it was conducted, and is discussed below.

3.2 Purpose

The purpose of the theoretical study was to predict the required heat power of an EHV to increase core body temperature up to 1°C, through modeling and simulating a simplified body thermoregulation system.

3.3 Methods

3.3.1 Model Selection

In Chapter 2, various thermoregulation models that can be used for simulations were discussed. As this study is a feasibility analysis and an estimate of the thermal power requirement, it does not require high accuracy or highly detailed descriptions. Hence, a less complex model which is easily implemented is considered primarily.

The body thermoregulation model by Stolwijk (shown in Figure 3-1) is selected in this study, which could forecast the impact of body heating with relatively low complexity. It is made up of four layers, six segments and a special central blood layer.

Most of the physiological parameters of this model were used as Stolwijk's model [64]. The surface area of the whole body was set at 1.8877 m^2. and the surface area of the torso was set at 0.6804 m^2. Other parameters and settings are shown in Appendix 1.

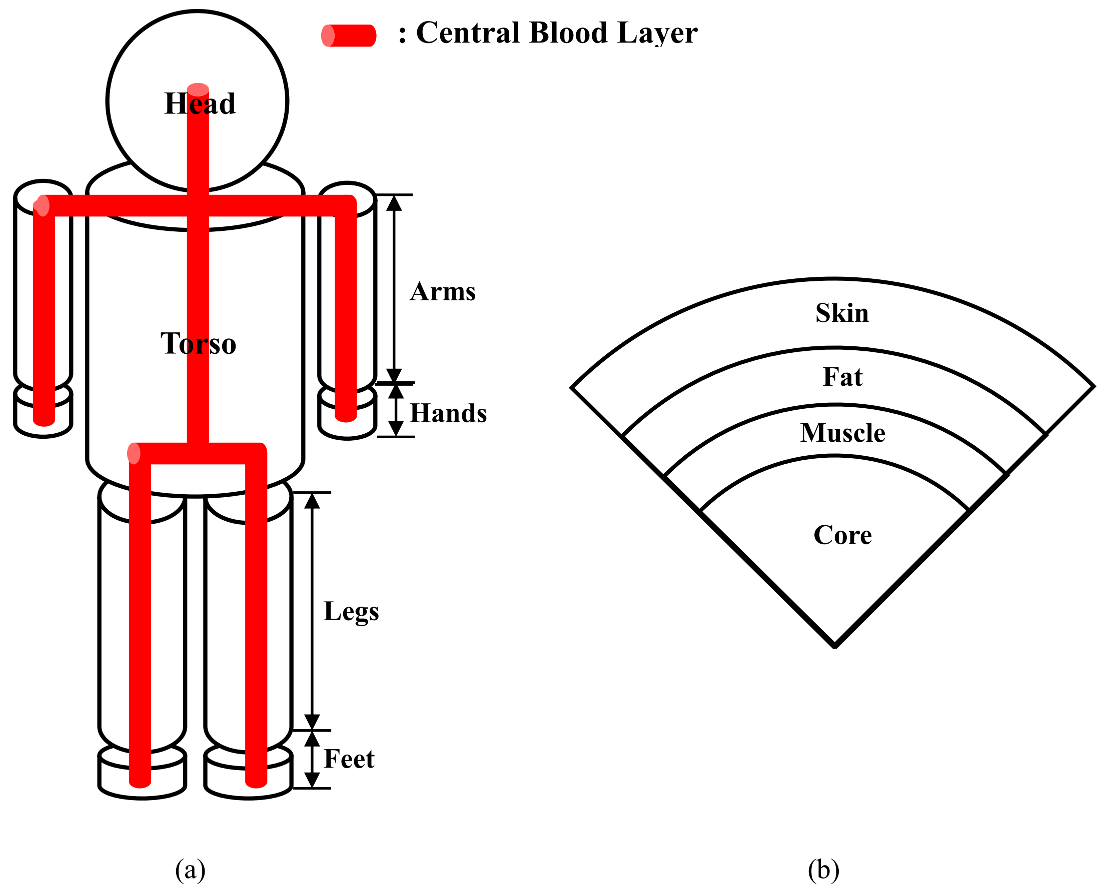


Figure 3-1 Stolwijk's model of the human thermoregulation system [64]
(a) six anatomical segments of the human body;
(b) four layers of each segments

3.3.2 Model Modification

Stolwijk's research model was designed to predict the effects of sweating during exercise on core body temperature under various environmental conditions [64]. However, our study focuses on the impacts of a non-uniform heat source attached to the torso. So, several modifications are required, and discussed below.

1) Internal Heat Production

Since the EHV is used in a rest state, the heat produced by work was assumed to be zero, and due to the warm conditions, there was no heat generated by shivering. So, the heat produced by the internal metabolism of each layer is equal to the basal metabolic heat production, as in:

$$Q_{i,j} = QB_{i,j} \tag{1}$$

where $Q_{i,j}$ is the heat produced by metabolism (Watt, W), $QB_{i,j}$ is the basal metabolic heat production (W), i is the index of segments, and j is the index of layers.

2) External Heat Receiving

The external heat sources were not considered in Stolwijk's model, which is essential for heating the body. Besides, the EHV only heats the torso, so the external heat supply on the skin of torso was the only input of heat for the body, and the heat supply of the other segments was set to zero. Normally, the generated heat was not equal to the heat absorbed by the body due to the heat loss. But for this simplified modeling and simulation, the power of the heat supply is assumed to be the thermal power absorbed by the body and the heat source was assumed to fully cover the skin of the torso segment.

In this model, the external heat energy only transferred to the torso skin. The environmental effect to torso was modified as the Equation 2, while effects to other segments were not changed and shown in Equation 3.

Torso segment: $$Env_2 = h_2(T_{2,4} - T_{external}) \quad (2)$$

Other segments: $$Env_{1,3,4,5,6} = h_2(T_{2,4} - T_{air}) \quad (3)$$

where h is the heat transfer coefficient of the torso segment (W/°C), $T_{2,4}$ is the temperature of the torso skin layer (°C), $T_{external}$ is the temperature of the air heated by the external heat supply (°C), and T_{air} is the room air temperature (°C).

The heat balance formulae of each layer in the six segments and the central blood layer were modified, as shown in Equations 4 to 8.

Core layers: $$c_{i,1}\frac{dT_{i,1}}{dt} = Q_{i,1} - B_{i,1} - D_{i,1} - E_{i,1} \quad (4)$$

Muscle layers: $$c_{i,2}\frac{dT_{i,2}}{dt} = Q_{i,2} - B_{i,2} + D_{i,1} - D_{i,2} \quad (5)$$

Fat layers: $$c_{i,3}\frac{dT_{i,3}}{dt} = Q_{i,3} - B_{i,3} + D_{i,2} - D_{i,3} \quad (6)$$

Skin layers: $$c_{i,4}\frac{dT_{i,4}}{dt} = Q_{i,4} + HS_i - B_{i,4} - E_{i,4} + D_{i,3} - Env_i \quad (7)$$

Central blood layers: $$c_{25}\frac{dT_{i,1}}{dt} = \sum_{i=1}^{6}\sum_{j=1}^{4} B_{i,j} \quad (8)$$

where: c_{25} is the heat capacity of each layer (W · h/°C), $T_{i,j}$ is the temperature of each layer (°C), t is the time (h) and HS_i is the heat supply of each segment from the external heat source (W).

$B_{i,j}$ is the heat exchange between the central blood layer and other layers (W), as:

$$B_{i,j} = BF_{i,j}(T_{i,j} - T_{25}) \quad (9)$$

where: $BF_{i,j}$ is the basal blood flow rate (*L/h*).

$D_{i,j}$ is the heat transferred by blood convection, (W), as:

$$D_{i,j} = c_{i,j}(T_{i,j} - T_{i,j+1}) \quad (10)$$

E is the heat loss by evaporation (W), as in:

Core layers: $$E_{i,1} = EB_{i,1} \quad (11)$$

Skin layers: $$E_{i,4} = \left(EB_{i,4} + s_i \cdot SWEAT\right) \cdot 2^{\frac{T_{i,4} - TSET_{i,4}}{10}} \quad (12)$$

where: $EB_{i,j}$ is the basal heat loss by evaporation, (W); s_i is the skin sweating factor temperature of each layer, (°C)

3) Environment Conditions

As the therapy was designed to be conducted indoors, it is assumed that the air velocity was a constant and changes of the air temperature can be completed immediately.

3.3.3 Simulation

The model was programmed in m-language (the language used in Matlab®) and simulated on the Matlab® platform (the MathWorks, Inc., United States). The simulating algorithm is shown in Figure 3-2, and the source code is listed in Appendix 1. The thermoregulation of the body was calculated with different external heating conditions, and the simulation can predict the change of the body temperature.

The temperature of the central blood layer was defined as the core body temperature, since this layer can transfer heat with all other parts of the model.

As discussed in the literature reviews in Chapter 2, the duration of heating for most thermal therapy methods is 15 to 30 minutes [32, 38-42, 45,46]. The reason is because too long heating session may cause discomfort for users, while too short heating duration cannot achieve a significant increase in core body temperature. So, the total heating time of this simulation was set at 30 minutes, and the virtual body was heated by an external heat supply with constant power. The data was calculated, plotted, and saved every five minutes during the simulation.

This research was initially intended to increase the core body temperature 1°C in 30 minutes. However, due to the limitations of portable batteries and electrical safety concern, the output power of the heat supply can be relatively low. If the 1°C increase in core body temperature cannot be achieved practically, the target will be changed to increase by 0.5°C. Thus, both power requirements for an increase of 0.5°C and 1°C in 30 minutes were calculated in the simulation.

The modeling and simulating algorithms were packaged as a Matlab function which provides five formal-variables (listed in Talbe 3-1). The formal-variables need to be assigned when called by the main program script, which contains instructions to deliver the values to the function. The values of input variables for the simulation function are shown in Table 3-1.

Table 3-1 The input variables of the simulation function in theoretical study

Variables	Set Value	Description
TestLabel	'Heating the Torso Only'	The label plotted in the figures
PlotType	'f'	To determine how to plot figures, 'f': plot all results
PlotSave	'y'	To determine whether to save the figures
HeatSupply	from 0 to 500	The amount of power absorbed from the external heat source
TestNum	6	The number of calculating loops to be run in the simulation (with 5-minute intervals)

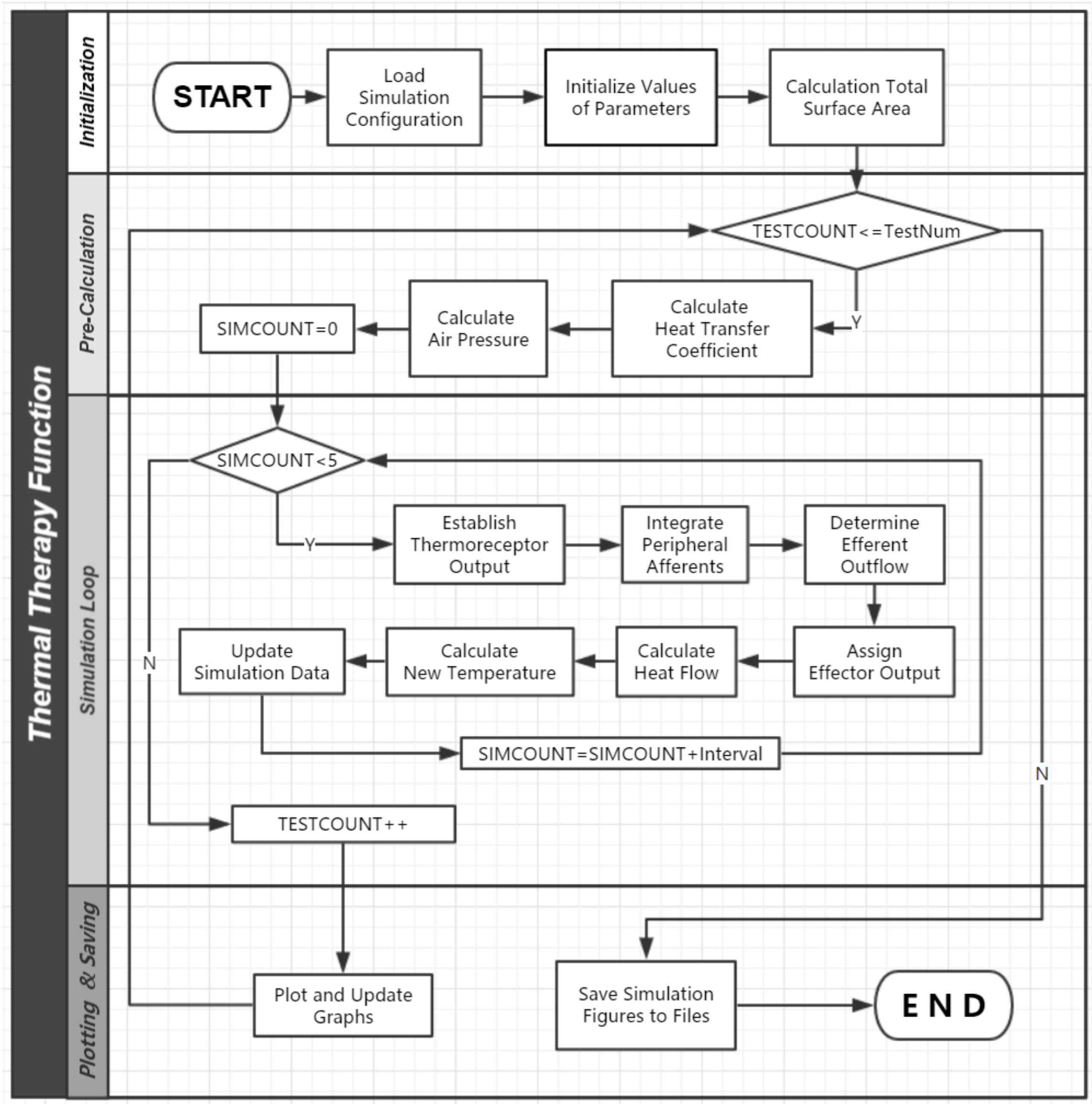


Figure 3-2 The block diagram of the thermal therapy function for simulation in theoretical study

3.4 Results

The output results of the function showed that the minimum power absorbed by the body to increase core temperature by 1°C in 30 minutes was 340W. Whereas, an absorbed power higher than 145W was required to achieve an increase of 0.5°C. The simulated results are shown in Figure 3-3.

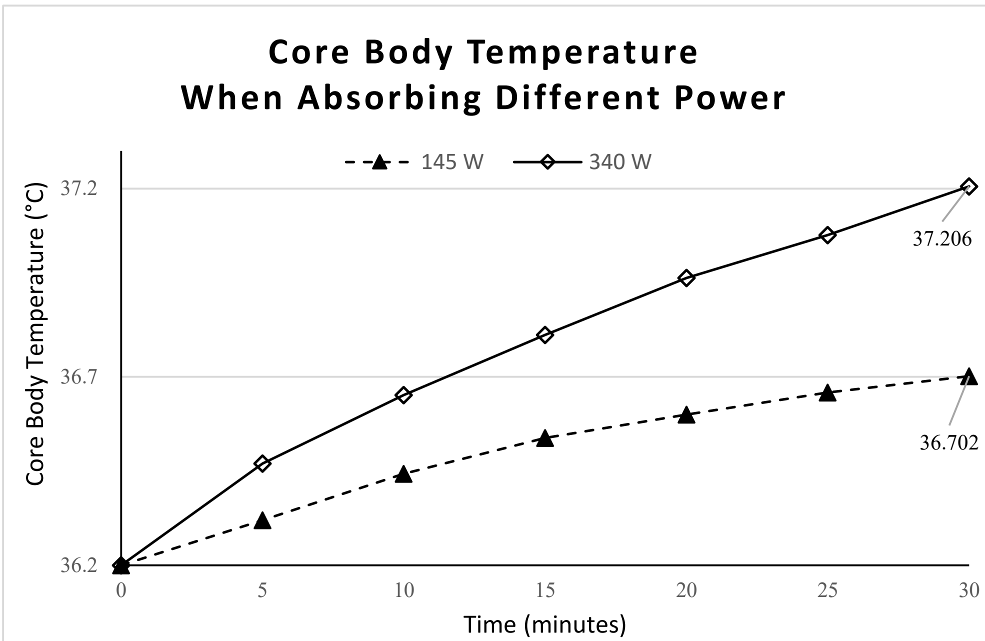


Figure 3-3 Simulated core body temperature when absorbing a power of 145W or 340W in theoretical study

3.5 Discussion

Ignoring power loss, the minimal absorbed power to increase core body temperature by 1°C, ($P_{body\_1°C}$) is equal to the minimal power of the supply for such an increment ($P_{supply\_1°C}$), which is $P_{body\_1°C} = P_{supply\_1°C} = 340\ \text{W}$. Similarly, $P_{body\_0.5°C} = P_{supply\_0.5°C} = 145\ \text{W}$.

However, before using these values to select required batteries, the electrical safety and practical battery limitations should be considered.

1) Electrical Safety

Electrical safety is critical for the EHV as a medical device. During the heating process, current flows from the battery through wires and heating elements which are close to or possibly touch the skin may cause some current to enter the body. For a human body with no visible damage on the skin, the mean value of a direct current (DC) for the threshold of perception is 5 milliamperes (mA), which might be perceived as a slight warming of the skin [90]. Larger currents can cause physiological effects, such as pain, fatigue, stimulation of nerves and muscles, and even involuntary muscle contractions that can prevent the subject from voluntarily withdrawing. The maximum current, at which the subject can withdraw voluntarily is called the 'let-go' current, and the minimum let-go threshold is 15 mA for DC [97,98]. To ensure the safety of the EHV, current flowing into the body cannot be larger than 15 mA under any condition.

The current entering the body is calculated as the applied voltage divided by the impedance of body tissues. The highest applied voltage of the EHV is the voltage of the power supply, and the impedance for DC is only resistance. The National Institute for Occupational Safety and Health (NIOSH) states that, "Under dry conditions, the resistance offered by the human body may be as high as 100,000 Ohms (Ω). Wet or broken skin may drop the body's resistance to 1,000 Ω." [99].

Thus, the power absorbed from the external heat supply is limited by the maximum output voltage of the battery that should ensure the current flowing into the body is less than 15 mA in a wet-or-broken-skin body resistance scenario. That limit voltage (V_{limit}) was calculated in Equation 14.

$$V_{limit} = I_{let-go} \cdot R_{wet} = 15\ mA \times 1000\ \Omega = 15V \tag{14}$$

The practical safe voltage (V_{safe}) of the battery was set at 12V, with reasonable redundancy and the required output current, $I_{supply\_0.5°C}$ and $I_{supply\_1°C}$, with V_{safe} was calculated for an increase of 0.5°C and 1°C in core body temperature (shown in Equations 15 and 16).

$$\text{For a 0.5°C increase:} \quad I_{supply\_0.5°C} = \frac{P_{supply\_0.5°C}}{V_{safe}} \approx 12.08 \text{ A} \tag{15}$$

$$\text{For a 1°C increase:} \quad I_{supply\_1°C} = \frac{P_{supply\_1°C}}{V_{safe}} = 28.33 \text{ A} \tag{16}$$

Once these requirements were determined, the safety of the battery could be ensured.

2) Battery Limitations

Assuming the duration of heating for a heating session is 30 minutes, the amounts of energy required for one therapy session, $E_{\text{supply\_0.5°C}}$ and $E_{\text{supply\_1°C}}$, are calculated as in Equations 17 and 18.

$$\text{For a 0.5°C increase:} \quad E_{\text{supply\_0.5°C}} = P_{supply\_0.5°C} \times 0.5 \text{ hour} = 72.5 \text{ W} \cdot \text{h} \tag{17}$$

$$\text{For a 1°C increase:} \quad E_{\text{supply\_1°C}} = P_{supply\_1°C} \times 0.5 \text{ hour} = 170 \text{ W} \cdot \text{h} \tag{18}$$

With the safety discussion above, the battery requirements to increase the core body temperature by 0.5°C or 1°C are shown in Table 3-2.

Table 3-2 The requirements of the battery for an increase of 0.5°C and 1°C in core body temperature determined by the simulation in theoretical study

Parameter (Unit)	For a 0.5°C Increase	For a 1°C Increase
Voltage (V)	12	12
Continuously discharging current (A)	12.08	28.33
Energy for one heating session (W·h)	72.5	170

As a portable device, an EHV must be lightweight and capable for at least two heating sessions in one charge-cycle. So, the capacity of the battery should be 72.5×2=145 W·h for an increase of 0.5°C in core body temperature and 170×2=340 W·h for an increase of 1°C.

The Lithium-ion battery (LIB) is a popular type of rechargeable batteries used in industry and daily life. The performance of a LIB is significantly better than traditional rechargeable batteries such as nickel cadmium (Ni-Cd) and nickel metal hydride (Ni-MH), particularly for maximum discharge current and energy density [100-103]. However, referring to the specifications of battery products on the market, the weight of a battery with a capacity of approximately 350W·h or 40 Ampere-hour (A·h) at 12V is from 5.1kg to 6.5kg, which is too heavy for a wearable device [104-107]. Due to overweight of current LIB products, the target of increasing core body temperature by 1°C in 30 minutes cannot be achieved by a portable EHV.

Meanwhile, a lighter LIB weighing approximately 2.5 to 3.5kg with a capacity of about 150 W·h is available, whose energy is enough for two 30-minute sessions with an increase of 0.5°C in core body temperature [108-111].

3.6 Conclusion

The foremost safety requirement is for an EHV battery to be electrically safe. Hence, the maximum voltage was limited to 12V. Portability is another important criterion for a wearable device. A battery that can increase a core body by 1°C in 30 minutes is too heavy to be practical. As a result, the target temperature change for increasing core body temperature was reduced from 1 °C to 0.5°C instead, which can be implemented with light-weight batteries available on the market. The final configuration of the battery parameters is shown in Table 3-3.

Table 3-3 The final configuration for parameters of the battery in theoretical study

Parameter (Unit)	Value
Voltage (V)	12
Continuously discharging current (A)	>12.08
Capacity (W·h)	>145
Capacity (A·h@12V)	>12.08

Chapter 4 Design of Electrical Heating Vest

4.1 Rationale

Considering the heating material and the battery requirements established in previous chapters, a practical design for carbon-fiber electrical heating vest (EHV) potentially for thermal therapy can be developed.

4.2 Purpose

The purpose of this chapter was to develop an EHV with a smart controller which can controllably and safely increase core body temperature by around 0.5°C within 30 minutes.

4.3 System Design

4.3.1 Overall design

The EHV system can be divided into several functional parts attached on a support belt: heating system, control system, batteries, and accessories.

The heating system was mainly comprised of several heating pads, which were positioned on the torso separately. To prevent the surface temperature of a pad from increasing to an undesired value, the control system should be able to manage the heating pad temperature under a set value. Simultaneously, the duration of the heating session also needs to be controlled. This requires a microcontroller to implement these functions.

Several sensors should be used to monitor the temperatures on heating pads. The microcontroller needs to compare temperature readings from sensors against the set temperature value, and generate control signals to power on or off heating pads based on this comparison. A timer is also required to control the duration of heating, which may be integrated in the microcontroller. In addition, the user interface is designed to input settings and for displaying the temperature and timing. The battery powers both heating and control systems. An overall diagram of the system design is shown in Figure 4-1.

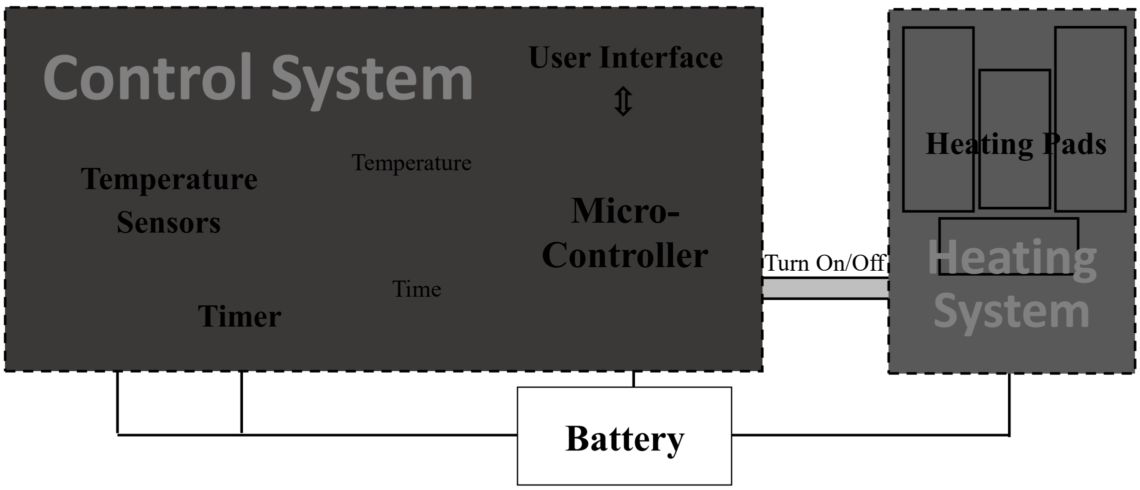


Figure 4-1 Overall diagram of system design of the electrical heating vest

4.3.2 Design of the Heating system

The heating system is the functional part of an EHV, as it generates heat transferred to the body. The main components of the heating system are heating pads which connect to the control system with the battery. The pads are attached on a support belt, and positioned around the torso.

4.3.2.1 Design Requirements

1) Materials

The heating material of the EHV is carbon-fiber filaments, whose performance was discussed in Chapter 2. Heating pads cannot be fabricated with carbon filaments alone and additional metallic filaments are required to connect all carbon-fiber filaments into the circuit loop with the controller and the battery for electrical conduction. Both the carbon and metallic filaments are placed on a structural substrate layer made of regular yarns.

2) Safety

Damage to any part of the heating pad may cause short-circuit resulting in higher local temperatures, which poses a safety risk to the user. In addition, it is highly possible for the body to sweat during the heating session, which may lead to short-circuit. For the safety, the layout and materials of the heating pads must be designed appropriately to prevent any short-circuit when in use.

4.3.2.2 Design Specifications

1) Materials

The heating pads of this EHV were produced by the Cixi Tanzhisu Electrical Appliance Factory (China), and the heating material is composed of polyacrylonitrile carbon fibers. The effective length of the formed carbon-fiber filament is 30 cm. The electrical conductivity of polyacrylonitrile is stable even under wet condition according to the instructions provided by the supplier.

Two copper threads, composed of 48 copper filaments with a diameter of 0.15 nm each, and a diameter of 5 mm in total were used as buses to connect every carbon filament to the controller and the power supply.

The substrate layer of the heating element is regular knitted Dacron cloth. Dacron is inflammable and provides electrical insulation, further improving the safety of the system.

2) Structural Form of the Heating Elements

Carbon filaments were designed to interweave with copper filaments, and this combination constituted the circuit of the heating pads.

The carbon filaments were embedded in the yarn in latitudinal direction with parallel intervals of 2cm, and copper threads were positioned longitudinally at two ends of the carbon filaments. Every copper thread was connected to a conductive cable. When voltage is applied, current flows from the copper threads through the carbon filaments and produces heat.

3) Accessories

The Velcro fastening was attached on both heating pads and the support belt, allowing the heating pads to be positioned at specific locations on the support belt. A plug installed at the end of cable was connected to a corresponding jack in the control system. With these accessories, heating pads can be easily installed or removed.

Table 4-1 shows the description of each component in the heating element, and the structure of the heating element is shown in Figure 4-2. The elements can be used to form heating pads with sizes of 40x30cm, 30x30cm, and 20x30cm.

Table 4-1 Descriptions of each component on the heating element used in the design of the heating system

Legend	Name	Material	Function
	Carbon filaments	Polyacrylonitrile carbon fibers	Heating materials
	Copper threads	Bare copper filaments	Electrical power bus
	Substrate cloth	Dacron filaments	Structural support
	Cables	(don’t care)	Power transmission
	Velcro	(don’t care)	To attach to the vest
	Plug	(don’t care)	Electrical Connection

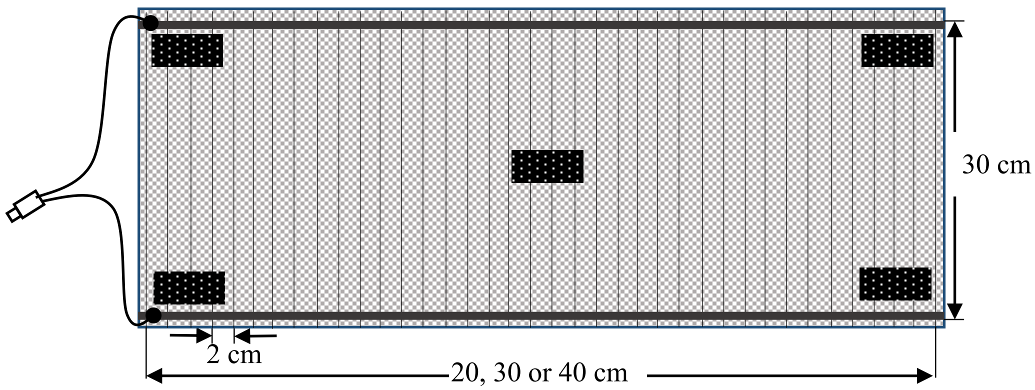


Figure 4-2 Structural diagram of the heating element used in the design of the heating system

4.3.3 Design of the Control System

This section consists of three sections: requirements, hardware design, and software design.

