Cardiac Rehab Effects of Heat and Cold

Therapeutic heat and cold in cardiac rehabilitation

Abstract

Background: Heart failure (HF) is an emerging epidemic that affects both sexes and all races. It is a complex clinical disease with symptoms caused from any structural or functional cardiac disorder, resulting in reduced longevity. HF is a weakening process that is difficult to treat and it exists in various conditions in which therapy needs to be customized. HF has reached epidemic scopes, mainly among the elderly, in whom it might be a reason for hospitalization. Common types of therapy for HF cases focus on pharmaceuticals and medical instrumentation. However, new approaches of patient-centered care that are based on complementary management strategies, improving quality of life without causing an economic worry or health side effects, are needed to decrease hospitalizations.

Purpose: Epidemiology, public health, risk factors, HF management, and several therapeutic heat and cold modalities have been investigated and discussed.

Results: Thermotherapy has a scientific evidence-based effect on the human body and can be used for treatment and rehabilitation of the heart.

Conclusion: The progress made in bioheat transfer modelling and energy delivery techniques will have an impact on the development of effective therapeutic modalities that deliver controlled heat and/or cold to the human body.

Keywords: Thermotherapy, epidemiology, risk profile, rehabilitation, heart failure management, heat transfer, thermoregulatory modeling

Review

The epidemic of the 21st century

HF is an enormous public health burden [1] with a worldwide prevalence that seems to have been increasing over the past few decades in an aging population [2]. It is also considered a global priority where the World Health Organization (WHO) estimates that cardiovascular diseases including HF are now responsible for one third of all deaths globally. In 1997, HF was singled out as an emerging epidemic [3] and today as the cardiovascular epidemic of the 21st century [4]. However, its epidemiology is complex because of the multiple factors that interact in a complex manner to impact the prevalence and incidence of HF. Most HF-related hospitalizations and deaths are sustained by a subgroup of patients who are noncompliant to guideline-based medical management, a group categorized as having advanced HF [5]. The epidemiology of HF reflects increased incidence, improved survival leading to increased prevalence, or both factors combined [6].This track may reflect the need for improvement in the management of HF.

The prevalence of HF is estimated to be at 1–2% in the Western world and the incidence approaches 5–10 per 1000 persons per year [7]. Individuals younger than 50 years are hardly ever found to have HF, but prevalence and incidence increases progressively with age in those over 50 years. In a US population-based study, the prevalence of HF was 2.2% (95 CI 1.6% to 2.8%), increasing from 0.7% in persons aged 45 to 54 years to 8.4% for those aged 75 years or older [8]. In Canada, the average annual in-hospital mortality rate is 9.5 deaths/100 hospitalized patients >65 years of age and 12.5 deaths/100 hospitalized patients >75 years of age [9]. In developed countries, the prevalence of HF is approximately 1-2% of the adult population, with the prevalence rising to ≥10% among persons 70 years of age or older [10]. In Europe, 1 million hospitalizations are attributed to acute episodes of HF every year [11]. In other countries, incidence and prevalence data for HF are scarce, and current epidemiological data from developing countries are inadequate for building an accurate assessment due to a lack of inclusive studies that assess the prevalence of HF and associated mortality. Although the level of HF burden in the developing world is not well measured, vast growth in the occurrence of HF is expected as developing countries shift from acute illness to chronic disease, population ages, and the prevalence of HF risk factors such as hypertension, coronary artery disease, and obesity increase [2].

Hospitalization represents a turning point for HF patients as hospital admissions are the key driver of health care costs in HF, therefore understanding the epidemiology of hospital admissions, its determinants and implications for the outcome of the disease as assessed by the proportion is a requirement [12].

It has become apparent that the emerging epidemic of HF calls for scientific breakthroughs and systematic treatment approaches adapted to the needs of individual patients, so people are living longer. Understanding the pathophysiology of HF allows one to achieve the goals of treatment, which are to relieve symptoms, decrease hospital admissions, prolong patient life, as well as improve the patient's overall quality of life [13].

Risk factors of heart failure

Clinically, HF is a condition in which the heart cannot pump enough blood for the body's need. It is a complex process that may result from any structural or functional cardiac disorder that weakens the ability of the ventricles to fill or eject blood [5,14]. It is the result of complex interactions among molecular, endocrine, and biodynamic systems. HF is a systematic process where a patient's heart becomes unable to produce equilibrium between the oxygenated blood delivered and the basal metabolism demands of the patient's organs [15]. Its most common symptoms are breathlessness which happens at rest or on action, fatigue, and ankle swelling.

Various risk factors are known to be related with HF. They are divided into two categories: major and contributing. Major risk factors have been proven to increase the risk of disease, whereas contributing risk factors may lead to an increased risk of disease. Major clinical risk factors include uncontrolled hypertension, myocardial infarction, valvular heart disease, obesity, high bad cholesterol, family history, and uncontrolled diabetes. Contributing risk factors include smoking, dyslipidemia, chronic kidney disease, albuminuria, sleep-disordered breathing, anemia, increased heart rate, physical inactivity, low socioeconomic status, and uncontrolled stress and anger.

Ischemic heart disease (IHD) is the most important risk factor for HF [16]. From the OPTIMIZE-HF (Organized Program to Initiate Lifesaving Treatment in Hospitalized Patients with HF) Registry [17], ischemia was identified as the primary cause of hospitalization in 15% of patients with HF. These patients had worse in-hospital mortality, as well as 60 and 90-day mortality after discharge.

It is known that hypertension is associated with HF and is the biggest risk factor for stroke and heart attacks. It contributes more to the population burden of HF because of its greater prevalence. In the Framingham cohort, 75% of incident HF cases had antecedent hypertension [8,18]. Men with hypertension had a twofold increase in risk of developing HF, and women threefold, whereas the population related risk for HF imparted by hypertension was estimated to be 39% in men and 59% in women [19]. Initial epidemiological studies have shown the leading cause of HF to be hypertension [20]. However, over the last few decades this has steadily changed to become IHD [21].

Diabetes as well as insulin resistance are also risk factors for HF. Diabetes increases the risk of HF by about twofold in men, and up to fivefold in women [1,16,17,22]. Diabetes is not only a risk factor for the development of HF, but also indicates worse outcomes in the presence of HF. The survival of HF is worse in the presence of diabetes; the 5-year survival was 46% in those with HF alone, but only 37% for those with both diabetes and HF [23].

High bad cholesterol and low good cholesterol levels are known as risk factor for atherosclerotic vascular disease. Dyslipidemia, therefore, is linked to the development of HF. However, elevated levels of total cholesterol are not a strong predictor of new-onset HF [24], and an increased ratio of total cholesterol to high-density lipoprotein (HDL) cholesterol is associated with elevated HF risk [25].

Tobacco is also a risk factor for cardiovascular diseases where smokers have a higher risk of HF development than ex-smokers, passive smokers and non-smokers. In the Coronary Artery Surgery Study (CASS) [26], smoking was associated with a 47% increased risk of developing HF. In the SOLVD trials (Studies of Left Ventricular Dysfunction) [27] ex-smokers had a 30% lower mortality than current smokers, a benefit that accrued within two years after smoking cessation.

Obesity increases the risk of HF, and studies suggest that having a body mass index (BMI) ≥ 30 kg/m^2 doubles the risk of HF [28]. However, in a study of 550 subjects without diabetes in Greece, BMI was not associated with HF risk, whereas metabolic syndrome was associated with a 2.5-fold increase in HF risk [29]. It was also found that 80% of HF patients show impairments on cognitive tests that assess language, memory, attention, and executive function. Obesity is thought to be a risk factor for the cognitive impairment that is observed in those with HF [30].

Uncontrolled stress and anger are also a risk factor for HF. A stressful life, anxiety and depression increase the risk of heart diseases. In this regard, yoga therapy has been found to offer extra benefits to African American HF patients by improving cardiovascular endurance, quality of life, inflammatory markers, and flexibility [31]. Another study found that relaxation techniques benefitted the quality of life of Chinese patients with chronic HF [32].

Other environmental factors, such as low socioeconomic status and social isolation are risk factors for HF. One study examined the reason for why low socioeconomic status leads to a greater prevalence of heart disease and found that 4% of the differences were accounted for by smoking and hypertension, whereas 30% was accounted for by alternative risk factors such as low job control and depression [33]. In addition, a variety of biomarkers and genetic factors identify patients who are at high risk of HF. Biomarkers include natriuretic peptide and ultrasensitive troponin levels. Genetic factors from single Mendelian mutations to genetic polymorphisms are also associated with HF [34].

As the prevalence of HF continues to increase, it is necessary to efficiently impede its occurrence and to address the global burden of this condition. More needs to be done to improve identification of those at risk, modify risk factors that contribute to HF pathogenesis at both the individual and population level, and to better understand the interactions of age, sex, and race in order to not impair existing differences. Furthermore, progress in understanding the etiology, epidemiology and pathophysiology of HF will not only better advance the treatment of HF patients, but also allows for improved preventive and management therapies.