4.3.3.1 Design Requirements

1) Functions

To ensure safety, the surface temperature of the heating pad must be monitored when operating. Because there are no restrictions for thermal safety of EHGs, the recommended water temperature for bathing to prevent injury was adopted as the safe temperature for heating pads. The Canada Safety Council and the Healthy Canadians advise that the temperature of tap water for shower should be less than 49°C to prevent scalding [106]. Thus, with reasonable redundancy, the threshold of the heating pad temperature control was set no more than 45°C. As four heating pads installed, each pad should have an individual temperature sensor and a controlled relay switch. When the temperature of any pad passes over the set threshold, the controller can turn it off, and turn it on again once the temperature drops below the set value.

The controller also regulates the duration of each heating session by turning the heating system off after a certain time duration.

2) Temperature Sensor

The temperature sensors need to provide readings to the microcontroller, for monitoring and controlling the heating pad temperature. The measurement range is from 25°C to 55°C. The static error of the sensor should be less than 0.5°C and the resolution required must be smaller than 0.2°C for reducing the adjustment time delay and preventing from frequently on-and-off switching.

The sensors may encounter wet conditions due to body sweating, so waterproof is a necessary requirement for the sensor. Meanwhile, four heating pads need at least four sensors working simultaneously, so the sensor should be designed to consume the least amount of input/output (I/O) ports on the microcontroller.

3) Power Consumption

Since the EHV is powered by portable batteries, the power consumption of the control system must be minimal, which requires low-power components in hardware circuit and energy-saving algorithms in software program.

4) Safety and Comfort

The control system must ensure thermal safety. An additional safety program with functions such as alarms and emergent shut-down should be designed to intervene when the temperature control cannot turn off heating pads and overheating occurs.

In addition, remote setting interface can optimize accessibility, and the form factor of the control system should be miniaturized.

4.3.3.2 Hardware Design

1) Microcontroller and the Minimum Application System

The microcontroller is the backbone of the control system. A series of 8-bit single-chip microcontroller (SCM) based on MCS-51 kernel architecture (8051) which is a complex instruction set computing, are widely used in many industries [113]. These SCMs can provide good compatibility for hardware resources, excellent functions, stable performance, low energy consumption, and a convenient integrate development environment at relatively low cost.

The EHV control system used a new-generation 8051 SCM, STC90C516RD+ provided by STC micro™ Limited (China). The instruction codes are fully compatible with traditional 8051 SCMs, whereas, the operating speed is 8 to 12 times faster than the speed of traditional ones. The main specifications of STC12C5A60S2 are shown in Table 4-2.

Table 4-2 Specifications of STC90C516RD+ single-chip microcontroller used in hardware design of the control system [114]

Item	Value	Description
Voltage	3.3-5.5 V	Wide voltage range
Current	4-7 mA	Low power consumption
Frequency	0-40 MHz@6T; 0-80 MHz@12T	6 T (clock cycles) per machine cycle for faster response than 12T per machine cycle.
Flash Storage	61 KB	Used for user's programs
RAM on chip	1280 Bytes	Static RAM type
Universal I/O Ports	35	Fully programmable for each input/output (I/O) port; Four 8 bit bi-directional ports
ISP	YES	In-system programmability allows downloading of a new code without removing the microcontroller from the product.
Watchdog Timer	YES	Auto-reset function
Timers	3@16-bit	Timer 0, Timer 1, and Timer 2
Working Tempearture	0°C - 75°C	For commercial use
Package	DIP-40	Only for prototypes; packaging for actual products is less

The SCM must be formed based on the minimum application system to function, which includes the SCM chip, an external clock circuit (for high-precision timing) and the reset circuit. The minimum application system of the STC12C5A60S2 is shown in Figure 4-3.

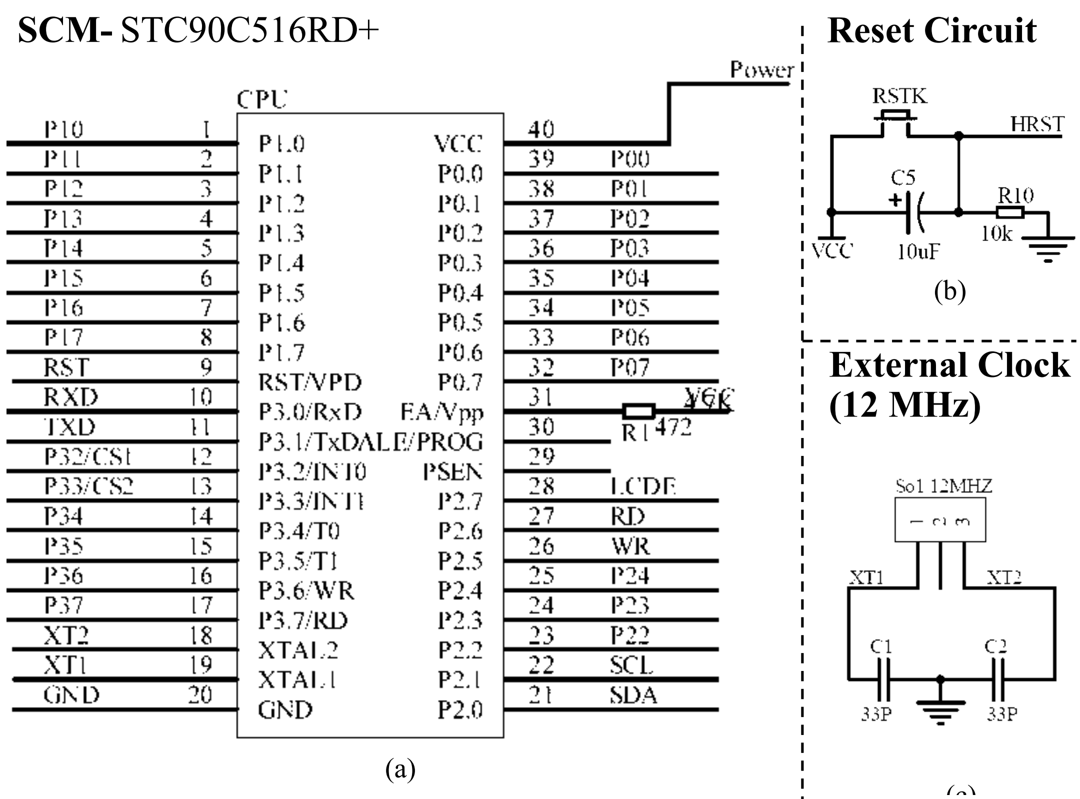


Figure 4-3 Minimum Application System of the microcontroller in hardware design of the control system: (a) the SCM STC90C516RD+ [102]; (b) Reset Circuit; (c) External clock source with a crystal oscillator at 12 MHz

2) Temperature Sensor

DS18B20 digital temperature sensors were selected for this design. These sensors can provide temperature readings at a resolution of 0.0625°C (12-bit mode) and a static error of ±0.5°C from 10°C to 85°C. As the DS18B20 chip provide serial digital signals, no external components such as analog-to-digital converter are required and data can be directly received though any universal I/O port on SCM [115]. Besides, DS18B20 sensor is fully water-resistant.

Four DS18B20 sensors were used, and each was placed on a heating pad. As illustrated in Figure 4-4 (a), there are three pins on DS18B20: VCC (power), GND (reference) and DQ (data queue). the DQ pins of all sensors were connected to I/O ports (P1.0 to P1.3) of the SCM, as shown in Figure 4-4 (b).

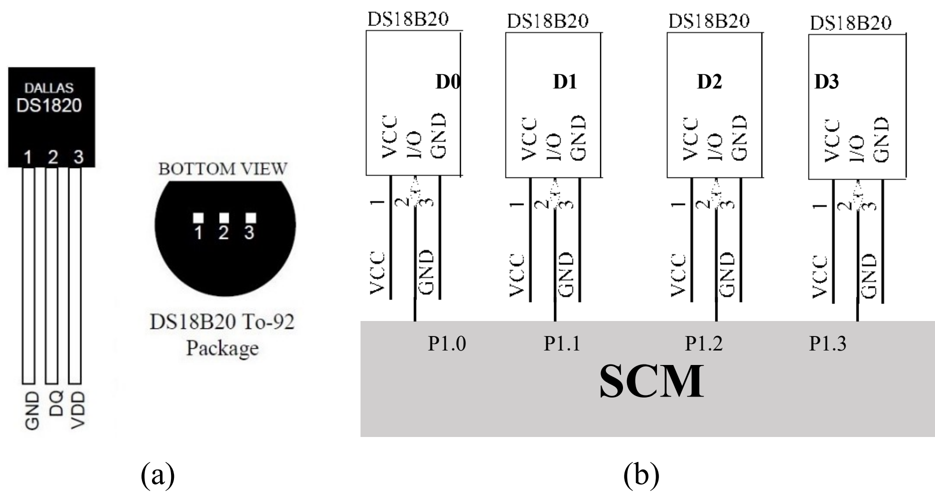


Figure 4-4 DS18B20 digital temperature sensor [109] (a) and the circuit with the single-chip microcontroller (b) in hardware design of the control system

3) Relay Switches

The current flowing in the heating loops is too large for the microcontroller to manage directly, so four relay switches from the Ningbo Songle of China Co. Ltd were used as the bridge between the control loop and the heating loop. A PNP-type transistor controlled by the SCM was used to directly manage a relay switch whose normal-open ports (‘NO’ in Figure 4-5) were connected to one heating pad and the battery.

For safety concern, one logical inverter was added between the corresponding I/O port on the SCM and the base terminal of the transistor. Only when the I/O port is sending high-level voltage signals ('1'), the transistor can be turned on. Otherwise, the transistor keeps 'off' and no current flows through the relay switch to the heating pad.

An example relay switch and the connection with the SCM are shown in Figure 4-5. The other three switches were formed as the same, but connected to different I/O ports (P3-5 to P3-7).

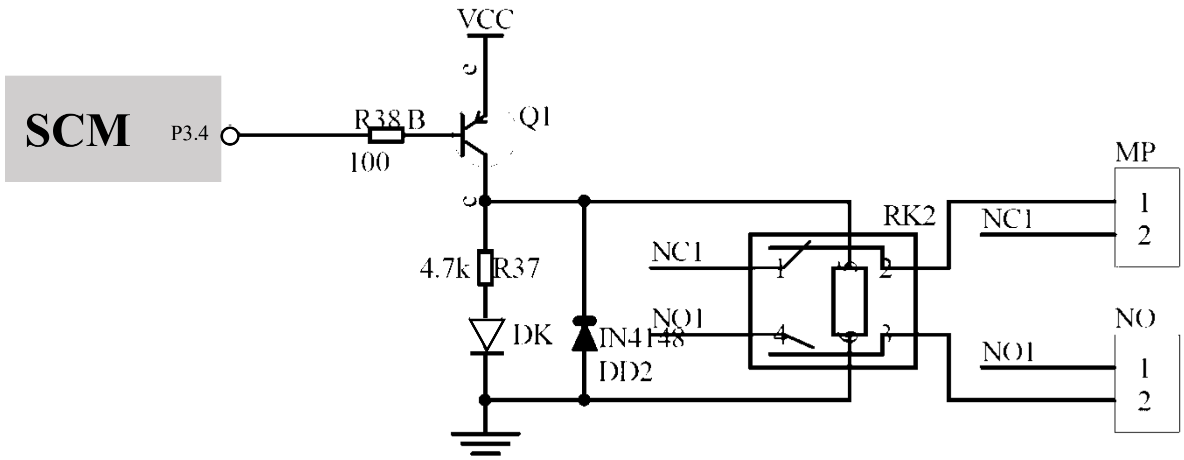


Figure 4-5 Circuit for one relay switch in hardware design of the control system

4) Keyboard

The keyboard is one of input methods to trigger the heating process and set the temperature threshold and the heating time. As only four buttons are required, an independent-button configuration was applied. Each button was connected to one of four I/O ports (P3.4 to P3.7) and the ground reference. The signal was inverted and then sent to the corresponding I/O port of the SCM to save energy, because the I/O port doesn't need to stay on the high-level voltage state ('1') to detect potential button actions which can consume extra power (Figure 4-6).

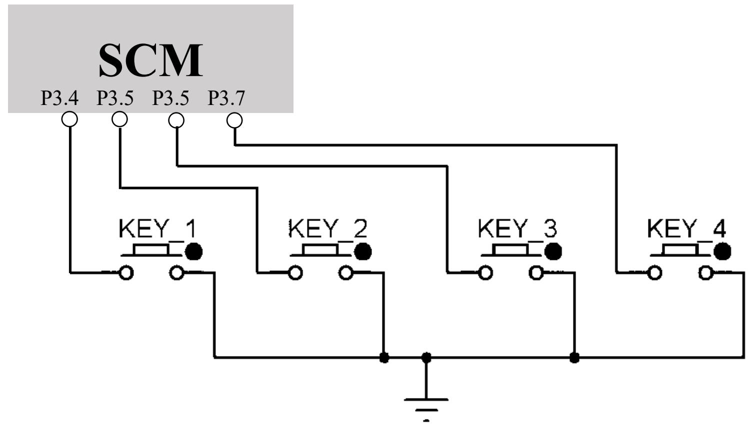


Figure 4-6 Circuit for the keyboard in hardware design of the control system

5) Display

The requirement for the display in this EHV system is to indicate only numerical values such as temperature and time. Due to the low cost and reasonable design complexity, eight-segment display (ESD) arrays composed of cathode light-emitting diodes (LEDs) were selected for the display. Eight ESDs are used, four to show temperature values and the other four to display the time.

To preserve energy and reduce the use of SCM I/O ports, an octal D-type transparent latch, 74HC573 (NXP Semiconductors N.V., Netherland), was applied to drive the ESDs. In addition, a 3-to-8-line decoder/de-multiplexer, 74HC138 ((NXP Semiconductors N.V., Netherland)), was used to implement the scanning display (or dynamic display strategy), which means that each ESD turns on to display and then off one by one quickly. Figure 4-7 presents the entire circuit of the display subsystem design.

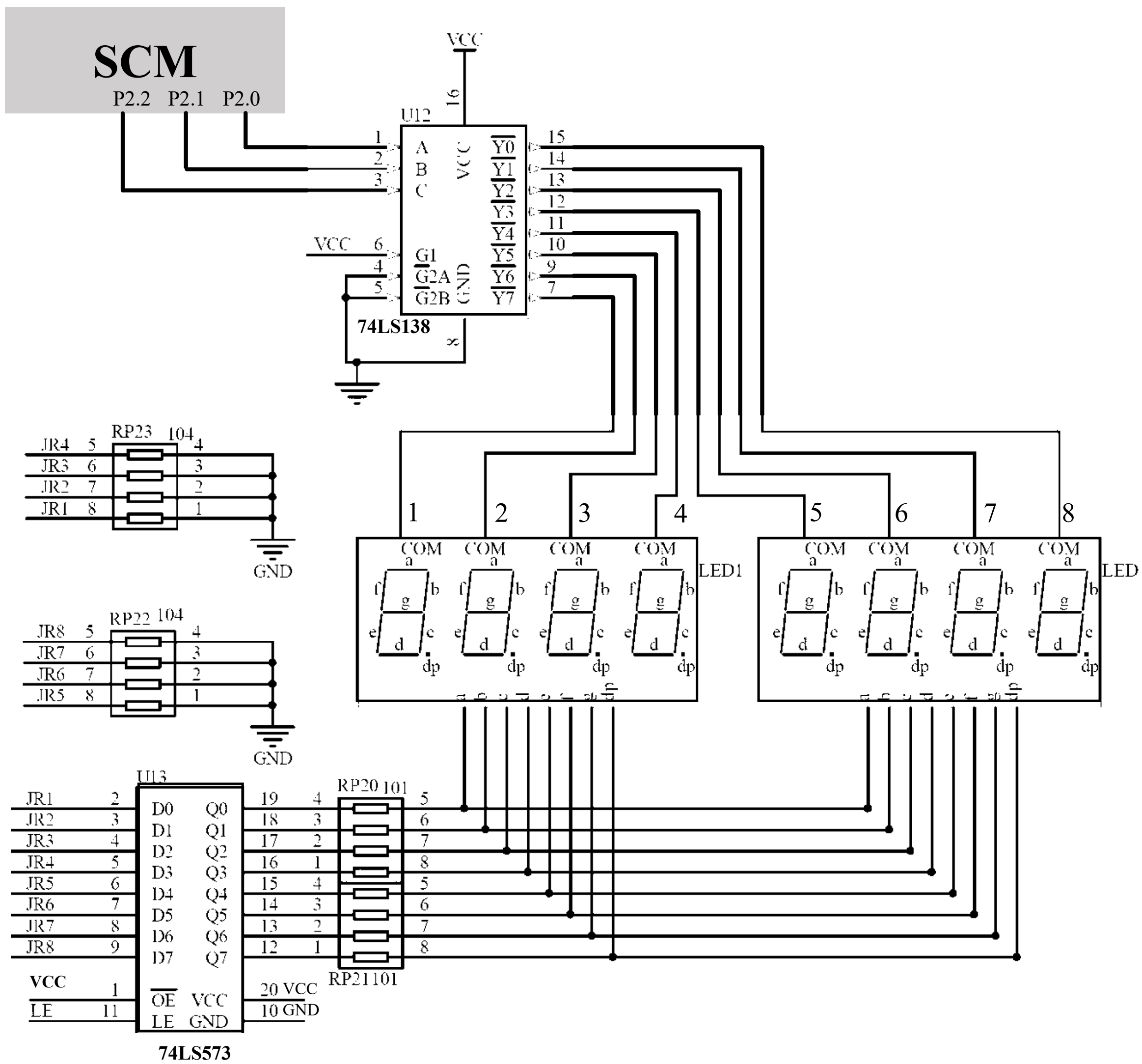


Figure 4-7 Circuit for display subsystem in hardware design of the control system

6) Infrared Remote Receiver & Buzzer

To enhance accessibility of the EHV, remote-control functionality was incorporated in the design. It uses an infrared remote receiver produced by ChengQiang Photoelectric Digital Co., LTD (China) to receive optical signals from a remote controller.

A buzzer was applied to make a feedback sound when there is a valid input, and alarm the user when overheating (1°C higher than the set value) occurs. Both circuits for the remote receiver and the buzzer are shown in Figure 4-8.

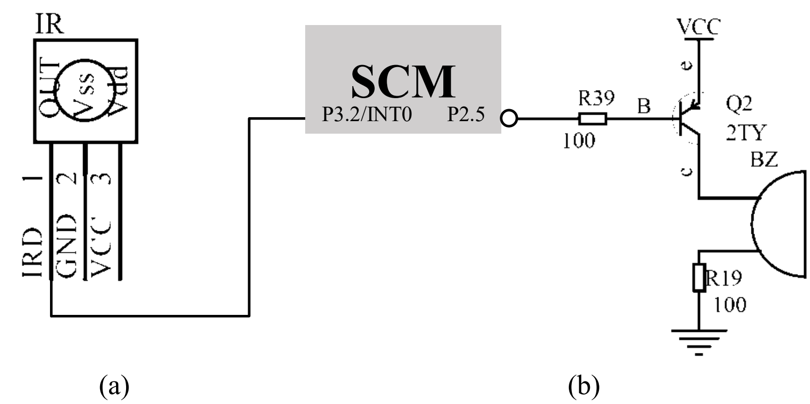


Figure 4-8 Circuit for other functional components in hardware design of the control system: (a) Infrared Receiver and (b) Buzzer

7) Overview of Hardware Design

All hardware components were connected by wires, jacks and plugs. The overview design diagram of the controller is shown in Figure 4-9.

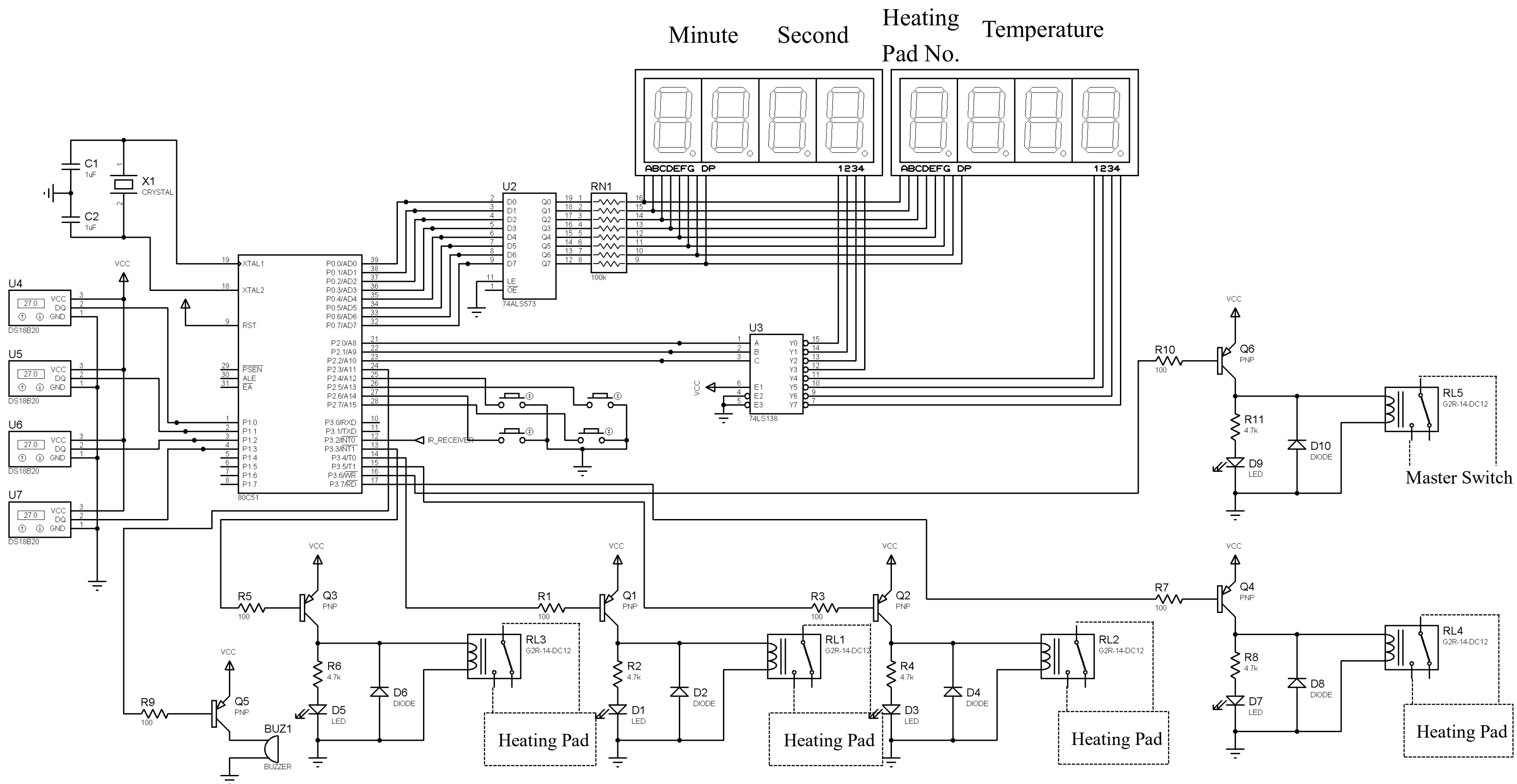


Figure 4-9 Overview diagram of hardware design for the control system

4.3.3.3 Software Design

The software designed for the control system is based on a specific C language for 8051 SCM. The design was divided into six sections for different purposes: definition, initialization sub-functions, interrupt service sub-functions, hardware driver sub-functions, application sub-functions, and the main function. These are described below.

1) Definition

In this section, the constants, variables, and sub-functions (see Appendix 2) used in the design were declared and defined. All time-sensitive variables were designed to be saved in the internal data storage area of the SCM, particularly variables related to DS18B20 sensors. The internal data storage area is defined as the first 128 registers (0x00-0x7F) in the memory of SCM, which have the fastest read/write speed [114].

2) Initialization Sub-Functions

All functional components and I/O ports are required to be initialized before operating. The I/O ports connected to the buzzer, relay switches and the infrared receiver were initially set as the low-level voltage state ('0'). The default values of the timing duration (30 minutes) and temperature threshold (45°C) were sent to the ports for the LED ESDs as the initial content for display.

There were two timers on the SCM used in this design: Timer 0 and Timer 1. Both can provide an interrupt signal to the processor to trigger interrupt service functions [114]. Timer 0 was responsible for the display service and input services operating normally, and Timer 1 is used to count down the heating time. The 8051 series SCMs control the operating modes of timers by several specific bit-programmable control bytes, including TMOD (timer mode), IE (interrupt enabling), IP (interrupt priority) and TCON (timer control), as defined in Table 4-3 [114]. The detailed initial settings of timers are shown in Table 4-4.

The digital temperature sensors (DS18B20) need to be initialized as well, but the initialization functions are described in the hardware drivers section. All initialization functions were listed in the program code (see Appendix 2).

Table 4-3 Settings for timers and the infrared signal receiver in software design of the control system

Items	Value	Description
EA	'1'	Enable the total allowance for all interrupts
For Timer 0		
TMOD	TMOD **OR*** 0x01	Set the Timer 0 working at Mode 1 (16-bit counting)
TH0 **TL0**	0xF8 0x2F	Set the number of one counting period for Timer 0 at 0xFFFF-0xF82F=0x07D0 (2000Dec). When $f_{SCM} = 11.0592$ MHz and $f_{timer} = f_{SCM}/12 = 0.9216$ MHz, the duration to overflow is $\frac{2000}{0.9216\ \text{MHz}} \approx 2$ ms
TR0	'1'	Start Timer 0 to run
ET0	'1'	Enable the interrupt when Timer 0 is overflowing
PT0	'0'	Set the interrupt priority from Timer 0 at 'Low'
IT0	'1'	Triggered by falling-edge
For Timer 1		
TMOD	TMOD **OR*** 0x10	Set the Timer 1 working at Mode 1 (16-bit counting)
TH1 **TL1**	0xEE 0x00	Set the number of one counting period for Timer 1 at 0xFFFF-0xEE00=0x11FF (4607Dec). When $f_{SCM} = 11.0592$ MHz and $f_{timer} = f_{SCM}/12 = 0.9216$ MHz, the duration to overflow is $\frac{4607}{0.9216\ \text{MHz}} = 4.998 \times 10^{-3} \approx 5$ ms
ET1	'1'	Enable the interrupt when Timer 1 is overflowing
PT1	'1'	Set the interrupt priority from Timer 1 at 'High'
min **sec**	Init_min Init_sec	Set the default duration for counting
For Infrared signal receiver (IR_Remote)		
EX0	'1'	Enable external interrupt 1 for the infrared signal receiver

***:** logic bitwise 'OR'; TMOD **OR** 0x01: only changing the lowest bit of TMOD to '1'

Table 4-4 Definitions of control bytes for interrupt sources and timers in 8051 single-chip microcontrollers [114]

Bytes	Bit-7	Bit-6	Bit-5	Bit-4	Bit-3	Bit-2	Bit-1	Bit-0
TMOD	T1:GATE	T1:C/$\overline{T}$	T1:M1	T1:M0	T0:GATE	T0:C/$\overline{T}$	T0:M1	T0:M0
TCON	TF1	TR1	TF0	TR0	IE1	IT1	IE0	IT0
IE	EA	/	ET2	ES	ET1	EX1	ET0	EX0
IP	/	/	PT2	PS	PT1	PX1	PT0	PX0

3) Interrupt Service Sub-Functions

If the SCM requires to stop the current task due to internal or external reasons, the current program will be quickly and correctly stalled and the processor starts to service for other more important issues. After completing these issues, the stopped program can continue [116]. This process is called interrupt, and the reasons that trigger interrupts are interrupt sources. The software must be able to logically manage interrupt sources efficiently. For 8051 microcontrollers, there are five interrupt sources: three internal interrupt sources (Timer 1, Timer 0, and the in-chip serial port) and two external interrupt sources (INT0 and INT1) for incoming signals [114]. Three interrupt sources, Timer 0, Timer 1, and the infrared signal receiver (INT0) are used in this design.

A specific control byte, TCON (timer control) is used to manage and prioritize the requests from timers and external interrupt sources. The settings for TCON was described in initialization section before (defined in Table 4-4).