Heart failure management

Management, including both diagnosis and treatment, starts at the point of first medical contact (FMC), defined as the point at which the patient is either initially assessed by a paramedic or physician or other medical personnel in the pre-hospital setting. A working diagnosis of HF must first be made [33], although difficult, especially in the early stages. Several criteria for HF diagnosis have been proposed, including the Framingham criteria [36], the Boston criteria [37], and the European Society of Cardiology criteria [38]. All the above require factual evidence of cardiac dysfunction, rely on similar indicators of symptoms, and combine data from systematic diagnosing. This includes detailed medical history, physical examination that involves Valsalva's maneuver, laboratory tests, and diagnostic tests such as the electrocardiogram (ECG), chest radiographs, echocardiography, magnetic resonance imaging (MRI), and computed tomography (CT). In particular, ECGs and echocardiograms are among the most important diagnostic tests where the data provided by these tests enable a preliminary working diagnosis and treatment strategy for HF patients.

Once the diagnosis of HF is established, additional classification requires the assessment of the treatment process which depends on HF severity. Despite major advances in pharmacology, medical devices, and surgical treatment of HF, mortality and morbidity remain considerably high. Accordingly, a need for better prevention and treatment management continues to stimulate scientists and engineers to investigate new technologies [39]. To effectively achieve this requires employing an array of therapeutic options including the best of biomedical technology as well as complementary care and treatment. Typical options consist of a combination of pharmacologic and non-pharmacologic therapies where each modality presents challenges for certain patient types. Management strategies complementary to pharmacologic therapies, which would enhance quality of life without posing an economic burden will attract attention. These strategies include exercise training of deconditioned skeletal musculature essential to ambulation [40]; nutraceuticals that correct deficiencies of macronutrients and micronutrients, including hypovitaminosis D, which contributes to muscle weakness and is common in housebound patients deprived of sunlight because of their symptomatic failure [41]; physical activity as appropriate, and consideration to weight gain; and thermal therapy, wherein heat and cold are utilized to improve circulatory function and promote dietary salt and fluid secretion.

Advancement in prevention techniques would lead to decreasing incidence of HF while improvement in medical care would lead to improved survival. Both incidence and survival in turn play a major role in increasing the burden of hospitalization among patients living with HF. A good understanding of this conceptual framework is required to recognize the HF epidemic and design strategies to manage it. While the importance of primary prevention measures aimed at delaying or preventing the onset of HF is obvious, HF rehabilitation is mainly involved with secondary prevention which relies on early detection of the disease process and an application of interventions to avoid its advance. These interventions may include, in addition to education, counseling and behavioral strategies to promote lifestyle change, modifying risk factors, and introducing non-pharmaceutical treatment modalities like thermotherapy.

Thermotherapy for rehabilitation of heart

"Thermo" refers to heat that changes the body temperature therapeutically to produce a hemodynamic effect. Thermotherapy includes all therapeutic treatments based on the transfer of thermal energy into or out of the human body. In clinical settings, the major objective of thermotherapy is to achieve an effective treatment outcome with minimal impact on intervening and surrounding tissues [42,43]. It consists of relatively small changes in the core body temperature occasionally for therapeutic purposes [44,45].

Thermotherapy may involve the application of heat or cold for the purpose of changing the cutaneous, intra-articular and core temperature of soft tissue with the intention of improving the symptoms of certain conditions [46]. It may be used for therapeutic purposes as well as in rehabilitation facilities or at home. For instance, heat improves blood circulation, enhances healing, increases soft tissue extensibility, decreases joint stiffness, and controls pain. Increased blood flow facilitates tissue healing by supplying protein, nutrients, and oxygen at the site of injury. While cold will numb the pain, decrease swelling, constrict blood vessels and block nerve impulses to the joint [47], deep heating is thought to minimize nerve sensitivity, increase blood flow, boost tissue metabolism, decrease muscle spindle sensitivity to stretch, and cause muscle relaxation [48]. For example, a 1°C increase in tissue temperature is associated with a 10% to 15% increase in local tissue metabolism [49].

Heat may be delivered to tissues via conduction, convection, or radiation [50]. The extent of initial tissue necrosis is mainly determined by thermal power and energy applied to the tissue [43]. Primary physiological effects of heat include vasodilation and increased blood flow, increased metabolic rate, relaxation of muscle spasm, pain relief via the gate-control mechanism and reduced ischemia, and increased elasticity of connective tissue [51], as shown in **Figure 1**.

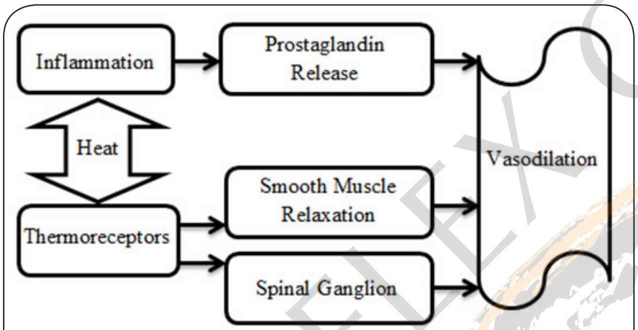

Figure 1. Thermotherapy causes vasodilation.

Several controlled clinical studies have been conducted using heat as a therapeutic modality for cardiovascular diseases such as hypertension, coronary artery disease, and congestive HF [52]. The findings in these clinical studies are consistent with epidemiologic statistics showing that morbidity and mortality from cardiovascular etiology are lower in hot environmental temperatures [53-56].

When considering the potential use of thermotherapy as a therapeutic modality, one may question the safety of this procedure, since HF is a complex disease that is often compounded by other conditions such as coronary artery disease and myocardial infarction [18]. In general, thermotherapy is safe for individuals with a normal skin sensation. When a patient has problems with thermal sensitivity, it could be dangerous in that they cannot feel if they are being burned due to the application. Skin burns may occur, especially in patients with diabetes mellitus, multiple sclerosis, poor circulation, and spinal cord injuries [57]. Another safety concern could be nonionizing electromagnetic (EM) radiative heat. The hazards depend on the ability to penetrate the human body and the absorption characteristics of various tissues. For public and consumer safety, exposure standards for EM energy have been developed by various organizations and governments [43].

Therapeutic modalities for heart

In this section, therapeutic modalities are categorized by source heat transfer modes as follows: conduction (hot pack), conversion (radiant heat), and convection (Finnish sauna, fluid therapy, hydrotherapy). Several aspects decide the level of the physiologic response to heat, including tissue temperature, duration of the tissue temperature change, rate of change in the tissue temperature, and size being treated.

Finnish sauna

The word 'sauna' means 'sweat' in the Finnish language. Since ancient times, saunas have been used for leisure and wellness with a widespread practice worldwide. Most of the time, saunas were powered by building a fire under the sauna, or heating rocks in a fire, which are then carried into the sauna. Today such rocks are heated by electricity.

The application of heat in either a dry or humid environment is commonly used in Scandinavia [44]. In healthy young volunteers, 20 to 40 minutes of moderate sauna bathing is accompanied by a 60% rise in heart rate, an associated rise in cardiac output, and a 40% fall in systemic vascular resistance with variable responses in arterial systolic and diastolic pressures [58-60]. These functional improvements correspond to comparable benefits seen with regular physical exercises. Sauna bathing is a popular recreational activity that is generally considered to be safe.

A traditional Finnish sauna is a combination of overheating the body with hot, dry air (humidity 10%-20%) with a relatively high temperature along with subsequent body cooling by application of procedures involving treatment with cold water. There has been evidence that repeated sauna therapy improves survival in those with HF, suggesting a new potential therapy. It has potential benefits in regards to reducing afterload from vasodilation and salt loss [61]. Laukkanen et al. [62] investigated the association of frequency and duration of sauna bathing with the risk of sudden cardiac death (SCD), fatal coronary heart disease (CHD), fatal cardiovascular disease (CVD), and all-cause mortality. They found that increased frequency of sauna bathing is associated with a reduced risk of SCD, CHD, CVD, and all-cause mortality.

Infrared saunas

The heating effect of infrared saunas is mainly due to radiant heating. It exists in two major types: near infrared and far infrared. Infrared energy as part of the EM spectrum has a shorter wave length than ultraviolet and visible light; therefore, it is undetectable by the human eye. Infrared wavelengths closest to visible light are called near infrared (NIR) and can produce thermal effects 5 to 10 mm deep in tissue. Far infrared (FIR) energy results in more superficial heating of the skin (about 2 mm deep). NIR lamp saunas use incandescent heat lamps which emit energy with a bit of middle infrared. FIR saunas use metallic, ceramic or black carbon elements for heating. As infrared heat penetrates more deeply than warmed air, users experience a more energetic sweat at a lower temperature than they would in traditional saunas.