When an interrupt request is accepted by the processor, a specific sub-function known as the interrupt service function can run immediately. This feature is essential for applications that are timing-sensitive, such as updating the display and scanning the keyboard (for Interrupt 1 from Timer 0), accumulating the counting number (for Interrupt 3 from Timer 1), and responding to received remote control commands (for Interrupt 0 from an external interrupt source, INT0). The interrupt service sub-functions are listed in Appendix 2.

4) Hardware Drivers

The driver is a medium between the hardware and the application program. It is directly related to the connections and the principles of electric components, and offers a relevant interface for applications to use hardware resources [116]. Most of the hardware components used in this control system require drivers.

a. LED ESDs (the display)

The dynamic display strategy was applied to drive the LEL ESDs. Three I/O ports are used to encode eight codes (‘000’=No.0, ‘001’=No.1, 010’=No.2, ‘011’=No.3, ‘100’=No.4, ‘101’=No.5, ‘110’=No.6, and ‘111’=No.7) to corresponding ESDs by the 74HC138 decoder. Another eight I/O ports provide the content of the selected ESDs to the display. And each port charges one LED segment of the selected ESD. After the content of the selected ESD displays for 5ms, all ESDs turn off and the next ESD is enabled and the next content can be displayed. This driving sub-function is called when the display content needs to be updated.

b. Keys (Buttons)

As the used four keys were connected independently and each occupied one I/O port, a scanning process was applied in the driver for keys to obtain the key-values and scan the four I/O ports to detect whether any button is pressed.

Due to the mechanism of the key, it cannot reliably switch on when pressed, and off when released. Thus, when the ‘pressed’ signal is detected, a short delay is added for 15 milliseconds (ms), which is enough to eliminate the key-vibration. Meanwhile, the 15ms is much shorter than the duration of a press by a person. After the short delay, the key status is then checked again to determine whether it is an valid press. In addition, the press actions for Keys 3 and 4 were designed to accept a ‘short-press’ and a ‘long-press’. The ‘short-press’ lasts from 15ms to 0.5s and triggers the key once. While a long-press (>0.5s) triggers, the key continuously increasing or decreasing the set values until the key is released.

c. DS18B20 temperature sensors

The DS18B20 sensor is a low-speed component that takes a relatively long time to transfer the temperature readings (max: 750 ms) [115]. Meanwhile, the sensor is also time-sensitive, as initializing, reading, or writing actions require high or low level signals with precise timing [115]. Thus, when the DS18B20 is initializing, reading or writing, the overall interrupt control bit (EA) in the IE control byte is set to '0' to disable any responses to interrupt requests, which prevents the DS18B20 from disturbing by other programs.

Before reading the temperature from the DS18B20, the Ds18b20Init() initialization sub-function is called to power on the sensor. Then the specific command to start transforming temperature values is sent to the sensor, which was implemented by the Ds18b20ChangTemp() function. After these processes, two reading actions are required to obtain the 12-bit temperature data, one for lower 8-bit data and the other for higher 8-bit data (the highest 4-bit data are disregarded after). All the temperature data received from the four sensors are saved in an array (temp_data [ ]) for following calculations.

d. Infrared receiver

The driver sub-function of the infrared receiver is an interrupt service function triggered by No.0 external interrupt (INT0). When a remote signal is received, an interrupt request is sent to the processor. If it is accepted, the sub-function Read_Ir () is executed to identify the received signal and provide a control code for the next process in the remote-control service sub-function.

5) Applications

The objectives of the software design are to implement applications. In this designed, there are five applications implemented and described below.

a. Temperature Calculation

The DS18B20 driver sub-function provides a series of raw Temp_data from four DS18b20 sensors. The temperature calculation function, Temp_trans(), computes the temperature readings per the equation related to Temp_data[] array (Equation 20) [115]. This sub-function updates the array variable of current temperature readings when the main function calls it.

$$\text{Temp\_value}[i] = \text{Temp\_data}[i] \times 0.0625 \times 100 + 0.5 \tag{20}$$

where i is the index of four temperature sensors: 'A', 'b', 'C' and 'd'.

b. Remote Command Service

There are four buttons on the remote control (increase, decrease, mode-selecting, and start), They are functionally equivalent to the four keys on keyboard. The Ir_service () function identifies the received remote commands, and updates the variable of the current pressed key value. This variable was used in the function of the key (Button) service.

c. Key (Button) Service

As the value of the pressed key is obtained by the keyboard driver or the remote control, the key service sub-function implements various actions, such as mode switching, bit selection of the display, and changing parameter values. The current role of the key depends on which user interface (UI) task is activated. The keys functions for all conditions are shown in Table 4-5.

The setting temperature range is from 30.0°C to 45.0°C, with the default value at 45.0°C. The longest duration that can be set for one heating session is 60 minutes and 59 seconds.

Table 4-5 The functions of the keys for running mode and setting mode in software design of the control system

UI Parts		Key 1 (+)	Key 2 (-)	Key 3 (Mode-Select)	Key 4 (Start)
RUNNING MODE		N/A	N/A	Enter "Setting mode"	Start counting
SETTING MODE	**Minute**	'Min'+1	'Min'-1	Switch to "Second"	N/A
	Second	'Sec'+1	'Sec'-1	Switch to "Temperature"	N/A
	Temperature	'Temp'+0.5	'Temp'-0.5	Exit "Setting mode"	N/A

d. Display

Similar to the key service function, the display contents of the running mode and setting mode are different. The content that needs to be displayed in each mode is shown in Table 4-6.

Table 4-6 The content to be displayed in Running Mode and Setting Mode in software design of the control system

Modes	Display #1-2	Display #3-4	Display #
RUNNING MODE	Counting 'Min'	Counting 'Sec'	Current Temperature reading
SETTING MODE	Set 'Min'	Set 'Sec'	Set threshold of the temperature

e. Comparison and Control

The comparison and control sub-function, Compar(), manages the time and temperature comparison process, and controls relay switches to make correct actions. As described previously, the design of the control loop allows each heating element to be controlled individually. Additionally, the controller was designed to turn off all relay switches when the setting mode is activated.

f. Safety

A safety strategy was designed in the sub-function, Safety(), to activate an alarm, display an error sign, and shut down the power when any of the four heating pads' surface temperatures is 1°C higher than the set point.

The state machine diagram of the heating control logic for any heating element is shown in Figure 4-10, and the state machine terms used are defined in Table 4-7.

Table 4-7 The definitions for terms used for the state machine of compare logics in software design of the control system

Terms	Definition
TC	'1': Temperature is higher than setting; '0': Temperature is lower than setting
TM	'1': The timer (Timer #1) is counting down; '0': Time out or no counting triggered
MD	'1': Setting mode; '0': Running mode
HT	'1': Heating; '0': No-heating

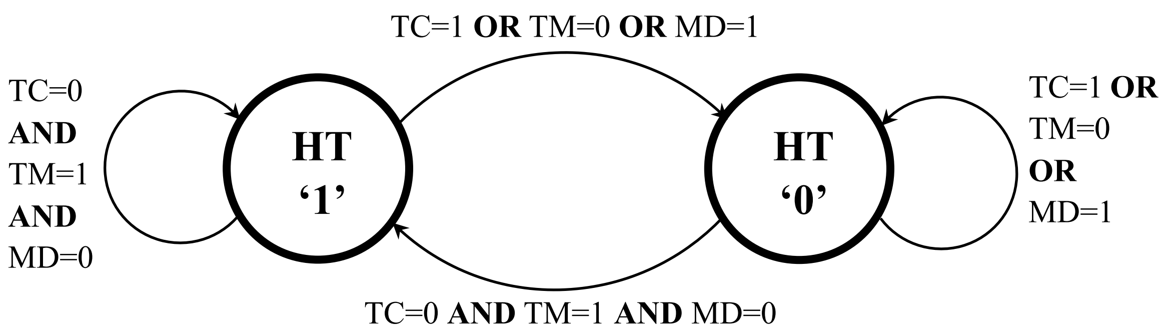


Figure 4-10 State machine diagram of the heating control logic in software design of the control system

6) The Main Function

In this design, the main() function was used as the entrance of the whole program including the initialization process and the control loop. Meanwhile, the watch dog timer (a hardware timer in the microcontroller) was used to automatically generate a system reset if the program neglects to periodically service it. It can prevent the controller from working in abnormal states no more than 3 seconds.

7) Overview of Software Design

The operating and control logic of the control system software design are shown in Figure 4-11, and the program codes are listed in Appendix 2.

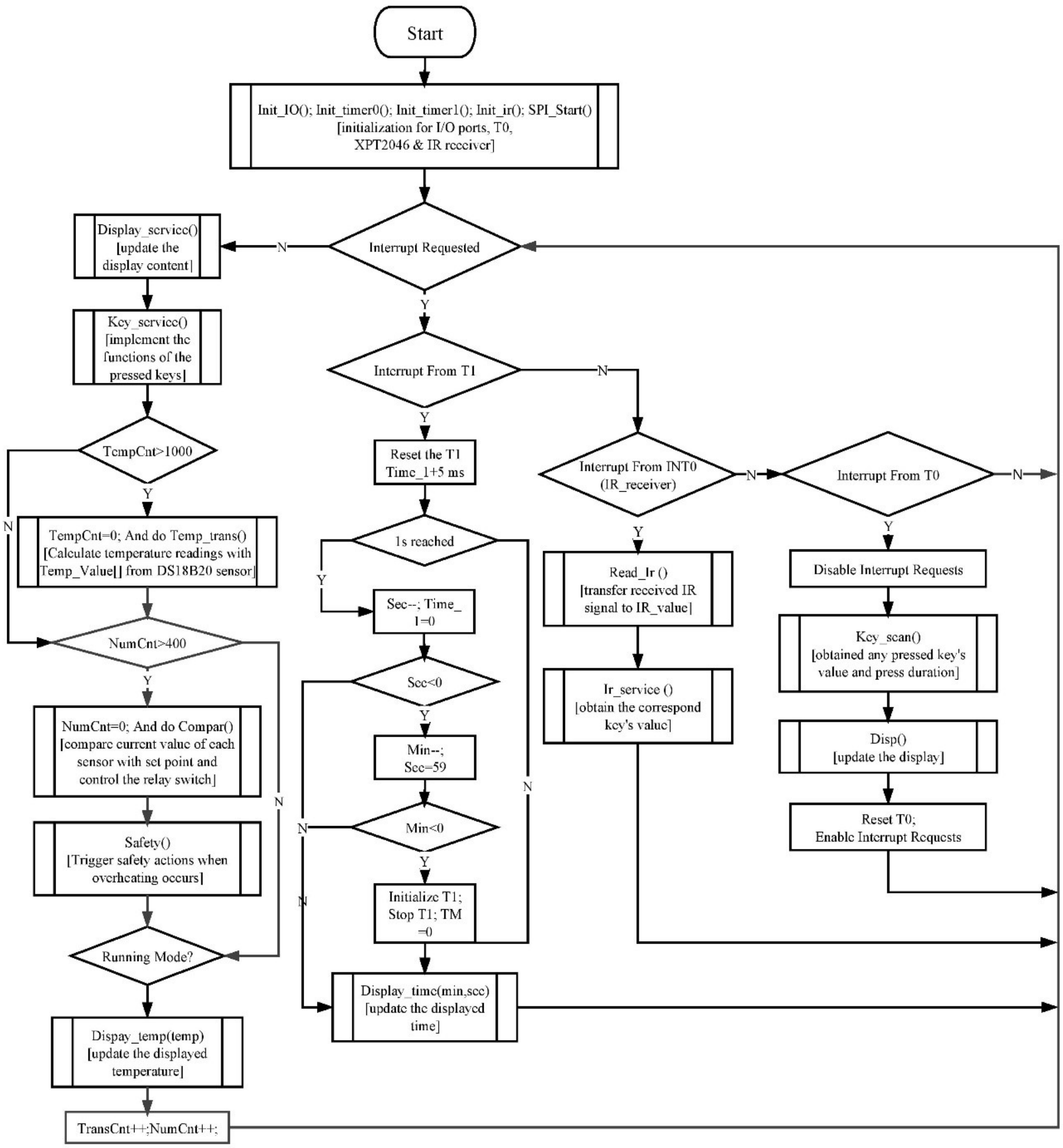


Figure 4-11 Flow diagram of the software design logics for the control system

4.3.4 Power Supply

4.3.4.1 Battery Requirement

According to the conclusion of simulation for the battery performance in Chapter 3, a 12-V battery is needed, which can provide current higher than 12.08 A with a capacity of 12.08 A·h (shown in Table 3-3).

4.3.4.2 Limitation of the battery on the market

From industrial suppliers of lithium-ion batteries, there are current products that meet these specifications on the market. However, due to additional protection circuit for so large current (12A), the heavy weight limits those batteries to be used in this EHV.

4.3.4.3 Applied Approach

The compromised approach applied in this design is using two LIBs (KXD Group Hong Kong Co., Ltd) as the power supply of the EHV. This type of battery is light-weighted and relatively small. Each battery provides power for two heating pads, which reduces the required current and capacity for single battery by 50%.

As two batteries are working simultaneously, an increase in the core body temperature of 0.5°C in 30 minutes can be achieved. The specifications of these batteries are shown in Table 4-8.

Table 4-8 The specifications of the battery used in the design

Parameters	Values
Voltage (V)	12
Continuous discharge current (A)	6
Capacity (A·h)	6
Size (mm)	25 x 62 x 115
Weight (kg)	1

4.3.4.4 Voltage Converter

The SCM and other components require a voltage of 3.3-5.0 V, but the output voltage of the battery is 12 V. To tailor the voltage of the control system, an adjustable power converter by Electronic Geek (Canada) was used to convert the voltage to 4.8 V for the control system (see Figure 4-12).

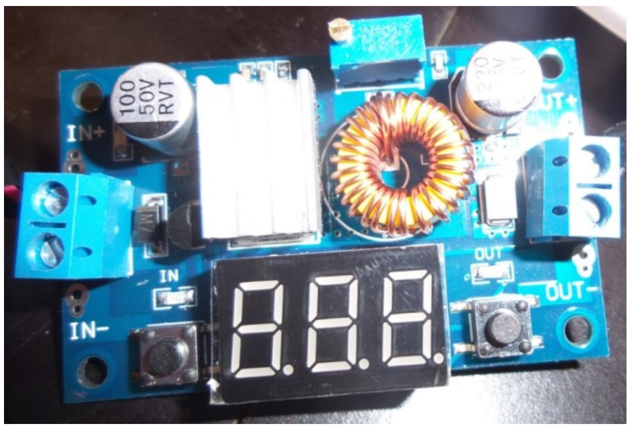


Figure 4-12 Adjustable power converter with LED voltmeter used in the design

4.3.5 Support Belt

4.3.5.1 Requirements

Though the support belt is not a functional component of the EHV system, it provides a fundamental framework to install heating system, control system, and batteries. So, the most important criteria for a suitable support belt are reliability and comfort. In addition, the support belt must be adjustable for patients with different body sizes.

4.3.5.2 Adopted product

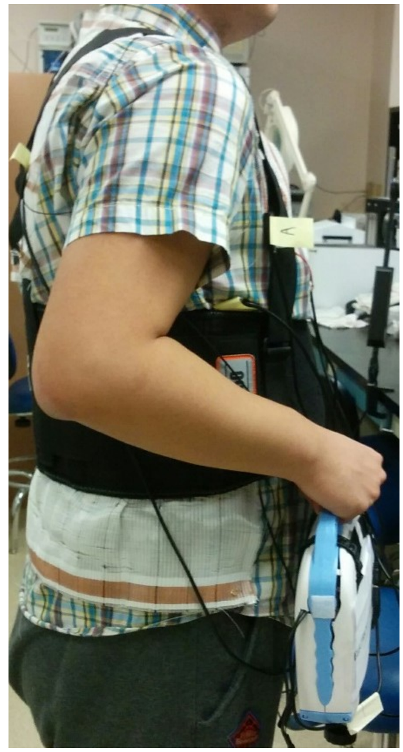
We selected a support belt offered by Ergodyne® (United Sates) which is a type of back support with elastic belts for adjustment. It is available in three sizes (small, medium, and large), which can accommodate most patients. Figure 4-13 is an image of the Ergodyne® 1600 Proflex Standard Elastic Back Support. Several Velcro tapes were attached on this support belt to install heating pads on.

Figure 4-13 Ergodyne® 1600 Proflex standard elastic back support belt used in the design [117]

4.4 Prototype of the Electrical Heating Vest

The individual designs for the heating system, control system, batteries and vest were detailed above. All the sub-systems and components were assembled as a prototype of the EHV. The control system and the batteries were placed together in a box, which can be attached on the support belt or carry by hand. Figure 4-14 showed the EHV prototype wearing on the body.

(a)



(b)

(c)

Figure 4-14 The prototype of the electrical heating vest
(a) Front, (b) Side, and (c) Back

Chapter 5 In-Vitro Study

5.1 Functional Test

5.1.1 Rationale

The designed electrical heating vest (EHV) is aimed to increase the ambient temperature close to the skin, and thereby raise the core body temperature by 0.5°C. Functional test is needed to assess performance of the EHV prototype.

5.1.2 Purpose

The purpose of this functional test was to evaluate the thermal performance and the control functionality of the EHV prototype in-vitro conditions.

5.1.3 Method

5.1.3.1 Test Object

A half-length manikin (Figure 5-1) was used in the test, and subjected to a complete heating session with the EHV prototype. During the heating process, the manikin was wearing the prototype covered by one layer of outerwear (Figure 5-2). The outerwear was removed after heating terminated.

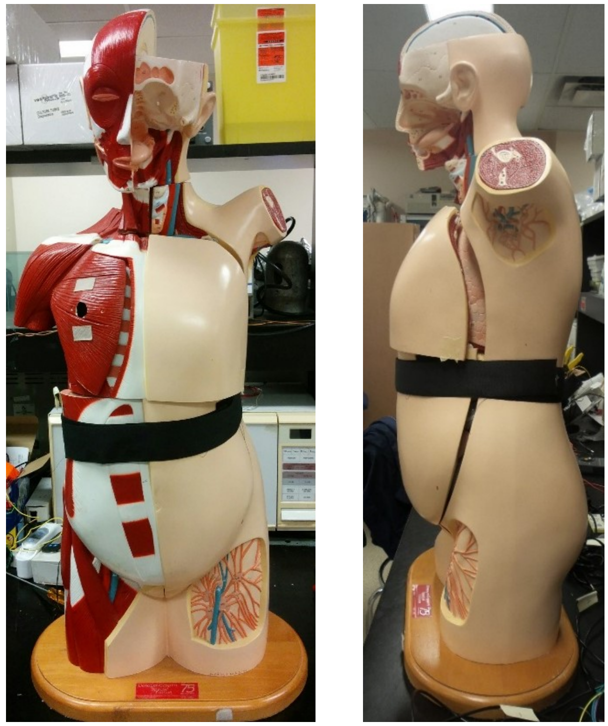


Figure 5-1 The manikin used for in-vitro studies

Figure 5-2 The manikin with the prototype of the electrical heating vest covered by a layer of outerwear

5.1.3.2 Test Setup

Rather than batteries, the EHV was powered by an adjustable DC power supply unit (PSU) with a constant voltage of 12V, which allowed the power consumption of the system to be evaluated.

The functional test was divided into two phases, heating (30 minutes) and post-heating (20 minutes) (Figure 5-3). The heating phase was triggered to start only when surface temperatures of all heating pads passed 35°C, to simulate the skin temperature of the human body. Configurations of the functional test are shown in Table 5-1. The output current of the PSU, and the surface temperatures of heating pads were recorded at 30-second intervals during the test, to observe the variations of temperature and power consumption.

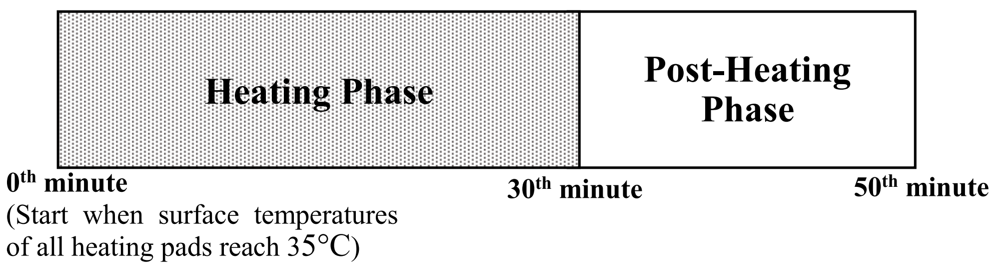


Figure 5-3 Process of the functional test

Table 5-1 The configurations for the functional test

Items	Set Value
Heating Time	30 minutes
Temperature to Start Timing	35°C
Threshold for the Heating Pad Surface Temperature	45°C
Output Voltage of the PSU	12 V
Recording Intervals	30 seconds
Size of Used Heating Pads	40 ×30 cm: 2 pcs (Right & Left around the wrist) 30 ×30 cm: 1 pc (Upper Back) 20 ×30 cm: 1 pc (Chest)

5.1.3.3 Data Analysis

The values of the heating pad surface temperature were plotted against the test timeline, and the maximal temperature values during the heating phase and the last record of the testing were labeled. The output current (I_{out}) of the PSU was also observed, and the power consumption of the prototype was calculated by $P_{out} = 12V \times I_{out}$.

5.1.4 Result

5.1.4.1 Surface Temperature of the Heating Pads

As shown in Figure 5-4, the heating pad on the back was the first to reach the threshold of surface temperature (45°C) from 35°C, taking only 8.0 minutes. The front heating pad achieved in 9.5 minutes, and the heating pads around the waist took 15.5 and 20.5 minutes respectively. The temperature controller maintained the heating pad temperature around the threshold effectively and the fluctuations was only from 44.6 to 45.1°C. When the set time was over, the controller cut off the relay switches and terminated the heating process. Compared to the rate of increase at the start of heating, the surface temperature decreased with a relatively gentle slope during the post heating phase. The temperature dropped to approximately 35°C in end of the test.

5.1.4.2 Power and Energy Consumption

When the relay switches remained off, the control system only consumed power. The output current at this moment was only 0.09A. During the heating phase, the output current of the PSU depended on the number of operating heating pads managed by the controller. The range of variation was from 0.09A (no heating) to 6.52A (fully heating). The observed current values and calculated power consumption are listed in Table 5-2.

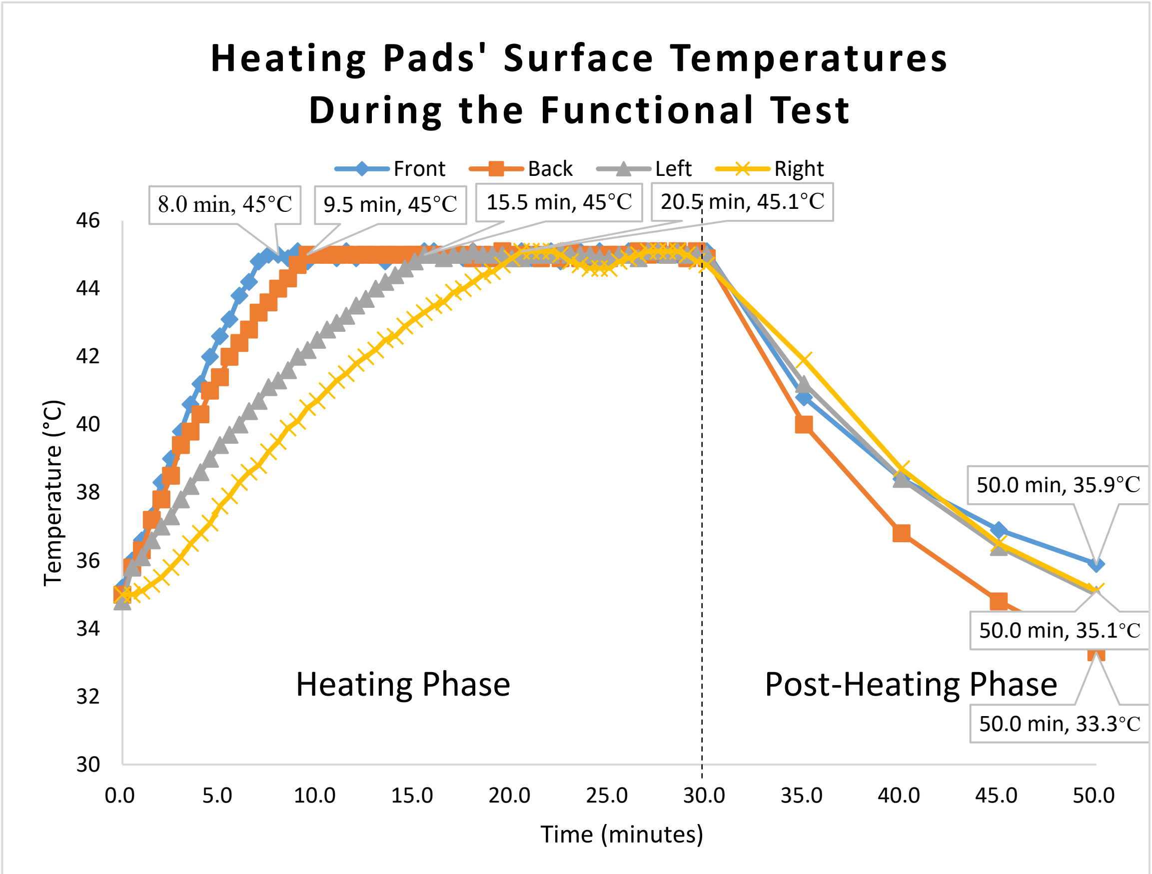


Figure 5-4 The surface temperature of heating pads during the functional test (Spreadsheet automatically joined points by lines)

Table 5-2 Output current of power supply unit and power consumption of the electrical heating vest during the functional test

Operating Heating Pads	Output Current of PSU	Power Consumption of EHV
None (minimum)	0.09 A	1.08 W
One	1.15 – 2.02 A	13.8 – 24.24W
Two	2.42 – 3.8 A	29.04 – 45.6 W
Three	4.35 – 5.22 A	52.2 – 62.64W
All Heating Pads (maximum)	6.52 A	78.24 W

5.1.5 Discussion

Heating pad temperatures took 8.5 to 20.5 minutes to reach the set threshold (45°C), which is approximately half of the heating phase. Then, the fluctuations of the values were in the range from -0.4°C to +0.1°C around 45°C, which is acceptable for the performance and safety requirements.

The diverse power consumption values were attributed to the separate control for each heating pad, which can conserve battery energy while maintaining the set temperature.

During the post-heating phase, raised surface temperature of heating pads returned to initial level (about 35°C) within 20 minutes, as carbon fiber cools down quickly after power-off.

5.1.6 Conclusion

The prototype of the EHV was functionally tested, and it was found that it can quickly increase heating pad temperatures to a set value of 45°C. Meanwhile, heating pad temperatures and session duration were managed as per designed control logic. The controller was able to effectively suspend or terminate heating at the preset conditions.

As the thermal and control performance of the EHV has been successfully tested, safety issues, particularly in extreme or abnormal cases, are considered as following.

5.2 Safety Tests

5.2.1 Rationale

Safety is the priority for medical devices. It is crucial to evaluate safety performance of the EHV prototype under practical extreme or abnormal conditions before any test on the human body.

The relatively hot environment during heating process will possibly cause the body to sweat, which means heating pads can become damp and the electrical conductivity can increase. Due to the proportional relationship between conductivity and flowing current, the increased current could possibly cause a shock-hazard. So, the electrical characteristics, particularly the resistance of heating pad in humid condition, must be assessed.

Even though the temperature controller was designed to prevent heating pads from overheating, the EHV still needs to be tested for a temperature-control failure. When temperature for any heating pad increases 1°C higher than the set value, the safety program should intervene to trigger an alarm, display an error sign, and terminate heating in a short time (less than 30 seconds).

5.2.2 Purpose

The purpose of the safety tests was to ensure the EHV is safe for users, even in extreme conditions such as wet heating pads or malfunction of the temperature control.

5.2.3 Methods

5.2.3.1 Test with Humid Heating Pad

The total resistance of one heating pad is calculated by $R_{total} = R_1/N$, where the R_1 is the resistance of single carbon filament and N is the number of carbon filaments on the heating pad. Due to more carbon filaments placed, the resistance of a larger pad is less than the smaller sizes. Whereas, the flowing current is larger when the resistance is less, which means greater risk of an electric shock hazard. Thus, a heating pad with the size of 40 cm x 30 cm, the largest form applied in the prototype, was used as a sample for the safety test.

This sample pad was first immersed in water for five minutes, to ensure it was thoroughly soaked. A resistance meter was used to monitor changes in resistance before and after the process (Figure 5-5).