Beever [63] examined the quantitative cardiovascular benefits from infrared sauna use. The results suggested that infrared sauna use may be beneficial for lowering blood pressure and waist circumference. Heart studies done by the Mayo Clinic [64] found that infrared sauna therapy significantly improved blood vessel functioning in high-cholesterol, diabetes and smoking patients. The therapy was also found to increase circulation, lower blood pressure, lower blood sugar, and help in weight loss. Another study looked at the effects of repeated 60°C sauna treatments on the cardiac arrhythmias in chronic HF patients and found that the treatments were successful [65]. Crinnion [66] showed a growing body of evidence on the clinical use of saunas for therapeutic purposes. Evidence suggests that sauna therapy is an effective and underutilized treatment for a variety of cardiovascular problems. Effectively, sauna therapy increases vasodilation, possibly through increased production of nitric oxide, and enhances left ventricular ejection fraction. Persons with class II, III, or IV chronic HF can experience improvements in chronic HF-related symptoms from just 15 minutes in low temperature FIR sauna sessions, 3-5 times weekly.

Waon therapy

Waon therapy comes from the Japanese words "wa" for soothing and "on" for warmth (so called soothing warmth therapy) [67]. Technically, Waon therapy is an experimental infrared-ray sauna, which is a form of thermal treatment in a dry sauna maintained at a temperature of 60°C. It warms the entire body in a uniformly heated chamber for 15 minutes and maintains the soothing effect outside the sauna for a further 30 minutes. It is a type of healing approach in which the entire body is warmed. This technique was originally developed as a thermotherapy for chronic HF in 1989. It has been studied exclusively by Tei et al. [68] in Japan. Dr. Teihas studied the effect of Waon therapy in more than 400 patients with moderate-to-severe HF including refractory HF. He opened the Waon clinic in 2014. Waon therapy dilates arteries and veins to decrease vascular resistance and reduce cardiac preload and afterload, resulting in an increase of stroke volume and cardiac output to stimulate blood circulation.

Miyata and Tei [69] examined the chronic effects of repeated Waon therapy on HF and found that four weeks of Waon therapy significantly improved symptoms, increased the ejection fraction (EF), and decreased the cardiac size on both the echocardiogram and chest X-ray. They also found that daily Waon therapy for two weeks decreased ventricular premature contractions and increased heart rate variability in patients with HF, implying that Waon therapy improved ventricular arrhythmias.

Diathermy

Diathermy means to heat through. There are three main types of diathermy: shortwave, microwave, and ultrasound. The first two types use energy from the nonionizing radio frequency (RF) part of the EM spectrum, while the third type uses sound waves. In diathermy, heat is generated in the tissue. This promotes blood flow into the treated area.

The initial investigation of the use of RF energy in the body is credited to d'Arsonval in 1891, which showed RF energy that passes through living tissue can cause an elevation in tissue temperature without causing neuromuscular excitation [43]. Diathermy, whether realized using short-wave RF (27 MHz) or microwave energy (434 and 915 MHz), or ultrasound utilizes physical effects and causes a range of physiological responses. Short-waved diathermy applicators employ either a two-condenserplate system or an inductioncoil system. The heating can be targeted by positioning the applicator on the human body correctly [69]. When RF radiation interacts with matter, it can be absorbed, transferring the energy to the medium. The amount of energy that a biological material will absorb from the source depends on the operating frequency, intensity of radiation, and duration of treatment [42].

Diathermy does not overheat the skin but increases the temperature at certain depths depending on the type of source. It may help to relieve pain and muscle spasm and promote vasodilation. The most important physiological response induced by diathermy is the regional increase in blood flow and a proliferation of nutrients and oxygen in the heated region [70].

Diathermy is part of thermotherapy and the rehabilitation process, however, studies on the application of diathermy for HF treatment are not available in the literature yet.

Hydrotherapy

Hydrotherapy or water therapy is an age-old natural medicine practice that involves the use of water for heating and cooling, either internally or externally, to maintain health and for pain relief and treatment. The term encompasses a broad range of approaches and therapeutic techniques that take advantage of the use of water in different forms and various physical properties of water, such as temperature and pressure, for therapeutic purposes in order to stimulate blood circulation and treat the symptoms of certain diseases. Simple forms of hydrotherapy include cold packs, hot towels, pools, and footbaths.

Many studies have shown that hydrotherapy is a useful technique for improving quality of life in HF patients. Michaelsen et al. [71] found that a thermal treatment program improves quality of life, HF-related symptoms and heart rate response to exercise in patients with mild HF. Another study found that physical training in warm water improved exercise capacity and muscle function in patients with HF [72].

One technique of hydrotherapy involves warm water immersion of the patient's body in a semi-recumbent position at a water temperature of 41°C [73]. Another technique was reported by a German research group that investigated home-based hydrotherapyin patients with New York Heart Association (NYHA) class II (mild) or III (moderate) HF. In this form of hydrotherapy, patients receive warm peripheral baths to a maximum of 40°C followed by the application of cold baths with a temperature of <18°C. This process was repeated three times a day for six weeks. The study resulted in clinically measurable improvements in HF and good patient compliance [71]. Tei et al. [74] assessed the effects of warm water immersion (41°C swimming pool) and found an improvement in hemodynamics in patients with HF.

Therapeutic hypothermia

Therapeutic hypothermia (TH) or cryotherapy is the process of using cold (lowering core body temperature to between 32°C and 34°C) to achieve therapeutic results. TH may be administered through systemic cooling (by surface or invasive techniques) and also via selective surface cooling. In a rehabilitation context, hypothermia withdraws heat from the body through the use of mild superficial cooling agents. When cold is applied to the skin, heat is removed or lost. This is referred to as heat abstraction. TH is used to control pain, edema, and inflammation to enhance movement and to attenuate spasticity.

The therapeutic effect of cold generally occurs through the actions on metabolic, neuromuscular, and hemodynamic processes [50]. The most common modes of heat transfer with cold application are conduction (cold packs, ice massage, cryopressure garments combining cold with compression, bags of frozen corn), convection (cold whirlpool immersion, contrast baths) and evaporation (vapocoolant sprays). The greater the temperature gradient between the skin and cooling source, the higher the resulting tissue temperature change.

TH is a recommended therapy for cardiac arrest and may be of value in terms of public health. The use of moderate hypothermia after cardiac arrest was initially reported in the late 1950s and early 1960s [75,76]. There were no further investigations conducted on hypothermia as a resuscitative measure until the 1990s, when laboratory studies demonstrated the benefit of mild hypothermia [77-80]. These studies led to the preliminary clinical research on mild hypothermia. Preliminary clinical studies have shown that patients treated with mild hypothermia after cardiac arrest have improved neurologic outcome, without noticeable side effects, as compared to the outcome in historical controls [81-84]. Recently, Young et al. [85] hypothesized that TH can be used to improve survival and reduce neurologic injury in adult patients with HF post-arrest. In this retrospective study, the investigators reported a series of five patients with complex HF who presented with sudden cardiac death and were treated with TH.

Complications of cryotherapy include nerve damage, frostbite, Raynaud's phenomenon, cold-induced urticaria, and slowed wound healing [46].

Contrast therapy

Contrast therapy (treatment that alternates between heat and cold) is commonly used in rheumatic conditions and regional pain syndrome [46]. The applications of therapeutic heat and cold utilize thermal energy to produce a local and occasionally generalized heating or cooling of superficial tissues with a maximum penetration depth of 1 cm or less [51].

Hot and cold contrast therapy is based off the principle that heat expands and cold contracts. When a human body is in a heat element, such as a Jacuzzi, blood vessels dilate and nutrient rich blood is able to flow throughout the body. When jumping into acold element, blood vessels constrict, driving blood to the body's core, and bringing nutrients to the organs. By alternating between hot and cold, the blood vessels act as a pump, squeezing nutrient rich blood into the body and pumping out any waste products. One treatment approach may involve a 3:1 or 4:1 ratio (hot to cold) for approximately 30 minutes. In subacute conditions, the treatment starts and finishes in cold prior to beginning therapeutic exercise. In chronic conditions, treatment is more often finished in the warm condition.

Continuous low-level cold and heat are newer concepts in thermotherapy. Cold and hot treatments have opposite effects on tissue metabolism, blood flow, inflammation, edema, and connective tissue extensibility. Cold decreases these effects, while heat increases them [46]. Using contrast heat and cold therapy increases the temperature of the body which helps increase muscle elasticity and reduce muscle tightness and soreness. Since the blood vessels are open and pumping more blood, there is also more oxygen flowing through the body, therefore increasing heart rate [86-88].

On risk and safety, heat and cold may harm the human body and its physiological processes in several ways. The main concern is a change of the body's core temperature beyond a healthy range. Horning and Guhde [89] advise patients to avoid exposure to extreme cold, which can be associated with rebound swelling or chapping of skin, and to keep away from prolonged (>15 minutes) exposure to heat, particularly hot tubs and saunas.

Contrast therapy, although having a long history of use in sports medicine, remains inadequately researched for HF. Therefore, it may be possible that the same mechanism can be used to help relieve symptoms of HF. It is an exciting new area that warrants engineering and clinical investigation with pilot trials. For example, semiconductor thermoelectric cooling (TEC) technologies or Peltier cooling modules can provide quiet and reliable solutions for contrast therapy without a need to use moving parts or liquids. While typically used for cooling, they can also be used for heating by reversing the electric current flow. Such modules can cyclically heat and cool an area of the human body, such as the chest. They are physically flexible, home-user affordable and controllable, and variable in operating parameters.