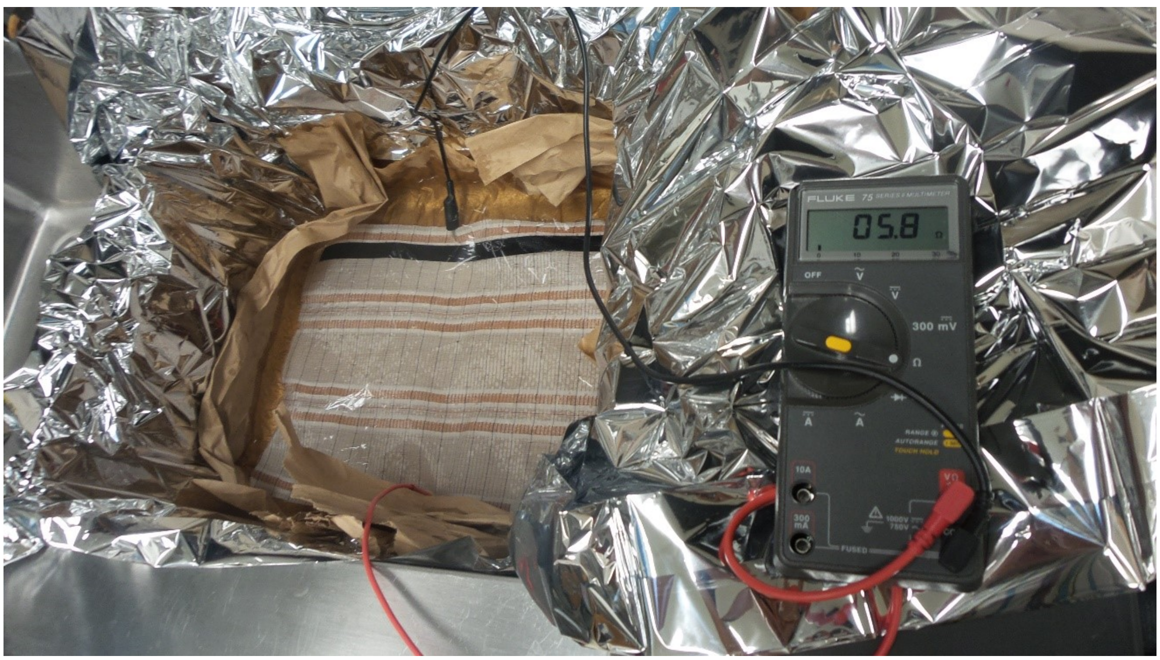


Figure 5-5 The safety test for resistance of a heating pad under wet condition

5.2.3.2 Heating Test with Temperature Control Failure

The control software was modified to simulate a temperature-control failure. The function to compare heating pads' temperatures with the threshold in the software program was disabled. Though the temperature control could not work, the temperature readings from sensors were still displayed.

The EHV system was put on the half-length manikin and set up in the same manner with the functional test. The duration of the heating phase was 30 minutes, and the set point of the heating pad's surface temperature was still 45°C, even if the heating process cannot be suspended at this point.

5.2.4 Results

5.2.4.1 Results of Test with Humid Heating Pad

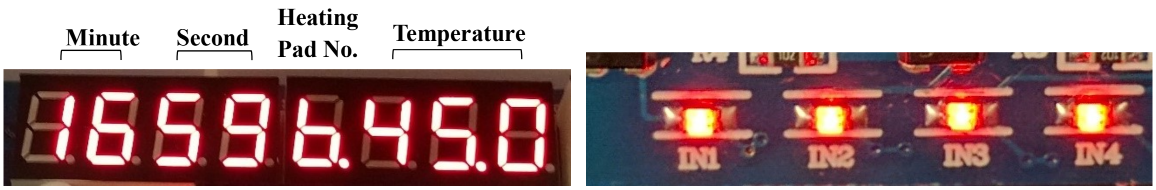
The resistance values of the heating pad sample before and after being soaked are shown in Table 5-3. Only a decrease of 0.1Ω (1.7%) was observed, which is insignificant and can be considered as measurement errors.

Table 5-3 Results of the safety test for resistance of a heating pad under dry or wet condition

Conditions	Resistance (Ω)	Relative Difference
Dry	5.9	1.7%
Wet	5.8	

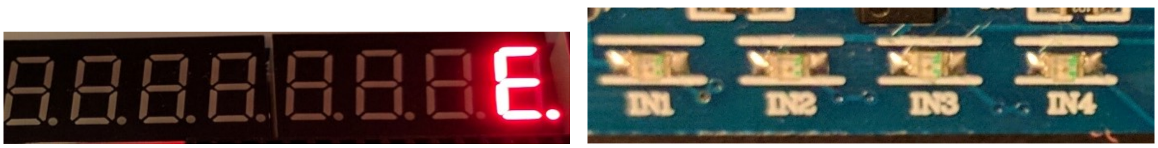
5.2.4.2 Results of Test without Temperature Control

In the test, the heating pad temperature increased continuously from 45°C without temperature control. When one of the four heating pad's surface temperature reached 46°C (1°C higher than the set point), the alarm was triggered and there was an 'E' on display. Meanwhile, the power was cut off to terminate the heating process automatically. All actions happened with no noticeable delay when the trigger value (45+1°C) was reached.



(a) (b)

Figure 5-6 Displayed content (a) and relay switch state-indicators (ON) (b) in normal heating state during the safety test for a temperature-control failure



(a) (b)

Figure 5-7 Displayed content (a) and relay switch state-indicators (OFF) (b) when safety program was activated during the safety test for a temperature-control failure

5.2.5 Conclusion

The results of the safety test with a wet heating pad suggested that humidity does not make significant difference in the resistance of heating pads. This means the electric characteristics of the heating system is stable under extremely humid conditions.

Without temperature control, the heating pad surface temperatures can exceed the set threshold. However, when the temperature of any pad is 1°C higher than the threshold, the safety program can be activated to trigger an alarm, to display an error sign, and terminate the heating process.

In conclusion, the safety of the prototype can be ensured under two conditions: 1) operating with wet heating pads; 2) heating without temperature control.

Chapter 6 Healthy Human Volunteer Study

6.1 Rationale

The capability of the electrical heating vest (EHV) to induce physiological changes must be evaluated on healthy individuals before any clinical tests or applications.

6.2 Purpose

The purpose of the healthy volunteer's test was to determine whether heating the body with an EHV can be potentially applied in thermal therapy for heart failure and/or hypertension patients.

6.3 Method

6.3.1 Study Design

6.3.1.1 Study Properties

This single-institute observational (non-interventional) study was conducted in the laboratory of the Cardiovascular Devices Division, University of Ottawa Heart Institute. Eligibility of the volunteers was based on inclusion/exclusion criteria and screen assessment which are listed below. As a data-collecting study focusing on healthy volunteers with a non-invasive device, there is no requirement for approval from the Research Ethics Board. But, all participating individuals signed and dated an Informed Consent Form before any study procedures were carried out.

6.3.1.2 Study Population

The study population was five male and five female volunteers from the University of Ottawa. They were recruited according to the following criteria.

6.3.1.3 Inclusion Criteria for Recruitment

a. Age $\geq$ 18 years;

b. No suspected or known heart failure or hypertension;

c. No cardiovascular disease history;

d. Able and willing to comply with the study procedures.

6.3.1.4 Exclusion Criteria for Recruitment

a. Any significant discomfort or condition;

b. Pregnancy or breastfeeding;

c. Unwilling or unable to provide informed consent.

6.3.1.5 Study Procedure

1) EHV Configurations

The prototype of the EHV that was designed and assembled as previously described was used in this study. The duration of heating was set at 30 minutes, and the set temperature to be reached was 45°C.

The size of the support belts varied, but the form factors of heating pads remained the same for testing on each volunteer. The batteries were fully charged for every test to ensure the similar output power, which ensured that the amount of heat received by each individual was not significantly different.

2) Volunteer's Responsibilities

Participating volunteers were asked to bring their own outer wear to cover the EHV during the tests. They were instructed to immediately report any discomfort before, during and after the heating session.

3) Study Visits

There were two visits in the study: a screening visit and a test visit.

At the screening visit, the recruited individuals were notified about the necessary information of the study, and the informed consent forms were offered to them. Only individuals who signed and dated the form were allowed to continue in the study.

Those participating volunteers were first asked about the general health status, then physiological parameters such as core body temperature, heart rate and systolic/diastolic blood pressure were measured to assess whether they were acceptable for the study.

The test visit was arranged for the day after the screening visit, and a complete heating session was conducted.

Seven days after the test visit, a phone call was made to collect the volunteers' questions and comments about the test.

4) Test Process

The test process was divided into three phases: rest, heating, and post-heating (Figure 6-1). Before the rest phase, the volunteers were asked to sit still and stay calm for additional ten minutes.

Rest Phase: This phase was ten minutes long, during which the volunteers remained in a sitting position wearing the EHV covered by their own outerwear. Then the EHV was power on in a non-heating state.

Heating Phase: The duration of this phase was equal to the heating duration, 30 minutes. It starts when the start button on the controller was pressed, and ends when the 30 minutes is up. The heating process was managed by the controller per the heating pad temperatures (as described in the Chapter 4).

Post-Heating Phase: During this final phase, volunteer outer wear was removed but the EHV was kept on the body. The post-heating phase lasted for 20 minutes.

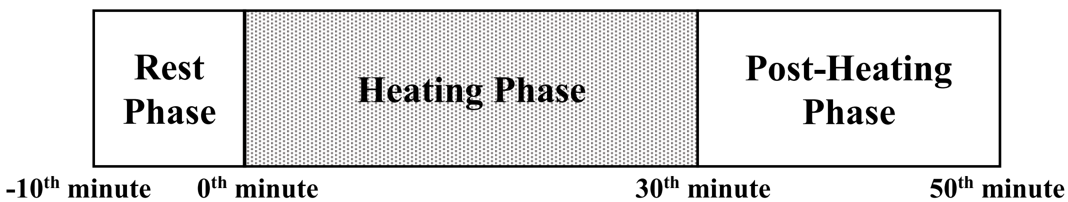


Figure 6-1 Process of the healthy volunteer test

Table 6-1 Conditions for the healthy volunteer test

Test Phases	Duration	Wearing Conditions	Heating Condition
Rest Phase	10 minutes	Outer wear + EHV	No heating
Heating Phase	30 minutes	Outer wear + EHV	Heating
Post-Heating Phase	20 minutes	Only EHV	No heating

6.3.1.6 Physical Parameters of Volunteers

For the testing, ten healthy volunteers were recruited and signed the Informed Content Form: five males and five females. The physical parameters, such as age, weight and height were collected during the first visit, and are shown in Table 6-2. The volunteers' indexes were sorted randomly.

6.3.2 Measurements of Parameters

During the tests, five parameters were recorded: the heating pad surface temperature, core body temperature, heart rate, systolic blood pressure and diastolic blood pressure. These parameters were recorded every five minutes during each of the three phases. The timing of the recordings is shown in Table 6-3. Specially, the start point (0 minute) of the heating session was included in the rest phase, and the heating phase contained the point of 30 minutes, which was the end of heating process.

Table 6-2 Physical parameters of individuals participated in healthy volunteer tests

No.	Gender	Age	Weight	Height
1	Female	25	51 kg	174 cm
4	Female	25	50 kg	155 cm
7	Female	24	55kg	160cm
8	Female	25	51 kg	165 cm
10	Female	25	46 kg	155 cm
Female Average:		24.8	50.6 kg	161.8 cm
Standard Deviation		0.45	3.21 kg	7.98 cm
2	Male	25	68 kg	180 cm
3	Male	24	81 kg	179 cm
5	Male	34	70 kg	173 cm
6	Male	24	71 kg	170 cm
9	Male	26	70 kg	176 cm
Male Average:		26.6	72 kg	175.6 cm
Standard Deviation		4.22	5.15 kg	4.15 cm

Table 6-3 Recording time for parameter measurements during volunteer tests

Phases	Recording No.	Time
Rest Phase	1	- 10th minute
	2	-5th minute
	3	**0th minute** (Start Heating)
Heating Phase	4	5th minute
	5	10th minute
	6	15th minute
	7	20th minute
	8	25th minute
	9	30th minute
Post-Heating Phase	10	35th minute
	11	40th minute
	12	45th minute
	13	50th minute

6.3.2.1 Measurement of the Heating Pad Surface Temperature

Similar to results of the functional test, there were no significant difference in the surface temperatures of the four heating pads. The mean of the four temperature observations was calculated and used in the following discussion.

6.3.2.2 Measurement of the Core Body Temperature

The change in core body temperature was measured with a digital thermometer from BrAun® ThermoScan™ IRT6020CA, Germany. This device measures the tympanic temperature, which represents the core body temperature and can be measured conveniently. The resolution of the device is 0.1°C, and due to the high accuracy, it has been recommended for clinical applications.

Five repeated measurements of the tympanic temperature were made at each recording time to ensure the validity of the measured data. The five tympanic temperature observations were then averaged as one record for the process. The position and depth of the probe in the ear should be as consistent as possible for every measurement.

6.3.2.3 Measurements of the Heart Rate and Blood Pressure

Changes in the heart rate, systolic blood pressure and diastolic blood pressure were measured using a blood pressure and heart rate monitor (LifeSource® UA-787EJ). This device has been recommended by Hypertension Canada for clinical applications.

The cuff of the monitor was wrapped around the upper left arm, about 2 cm above the middle of medial elbow joint, to provide the readings in the same conditions for each volunteer. The wrapping remained on the arm during the whole test.

The measurements were repeated in triplicate at each recording time, and the average value was used for statistical analysis.

6.3.3 Statistical Analysis

6.3.3.1 Individual Analysis

The variations of measured parameters for each volunteer were analyzed. To simplify the analysis, only three representative records extracted from each of the three phases were compared to assess if any potential changes of parameters occurred. The extracted record from heating phase was the maximal or minimal record depending on different parameters while the other two are the first and the last records of the whole test shown in Table 6-4.

Table 6-4 Representative values extracted in each phase for different parameters during volunteer tests

Parameters	Rest Phase	Heating Phase	Post-Heating Phase
Heating Pad's Surface Temperature	First Record (at -10th minute)	Maximal Record	Last Record (at 50th minute)
Core Body Temperature		Maximal Record	
Heart Rate		Maximal Record	
Systolic/Diastolic Blood Pressure		Minimal Record	

6.3.3.2 Overall Analysis

The same-time records of all volunteers were averaged for each measured parameter, and the standard deviations were derived to assess the overall dispersion.

The averaged data for the same parameter were collected, grouped, and statistically analyzed using the generalized linear model (GLM). And the differences between the group means were assessed using the least significant difference (LSD). The statements of statistical significance are based on $P < 0.05$.

Data without significant differences are represented by the same letter, and significant differences are marked by different letters

6.3.3.3 Comparison Between the Female and the Male

As both male and female volunteers are involved, it is possible that gender factors affect the outcome of the test. Therefore, additional analysis was conducted for volunteers of the same gender using the identical overall method described above.

6.4 Results

6.4.1 Changes of the Heating Pad Surface Temperature

The same-time temperature observations from sensors on four heating pads were averaged and plotted in Figure 6-2. At rest, the heating pad was warmed a little by the heat from the body, and the surface temperatures at the end of this phase were about 30°C (from 28.5 to 33.2°C).

When the heating session started, the surface temperature increased to approximately 42°C in five minutes (0^{th} to 5^{th} minute), and stabilized near the set point (45°C) for the rest of heating phase. After heating was terminated, the heating pad's temperature dropped from 45°C to 35°C in ten minutes (30^{th} to 40^{th} minute). At the end of the whole test, the pads cooled down with the similar temperature observed in the beginning.

The comparison of three representative records for each volunteer is listed in Table 6-5. Due to these significant and consistent fluctuations of heating pad temperature, there was no need to analyze statistical significance levels or the differences between genders.

Table 6-5 Individual analysis of heating pad surface temperature change during volunteer tests (°C) (°C)

Volunteers' No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
First record (at -10^{th} minute)	28.9	29.8	28.8	31.0	29.2	26.5	25.1	28.6	28.0	28.3
Maximal Record in Heating Phase	45.2	45.0	44.8	45.0	45.0	44.8	45.0	45.0	44.8	45.0
Last record (at 50^{th} minute)	30.2	30.4	30.2	30.7	32.2	28.8	30.1	30.6	28.7	27.7

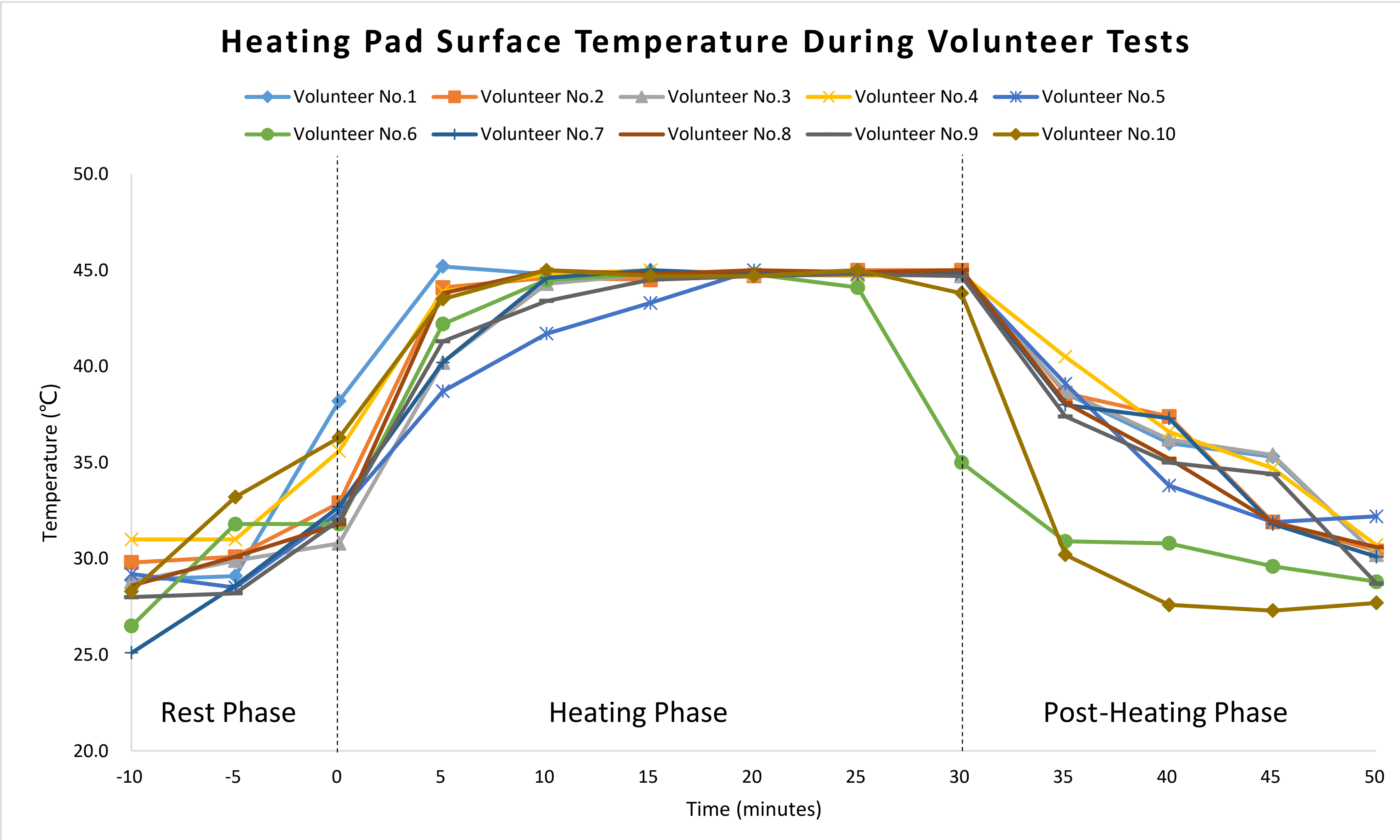


Figure 6-2 Heating pads temperature of each individual during volunteer test (Spreadsheets automatically join points by lines)

6.4.2 Impact on the Core Body Temperature

6.4.2.1 Individual Analysis

Changes in the core body temperature during the tests for all volunteers are presented in Figure 6-3. Generally, the core body temperature maintained the same level in the rest phase except the Volunteer No.3.

During the heating phase, an increase in core body temperature was observed on every individual. With the comparison among three phases (Table 6-6), there were four volunteers, whose core body temperature increased by 0.4°C, three by 0.2°C and one other by 0.3°C. The core body temperature of Volunteer No. 4 showed the smallest increment at 0.1°C, which can be caused by the higher basal body temperature. The No.3 volunteer was observed an increase of 1.2°C, due to the abnormal rise in the rest phase.

In the post-heating phase, it was observed that the core body temperature didn't decrease on four volunteers. Whereas, a drop of 0.1°C was seen in five cases. There was an increase of 0.1°C for volunteer No.3

Table 6-6 Individual analysis of core body temperature change during volunteer tests (°C)

Volunteers' No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
First Record (at -10th minute)	37.1	36.7	35.8	37.0	36.9	36.7	37.0	37.0	37.0	36.7
Increase Induced by Heating	0.3	0.2	1.2	0.1	0.4	0.4	0.2	0.4	0.2	0.4
Maximal Record in Heating Phase	37.4	36.9	37.0	37.1	37.3	37.1	37.2	37.4	37.2	37.1
Decrease After Heating	0.1	0.1	-0.1	0	0.1	0.1	0.1	0	0	0
Last Record (at 50th minute)	37.3	36.8	37.1	37.1	37.2	37.0	37.1	37.4	37.2	37.1

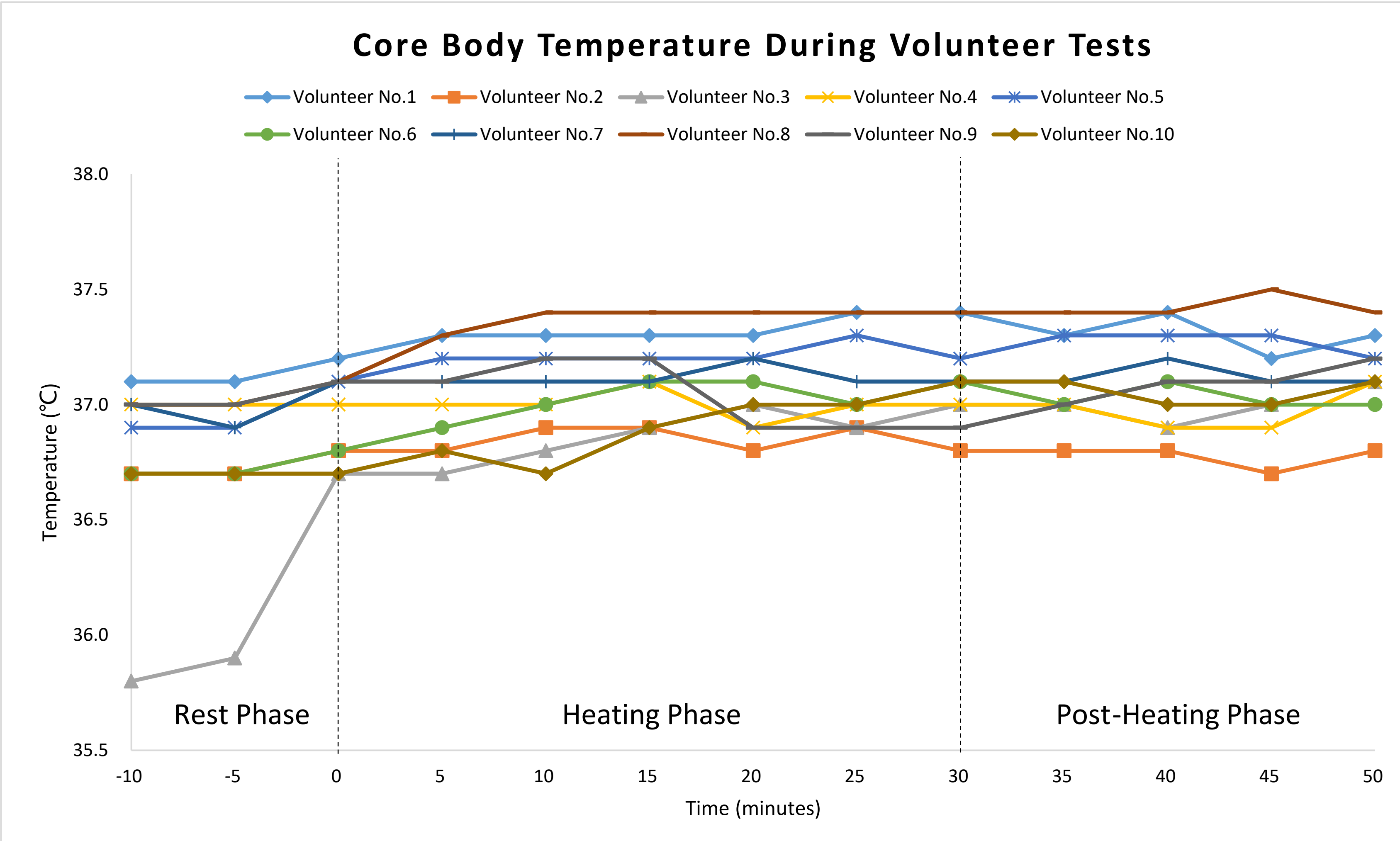


Figure 6-3 Core body temperature of each individual during volunteer tests (Spreadsheets automatically join points by lines)

6.4.2.2 Overall Analysis

The core body temperatures of all volunteers at the same recording time were averaged and plotted with significance marks and standard deviations (Figure 6-4). Meanwhile, the comparison of averaged values for the three phases was shown in Table 6-7.

Heating with the EHV induced a significant increase of 0.3°C in core body temperature and the average of last records of all volunteers is still 37.1°C, which is the same as the average highest core body temperature reached during the heating session. This indicated that the impact of the heating process on the core body temperature persisted for at least 20 minutes.

Table 6-7 Overall analysis of core body temperature changes during volunteer tests *(*Overall *P*=0.0053*)*

Items	Mean (°C)	Significance
First Record (at -10th minute)	36.8	B
Increase Induced by Heating	0.3	*P*=0.0024
Maximal Record in Heating Phase	37.1	A
Decrease After Heating	0	*P*=0.8468
Last Record (at 50th minute)	37.1	A

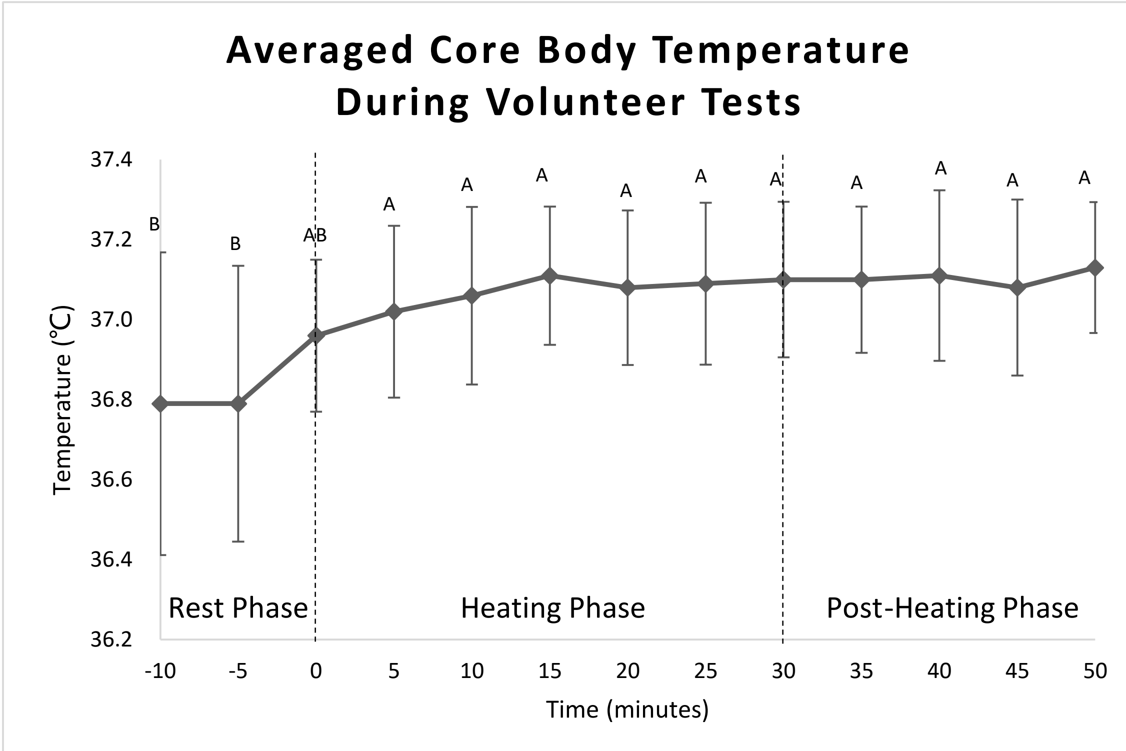


Figure 6-4 Averaged core body temperature during volunteer tests
(Spreadsheets automatically join points by lines)

6.4.2.3 Comparison between Females and Males

The first, the highest, and the last records of core body temperature for volunteers with the same gender were separately averaged and compared between genders. Those mean values and corresponding standard deviations (SD) were listed in Table 6-8. Initially, the female core body temperature was, on average, 0.4°C higher than the male's. However, the mean of maximal values reached in heating phase was the same for both genders.