Thermoregulatory modeling

Thermoregulation is an elaborate feedback control system to maintain internal human body temperatures near a physiological set point under a wide range of surrounding environmental conditions and metabolic rate activities. The thermoregulatory response is evaluated by knowing the temperature of the human body core and skin and comparing them with reference values. Based on this approach, thermoregulation models can be developed to design systems that interact thermally with the human body (such as therapeutic suits or vests) without compromising health and safety.

Bioheat transfer

Bioheat transfer is the study of the transport of thermal energy in living systems. Because biochemical processes are temperature dependent, heat transfer has a major role in living systems. Conduction, convective and conversion heat transfer (whether the purpose is heating or cooling) via the blood flow, local generation of thermal energy, and thermal boundary conditions comprise the major control of the thermoregulation process. Once bioheat transfer mechanisms are understood, they can be combined to create mathematical models to simulate and predict thermoregulatory behavior which have significant applications in biomedical engineering and therapeutic procedures involving either raising or lowering temperature.

The human body bioheat transfer may be modelled using a combination of passive and active systems. The passive system consists of transport in arteries and solid tissues, and the active system is the thermoregulatory part of the model that keeps the body temperature within a determined limit. Pennes [90] proposed a model that describes the impact of metabolism and blood perfusion on the energy balance within living systems. These two effects were incorporated into the standard thermal diffusion equation to generate a simple analytical form.

$$pc\frac{\partial T}{\partial t} = \nabla \bullet \left(k\nabla T\right) + \dot{q}^{m} + \omega\rho_b c_b\left(T_a - T\right) + Q_{met} \quad (1)$$

Where q^m is the metabolic heat source rate in W/m^3, ω the volumetric flow rate of blood per volume of tissue in s^{-1}, and Q_{met} is metabolic heat generation. In this model, blood enters the capillaries at the temperature of arterial blood, T_a, where heat exchange occurs to bring the temperature to that of the surrounding tissue, T. The total energy exchange between blood and tissue is directly proportional to the density, ρ_b, specific heat, c_b, and ω. This model is analogous to the process of mass transport between blood and tissue, which is confined primarily to the capillary bed. Limitations include its restriction to steady state conditions. The Pennes model has been a reference for predicting temperature distributions in living systems for more than half a century. Weinbaum and Jiji [91] developed another model following Pennes model that takes into consideration the heat transfer between tissue, arteries, veins and skin. A combination model that applies the above two models would be most appropriate for simulations of bioheat transfer in perfused tissue [92].

The bioheat transfer models for a human body may be divided into lumped, multi-dimensional, and segmented models. The lumped models are simple as they treat the human body as a single point with temperature change allowed only in time. Since the thermoregulation effects and heat transfer processes within the body are not accounted for in this model, its application is limited. Three-dimensional models represent thermal changes in a human body close to reality but are, however, difficult to apply. Therefore, the segmented models that consider various biological and physical processes may be the preferred models [93]. Investigators have considered alternative models to describe whole-body heat transfer, from just two nodes describing core and periphery (for example, Gagge [94]) to multi-segmented, multi-layered models. Gagge [94] proposed a two layer lumped model by balancing the energy of the core and skin to predict thermal comfort. The model is catered for moderate activity levels and uniform environmental conditions but neglects to describe heat exchange for blood vessels, and variation in clothing resistance. Stolwijk [95] developed a model setting a total of 25 segments representing the head, trunk, arms, hands, legs and feet, with the twenty-fifth node representing the central blood. Each segment is divided into four concentric lumped layers representing the core, muscle, fat and skin. This model predicts the absolute and tendency values in transient mean skin temperature under low activity [96]. Wissler [97] built an extension of the Pennes model with conductivity due to blood flow. The model consists of 15 elements connected by a vascular system. The vascular network is composed of arteries, veins, and capillaries and the blood temperatures are assumed to be uniform. Arteries link the heart to the arterial pool of each element and further into the capillaries. From the capillaries, the blood circulates to the venous pool of the element and back to the heart but the model does not take in consideration the axial variation and local mean temperature [98]. Fu [99] used a three dimensional finite element method to develop a model that includes heat exchanged by perfusion in tissue. The model is designed to account for non-uniform and non-symmetric environmental conditions for each of the body element. However, it ignores the effect of pulsating blood flow in large arteries. Like human models, modeling a clothed body is also a challenge. Henry [100] modeled pieces of clothing by assuming a one dimensional flow, where heat flow occurs along the thickness of the fiber. Farnworth [101] builds on Henry's model by deriving a model for the transport of heat (conduction and radiation) and water vapor (diffusion) transport in a multi-layered clothing model.

Jones [102] worked off of Farnworth's model to mathematically formulate heat and mass transport. The model includes the phenomenon of sweat secretion on the skin and assumes negligible moisture between fibers. The author was able to accurately calculate the vapor pressure and the rate of moisture accumulation at the skin.

Modeling for design

From the above review, it may be noted that the Pennes model could be considered a starting point to design and build a therapeutic system. In general, there are three engineering parameters to consider when designing such a system. The first parameter is the amount of local volumetric heat generation, the second parameter is the shape of the heating field, and the third parameter is the depth of penetration.

In order to create a detailed bioheat transfer analysis, a more sophisticated set of equations is needed. The two segment models return core and skin temperatures but no regional temperatures. The multi-segmented models are simple enough to be integrated to clothing models however input blood perfusion is taken as a constant. The finite element models are found to be the most accurate as they include further details of the human body anatomy, however the input blood perfusion is also taken as a constant.

A multi-segmented model could be used as a starting point for a nude young human adult. This model is proposed by Salloum et al. [103] and is designed to predict thermal and regulatory responses within human body segments and the environment. The model is based on the assumption that blood flow is the primary method of heat dissipation in the human body. To begin, the arterial system is divided into 128 segments representing the main and peripheral arteries. The blood going from the arteries to the capillaries is divided into blood flowing in the core and the skin. The blood entering a segment is divided into blood flow to the skin and blood flow to the next segment as shown in Figure 2. Olufsen et al. [104] modified the model proposed by Salloum et al. [103] by replacing the impedance of peripheral arteries with one calculated and assuming artery trees, which end with a minimum artery radius of 0.03 mm.

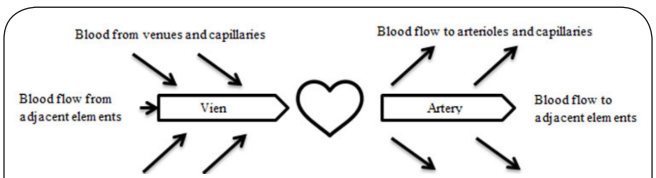

Figure 2. Heat exchange in arteries and veins.

Avolio [105] built another model that is used to determine the blood through all the different segments by modeling the flow resistance in each element. The input to the model is a standard cardiac ejection waveform. The segments are grouped into 15 body parts. Each of the body parts are considered to have a uniform temperature. The mathematical formulation is based on heat exchange through convection, conduction and perfusion in each of the body segment's four nodes; core, skin, artery and vein.

Based on appropriate modeling, authors are currently engaged in developing a controlled contrast therapy test bed that operates at a wide range of temperatures by using solid-state TEC technology. Although this technology is mostly used for cooling, it can also be used for both heating and cooling under controlled conditions, providing the comfort of avoiding the use of motors and liquids in the system. A multi-segmented human model with a proposed vest for contrast therapy is shown in Figure 3.

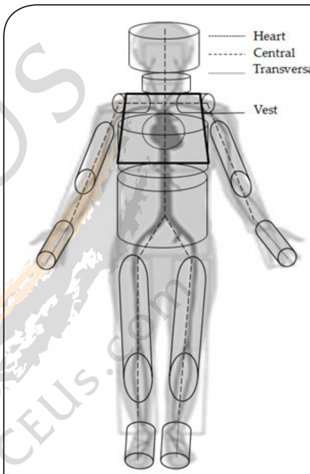

Figure 3. Multi-segmented human model with vest for contrast therapy.

The systemic blood circulation is subdivided into large and small vessels to investigate the temperature changes in subcutaneous and intramuscular tissue during a 30-minute cold- and hot-contrast therapy session.

Concluding remarks

HF is a staggering clinical and public health concern. It is, and will continue to be a substantial burden on health care systems and societies. In this article, research work on epidemiology, public health, and risk factors associated with HF have been reviewed. A rationale for the use of heat and/or cold as a treatment modality for HF was presented. Advancement in bioheat transfer modelling coupled with improvements in delivery techniques will have an impact in the design and analysis of a thermotherapy system (such as suits or vests) that deliver controlled heat and/or cold to the human body.

Conclusion

Thermotherapy in general and contrast therapy in particular are not yet fully developed modalities. There are still challenges in their routine clinical application, and there is still room for further improvements. However, the development of contrast therapy is a viable example of an effective research and clinical program that is clearly important and from which physicians, physical therapists, engineers, and patients will benefit.