Table 6-8 Comparison of core body temperature change between two genders during volunteer tests

	Female		Male	
	Mean (°C)	SD	Mean (°C)	SD
First Record (at -10th minute)	37.0	0.152	36.6	0.434
Increase Induced by Heating	0.2	(N/A)	0.5	(N/A)
Maximal Record in Heating Phase	37.2	0.187	37.1	0.152
Decrease After Heating	0	(N/A)	0	(N/A)
Last Record (at 50th minute)	37.2	0.141	37.1	0.167

6.4.3 Impact on the Heart Rate

6.4.3.1 Individual Analysis

The fluctuations in the heart rate of each volunteers during the tests are shown in Figure 6-5 and the comparisons of the changes among three test phases were listed in Table 6-9. During the tests, the heart rates of volunteers No. 5, No. 6 and No. 8 increased only 4 to 8 bpm, while the others increased over 10 bpm. Besides, the maximal heart rates of volunteers were observed at different recording time, which implied that heart rate changes induced by heating largely depends on individuals.

During the post-heating phase, a decrease in heart rate was observed on most volunteers. But the last record (at 50th minute) was still higher than the initial value (at -10th minute), which was found on eight individuals. It means that the induced impact on the heart rate was weaker but still present, even 20 minutes after heating terminated.

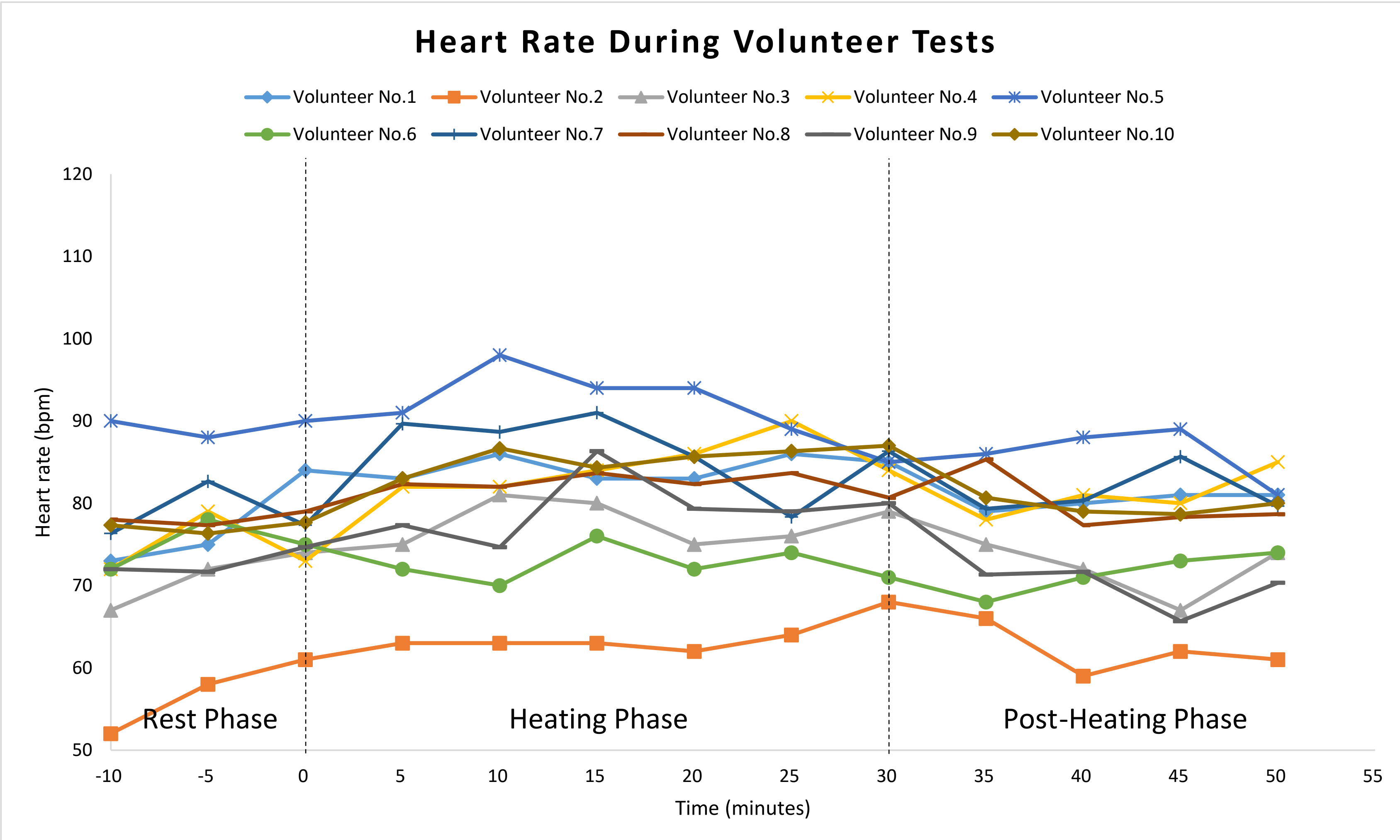


Figure 6-5 Heart rate of each individual during volunteer tests
(Spreadsheets automatically join points by lines)

Table 6-9 Individual analysis of heart rate change during volunteer tests (bpm)

Volunteers' No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
First Record (at -10th minute)	73	52	67	72	90	72	76	78	72	77
Increase Induced by Heating	13	16	15	18	8	4	15	6	14	10
Maximal Record in Heating Phase	86	68	81	90	98	76	91	84	86	87
Decrease After Heating	5	7	7	5	17	2	11	5	16	7
Last Record (at 50th minute)	81	61	74	85	81	74	80	79	70	80

6.4.3.2 Overall Analysis

The averaged heart rates of all volunteers are plotted in Figure 6-6, along with the significance levels and standard deviations. The average data highlight the pattern of heart rate changes described in individual analysis and the relatively large standard deviations indicate that heart rates were highly diverse for different volunteers.

The maximal heart rate in heating phase along with the first and the last records for each volunteer was averaged and compared (Table 6-10). It was found that on average, the heart rate increased significantly by 9.5 bpm ($P<0.05$) because of the heat delivered from the EHV, while the average post-heating decrease was only 6 bpm which is not significant ($P>0.05$).

Table 6-10 Overall analysis of heart rate change during volunteer tests (Overall P = 0.2785)

Items	Mean (bpm)	Significance
First Record (at -10th minute)	73.0	B
Increase Induced by Heating	9.5	P = 0.01
Maximal Record in Heating Phase	82.5	A
Decrease After Heating	6	P = 0.1046
Last Record (at 50th minute)	76.5	AB

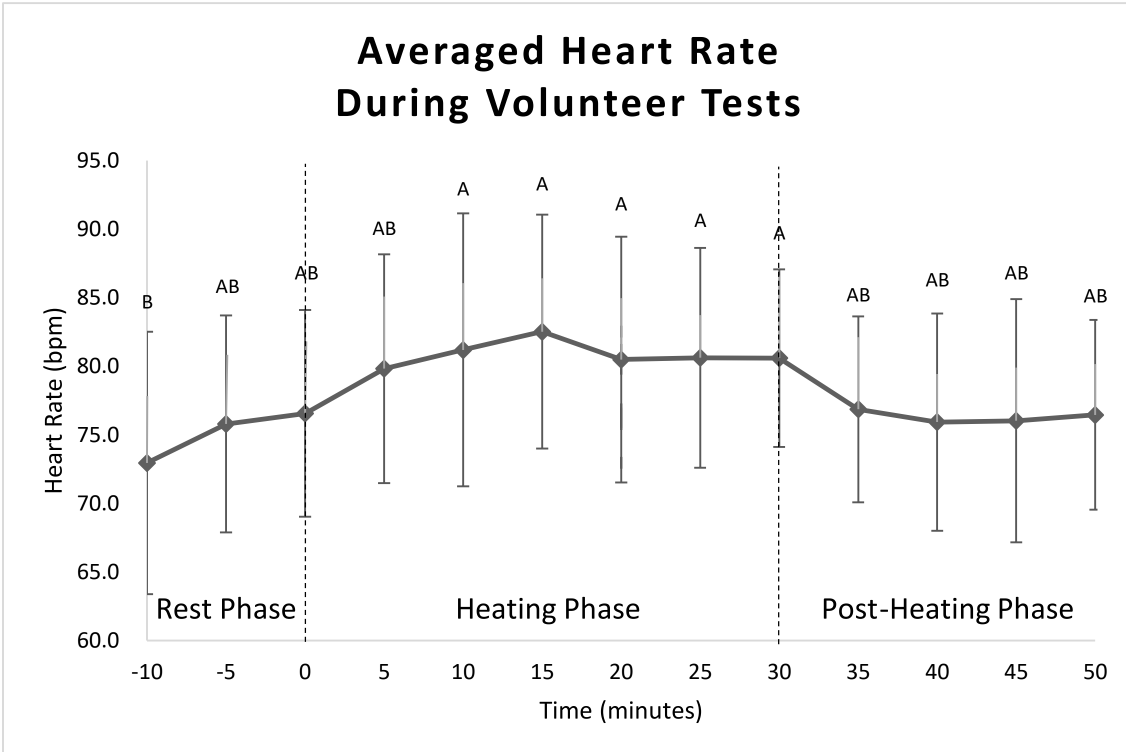


Figure 6-5 Averaged heart rate during volunteer tests
(Spreadsheets automatically join points by lines)

6.4.3.3 Comparison Between Males and Females

Heart rate data were grouped by gender, and overall analysis was applied to each group. The changes between male and female volunteers were compared (shown in Table 6-11). Though average heart rate level of females was higher than the level of males, the increment induced by heating was about the same. Whereas, the average decrease in heart rate observed on males in post-heating phase was approximately twice larger than the decrease of females on average.

Table 6-11 Comparison of heart rate change between two genders during volunteer tests

	Female		Male	
	Mean (bpm)	**SD**	**Mean (bpm)**	**SD**
First Record (at -10th minute)	75.3	2.677	70.6	0.434
Increase Induced by Heating	9.9	(N/A)	9.3	(N/A)
Maximal Record in Heating Phase	85.2	3.280	79.9	11.630
Decrease After Heating	4.3	(N/A)	7.8	(N/A)
Last Record (at 50th minute)	80.9	2.456	72.1	7.293

6.4.4 Impact on the Systolic Blood Pressure

6.4.4.1 Individual Analysis

Variations in systolic blood pressure during tests for each volunteer were shown in Figure 6-6. At rest, no significant change was observed except volunteer No.3, whose systolic blood pressure increased without heating.

A coincidental decrease was found on all volunteers during the early heating phase (0th-15th minute). However, there was an increase of about 5 mmHg followed. The rise of systolic blood pressure represents the effect of body's blood pressure regulation mechanism was triggered. Then another drop was observed near the end of heating phase.

During the post-heating phase, an increase in systolic pressure were found on nine volunteers, and the level observed at rest was re-established.

Table 6-12 shows the comparison of changes between phases. It was found in 9 volunteers that a drop in systolic blood pressure induced by heating was 5 to 13 mmHg and the re-increase after heating was 2 to 9 mmHg. The last records (at 50th minute) are similar but not higher than the initial values measured at -10th minute. This could be due to the continuous impact of heating.

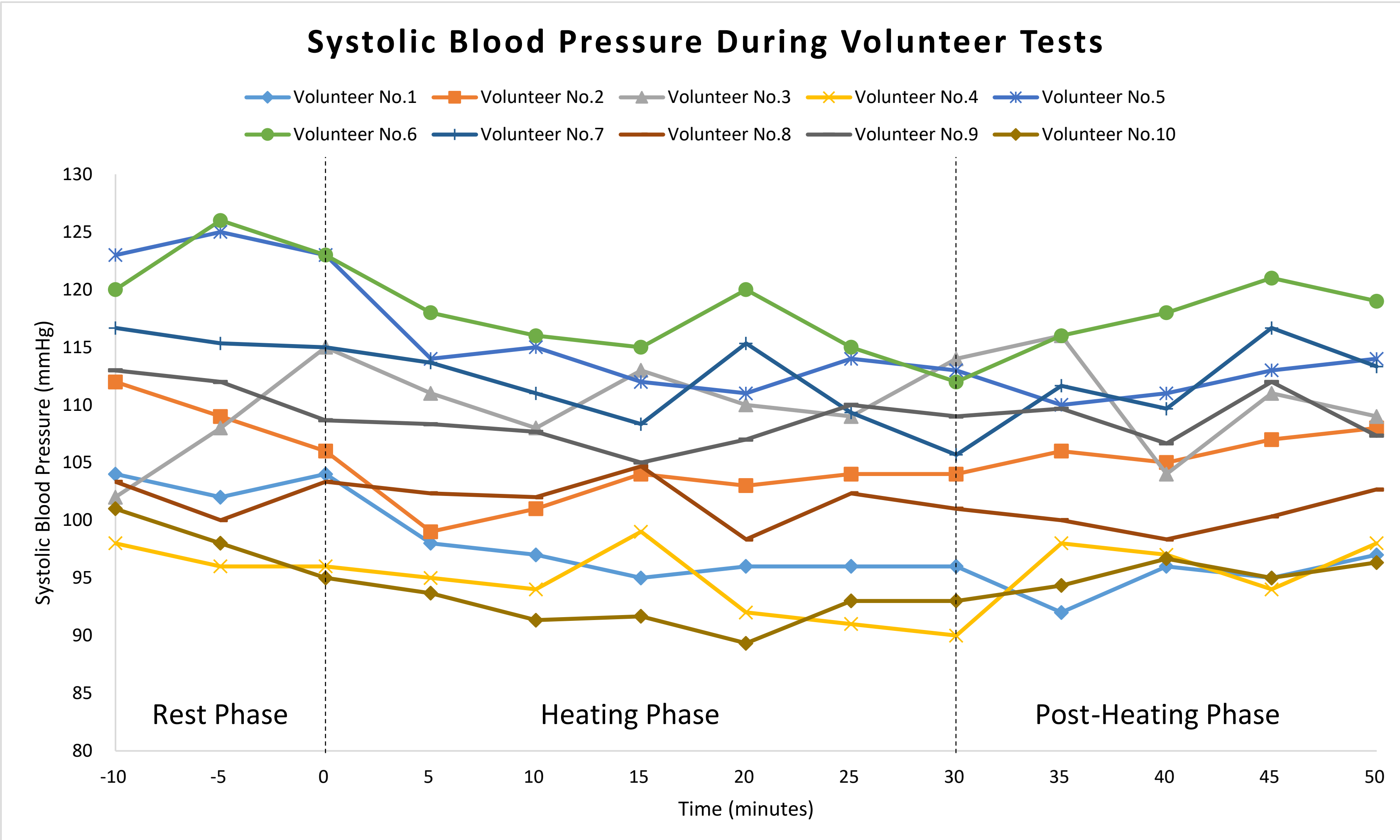


Figure 6-6 Systolic blood pressure of each individual during volunteer tests
(Spreadsheets automatically join points by lines)

Table 6-12 Individual analysis of systolic blood pressure change during volunteer tests (mmHg)

Volunteers' No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
First Record (at -10th minute)	104	112	102	98	123	120	117	103	113	101
Decrease Induced by Heating	11	13	-6*	8	14	8	11	5	8	12
Minimal Record in Heating Phase	95	99	108	90	111	112	106	98	105	89
Increase After Heating	2	9	1	8	3	7	8	4	2	7
Last Record (at 50th minute)	97	108	109	98	114	119	113	103	107	96

* there was an increase observed on Volunteer No.3 during the heating phase.

6.4.4.2 Overall Analysis

Figure 6-4 plots average values of systolic blood pressures at each recording time. The decrease-then-increase pattern of changes is noticeable but insignificant. The representative records for three phases were averaged and shown in Table 6-13. It was seen that an average decrease of systolic blood pressure induced by heating was only 5.5 mmHg, and the mean increase during the post-heating phase was 2.7 mmHg. Both these results were not significant.

6.4.4.3 Comparison Between Males and Females

Separate overall analyses for the systolic blood pressure of male and female volunteers were conducted, and the comparison between two genders is shown in Table 6-14. Though the average systolic pressure of males was higher than that of females, the induced decrease was similar. But during the post heating phase, the average re-increase of male systolic blood pressures was only about half of the average for female volunteers.

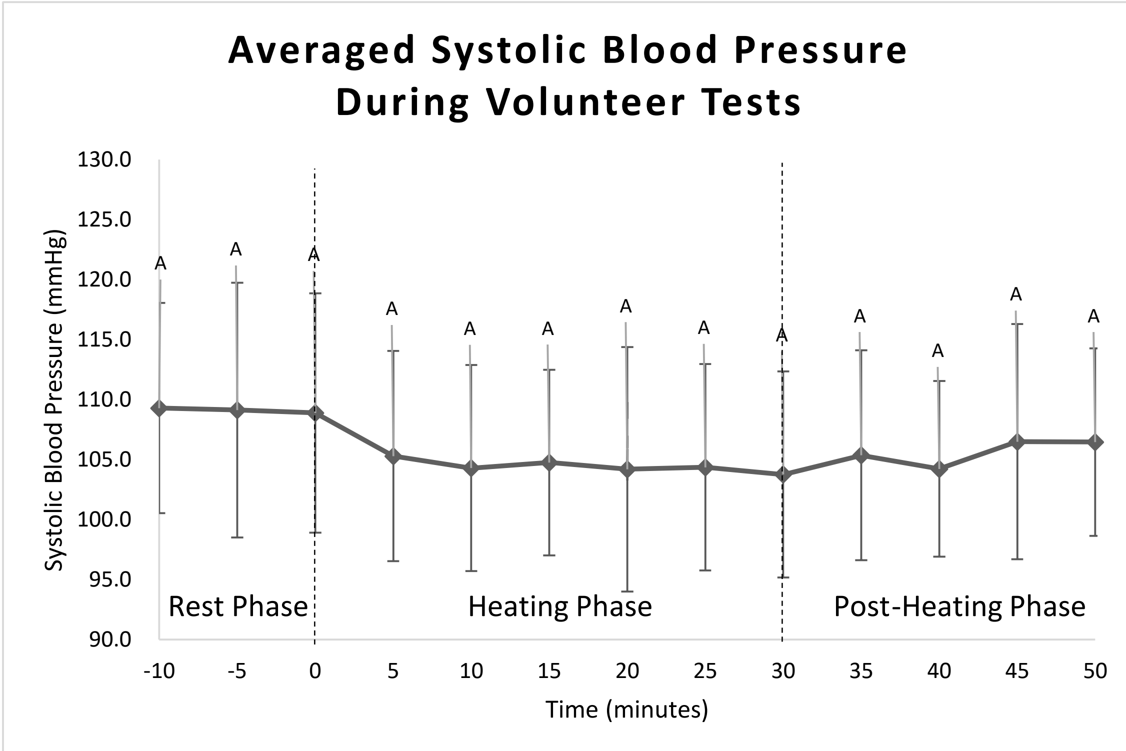


Figure 6-7 Averaged systolic blood pressure during volunteer tests (Spreadsheets automatically join points by lines)

Table 6-13 Overall analysis of systolic blood pressure change during volunteer tests (Overall *P*=0.9084)

Items	Mean (mmHg)	Significance
First Record (at -10th minute)	109.3	A
Decrease Induced by Heating	5.5	*P*=0.1724
Minimal Record in Heating Phase	103.8	A
Increase After Heating	2.7	*P*=0.5176
Last Record (at 50th minute)	106.5	A

Table 6-14 Comparison of systolic blood pressure change between two genders during volunteer tests

	Female		Male	
	Mean (mmHg)	**SD**	**Mean (mmHg)**	**SD**
First Record (at -10th minute)	104.6	7.143	116.0	8.803
Decrease Induced by Heating	7.5	(N/A)	6.5	(N/A)
Minimal Record in Heating Phase	97.1	6.265	109.5	6.131
Increase After Heating	4.4	(N/A)	2	(N/A)
Last Record (at 50th minute)	101.5	7.081	111.5	4.959

6.4.5 Impact on the Diastolic Blood Pressure

6.4.5.1 Individual Analysis

The fluctuations in diastolic blood pressure were found to resemble those in systolic pressure, as shown in Figure 6-8. After heating began, there was an observed decrease in diastolic pressure on every volunteer followed by a small increase. During the post-heating phase, the diastolic blood pressure remained relatively low, as seen on six of ten individuals.

The differences between test phases were compared and listed in Table 6-15. The drop in the diastolic blood pressure induced by heating was 3 to 18 mmHg, and the changes observed during the post-heating phase were -2 to 12 mmHg. The variations in diastolic pressure after heating had no obvious regularity for all volunteers.

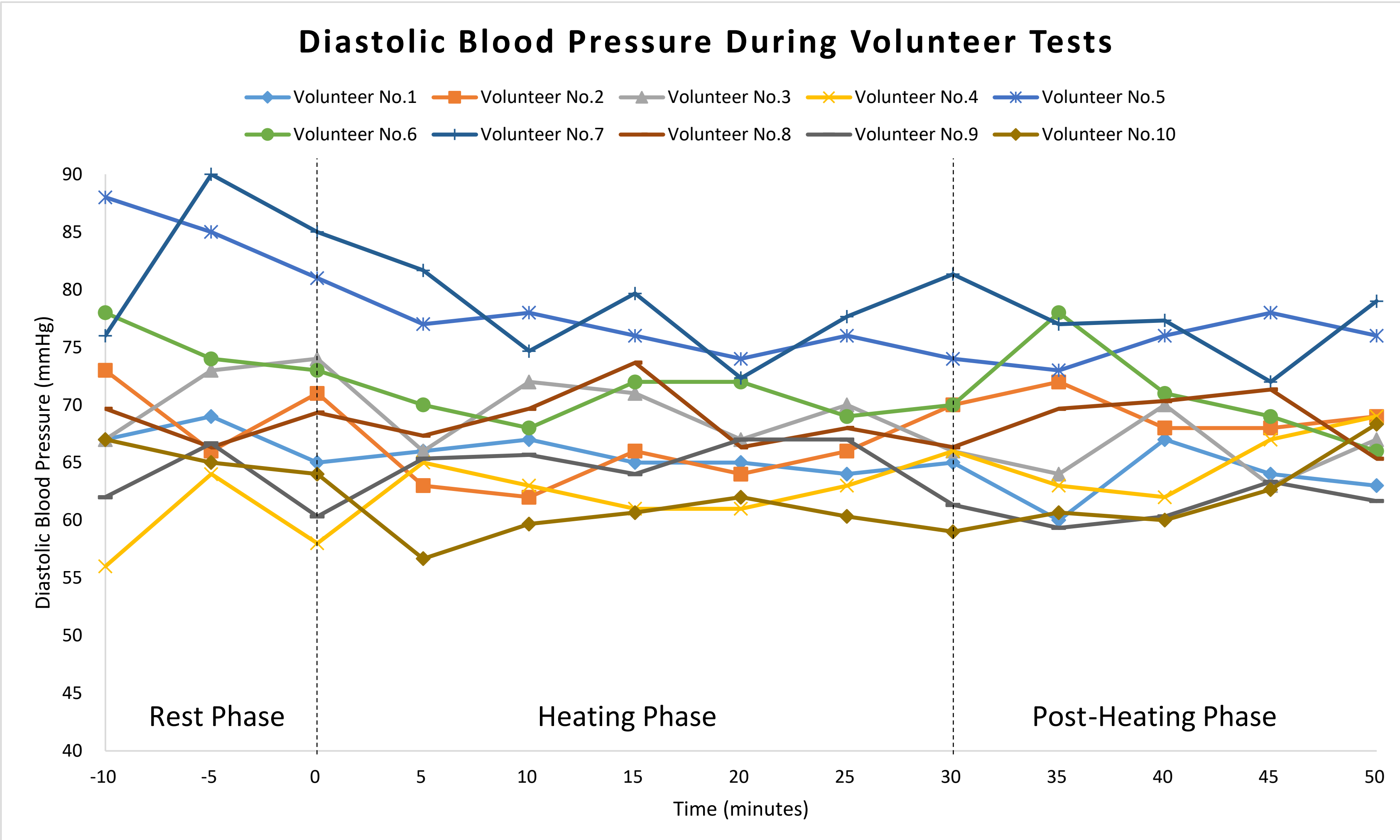


Figure 6-8 Diastolic blood pressure of each individual during volunteer tests
(Spreadsheets automatically join points by lines)

Table 6-15 Individual analysis of diastolic blood pressure change during volunteer's tests (mmHg)

Volunteers' No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
First Record (at -10th minute)	67	73	67	56	88	78	76	70	62	67
Decrease Induced by Heating	3	11	1	2	14	10	4	4	2	10
Minimal Record in Heating Phase	64	62	66	58	74	68	72	66	60	57
Increase After Heating	-1*	7	1	11	2	-2*	7	-1*	1	12
Last Record (at 50th minute)	63	69	67	69	76	66	79	65	62	68

* there was an decrease observed on Volunteer No.1, No.6 and No.8 during the post-heating phase.

6.4.5.2 Overall Analysis

Heating reduced diastolic blood pressure reduced by 3.3 mmHg on average. A *P*-value of 0.2624 suggests this change is not significant. Besides, there were no visible changes during the post-heating phase. These results are shown in Table 6-16 and Figure 6-9.

Table 6-16 Overall analysis of diastolic blood pressure change during volunteer tests (Overall *P*=0.9580)

Items	Mean (mmHg)	Significance
First Record (at -10th minute)	70.4	A
Decrease Induced by Heating	3.3	*P*=0.2624
Minimal Record in Heating Phase	67.1	A
Increase After Heating	1.3	*P*=0.6437
Last Record (at 50th minute)	68.4	A

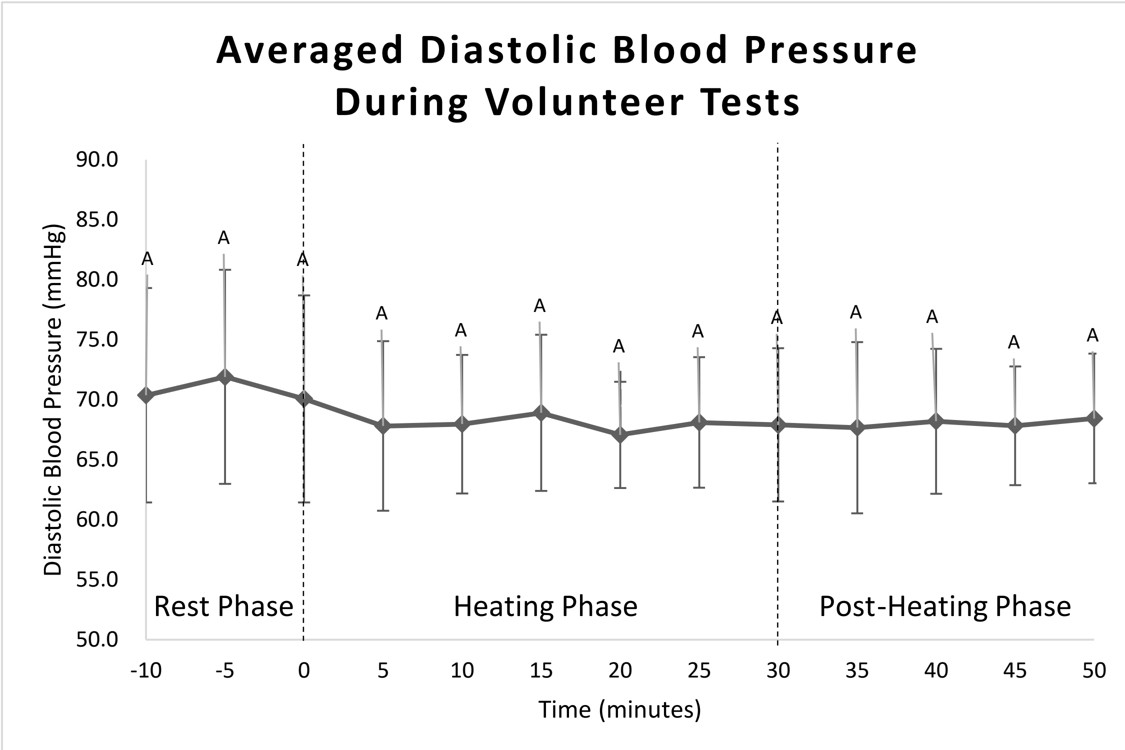


Figure 6-9 Averaged systolic blood pressure during volunteer tests
(Spreadsheets automatically join points by lines)

6.4.5.3 Comparison Between Males and Females

As shown in Table 6-17, the first, lowest and the last records of diastolic blood pressure for all volunteers were averaged separately by gender. The female mean diastolic pressure was slightly lower than the male diastolic pressure, and the induced decrease by heating was almost identical (5.6 mmHg versus. 5.3 mmHg). However, the average change during the post-heating phase for female volunteers was 3.6 mmHg, while the average for males was only 0.4 mmHg.

Table 6-17 Comparison of diastolic blood pressure changes between two genders during volunteer's tests

	Female		Male	
	Mean (mmHg)	SD	Mean (mmHg)	SD
First Record (at -10th minute)	70.9	10.859	73.6	10.065
Decrease Induced by Heating	5.6	(N/A)	5.3	(N/A)
Minimal Record in Heating Phase	65.3	4.472	68.3	4.087
Increase After Heating	3.6	(N/A)	0.4	(N/A)
Last Record (at 50th minute)	68.9	6.121	67.9	5.246

6.5 Discussion

The use of the EHV has been observed to induce an average increase of 0.3°C in the core body temperature ($P<0.05$), and an increase of 9.5 bpm in heart rate ($P<0.05$). Though fluctuations in the systolic blood pressure were not significant, there was still a noticeable drop of 5.5 mmHg on average. Similarly, the diastolic blood pressure reduced by 4.8 mmHg on average, which is not significant but evident. These results are summarized in Table 6-18.

Table 6-18 Summary of average results during volunteer tests

	Core Body Temperature Change (°C)	Heart Rate Change (bpm)	Systolic Blood Pressure Change (mmHg)	Diastolic Blood Pressure Change (mmHg)
Changes Induced by Heating*	+ 0.3 (Significant)	+ 9.5 (Significant)	- 5.5 (Not Significant)	-3.3 (Not Significant)
Changes After Heating*	0	- 6 (Not Significant)	+2.7 (Not Significant)	+ 1.3 (Not Significant)

* '+': an increase and '-': a decrease.

A comparison of the test results between female and male volunteers was listed in Table 6-19. The average increase in the core body temperature of males was more than twice the average of females, but the increase in heart rate and reduction in systolic and diastolic blood pressure were about the same. Regarding the post-heating phase, the average re-increase in heart rate for males was higher than the female's, while the rise in systolic and diastolic pressure for males was much less than for females on average.

In conclusion, there is no special difference for the heat-induced impacts between males and females, on core body temperature, heart rate, systolic and diastolic blood pressure during the tests. But the consumed time for recovery from the impacted levels to normal range observed before heating is different for parameters such as heart rate, systolic and diastolic blood pressure.

Table 6-19 Comparison of average results between two genders during volunteer tests

	Core Body Temperature Change (°C)		**Heart Rate Change (bpm)**		**Systolic Blood Pressure Change (mmHg)**		**Diastolic Blood Pressure Change (mmHg)**	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Changes Induced by Heating*	+ 0.2	+0.5	+ 9.9	+ 9.3	- 7.5	- 6.5	- 5.6	- 5.3
Changes After Heating*	0	0	- 4.3	- 7.8	+ 4.4	+ 2	+ 3.6	+ 0.4

* '+': an increase and '-': a decrease.

6.6 Comparison with Previous Water Heating Vest

Robert, A. designed a water heating vest (WHV) for thermal therapy in 2010 and he also conducted a pilot study on five healthy human volunteers [32]. The configurations of current study for the EHV and the Robert's pilot study are listed in Table 6-20.

Table 6-20 Comparison between configurations of current study for the electrical heating vest and the Robert, A.'s pilot study for the water heating vest [32]

	Current EHV	WHV by Robert, A. [32]
Heating Medium	Resistive Carbon Fibers	Water
Set Temperature for the Heating Medium	45°C	65°C
Duration of Heating Phase	30 minutes	40 minutes
Power Supply	Lithium-ion Batteries (12V)	Electricity System (110V)
Energy Consumption	Approximately 100 W·h	Approximately 375 W·h
Test Population	10 healthy volunteers	5 male healthy volunteers

The average physiological changes in parameters such as core body temperature, heart rate, systolic and diastolic blood pressure, induced by current EHV and Robert's WHV, were shown in Table 6-21.

On average, the current EHV can induce a 0.1°C greater increase in core body temperature compared to changes observed with the WHV. Whereas, the EHV consumed less energy and the heating media maintained at a lower temperature, which may explain the less fluctuations in heart rate. The users can benefit from less heat stress with the EHV, compared to the effects with the WHV. Except the differences of changes in core temperature and heart rate, the variations in systolic and diastolic blood pressure were similar for both heating vests. In conclusion, the EHV is safer and more acceptable for heart failure and/or hypertension patients.

Table 6-21 Comparison of physiology changes observed in current study and the Robert, A.'s pilot study for the water heating vest [32]

	Core Body Temperature Change (°C)		Heart Rate (bpm)		Systolic Blood Pressure (mmHg)		Diastolic Blood Pressure (mmHg)	
	EHV	**WHV**	**EHV**	**WHV**	**EHV**	**WHV**	**EHV**	**WHV**
Changes Induced by Heating*	+ 0.3	+ 0.2	+ 9.5	+ 40	- 5.5	- 8.8	- 4.8	-5.1
Changes After Heating*	0	- 0.2	- 6	- 33.6	+2.7	+ 4.4	+ 1.3	+1.4

* '+': an increase and '-': a decrease.

6.7 Theoretical Study Results versus. Volunteer Study Results

The results of healthy volunteer tests and the simulation results of theoretical study were not comparable. Firstly, the nominal maximal output power of the battery (120W) cannot be reached in tests due to the battery's protective circuit to avoid overheating and overcurrent conditions. In the functional test, the observed output power of the battery was only approximately 80W.

Meanwhile, the electrical energy cannot be completely transferred to heat energy, whereas the simulation assumed the heat power absorbed by the body was equal to the output power of the battery. Moreover, the heat loss during the heating process was also ignored in the theoretical model, which can partly explain the differences between simulation results and practical observations.

Additionally, the simulation study found a general estimate of the minimal power to increase the core temperature by 0.5°C is 145W. The EHV with the power supply of 120W induced an average increase of 0.3°C, which indicates that the result of the simulation is acceptable.

6.8 Potential Effectiveness of an EHV for Heart Failure and/or Hypertension

Heart failure and/or hypertension can be improved by increasing the core body temperature for a period of time. The potential pathways can be the sympathetic nervous activity, the heat shock protein, shear stress, and/or the tetrahydrobiopterin, which were discussed in Section 2.1.

According to the results of healthy volunteer tests, it can be hypothesized that hypertension patients will directly benefit from the induced drop of blood pressure by using the proposed EHV. Besides, the improvements may be also expressed as fluctuations of the stroke index, the vascular resistance and/or the ejection fraction, which were observed in literatures reviews related to thermal therapy for cardiovascular diseases [1]. Further studies are required to understand how the EHV can change those parameters above on patients with heart failure and hypertension and to determine the specification needed for the two types of patients. However, the design should be modified to be able to increase the core body temperature by around 1 °C for better effectiveness of treatments. It can be implemented by more powerful batteries, larger area of heating elements, and more efficient thermal insulation.

6.9 Summary

In the healthy human volunteer study, the physiological impacts of the EHV on five males and five females were observed, and the differences between individuals, test phases and genders were compared. It indicates that torso heating using the EHV can lead to a significant increase in core body temperature and heart rate. In addition, the observable drops of systolic and diastolic blood pressure suggest that the EHV can decrease the blood pressure even for healthy individuals and patients with heart failure and/or hypertension could possibly benefit from this device as well. Though the WHV designed by Robert, A. can achieve similar results [32], the current electrical heating solution is less irritant, more portable, more comfortable, smarter, and safer.

Chapter 7 Summary of Key Results

This section presents the key results of the theoretical study, system design and the subsequent in-vitro and healthy human volunteer tests.

7.1 Theoretical Study

a. Energy absorption rate larger than 340W in the torso alone can achieve an increase of 1°C in the core body temperature within 30 minutes.

b. The thermal power required with 30-minute torso heating to increase by 0.5°C is 145W.

c. Considering the safety and limitations of practical battery technology, the target was set to induce an increase in core temperature increase by 0.5°C.

d. The power supply of the EHV was determined as lithium-ion batteries which can continuously provide a current of 12.08A with a voltage of 12V and a capacity of 145W·h.

7.2 System Design

a. The heating system of the EHV was designed as four pads with carbon-fiber heating filaments.

b. The control system was developed on a single-chip microcontroller with temperature sensors, LED-array displays, relay switches, a keyboard, an infrared remote receiver, and a buzzer.

c. The software for temperature and timing controls was designed with hardware drivers, interrupt services and a multi-input/output temperature-control strategy.

d. The prototype of the EHV was assembled and consisted of heating system, control system, two lithium-polymer batteries, and a support belt.

7.3 In-Vitro Study

a. The functional tests on a manikin showed that heating pads could reach a temperature of 45°C in ten minutes. The control system can ensure that the pad temperature did not exceed the set threshold, and terminated heating when the set time transpired.

b. The results of safety tests proved that the EHV is safe in extreme conditions, such as a high-humidity environment and a temperature-control failure.

7.4 Healthy Volunteer's Study

a. On average, the EHV achieved increases in core body temperature of 0.3°C ($P<0.05$) and heart rate of 9.5 bpm ($P<0.05$) in 30 minutes.

b. The average decreases in systolic blood pressure of 5.5 mmHg and diastolic blood pressure of 4.8 mmHg.

7.5 Advantages and Disadvantages of the Proposed Design

The EHV is a device intended to heat the body. Though similar commercial products exist on the market, there purpose is mainly protection against cold environments. Therefore, they have relatively low heating capacity and there is an absence of precise temperature control.

The output power of the proposed EHV is 120W and it not only keeps the body warm but also increases the core body temperature by around 0.3°C in 30 minutes. Meanwhile, the multi-sensor temperature controller makes the heating process safe and controllable. In addition, the whole EHV is portable, washable and lightweight due to the use of carbon-fiber heating materials, high-density lithium-ion batteries and a control system based on a micro-controller.

However, the output power of the battery is still incapable of increasing the core body temperature by over 0.5°C in 30 minutes, which is the most critical disadvantage of this design. Meanwhile, in order to commercialize the EHV, the design should be miniaturized and the appearance of the product should be more aesthetic.

Chapter 8 Conclusion

In this research, a carbon-fiber electrical-heating vest was developed and tested to determine if it can be a potential means of thermal therapy for heart failure and/or hypertension patients. No other study of this kind was found in the literature.

a. It was demonstrated that the vest can increase core body temperature by around 0.3°C within 30 minutes.

b. It was also demonstrated that an increase in core body temperature can induce physiological changes such as heart rate, systolic and diastolic blood pressure.

c. These results suggest that the vest could potentially be a viable alternative method for reduction of blood pressure of hypertension patients and may be also potentially tested for heart failure patients.

8.1 Future Directions

Further research should focus on miniaturizing the device, enhancing thermal performance, and verifying the observed results on heart failure and/or hypertension patients in clinical trials. It would also be valuable to investigate the potential induced short or long-term improvements of physiological parameters related to cardiovascular conditions such as vascular resistance, ejection fraction and cardiac index.

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Appendix 1 Theoretical Matlab® Model

1. Main Script for Scanning the Power Range

```
clear all;
Label = 'Heat the Torso Only';
Plot = 'k';
Save = 'n';
%Power = 1:500;
Test = 6;
Temperature = zeros;
Power_0_5 = zeros;
Power_1 = zeros;
n=1;m=1;
for i=1:500
[ Temperature(i,1:7) ] = Model( Label, Plot, Save, i, Test);
if (max(Temperature(i,:))-(36.2+0.5)>0)
Power_0_5(n) = i;
n=n+1;
if (max(Temperature(i,:))-(36.2+1.0)>0)
Power_1(m)=i;
m=m+1;
%break;
end;
end;
end;
disp('Power for 0.5 C =');
disp(Power_0_5(1));
disp('Power for   1 C =');
disp(Power_1(1));
run('d:\SkyDrive\Simulations\Thesis\Plotting.m');
```

2. Modeling and Simulation Function

```
function [ TB ] = Model( TestLabel, PlotType, PlotSave, HeatSupply, TestNum )

if HeatSupply<10
    Temp_Pad = 25;
elseif HeatSupply<50
    Temp_Pad = 35;
elseif HeatSupply<100
    Temp_Pad = 40;
else
        Temp_Pad = 45;
    end;
    %----------------------------------------------------------------------
    %Settings
    %----------------------------------------------------------------------
    Coeff_HeatTransfer=zeros;
    TB(1) = 36.2;
    HeatProd_meta_Layer=zeros;
    Flow_Blood_Layer=zeros;
    HeatLoss_Evap_Layer=zeros;
    MaxEvapRate=zeros;
    HeatTransfer_Conv_CentralBlood=zeros;
    HeatTransferRate_Cond=zeros;
    HeatLossRateA=zeros;
    HeatLossRateE=zeros;
    CO=zeros;
    HP=zeros;
    EV=zeros;
    TS=zeros;
    HFLOW=zeros;
    SBF=zeros;
    HeatSupply_Skin=zeros;
    %----------------------------------------------------------------------
```

```
%PARAMETERS
%-----------------------------------------------------------------
Segment_Name        = {'Head'  'Trunk' 'Arms' '  Hands'  'Legs' 'Feet'};
Segment_SurfArea     = [0.1326  0.6804   0.2536   0.0946  0.5966 0.1299];
Frac_SkinReceptor    = [0.21    0.42,    0.1      0.04    0.2 0.03  ];
Frac_SkinSweat       = [0.081   0.481    0.154    0.031   0.218 0.035 ];
Frac_SkinDil     = [0.132   0.322    0.095    0.121   0.23 0.1   ];
Frac_SkinCons    = [0.01    0.05     0.19     0.2     0.2 0.35  ];
Frac_MuscleShiver    = [0.02    0.85     0.05     0       0.07 0     ];
Coeff_RadHeatTransfer= [4.8     4.8      4.2      3.6     4.2 4     ];
Coeff_ConvHeatTransfer=[3       2.1      2.1      4       2.1 4     ];

Segment_Layer       = {'head_core'; 'head_muscle'; 'head_fat'; 'head_skin';
'trunk_core';'trunk_muscle';'trunk_fat';'trunk_skin';
                        'arms_core'; 'arms_muscle'; 'arms_fat'; 'arms_skin';
'hands_core';'hands_muscle';'hands_fat';'hands_skin';
                        'legs_core'; 'legs_muscle'; 'legs_fat'; 'legs_skin';
                        'feet_core'; 'feet_muscle'; 'feet_fat'; 'feet_skin';'blood_core'};
Heat_Cap_Layer           = [2.57  0.39  0.26  0.28  11.44 18.8 4.94  1.41  1.64  3.54  0.67  0.5   0.15  0.7   0.1   0.2   4.93 10.67 1.66  1.25  0.27  0.07  0.15  0.26  2.6 ];
HeatProd_BasalMeta_Layer  = [14.95 0.12  0.13  0.1   52.63 5.81
```

```
    2.49  0.47  0.82  1.11  0.21  0.15  0.09  0.23  0.04  0.06  2.59  3.32
    0.5   0.37  0.15  0.02  0.05  0.08  0];
HeatLoss_BasalEvap_Layer  = [0     0     0     0.81  10.45 0     0
    3.78  0     0     0     1.4   0     0     0     0.52  0     0     0
    3.32  0     0     0     0.72  0 ];
Flow_BasalBlood_Layer     = [45    0.12  0.13  1.44  210   6
    2.56  2.1   0.84  1.14  0.2   0.5   0.1   0.24  0.04  2     2.69  3.43
    0.52  2.85  0.16  0.02  0.05  3     0];
ThermalConductance_Layer  = [1.61  13.25 16.1  0     1.59  5.53
    23.08 0     1.4   10.3  30.5  0     6.4   11.2  11.5  0     10.5  14.4
    74.5  0     16.3  20.6  16.4  0     0];
Temp_SetReceptor_Layer    = [36.96 35.07 34.81 34.58 36.89
    36.28 34.53 33.62 35.53 34.12 33.59 33.25 35.41 35.38 35.3  35.22
    35.81 35.3  35.31 34.1  35.14 35.03 35.11 35.04 36.71];
Temp_Layer                = [36.96 35.07 34.81 34.58 36.89 36.28
    34.53 33.62 35.53 34.12 33.59 33.25 35.41 35.38 35.3  35.22 35.81
    35.3  35.31 34.1  35.14 35.03 35.11 35.04 36.71];
RateTempChange_Layer      = [0     0     0     0     0     0     0
    0     0     0     0     0     0     0     0     0     0     0     0     0
    0     0     0     0     0];
FlowRate                  = [0     0     0     0     0     0     0
    0     0     0     0     0     0     0     0     0     0     0     0     0
    0     0     0     0     0];

Time_Interval             = [ 5   5   5   5   5   5   5   5   5   5
    5   5   5   5   5];
Temp_Air                  = [25  25  25  25  25  25  25  25  25  25
    25  25  25  25  25]; %3rd should be 45
Velocity_Air              = [0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
    0.1 0.1 0.1 0.1 0.1 0.1];
RelHumidity_Air           = [0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3
    0.3 0.3 0.3 0.3 0.3 0.3];

VaporPressure_LookUp      = [6.541 9.205 12.78 17.51 23.69 31.71
    42.02 55.13 71.66 92.3 120];
Coeff_HeadCoreSweat       = 372;
Coeff_SkinSweat           = 33.7;

```

```
Coeff_HeadCoreDil     = 136;
Coeff_SkinDil        = 17;

Coeff_HeadCoreCons    = 10.8;
Coeff_SkinCons       = 10.8;

Coeff_HeadCoreShiver     = 13;
Coeff_SkinShiver         = 0.4;
Coeff_TotalShiver        = 1;
o_time_vector             = 0;
Time_ElapsedInHour       = 0;
Time_ElapsedByNowInMin    = 0;
Temp_Garment = 32;

%----------------------------------------------------------------------
%Calculate the Total Surface Area
%----------------------------------------------------------------------
TotalSurfaceArea = sum(Segment_SurfArea);
%----------------------------------------------------------------------
%Initialization the Simulation
%----------------------------------------------------------------------
TESTCOUNT    = 1;
SIMDATACOUNT = 1;
%----------------------------------------------------------------------
%Test Loop
%----------------------------------------------------------------------
while TESTCOUNT <= TestNum
%0. Initialization the New Test
    %No need to calculate the internal work performed due to sit still
    %condition
%0.1. Heat Transfer Coefficients for Each Segment (Radiant and
```

```
Convective)
      for i=1:6
          Coeff_HeatTransfer(i) = (Coeff_RadHeatTransfer(i)+3.16*Coeff_ConvHeatTransfer(i)*sqrt(Velocity_Air(TESTCOUNT)))*Segment_SurfArea(i);
      end;
  %0.2. Air Pressure based on the Air Temperature
      Index = round(Temp_Air(TESTCOUNT)/5);
      Pres_Vapor = RelHumidity_Air(TESTCOUNT)*(VaporPressure_LookUp(Index)+(VaporPressure_LookUp(Index+1)-VaporPressure_LookUp(Index))*(Temp_Air(TESTCOUNT)-5*Index)/5);
  %0.3 Run the Simulations
      SIMCOUNT=0;
  %1.0 -------------------Simulation Loop----------------------------------
      while SIMCOUNT<5
          % 1.1. Thermoreceptor outputs
          Cold_Layer = zeros(1,25);
          Warm_Layer = zeros(1,25);
          Error_Receptor = Temp_Layer-Temp_SetReceptor_Layer;
          for i=1:25
              if (Error_Receptor(i)<0)
                  Cold_Layer(i) = -Error_Receptor(i);
              end;
              if (Error_Receptor(i)>0)
                  Warm_Layer(i) = Error_Receptor(i);
              end;
          end;

          %1.2. Integrate peripheral Afferents
          Cold = 0;
          Warm = 0;
          for i=1:6; %Selecting the Skin layers
              Warm = Warm + Warm_Layer(i*4) * Frac_SkinReceptor(i);
              Cold = Cold + Cold_Layer(i*4) * Frac_SkinReceptor(i);
          end;
```

```
        %1.3. Determine efferent outflow
        Sweat = Coeff_HeadCoreSweat *Error_Receptor(1)+Coeff_SkinSweat*(Warm-Cold);
        Dilat = Coeff_HeadCoreDil *Error_Receptor(1)+Coeff_SkinDil*(Warm-Cold);
        Cons  = -Coeff_HeadCoreCons *Error_Receptor(1)+Coeff_SkinCons*(Cold-Warm);
        %Shiver =-Coeff_HeadCoreShiver*Error_Receptor(1)+Coeff_SkinShiver*(Cold-Warm)+Coeff_TotalShiver*Cold*Cold_Layer(1);
        Shiver=(Coeff_HeadCoreShiver*Error_Receptor(1)+Coeff_SkinShiver*(Cold-Warm))*Coeff_TotalShiver*(Warm-Cold);
        if (Sweat<=0)
            Sweat = 0;
        end;
        if (Dilat<=0)
            Dilat = 0;
        end;
        if (Cons<=0)
            Cons = 0;
        end;
        if (Shiver<=0)
            Shiver = 0;
        end;

        %1.4. Assign effector outputs
        %Heating only for the torso

        for i=1:6
            if (i==2) % && TESTCOUNT>2 && TESTCOUNT<9)
                HeatSupply_Skin(i) = HeatSupply;
            else
                HeatSupply_Skin(i) = 0;
            end;
            layer = 4*i-3;
            %Core
            HeatProd_meta_Layer(layer) =
```

```
HeatProd_BasalMeta_Layer(layer);
            Flow_Blood_Layer(layer)= Flow_BasalBlood_Layer(layer);
            HeatLoss_Evap_Layer(layer) = HeatLoss_BasalEvap_Layer(layer);
            %Muscle
            HeatProd_meta_Layer(layer+1) = HeatProd_BasalMeta_Layer(layer+1)+Frac_MuscleShiver(i)*Shiver;
            Flow_Blood_Layer(layer+1)= Flow_BasalBlood_Layer(layer+1)+Frac_MuscleShiver(i)*Shiver;
            HeatLoss_Evap_Layer(layer+1) = 0;
            %Fat
            HeatProd_meta_Layer(layer+2) = HeatProd_BasalMeta_Layer(layer+2);
            Flow_Blood_Layer(layer+2)= Flow_BasalBlood_Layer(layer+2);
            HeatLoss_Evap_Layer(layer+2) = 0;
            %Skin
            HeatProd_meta_Layer(layer+3) = HeatProd_BasalMeta_Layer(layer+3)+HeatSupply_Skin(i);
            Flow_Blood_Layer(layer+3)= ((Flow_BasalBlood_Layer(layer+3)+Frac_SkinDil(i)*Dilat)/(1+Frac_SkinCons(i)*Cons))*power(2,(Error_Receptor(layer+3)/10));
            HeatLoss_Evap_Layer(layer+3) = (HeatLoss_BasalEvap_Layer(layer+3)+Frac_SkinSweat(i)*Sweat)*power(2,((Temp_Layer(layer+3)-Temp_SetReceptor_Layer(layer+3))/10));
            k = round(Temp_Layer(layer+3)/5);
            if (k==0)
                k=1;
            end
            Pres_Skin = VaporPressure_LookUp(k)+(VaporPressure_LookUp(k+1)-VaporPressure_LookUp(k))*(Temp_Layer(layer+3)-5*k)/5;
            MaxEvapRate(i) = (Pres_Skin-Pres_Vapor)*2.14*(Coeff_HeatTransfer(i)-Coeff_RadHeatTransfer(i)*Segment_SurfArea(i));
            if (HeatLoss_Evap_Layer(layer+3)>MaxEvapRate(i))
                HeatLoss_Evap_Layer(layer+3)=MaxEvapRate(i);
```

```
            end;
        end

        %1.5. Calculate the heat flow
        for i=1:24
            HeatTransfer_Conv_CentralBlood(i) = Flow_Blood_Layer(i)*(Temp_Layer(i)-Temp_Layer(25));
            HeatTransferRate_Cond(i) = ThermalConductance_Layer(i)*(Temp_Layer(i)-Temp_Layer(i+1));
        end
        for i=1:6
            k=4*i-3;
            %Core
            FlowRate(k) = HeatProd_meta_Layer(k)-HeatLoss_Evap_Layer(k)-HeatTransfer_Conv_CentralBlood(k)-HeatTransferRate_Cond(k);
            %Muscle
            FlowRate(k+1) = HeatProd_meta_Layer(k+1)-HeatTransfer_Conv_CentralBlood(k+1)+HeatTransferRate_Cond(k)-HeatTransferRate_Cond(k+1);
            %Fat
            FlowRate(k+2) = HeatProd_meta_Layer(k+2)-HeatTransfer_Conv_CentralBlood(k+2)+HeatTransferRate_Cond(k+1)-HeatTransferRate_Cond(k+2);
            %Skin
            HeatLossRateE(k+3) = HeatLoss_Evap_Layer(k+3);
            if (i==1||i==4)
                FlowRate(k+3) = HeatProd_meta_Layer(k+3)-HeatTransfer_Conv_CentralBlood(k+3)-HeatLoss_Evap_Layer(k+3)+HeatTransferRate_Cond(k+2)-Coeff_HeatTransfer(i)*(Temp_Layer(k+3)-Temp_Air(TESTCOUNT));
                HeatLossRateA(k+3) = Coeff_HeatTransfer(i)*(Temp_Layer(k+3)-Temp_Air(TESTCOUNT));
            end;
            if (i==2)
                FlowRate(k+3) = HeatProd_meta_Layer(k+3)-HeatTransfer_Conv_CentralBlood(k+3)-HeatLoss_Evap_Layer(k+3)+HeatTransferRate_Cond(k+2)-Coeff_HeatTransfer(i)*(Temp_Layer(k+3)-Temp_Pad);
```

```
                HeatLossRateA(k+3) = Coeff_HeatTransfer(i)*(Temp_Layer(k+3)-Temp_Pad);
            end;
            if (i==3||i==5||i==6)
                FlowRate(k+3) = HeatProd_meta_Layer(k+3)-HeatTransfer_Conv_CentralBlood(k+3)-HeatLoss_Evap_Layer(k+3)+HeatTransferRate_Cond(k+2)-Coeff_HeatTransfer(i)*(Temp_Layer(k+3)-Temp_Garment);
                HeatLossRateA(k+3) = Coeff_HeatTransfer(i)*(Temp_Layer(k+3)-Temp_Garment);
            end;
        end;
        for i=1:24
            FlowRate(25) = FlowRate(25)+HeatTransfer_Conv_CentralBlood(i);
        end;

        %Determine the optimum integration step
        IntergralStepInHour = 0.0166666667;
        for i=1:25
            RateTempChange_Layer(i) = FlowRate(i)/Heat_Cap_Layer(i);
            U=abs(RateTempChange_Layer(i));
            if ((U*IntergralStepInHour-0.1)>0)
                IntergralStepInHour = 0.1/U;
            end;
        end;

        %1.7. Calculate the new temperature
        HeatLossA = 0;
        HeatLossE = 0;
        for i=1:6
            k=i*4-3;
            HeatLossA = HeatLossA+HeatLossRateA(k+3);
            HeatLossE = HeatLossE+HeatLossRateE(k+3);
        end;
        HeatLossA = HeatLossA/TotalSurfaceArea;
        HeatLossE = HeatLossE/TotalSurfaceArea;
```

```
        for i=1:25
Temp_Layer(i)=Temp_Layer(i)+RateTempChange_Layer(i)*IntergralStepInHour;
        end;

        %1.8. Calculate the experimental time
        Time_ElapsedInHour = Time_ElapsedInHour+IntergralStepInHour;
        Time_ElapsedInMin = 60*Time_ElapsedInHour;
        %--Store temperatures and time for plotting
        if (o_time_vector==0)
            NextTimeVectorPos = 1;
        else
            NextTimeVectorPos = size(o_time_vector,2)+1;
        end;
        o_time_vector(NextTimeVectorPos) = Time_ElapsedInMin;
        o_temperatures_array1(NextTimeVectorPos,:) = Temp_Layer;
        o_heatLoss_vectorA(NextTimeVectorPos,:) = HeatLossA;
        o_heatLoss_vectorE(NextTimeVectorPos,:) = HeatLossE;

        %1.9. Prepare for updating simulation
        %----Check if duration of current run has exceeded experiment time limit
        if ((Time_ElapsedInMin-Time_Interval(TESTCOUNT)-Time_ElapsedByNowInMin)<0)
            %Null
        else
            SIMDATACOUNT = SIMDATACOUNT+1;
            Time_ElapsedByNowInMin = Time_ElapsedByNowInMin+Time_Interval(TESTCOUNT);
            CO(SIMDATACOUNT) = 0;
            HP(SIMDATACOUNT) = 0;
            EV(SIMDATACOUNT) = 0;
            TS(SIMDATACOUNT) = 0;
            TB(SIMDATACOUNT) = 0;
            HFLOW(SIMDATACOUNT) = 0;
            SBF(SIMDATACOUNT)= 0;
```

```
                for i=1:24,
                    CO(SIMDATACOUNT) = CO(SIMDATACOUNT) + Flow_Blood_Layer(i)/60;
                    HP(SIMDATACOUNT) = HP(SIMDATACOUNT) + HeatProd_meta_Layer(i);
                    EV(SIMDATACOUNT) = EV(SIMDATACOUNT) + HeatLoss_Evap_Layer(i);
                end;
                for i=1:6,
                    SBF(SIMDATACOUNT) = SBF(SIMDATACOUNT) + Flow_Blood_Layer(4*i)/60;
                    TS(SIMDATACOUNT) = TS(SIMDATACOUNT) + Temp_Layer(4*i)*Heat_Cap_Layer(4*i)/3.90;
                end;
                for i=1:25,
                    TB(SIMDATACOUNT) = TB(SIMDATACOUNT)+ Temp_Layer(i)*Heat_Cap_Layer(i)/68.79;
                    HFLOW(SIMDATACOUNT) = HFLOW(SIMDATACOUNT)+FlowRate(i);
                end;
                HFLOW(SIMDATACOUNT) = HFLOW(SIMDATACOUNT)/TotalSurfaceArea;
                EV(SIMDATACOUNT) = EV(SIMDATACOUNT) /TotalSurfaceArea;
                HP(SIMDATACOUNT) = HP(SIMDATACOUNT)/TotalSurfaceArea;
                SIMCOUNT= SIMCOUNT + Time_Interval(TESTCOUNT);
            end;
        end;

        TESTCOUNT = TESTCOUNT +1;
    %----------------------------------------------------------------------
    %Perpare for Plotting and Updating Graphs
    %----------------------------------------------------------------------
        numDiffPlots = 24;

        if(PlotType == 'f')          %individual
```

```
        for i=1:1:numDiffPlots,
            handleFigure = figure (i+1);
            titleString = strcat(Segment_Layer(i),' Temperature versus Time :Test - ',TestLabel);
            layerString = strcat(Segment_Layer(i),' Test - ',TestLabel);
            set(handleFigure,'Name',char(layerString));
            plot(o_time_vector,o_temperatures_array1(:,i));
            xlabel('Time in minutes','FontSize',16);
            ylabel('Temperature','FontSize',16);
            title(titleString,'FontSize',16);
        end;
    elseif(PlotType == 'g') %grouped
        for i=1:1:numDiffPlots,
            graphNumber = floor((i-1)/4)+1;
            figureNumber = mod(i-1,4)+1;
            handleFigure = figure (graphNumber);
            titleString = strcat(Segment_Layer(i),' Temperature : Test -',TestLabel);
            handleString = strcat(Segment_Name(graphNumber),' Test - ',TestLabel);
            set(handleFigure,'Name',char(handleString));
            subplot(1,4,figureNumber);
            plot(o_time_vector,o_temperatures_array1(:,i));
            xlabel('Time(mins)','FontSize',10);
            ylabel('Temperature(oC)','FontSize',10);
            title(titleString,'FontSize',10);
        end;

    elseif(PlotType=='a') %all in subplots
        for i=1:1:numDiffPlots,
            handleFigure = figure (2);
            handleString = strcat(Segment_Layer(i),' ',TestLabel);
            set(handleFigure,'Name',char(handleString));
            titleString = strcat(Segment_Layer(i),' Test - ',TestLabel);
            subplot(6,4,i);
```

```
            plot(o_time_vector,o_temperatures_array1(:,i));
            title(titleString,'FontSize', 6);
        end;

    elseif(PlotType=='b') %all in one big plot
        numDiffPlots = 24;
        lineColor = ['k','b','g','y','m','c','r'];
        lineWidth = [3,3,2,2];
        %figure 1 - all
        handleFigure = figure (2);
        figureName= 'All Body';
        hold on;
        for i=1:1:numDiffPlots,
            if((mod(i-1,4)+1 == 2)||(mod(i-1,4)+1 == 4))
                plot(o_time_vector,o_temperatures_array1(:,i),'--','Color',lineColor(floor((i-1)/4)+1),'LineWidth',lineWidth(mod(i-1,4)+1));
            else
                plot(o_time_vector,o_temperatures_array1(:,i),'-','Color',lineColor(floor((i-1)/4)+1),'LineWidth',lineWidth(mod(1-1,4)+1));
            end;
        end;
        plot(o_time_vector,o_temperatures_array1(:,25),'-','Color',lineColor(floor((25-1)/4)+1),'LineWidth',lineWidth(mod(25-1,4)+1));
        hold off;
        titleString= strcat(figureName,' Test ',TestLabel,sprintf('%d', HeatSupply(1)));
        handleString = titleString;
        set(handleFigure,'Name',char(handleString));
        title(titleString,'FontSize', 12);
        legend('head core','head muscle','head fat','head skin','trunk core','trunk muscle','trunk fat','trunk skin','arms core','arms muscle','arms fat','arms skin','hands core','hands muscle','hands fat','hands skin','legs core','legs muscle','legs fat','legs skin','feet core','feet muscle','feet fat','feet skin', 'blood');
```

```
        %figure 2 - core
        handleFigure = figure (3);
        figureName= 'All Body core';
        hold on;
        for i=1:4:numDiffPlots,
            plot(o_time_vector,o_temperatures_array1(:,i),'-','Color',lineColor(floor((i-1)/4)+1),'LineWidth',2);
        end;
        plot(o_time_vector,o_temperatures_array1(:,25),'-','Color',lineColor(floor((25-1)/4)+1),'LineWidth',2);
        hold off;
        titleString= strcat(figureName,' Test :',TestLabel,sprintf('%d', HeatSupply(1)));
        handleString = titleString;
        set(handleFigure,'Name',char(handleString));
        title(titleString,'FontSize', 12);
        legend('head','trunk','arms','hands','legs','feet','blood');
        %figure 3 - muscle
        handleFigure = figure (4);
        figureName= 'All Body muscle';
        hold on;
        for i=2:4:numDiffPlots,
            plot(o_time_vector,o_temperatures_array1(:,i),'-','Color',lineColor(floor((i-1)/4)+1),'LineWidth',2);
        end;
        plot(o_time_vector,o_temperatures_array1(:,25),'-','Color',lineColor(floor((25-1)/4)+1),'LineWidth',2);
        hold off;
        titleString= strcat(figureName,' Test :',TestLabel,sprintf('%d', HeatSupply(1)));
        handleString = titleString;
        set(handleFigure,'Name',char(handleString));
        title(titleString,'FontSize', 12);
        legend('head','trunk','arms','hands','legs','feet','blood');
        %figure 4 - fat
        handleFigure = figure (5);
```

```
            figureName= 'All Body fat';
            hold on;
            for i=3:4:numDiffPlots,
                plot(o_time_vector,o_temperatures_array1(:,i),'-','Color',lineColor(floor((i-1)/4)+1),'LineWidth',2);
            end;
            plot(o_time_vector,o_temperatures_array1(:,25),'-','Color',lineColor(floor((25-1)/4)+1),'LineWidth',2);
            hold off;
            titleString= strcat(figureName,' Test',TestLabel,sprintf('%d', HeatSupply(1)));
            handleString = titleString;
            set(handleFigure,'Name',char(handleString));
            title(titleString,'FontSize', 12);
            legend('head','trunk','arms','hands','legs','feet','blood');
            %figure 5 - skin
            handleFigure = figure (6);
            figureName = 'All Body skin';
            hold on;
            for i=4:4:numDiffPlots,
                plot(o_time_vector,o_temperatures_array1(:,i),'-','Color',lineColor(floor((i-1)/4)+1),'LineWidth',2);
            end;
            plot(o_time_vector,o_temperatures_array1(:,25),'-','Color',lineColor(floor((25-1)/4)+1),'LineWidth',2);
            hold off;
            titleString= strcat(figureName,' Test',TestLabel,sprintf('%d', HeatSupply(1)));
            handleString = titleString;
            set(handleFigure,'Name',char(handleString));
            title(titleString,'FontSize', 12);
            legend('head','trunk','arms','hands','legs','feet','blood');

        elseif(PlotType=='z') %all in one big plot
            numDiffPlots = 24;
            lineColor = ['k','b','g','y','m','c','r'];
```

```
            lineWidth = [3,3,2,2];
            %figure 6 blood only
            handleFigure = figure (7);
            figureName = ' Core Blood';
            hold on;
            plot(o_time_vector,o_temperatures_array1(:,25),'-
   ','Color',lineColor(floor((25-1)/4)+1),'LineWidth',2);
            hold off;
            titleString= figureName;
            handleString = titleString;
            set(handleFigure,'Name',char(handleString));
            title(titleString,'FontSize', 12);
            legend('blood');

            handleFigure = figure(2001);
            hold on;
            plot(o_time_vector,o_heatLoss_vectorA, 'g');
            plot(o_time_vector,o_heatLoss_vectorE,'b');
   plot(o_time_.vector ,o_heatLoss_vectorA+o_heatLoss_vectorE,'k');
            hold off;
        end;
    end;


    % END OF ALL EXPERIMENTS


    savePath = 'E:\Matlab\';
    saveTime = strcat(' at ',datestr(now,'yyyymmddHHMMSS'));


    % Special plots



    handleFigure = figure(1001);
    hold on;
```

```
plot(0:5:TestNum*5,TS);

hold off;
xlabel('Time in minutes','FontSize',6);
ylabel('Temperature','FontSize',6);
title('Average Body Skin Temperature','FontSize',10);
layerString = strcat(savePath,' Average Skin Temperature -Test',TestLabel,saveTime);
if(PlotSave =='y')
    hgsave(handleFigure,char(layerString));
    handleFigure = figure(1002);
    hold on;
    plot(0:5:TestNum*5,TB);

    hold off;
    layerString = strcat(savePath,' Core Blood Temperature ',TestLabel,saveTime);
    xlabel('Time(mins)','FontSize',12);
    ylabel('Core Blood Temperature(oC)','FontSize',12);
    title('Change in Core Blood Temperature at Different Rate of Heat Absorption in the Torso','FontSize',12);
    if(PlotSave =='y')
        hgsave(handleFigure,char(layerString));
    end;
end;

% PREPARE FOR SAVE PLOTS TO DISK GRAPHS

if(PlotSave =='y')
    if(PlotType == 'f')
        for i=1:1:numDiffPlots,
            handleFigure = figure (i+1);
            layerString = strcat(savePath,Segment_Layer(i),'-Test' ,TestLabel,saveTime);
            hgsave(handleFigure,char(layerString));

        end;
    elseif(PlotType=='9')
```

```
            for i=1:1:numDiffPlots/4,
                graphNumber = floor((i-1)/4)+2;
                handleFigure = figure (graphNumber);
                layerString = strcat(savePath,Segment_Name(i),'-Test' ,TestLabel,saveTime);
                hgsave(handleFigure,char(layerString));
            end;
        elseif(PlotType=='b')
            handleFigure = figure (2);
            layerString = strcat(savePath,' All body','- Test ',TestLabel,'- Power',sprintf('%d', HeatSupply),saveTime);
            hgsave(handleFigure,char(layerString));
            handleFigure = figure (3);
            layerString = strcat(savePath,' All body Core','- Test ',TestLabel,'-Power ',sprintf('%d', HeatSupply),saveTime);
            hgsave(handleFigure,char(layerString));
            handleFigure = figure (4);
            layerString = strcat(savePath,' All body Muscle','- Test ',TestLabel,'-Power ',sprintf('%d', HeatSupply),saveTime);
            hgsave(handleFigure,char(layerString));
            handleFigure = figure (5);
            layerString = strcat(savePath,' All body Fat','- Test ',TestLabel,'- Power',sprintf('%d', HeatSupply),saveTime);
            hgsave(handleFigure,char(layerString));
            handleFigure = figure (6);
            layerString = strcat(savePath,' All body Skin','- Test ',TestLabel,'-Power ',sprintf('%d', HeatSupply),saveTime);
            hgsave(handleFigure,char(layerString));
        else
            allLayerString = strcat(savePath,'All Layer Temperature - Test ',TestLabel,saveTime);
            handleFigure = figure (2);
            hgsave(handleFigure,allLayerString);
        end;
    end;
```

3. Plotting Script

```
for i=50:50:length(Temperature)
plot(Temperature(i,:));
hold on;
end;
hold off;
```

Appendix 2 Software Design for Control System

1. Definition of Constants

NAME	VALUE	DESCRIPTION
For Key De-bounce		
const_keyTime_level	15	Key de-bounce delay
const_keyTime_short3	15	De-bounce delay for short-press
const_keyTime_long3	512	De-bounce delay for long-press
For Display Blink		
const_dpy_time_half	2000	
const_dpy_time_full	4000	
For Buzzer Sounding		
const_voice_short	40	
const_voice_long	120	
For Time and Temperature Constants		
const_time_0_25s	111	The count number for 0.25s
const_time_1s	444	The count number for 1s
const_Init_min	1	Initial minute setting
const_Init_sec	0	Initial second setting
const_Init_temp	450	Initial temperature setting

2. Definition of Variables

TYPE	NAME	INITIAL VALUE	DESCRIPTION
Look-up Tables			
static unsigned char **data**	LEDcode[]	{0x3F,0x06,0x5B,0x4F, 0x66,0x6D,0x7D,0x07, 0x7F,0x6F, 0xBF,0x86,0xDB,0xCF, 0xE6,0xED,0xFD,0x87, 0xFF,0xEF,0x48,0,0xfc,0xb9,0xde}	For the LED ESDs to display: 0-9, 0.-9. (with DP), ‘=’, Null, ‘A’, ‘b’, ‘C’ and ‘d’
For Time out Alarm			

unsigned char **data**	serial	22	To display the port's No
unsigned char	time_allow	0	Alarm-on allowance
unsigned char	fmq_times	0	Buzzer-on duration
unsigned char	spk	0	Buzzer-off
unsigned char	ms5_times	0	5 ms for Buzzer
For the Timer Counting down and Current Temperature			
signed char **data**	sec	0	
signed char **data**	min	0	
unsigned int **data**	temp_raw[]	[0,0,0,0,0]	Received raw data from sensors
unsigned int **data**	temp_data[]	[0,0,0,0,0]	Transformed data from sensors
unsigned int **data**	temp_value[]	[0,0,0,0,0]	Calculated temperature values
For Setting the Parameters of the Controller			
signed char	Init_min	1	Initial setting for timer
signed char	Init_sec	0	
unsigned int	Init_temp	0	Initial temperature reading
unsigned char **data**	Timing	0	Signal for timer counting down
unsigned char	Heating	0	Signal for heating
unsigned char **data**	IrValue[6]	{0,0,0,0,0,0}	Reading for Infrared Receiver
unsigned char **data**	IR_Time	0	Delay used for IR_remote
For the main function			
unsigned int **data**	TransCnt	0	For the frequency to change the displayed temperature from which sensor
unsigned int **data**	TempCnt		For the frequency of reading the temperature
unsigned int **data**	Cnt	0	
For hardware Ports Definition			
sbit	LSA	P2^0	LED Figure Selection
sbit	LSB	P2^1	
sbit	LSC	P2^2	
sbit	RELAY	P3^0	Master Switch for Relays

sbit	RELAY0	P3^7	
sbit	RELAY1	P3^6	
sbit	RELAY2	P3^5	
sbit	RELAY3	P3^4	
sbit	SPEAK	P2^3	Alarm
sbit	IRIN	P3^2	IR_remote
sbit	Key_sr1	P3^7	Increase-Selection
sbit	Key_sr2	P3^6	Decrease-Selection
sbit	Key_sr3	P3^5	Part-Select Key
sbit	Key_sr4	P3^4	Timer-start Button
sbit	DSPORT0	P1^0	DS18B20 data ports for four ways
sbit	DSPORT1	P1^1	
sbit	DSPORT2	P1^2	
sbit	DSPORT3	P1^3	
Sfr	WDT_CONTR	0xe1	Watch Dog Timer
For Key Service			
unsigned char	ucShortTouchFlag3	0	Self-Lock flag for short-press
unsigned char	ucShortTouchFlag4	0	
unsigned int	uiKeyTimeCnt1	0	De-bounce delay counters
unsigned int	uiKeyTimeCnt2	0	
unsigned int	uiKeyTimeCnt3	0	
unsigned int	uiKeyTimeCnt4	0	
unsigned char	ucKeyLock1	0	key triggered self-lock flags
unsigned char	ucKeyLock2	0	
unsigned char	ucKeyLock3	0	
unsigned char	ucKeyLock4	0	
unsigned char	ucKeySec	0	Triggered key's number
unsigned char	ucKeyStartFlag1	0	Timing-interrupt started flags
unsigned char	ucKeyStartFlag2	0	
unsigned char	ucKeyStartFlag3	0	
unsigned char	ucKeyStartFlag4	0	
unsigned int	uiKeyCtntyCnt1	0	Continuous interrupt counters
unsigned int	uiKeyCtntyCnt2	0	
For Displaying			
unsigned char **data**	ucDpyTimeLock	0	To determine whether the LEDs flickers

unsigned int **data**	uiDpyTimeCnt	0	Counter for flickering
unsigned char **data**	ucDigStep	1	Step-select variable
unsigned char **data**	ucDigShowTemp	0	Temporary variable for LED display
unsigned char **data**	ucPart	0	Core variable, Part-display variable
unsigned char **data**	ucUpdate	1	Full update display flag
unsigned char **data**	ucPart1Update	1	Part 1 update display flag
unsigned char **data**	ucPart2Update	1	Part 2 update display flag
unsigned char **data**	ucPart3Update	1	Part 3 update display flag
unsigned char **data**	ucDigShow8	0	The following content to display on each figure
unsigned char **data**	ucDigShow7	0	
unsigned char **data**	ucDigShow6	0	
unsigned char **data**	ucDigShow5	0	
unsigned char **data**	ucDigShow4	0	
unsigned char **data**	ucDigShow3	0	
unsigned char **data**	ucDigShow2	0	
unsigned char **data**	ucDigShow1	0	
For Buzzer sounding			
unsigned int **data**	uiVoiceCnt	0	counter for Beep
unsigned char **data**	ucVoiceLock	0	Buzzer beeping self-lock

3. Declaration of Sub-functions

Function Name	Arguments	Description
For Initialization		
void Init_IO	void	Initialization The IO Ports
void Init_timer0	void	Initialization The Timer 0
void Init_timer1	void	Initialization The Timer 1
void Init_ir	void	Initialization IR-Remote Function
For Display		
void Display_time	unsigned char minute, unsigned char second	Display The Time
void Display_temp	unsigned int temperature, unsigned	Display Temperature with the value and the port number to be displayed

	char num	
void Disp	void	LEDs Display Service Function
void Display_service	void	Display Content Function
For Keys		
void Key_scan	void	Keys Scan Function
void Key_service	void	Key Service Function
For Delay		
void Delay	unsigned int delay_ms	Delay Function for 1 ms
void Delay_Ir	unsigned int delay_ms	Delay function for IR_remote
void Delay1ms	unsigned int y	Delay function for DS18B20
void Delay_long	unsigned int uiDelayLong	Long Delay Function
For Reading Data Of Sensors Or ADC		
void Temp_trans	void	Temperature Data Transforming Function
void Ir_service	void	IR Remote Service Function
For Driving DS18B20 Chips		
unsigned char Ds18b20Init()	void	Initialization chips before reading the temperature values
void Ds18b20WriteByte	void	Writing commands to the chips
void Ds18b20ReadByte()	void	Reading one byte from each chip
void Ds18b20ChangTemp()	void	Temperature transforming function
void Ds18b20ReadTempCom()	void	To send the reading commands to each chip
void Ds18b20ReadTemp()	void	Temperature reading function for DS18B20 chips
For Comparison of temperature and time		
void Compar	void	Temperature & Time Comparison
For Safety		
void Safety	void	Safety Program
Interrupt Functions		
void T0_time **interrupt 1**	void	Timer 0 Interrupt Function For System Running
void ReadIr **interrupt 0**	void	IR Remote Read Function
void Timer1 **interrupt 3**	void	Timer 1 Interrupt Function For Timer Counting Down

4. Program Codes

```
/* Main.c file generated by Fanqin Meng
 *
 * Created:   03/16/2016
 * Processor: 80C51
 * Compiler:  Keil for 8051
 */
/*==============================================================
Initialization for Timer0 was modified on 2016/10/04 for TH0<=TH, TL0<=TL1
==============================================================*/
#include <reg51.h>
#include <intrins.h>
//#define DSPORTS P1
#define const_keyTime_level 15     //Key De-twitter delay time
#define const_keyTime_short3 15    //De-twitter for short-press
#define const_keyTime_long3 512    //De-twitter for long-press
//Define the constants
#define const_dpy_time_half 1000
#define const_dpy_time_full 2000
#define const_voice_short 40
#define const_voice_long 120
#define const_time_0_25s 111       //The count of interrupts for 0.25s
#define const_time_1s 444              //1 second
#define const_Init_min 1       //Inital minute setting
#define const_Init_sec 0       //Inital second setting
#define const_Init_temp 450        //Inital temperature setting
```

```
static unsigned char code LEDcode[] = {0x3F,0x06,0x5B,0x4F,
                         0x66,0x6D,0x7D,0x07,0x7F,0x6F,
                              0xBF,0x86,0xDB,0xCF,
                         0xE6,0xED,0xFD,0x87,0xFF,0xEF,
                         0x48,   0,0xf7,0xfc,0xb9,0xde};


unsigned char data serial=22; //Ports' serial letters
unsigned char time_allow; //Ontime Alarm
unsigned char fmq_times; //Buzzer continuing time
unsigned char spk;   //Buzzer off
unsigned char ms5_times; //5 ms
signed char data sec;
signed char data min;
unsigned int data temp_raw[]={0,0,0,0};
unsigned int data temp_data[]={0,0,0,0};
unsigned int data temp_value[]={0,0,0,0};
unsigned int data temp;
//unsigned int AD_temp;
signed char Init_min=1;
signed char Init_sec;
unsigned int data Init_temp;
unsigned char data Timing = 0; //Timer is not working
unsigned char Heating0 = 0; //Not Heating
unsigned char Heating1 = 0;
unsigned char Heating2 = 0;
unsigned char Heating3 = 0;
unsigned char data IrValue[6];
unsigned char data IR_Time;
unsigned int data TempCnt=0;
unsigned int data TransCnt=0;
unsigned int data Cnt=0;


sbit LSA=P2^0;
sbit LSB=P2^1;
sbit LSC=P2^2;
sbit RELAY0 = P3 ^ 7; //Relay
```

```
sbit RELAY1 = P3 ^ 6;
sbit RELAY2 = P3 ^ 5;
sbit RELAY3 = P3 ^ 4;
sbit RELAY = P3^0;
sbit SPEAK = P2 ^ 3; //Speaker
sbit IRIN = P3^2;     //IR_remote

sbit Key_sr1  =P2^7; //up-selection
sbit Key_sr2  =P2^6; //down-selection
sbit Key_sr3  =P2^5; //Confirm/Select Key
sbit Key_sr4  =P2^4; //Power-on button

sbit DSPORT0 = P1^0; //DS18B20 DATA ports
sbit DSPORT1 = P1^1;
sbit DSPORT2 = P1^2;
sbit DSPORT3 = P1^3;



unsigned char ucShortTouchFlag3 =0;//Self-Lock flag for short-press
unsigned char ucShortTouchFlag4 =0;//Self-Lock flag for short-press

unsigned int  uiVoiceCnt = 0;       //counter for Beep
unsigned char ucVoiceLock=0;    //Buzzer beeping self-lock

unsigned int  uiKeyTimeCnt1 = 0;  //De-twitter delay counter 1
unsigned char ucKeyLock1 = 0;    //key after-trigger self-lock flag 1
unsigned char ucKeySec = 0;  //Triggered key's number

unsigned int  uiKeyTimeCnt2 = 0;  //De-twitter delay counter 2
unsigned char ucKeyLock2 = 0;    //key  after-trigger  self-lock flag 2

unsigned int  uiKeyTimeCnt3 = 0;  //De-twitter delay counter 3
unsigned char ucKeyLock3 = 0;    //key  after-trigger  self-lock flag 3
```

```
unsigned int  uiKeyTimeCnt4 = 0;  //De-twitter delay counter 4
unsigned char ucKeyLock4 = 0;    //key  after-trigger  self-lock flag 4
unsigned char ucKeyStartFlag1=0; //Timing-interrupt start 1
unsigned char ucKeyStartFlag2=0; //Timing-interrupt start 2
unsigned char ucKeyStartFlag3=0; //Timing-interrupt start 3
unsigned char ucKeyStartFlag4=0; //Timing-interrupt start 4
unsigned int uiKeyCtntyCnt1 = 0; //Continuous interrupt counter 1
unsigned int uiKeyCtntyCnt2 = 0; //Continuous interrupt counter 2
unsigned char data ucDpyTimeLock=0; //To determine whether the LEDs flickers
unsigned int  data uiDpyTimeCnt=0;  //Counter for flickering
unsigned char data ucDigStep       =1; //Step variable
unsigned char data ucDigShowTemp=0;    //Temporary variable for LED display
unsigned char data ucPart=0;        //Core    variable,    Part-display variable (or second-level menu)
unsigned char data ucUpdate = 1;       //Full   update   display flag
unsigned char data ucPart1Update =1; //Part 1 update display flag
unsigned char data ucPart2Update =1; //Part 2 update display flag
unsigned char data ucPart3Update =1; //Part 3 update display flag
```

```
unsigned char data ucDigShow8;   //The following content to display for LEDbit.8 (Celsius)
unsigned char data ucDigShow7;   //The following content to display for LEDbit.7 (Temperature_fractional)
unsigned char data ucDigShow6;   //The following content to display for LEDbit.6 (Temperature_int_low & Decimal_Point)
unsigned char data ucDigShow5;   //The following content to display for LEDbit.5 (Temperature_int_high)
unsigned char data ucDigShow4;   //The following content to display for LEDbit.4 (Seccond_low)
unsigned char data ucDigShow3;   //The following content to display for LEDbit.3 (Second_high)
unsigned char data ucDigShow2;   //The following content to display for LEDbit.2 (Minute_low)
unsigned char data ucDigShow1;   //The following content to display for LEDbit.1 (Minute_high)


void Init_IO(void);
void Init_timer(void);
void Init_ir();
void Display(unsigned char dis[]);
void Display_time(unsigned char minute, unsigned char second);
void Display_temp(unsigned int temperature, unsigned char num);
void Key_scan(void);
void Key_service(void);
void Disp(void);
void Display_service(void);
void Compar();
void Safety();

void Delay(unsigned int delay_ms);
void Delay_long(unsigned int uiDelayLong);
void Temp_trans();
void Ir_service();

unsigned char Ds18b20Init();
void Ds18b20WriteByte(unsigned char com);
```

```
void Ds18b20ReadByte();
void  Ds18b20ChangTemp();
void  Ds18b20ReadTempCom();
void Ds18b20ReadTemp();


/*****************************************************************
iNITIALIZATION THE IO PORTS
****************************************************************/
void Init_IO(void)
{
    SPEAK = 1;//No speaking
    RELAY0 = 1;
    RELAY1 = 1;
    RELAY2 = 1;
    RELAY3 = 1;
    Init_min=const_Init_min;
    Init_sec=const_Init_sec;
    Init_temp=const_Init_temp;
}


/*****************************************************************
INTIALIZATION THE TIMER 0
****************************************************************/
void Init_timer0(void)
{
    TMOD |= 0x01;
    TH0 = 0xF8;   //Modified on 10/04/2016
    TL0 = 0x2F;  //Modified on 10/04/2016

    ET0 = 1;
    EA = 1;
    TR0 = 1;
```

```
        PT0 = 0;
        Delay_long(30);

    }

    /****************************************************************
    INTIALIZATION THE TIMER 1
    ****************************************************************/
    void Init_timer1(void)
    {
        TMOD|=0x10;
        TH1=0xEE;
        TL1=0x00;

        ET1=1;
        EA =1;
        PT1=1;

        min=Init_min;
        sec=Init_sec;

    }

    /****************************************************************
    INIIALIZATION IR_REMOTE FUNCTION
    ****************************************************************/
    void Init_ir()
    {
        IT0=1;//Triggered by failing edge
        EX0=1;//Open the external interrupt 0
        IRIN=1;//Initialize the IR_remote Port
        PX0=1;
        //for(i=0;i<6;i++)
            //IrValue[i]=0;
```

```
}


/******************************************************************
DISPLAY THE TIME
******************************************************************/
void Display_time(unsigned char minute, unsigned char second)
{
    ucDigShow4=second%10;
    ucDigShow3=second/10;
    ucDigShow2=minute%10;
    ucDigShow1=minute/10;
    //Disp();

}


/******************************************************************
TEMPERATURE DISPLAY FUNCTION
*****************************************************************/
void Display_temp(unsigned int temperature,unsigned char num)
{
    ucDigShow8=temperature%10/1;
    ucDigShow7=temperature%100/10+10;
    ucDigShow6=temperature%1000/100;
    ucDigShow5=num;
    //Disp();
}


/******************************************************************
TIMER 1 INTERRUPT FUNCTION
***************************************************************
```

```
***/
void Timer1(void) interrupt 3
{
    TH1 = 0xEE;    //Intial
    if (++ms5_times >= 217)  //1s
    {
        ms5_times = 0;
        sec--;
        if (sec < 0)
        {
            sec = 59;
            min--;
            if (min < 0)
            {
                min = Init_min;
                sec = Init_sec;
                time_allow = 1;//Stop and Initialization
                Init_timer1();
                TR1=0;
                Timing=0;
            }
        }
        if(ucPart==0)
        {
        Display_time(min, sec);//Display the time

        }
    }
    if (time_allow)
    {
        if (fmq_times++>200)
        {
            fmq_times = 0;
            SPEAK = 1;

        }
        if (100 == fmq_times)
        {
```

```
            SPEAK = 0;
            time_allow = 0;
        }
    }


}



/*******************************************************************
Keys scan FUNCTION
Functions:
    1.when pressing key_sr1, increase 1. If continuous pressing, increase continuously
    2.when pressing key_sr2, decrease 1. If continuous pressing, decrease continuously
    3.when pressing key_sr3, single-click trigger or continuous trigger ??!!!!!
*****************************************************************/
void Key_scan(void)
{
    static unsigned char KeyChangeTimeFlag3;

    if(Key_sr1 == 1)                    //Key 1 (not triggering)
    {
      ucKeyStartFlag1 = 0;          //Start counting timer-interrupt
      uiKeyTimeCnt1 = 0;            //Clear the delay counter for de-twitter
      ucKeyLock1 = 0;                   //Clear the after-trigger self-lock flag

    }
    else if(ucKeyLock1 == 0)
    {
```

```
            ucKeyStartFlag1 = 1;   //start counting

           if(uiKeyTimeCnt1>=const_keyTime_level)
           {
            ucKeyStartFlag1 = 0;      //stop counting
              ucKeyLock1 = 1;                //Set the self-lock to avoid continuous trigger
              uiKeyTimeCnt1 = 0;          //Clear the delay counter for de-twitter
              ucKeySec = 1;                  //triggner the Key 1
           }
       }

       else if(uiKeyTimeCnt1<const_time_1s)
       {
           uiKeyTimeCnt1++;
       }
       else
       {
           uiKeyCtntyCnt1++;          //Counting the continous trigger delay

           if(uiKeyCtntyCnt1>const_time_0_25s)
           {
              uiKeyCtntyCnt1 = 0;
              ucKeySec = 1;            //trigger the key 1
           }
       }


       if(Key_sr2 == 1)                //Key 2 (not triggering)
       {
         ucKeyStartFlag2 = 0;      //Start counting timer-interrupt
         uiKeyTimeCnt2 = 0;        //Clear the delay counter for de-twitter
         ucKeyLock2 = 0;              //Clear the after-trigger self-lock flag
       }
```

```
    else if(ucKeyLock2 == 0)
    {
         ucKeyStartFlag2 = 1;   //start counting

        if(uiKeyTimeCnt2>=const_keyTime_level)
        {
            ucKeyStartFlag2 = 0; //stop counting
            ucKeyLock2 = 1;                 //Set the self-lock to avoid continuous trigger
            uiKeyTimeCnt2 = 0;          //Clear the delay counter for de-twitter
            ucKeySec = 2;               //triggner the Key 2
        }
    }
    else if(uiKeyTimeCnt2<const_time_1s)
    {
         uiKeyTimeCnt2++;
    }
    else
    {
         uiKeyCtntyCnt2++; //Counting the continous trigger delay

        if(uiKeyCtntyCnt2>const_time_0_25s)
        {
            uiKeyCtntyCnt2 = 0;
            ucKeySec = 2;      //trigger the key 2
        }
    }

    if(Key_sr3 == 1)      //KEY 3
    {
       ucKeyStartFlag3 = 0;   //Start counting timer-interrupt
       uiKeyTimeCnt3 = 0; //Clear the delay counter for de-twitter
       ucKeyLock3 = 0;     //Clear the after-trigger self-lock flag
       ucShortTouchFlag3 = 0; //Clear the short-press self-lock flag
```

```
          KeyChangeTimeFlag3 = 0;
      }
      else if(ucKeyLock3 == 0)
      {
           ucKeyStartFlag3 = 1;       //start counting

          if(ucShortTouchFlag3 == 0)
          {
              if(uiKeyTimeCnt3>=const_keyTime_short3)   //According to the time between short-presses
              {
                  ucShortTouchFlag3 = 1;
                  ucKeySec = 3;       //Trigger the KEY 3
              }
          }

          if(uiKeyTimeCnt3>=const_keyTime_long3&&KeyChangeTimeFlag3 == 0)
          {
              KeyChangeTimeFlag3 = 1;
              ucKeySec = 17;          //Trigger the KEY 17??
          }
          if(uiKeyTimeCnt3>=const_keyTime_long3+const_keyTime_long3)
          {
              ucKeyStartFlag3 = 0; //Stop counting
              ucKeyLock3 = 1;          //Self-lock is reset to avoid re-trigger
              uiKeyTimeCnt3 = 0;      //Clear the de-twitter delay counter
              ucKeySec = 18;          //Trigger the KEY 18???
          }

      }


      if(Key_sr4 == 1)      //the Key 4
      {
```

```
          ucKeyStartFlag4 = 0;   //Start counting timer-interrupt
          uiKeyTimeCnt4 = 0;   //Clear the delay counter for de-twitter
          ucKeyLock4 = 0;          //Clear the after-trigger self-lock flag
          ucShortTouchFlag4 = 0; //Clear the short-press self-lock flag

       }
       else if(ucKeyLock4 == 0)
       {
            ucKeyStartFlag4 = 1;       //start counting

           if(ucShortTouchFlag4 == 0)
           {
               if(uiKeyTimeCnt4>=const_keyTime_level)
               {
                   ucShortTouchFlag4 = 1;
                   ucKeySec = 4;       //trigger the KEY 4
               }


           }

          if(uiKeyTimeCnt4>=const_keyTime_long3)
          {
               ucKeyStartFlag4 = 0; //Stop counting
               ucKeyLock4 = 1;           //Self-lock is reset to avoid re-trigger
               uiKeyTimeCnt4 = 0;     //Clear the de-twitter delay counter
               ucKeySec = 5;          //Trigger the KEY 5

          }
       }

   }

```

```
/*****************************************************************
KEY SERVICE FUNCTION
*****************************************************************/
void Key_service(void)
{
    switch(ucKeySec) //According to the Key Service Status
    {
        case 1: //Incre-Key
            switch(ucPart) //According to different LEDbits
            {
                case 1: //Minute
                    Init_min++;
                    if(Init_min>60)
                        Init_min=0;
                    ucPart1Update=1; //Updating the display
                    break;
                case 2: //Second
                    Init_sec++;
                    if(Init_sec>59)
                        Init_sec=00;
                    ucPart2Update=1; //Updating the display
                    break;
                case 3://Temperature
                    Init_temp=Init_temp+5;
                    if(Init_temp>500||Init_temp<300)
                        Init_temp=300;
                    ucPart3Update=1; //Updating the display
                    break;

            }
            ucVoiceLock=1; //Lock and protect the main and interrupt functions' shared variable
            uiVoiceCnt=const_voice_short;//Beep a short period for the press
            ucVoiceLock=0; //Unlock and protect uiVoiceCnt
            ucKeySec=0; //Clear the saved Key number after
```

```
responsed the interrupt
            break;
        case 2: //Decre-Key
            switch(ucPart) //According to different LEDbits
            {
                case 1: //Minute
                    Init_min--;
                    if(Init_min>60)
                        Init_min=0;
                    if(Init_min<0)
                        Init_min=60;
                    ucPart1Update=1; //Updating the display
                    break;
                case 2: //Second
                    Init_sec--;
                    if(Init_sec>59)
                        Init_sec=00;
                    if(Init_sec<0)
                        Init_sec=59;
                    ucPart2Update=1; //Updating the display
                    break;
                case 3://Temperature
                    Init_temp=Init_temp-5;
                    if(Init_temp>500||Init_temp<300)
                        Init_temp=300;
                    ucPart3Update=1; //Updating the display
                    break;
            }
            ucVoiceLock=1; //Lock and protect the main and interrupt functions' shared variable
            uiVoiceCnt=const_voice_short;//Beep a short period for the press
            ucVoiceLock=0; //Unlock and protect uiVoiceCnt
            ucKeySec=0; //Clear the saved Key number after responsed the interrupt
            break;
        case 3: //Set-Key
        ucPart++;
```

```
            if(ucPart>3) //Setting completed
            {
               ucPart=0;//DON'T FLICKER!!!
               ucUpdate=1; //Display need to be updated
            }
            ucVoiceLock=1; //Lock and protect the main and interrupt functions' shared variable
            uiVoiceCnt=const_voice_short;//Beep a short period for the press
            ucVoiceLock=0; //Unlock and protect uiVoiceCnt
            ucKeySec=0; //Clear the saved Key number after responsed the interrupt
            break;
            case 4: //Trigger the timer
            Init_timer1();

            TR1=1;
            Timing = 1;//Timer is working

            ucVoiceLock=1; //Lock and protect the main and interrupt functions' shared variable
            uiVoiceCnt=const_voice_short;//Beep a short period for the press
            ucVoiceLock=0; //Unlock and protect uiVoiceCnt
            ucKeySec=0; //Clear the saved Key number after responsed the interrupt
            break;
         }
   }

   /****************************************************************
   LEDs DISPLAY SERVIVCE FUNCTION
   ***************************************************************/
   void Disp(void)
   {
      unsigned char i;
```

```
        for(i=0;i<8;i++)
        {
        switch(ucDigStep)//According to LEDbit
        {
            case 1:
                LSA=0;LSB=0;LSC=0;

                P0=LEDcode[ucDigShow1];

                ucDigStep=2;
            break;
            case 2:
                LSA=1;LSB=0;LSC=0;

                P0=LEDcode[ucDigShow2];

                ucDigStep=3;
            break;
            case 3:
                LSA=0;LSB=1;LSC=0;

                P0=LEDcode[ucDigShow3];

                ucDigStep=4;
            break;
            case 4:
                LSA=1;LSB=1;LSC=0;

                P0=LEDcode[ucDigShow4];

                ucDigStep=5;
            break;
            case 5:
                LSA=0;LSB=0;LSC=1;

                P0=LEDcode[ucDigShow5];

                ucDigStep=6;
```

```
        break;
        case 6:
            LSA=1;LSB=0;LSC=1;
            P0=LEDcode[ucDigShow6];
            ucDigStep=7;
        break;
        case 7:
            LSA=0;LSB=1;LSC=1;
            P0=LEDcode[ucDigShow7];
            ucDigStep=8;
        break;
        case 8:
            LSA=1;LSB=1;LSC=1;
            P0=LEDcode[ucDigShow8];
            ucDigStep=1;
        break;
    }
    Delay(5);
            P0=0;
    }
}
/*******************************************************************
DISPLAY CONTENT FUNCTION
*******************************************************************/
void Display_service(void)
{
    switch (ucPart) //Determine whether flicker or not according
```

```
   to 'ucPart'
        {
        case 0: //Don't flicker
            if (ucUpdate == 1)
            {
                ucUpdate = 0;
                ucPart1Update = 1;
                ucPart2Update = 1;
                ucPart3Update = 1;
            }
            if (ucPart1Update == 1)
            {
                ucPart1Update = 0;
                if(Timing==1)
                    Display_time(min, sec);
                else
                    Display_time(Init_min,Init_sec);
            }
            if (ucPart2Update == 1)
            {
                ucPart2Update = 0;
                if(Timing==1)
                    Display_time(min, sec);
                else
                    Display_time(Init_min,Init_sec);
            }
            if (ucPart3Update == 1)
            {
                ucPart3Update = 0;
                Display_temp(temp,serial);
            }
            //Disp();
            break;
        case 1: //The MINUTE Flickers!
            if (uiDpyTimeCnt == const_dpy_time_half) //Displaying
            {
                Display_time(Init_min, Init_sec);
                Display_temp(Init_temp,20);
```

```
                //Disp();
            }
            else if (uiDpyTimeCnt > const_dpy_time_full) //Turn OFF
            {
                ucDpyTimeLock = 1; //Lock the Displaying time
                uiDpyTimeCnt = 0; //Clear the flicker counter
                ucDpyTimeLock = 0; //unLock the Displaying time
                ucDigShow1 = 21; //LEDs to display are NOP
                ucDigShow2 = 21;
                //Disp();
            }
            break;
        case 2: //The SECOND Flickers!
            if (uiDpyTimeCnt == const_dpy_time_half)
            {
                Display_time(Init_min, Init_sec); //Displaying
                Display_temp(Init_temp,20);
                //Disp();
            }
            else if (uiDpyTimeCnt > const_dpy_time_full)
            {
                ucDpyTimeLock = 1; //Lock the Displaying time
                uiDpyTimeCnt = 0; //Clear the flicker counter
                ucDpyTimeLock = 0; //unLock the Displaying time
                ucDigShow3 = 21; //LEDs to display are NOP
                ucDigShow4 = 21;
                //Disp();
            }
            break;
        case 3: //The TEMPERATURE Flickers
            if (uiDpyTimeCnt == const_dpy_time_half)
            {
                Display_temp(Init_temp,20); //Displaying
                Display_time(Init_min, Init_sec);
                //Disp();
            }
            else if (uiDpyTimeCnt > const_dpy_time_full)
            {
```

```
                ucDpyTimeLock = 1; //Lock the Displaying time
                uiDpyTimeCnt = 0; //Clear the flicker counter
                ucDpyTimeLock = 0; //unLock the Displaying time
                ucDigShow5 = 21; //LEDs to display are NOP
                ucDigShow6 = 21;
                ucDigShow7 = 21;
                ucDigShow8 = 21;
                //Disp();
            }
            break;
        }
    }
/******************************************************************
SAFETY FUNCTION
******************************************************************/
void Safety()
{
    unsigned char data i,j;
    for (i=0;i<4;i++)
    {
            if (temp_value[i] > (Init_temp + 10))
            {
                    while(1)
                    {
                        EA=0;
                        SPEAK = 1;
                        P0 = 0xf9; //Display 'E'
                        for(i=5; i > 0; i--)
                            for(j = 200; j > 0; j--);
                        SPEAK = 0;
                        for(i=5; i > 0; i--)
                            for(j = 200; j > 0; j--);
                        RELAY = 1;
                        WDT_CONTR = 0x35;  //Reset watch dog timer
                    }
            }
```

```
    }
}
/*****************************************************************
TEMPERATURE & TIME COMPARISON FUNCTION
*****************************************************************/
void Compar()
{

    if (ucPart != 0) //When setting, stop heating
    {
        Heating0 = 0;//Stop heating when Timer is working OR temperature reaches the target
        Heating1 = 0;
        Heating2 = 0;
        Heating3 = 0;
        //RELAY=0;
        RELAY0 = 1; //Relay is off
        RELAY1 = 1;
        RELAY2 = 1;
        RELAY3 = 1;
        ucUpdate = 1;//Update and display the current time and temperature
    }
    if ((Timing == 1)&& (ucPart == 0))//avoid the zero-drift & No Setting
    {
        //RELAY=0;
        if ((Heating0 == 0) && (temp_value[0] < Init_temp)) //NO Heating0
        {
            RELAY0=0; //Relay0 is on
            Heating0=1;//Start heating0 when Timer is working AND temperature is low
        }
        if ((Heating1 == 0) && (temp_value[1] < Init_temp))
        {
```

```
            RELAY1=0; //Relay1 is on
            Heating1=1;//Start heating1 when Timer is working AND temperature is low
        }
        if ((Heating2 == 0) && (temp_value[2] < Init_temp))
        {
            RELAY2=0; //Relay2 is on
            Heating2=1;//Start heating2 when Timer is working AND temperature is low
        }
        if ((Heating3 == 0) && (temp_value[3] < Init_temp))
        {
            RELAY3=0; //Relay3 is on
            Heating3=1;//Start heating3 when Timer is working AND temperature is low
        }
        ucUpdate = 1;//Update and display the current time and temperature
    }
    if  (Timing==0)
    {
        //RELAY=1;
        RELAY0=1;
        RELAY1=1;
        RELAY2=1;
        RELAY3=1;
        ucUpdate=1;
        Heating0 = 0;//Stop heating when Timer is working OR temperature reaches the target
        Heating1 = 0;
        Heating2 = 0;
        Heating3 = 0;

    }
    else if  ((Heating0 == 1) && (temp_value[0] > Init_temp))
    {
        Heating0 = 0;//Stop heating when Timer is working OR temperature reaches the target
```

```
            RELAY0 = 1; //Relay0 is off
            ucUpdate = 1;//Update and display the current time and temperature
        }
        else if ((Heating1 == 1) && (temp_value[1] > Init_temp))
        {
            Heating1 = 0;//Stop heating when Timer is working OR temperature reaches the target
            RELAY1 = 1; //Relay1 is off
            ucUpdate = 1;//Update and display the current time and temperature
        }
        else if ((Heating2 == 1) && (temp_value[2] > Init_temp))
        {
            Heating2 = 0;//Stop heating when Timer is working OR temperature reaches the target
            RELAY2 = 1; //Relay2 is off
            ucUpdate = 1;//Update and display the current time and temperature
        }
        else if ((Heating3 == 1) && (temp_value[3] > Init_temp))
        {
            Heating3 = 0;//Stop heating when Timer is working OR temperature reaches the target
            RELAY3 = 1; //Relay3 is off
            ucUpdate = 1;//Update and display the current time and temperature
        }

    }

    /****************************************************************
    TIMER 0 INTERRUPT FUNCTION
    ***************************************************************/
    void T0_time() interrupt 1
    {
```

```
    TF0 = 0;//Clear the INT flag (T0);
    TR0 = 0;//INT off

    Key_scan();
    //Ir_service();
    Disp();

    if (ucKeyStartFlag1 == 1) //KEY 1
    {
        if (uiKeyTimeCnt1 < 0xFFFF)//Avoid the timer overflowing
        {
            uiKeyTimeCnt1++;
        }
    }
    if (ucKeyStartFlag2 == 1) //KEY 2
    {
        if (uiKeyTimeCnt2 < 0xFFFF)//Avoid the timer overflowing
        {
            uiKeyTimeCnt2++;
        }
    }
    if (ucKeyStartFlag3 == 1) //KEY 3
    {
        if (uiKeyTimeCnt3 < 0xFFFF)//Avoid the timer overflowing
        {
            uiKeyTimeCnt3++;
        }
    }
    if (ucKeyStartFlag4 == 1) //KEY 4
    {
        if (uiKeyTimeCnt4 < 0xFFFF)//Avoid the timer overflowing
        {
            uiKeyTimeCnt4++;
        }
    }
    if (uiVoiceCnt != 0)
    {
        uiVoiceCnt--; //Self=decrease 1 until zero when enter
```

```
INT1 everytime
            SPEAK = 0; //Speaking
        }
        else
        {
            SPEAK = 1;//Stop speaking
        }
        TH0 = 0xF8; //reset Timer0 to (65535-2000=63535=0xF82F)
        TL0 = 0x2F;
        EA = 1;
        ET0 = 1;
        TR0 = 1;//Open the INT1
    }

    /************************************************************
****
    DELAY FUNCTION
    *************************************************************
***/
    void Delay(unsigned int delay_ms)
    {
        unsigned int data i, j;
        for (i = delay_ms; i > 0; i--)
            for (j = 10; j > 0; j--);

    }
    /************************************************************
****
    1ms DELAY FUNCTION
    *************************************************************
***/
    void Delay1ms(unsigned int y)
    {
        unsigned int data x;
        for( ; y>0; y--)
        {
            for(x=110; x>0; x--);
        }
```

```
}

/******************************************************************
LONG DELAY FUNCTION
*****************************************************************/
void Delay_long(unsigned int uiDelayLong)
{
    unsigned int data i, j;
    for (i = uiDelayLong; i > 0; i--)
        for (j = 50; j > 0; j--);
}



/******************************************************************
TEMPERATURE TRANSFORM FUNCTION
*****************************************************************/
void Temp_trans(void)
{

    float tp;
    unsigned char data i;
    //TR0 = 0;
    Ds18b20ReadTemp();
    for (i=0;i<4;i++)
    {
        tp=temp_data[i];
        temp_value[i]=(tp*0.0625*100+0.5)/10;         //Calculate temperature readings
    }
    //TR0 = 1;
}

/**************************************************************
```

```
****
DS18B20 INITIALIZATION FUNCTION
******************************************************************/
unsigned char Ds18b20Init()
{
    unsigned char data i;
    EA=0;
    P1 = 0x00;        ////Pull down the ports for 480us~960us
    i = 70;
    while(i--);//Delay for 495us

    P1 = 0xff;        //Then Pull up the portS and waiting for response
    i = 0;
    while(DSPORT0)    //Waiting for DS18B20 pulling down the bus (P1^0)
    {
        Delay1ms(1);
        i++;
        if(i>5)//Waiting for >5MS
        {
            return 0;//Initialization Failure
        }

    }
    EA=1;
    return 1;//Initialization Success
}

/*****************************************************************
****
DS18B20 WRITE BYTE FUNCTION
******************************************************************/

void Ds18b20WriteByte(unsigned char dat)
{
```

```
    unsigned int data i, j;
    EA=0;
    for(j=0; j<8; j++)
    {
        P1 = 0x00;          //Pull down the ports for 1us before writing
        i++;                //Delay for 1us
        DSPORT0 = dat & 0x01;  //Writing data from the low bit
        DSPORT1 = dat & 0x01;
        DSPORT2 = dat & 0x01;
        DSPORT3 = dat & 0x01;
        i=6;
        while(i--); //Delay for 6us
        P1=0Xff;   //Release the ports
        dat >>= 1;
    }
    EA=1;
}
/*******************************************************************
DS18B20 READ BYTE FUNCTION
******************************************************************/
void Ds18b20ReadByte()
{
    unsigned char data b0,b1,b2,b3;
    unsigned int data i, j;
    for(j=0;j<4;j++)
    {
        temp_raw[j]=0;
    }
    EA=0;
    for(j=8; j>0; j--)
    {
        P1=0x00;//Pull down the ports for 1us
        i++;
        P1=0xff;//Then Realse the ports
        i++;
```

```
        //i++;//Wait 1us for stable readings
        b0 = DSPORT0;  //Reading data from the lowest bit
        b1 = DSPORT1;
        b2 = DSPORT2;
        b3 = DSPORT3;
        /*Left-shift the raw data 1-bit AND right-shift bi*/
        temp_raw[0] = (temp_raw[0]>> 1) | (b0 << 7);
        temp_raw[1] = (temp_raw[1]>> 1) | (b1 << 7);
        temp_raw[2] = (temp_raw[2]>> 1) | (b2 << 7);
        temp_raw[3] = (temp_raw[3]>> 1) | (b3 << 7);
        i = 4;     //Ready for the next reading after 48us delay
        while(i--);
    }
    EA=1;
}

/*****************************************************************
DS18B20 TRANSFORM TEMPERATURE FUNCTION
****************************************************************/
void  Ds18b20ChangTemp()
{

    Ds18b20Init();
    Delay1ms(1);
    Ds18b20WriteByte(0xcc);     //Skip the ROM control command
    Ds18b20WriteByte(0x44);     //Command for temperature transform
    //  Delay1ms(100);    //***Waiting for transform completed

}

/*****************************************************************
DS18B20 READ TEMPERATURE COMMAND FUNCTION
```

```
*****************************************************************/
void  Ds18b20ReadTempCom()
{

    Ds18b20Init();
    Delay1ms(1);
    Ds18b20WriteByte(0xcc);  //Skip the ROM control command
    Ds18b20WriteByte(0xbe);  //Send the reading command
}

/*******************************************************************
DS18B20 READ TEMPERATURE FUNCTION
*****************************************************************/
void Ds18b20ReadTemp()
{
    unsigned char data i;
    unsigned char data tmh[]={0,0,0,0};
    unsigned char data tml[]={0,0,0,0};
    Ds18b20ChangTemp();             //Run the transfer function
    Ds18b20ReadTempCom();           //Run the temperature command function
    Ds18b20ReadByte();       //Toltal 16-bit data for temperature
                           //Reading the lower 8-bit data
    for (i=0;i<4;i++)
    {
        tml[i]=temp_raw[i];
    }
    Ds18b20ReadByte();       //Reading the higher 8-bit data
    for (i=0;i<4;i++)
    {
        tmh[i]=temp_raw[i];
        temp_data[i] = tmh[i];
        temp_data[i] <<= 8;
        temp_data[i] |= tml[i];
    }
```

```
}

/****************************************************************
IR REMOTE READ FUNCTION
*****************************************************************/
void ReadIr() interrupt 0
{
    unsigned char j,k;
    unsigned int err;
    IR_Time=0;
    Delay_Ir(70);

    if(IRIN==0)       //Comfirm whether correct signal is received
    {

        err=1000;            //1000*10us=10ms. Overflow means incorrect signal received

        while((IRIN==0)&&(err>0))   //wait for the 9ms Low-level passing
        {
            Delay_Ir (1);
            err--;
        }
        if(IRIN==1)           //If the 9ms Low-level passed
        {
            err=500;
            while((IRIN==1)&&(err>0))        //wait for 4.5ms initial High-level passing
            {
                Delay_Ir (1);
                err--;
            }
            for(k=0;k<4;k++)      //4 groups data
            {
```

```
            for(j=0;j<8;j++)  //Receiving one group of data
            {

                err=60;
                while((IRIN==0)&&(err>0))//wait for the 560us Low_level passing before the signal
                {
                    Delay_Ir (1);
                    err--;
                }
                err=500;
                while((IRIN==1)&&(err>0))    //Count the period of High_level
                {
                    Delay_Ir (1);//0.14ms
                    IR_Time++;
                    err--;
                    if(IR_Time>30)
                    {
                        EX0=1;
                        return;
                    }
                }
                IrValue[k]>>=1;    //k means the number of the data group
                if(IR_Time>=8)           //if High_level last for 565us,it should be '1'
                {
                    IrValue[k]|=0x80;
                }
                IR_Time=0;    //Reset the time before re_assignment
            }
        }
    }
    if(IrValue[2]!=~IrValue[3])
    {
        return;
```

```
        }
    }
    IrValue[4]=IrValue[2]>>4;           //Higher bit
    IrValue[5]=IrValue[2]&0x0f;     //Lower bit
    EX0 = 0;

    Ir_service();

}

/****************************************************************
IR REMOTE SERVICE FUNCTION
***************************************************************/
void Ir_service()
{
    unsigned char data i;
    if(IrValue[4]==4 && IrValue[5]==5)
    {
        ucKeySec=4;
        for(i=0;i<6;i++)
            IrValue[i]=0;
    }
    if(IrValue[4]==4 && IrValue[5]==6)
    {
        ucKeySec=3;
        for(i=0;i<6;i++)
            IrValue[i]=0;
    }
    if(IrValue[4]==1 && IrValue[5]==5)
    {
        ucKeySec=2;
        for(i=0;i<6;i++)
            IrValue[i]=0;
    }
    if(IrValue[4]==0 && IrValue[5]==9)
    {
```

```
            ucKeySec=1;
            for(i=0;i<6;i++)
                IrValue[i]=0;
        }

    }

    /******************************************************************
    MAIN FUNCTION
    *****************************************************************/
    void main(void)
     {


         Init_IO();
         Init_timer0();
         Init_ir();
         RELAY = 0;
         while(1)
         {
             Display_service();
             Key_service();

             if(Cnt>10)
             {
                 EX0 = 1;
                 Cnt = 0;
             }
             if(ucPart==0 && TempCnt>150)
             {
                 TempCnt=0;
                 Temp_trans();

             }
             if(TransCnt>400)
             {
```

```
                serial++;
                if (serial>25)
                {
                    serial=22;
                    Compar();
                    Safety();
                }
                TransCnt=0;
                temp=temp_value[serial-22];

            }
            if(ucPart==0)
            {
                 Display_temp(temp,serial);
            }

            if (ucDpyTimeLock == 0) //For controlling the LEDs flickers or not
            {
                 uiDpyTimeCnt++; //Flickering counter
            }
            TransCnt++;
            Cnt++;
            TempCnt++;
            WDT_CONTR = 0x35;
        }

    }
```