생활과학박사학위논문

Prediction of Heat Strain by Heart Rate for Firefighters in Protective Clothing

보호복 착용 시 심박수를 이용한 소방관의 서열 부담 예측

2018년 8월

서울대학교 대학원
의류학과
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Prediction of Heat Strain by Heart Rate for Firefighters in Protective Clothing

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August 2018

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Abstract

The current study aimed to design simple physiological heat strain models and criteria which can be used in real-time monitoring system of firefighters' health to prevent heat-related illness on the line of duty. Heart rate was chosen as the main predictor because of its simple instrumentation and popularity. The study consists of two parts: First, an investigation on the actual frequency of Korean firefighters' heat-related illness and influential factors aggravating heat strain. Second, development of heat strain models mainly using well stabilized resting heart rate. In the second part, potent additional variables were searched along with a series of validity tests in various conditions.

In the first part, nationwide survey on Korean firefighters' heat strain was conducted (N=674 in total). It was revealed that firefighters routinely experienced mild heat-related illness (HRI) symptoms. Among firefighters, 74.8% of them experienced HRI symptoms, and 5% of firefighters experienced more than 30 times of muscle cramps, headache in a year. Also, these firefighters experience more than 40 times of dizziness and more than 50 times of nausea. Nevertheless, majority of firefighters (98.5%) did not report those experiences because they have always done that. Firefighters' heat strain was aggravated by short duration of rest and inefficient cooling practices during the rest periods. However, the primary difficulties to meet the sufficient rest were: 1) Firefighters were pushed to re-start working in emergent situations. It can be contributed by lack of personnel and rehabilitation system, 2) Self-identified physiological restoration commonly used by firefighters (41%) cannot work well in detecting their heat strain especially for the heat-acclimatized group like firefighters. The following step was carried out to develop an easy physiological method to replace firefighters' self-diagnosis of heat strain and to facilitate real-time heat strain monitoring system.

The second part was prediction of rectal temperature by well stabilized resting heart

rate (rHR). Stabilized heart rate was used because heart rate for initial 1-2min after exercise is drastically changing and is affected by physical exertion. Three models were presented: Model 1 for the prediction of rectal temperature (rT_{re}), Model 2 for the prediction of increase in rectal temperature during exercise (ΔT_{re}) for duration time of t, and Model 3 for the prediction of rectal temperature at the end of exercise (eT_{re}):

Model 1: $rT_{re} = 36.36 + 1.3 \times 10^{-4} \times rHR^2$ (Marginal R^2=0.8, 95% PI: 0.61°C)

Model 2A: $\Delta T_{re} = = -0.71854 + 0.00535 \cdot rHR + 0.05173 \cdot t$ (Marginal R^2=0.865)

Model 3A: $eT_{re} = rT_{re} + \Delta T_{re}$ (Pseudo-R^2=0.716, 95% PI: 0.54°C)

From this model, resting heart rate criteria was suggested, which allowed firefighters to evaluate the current heat strain and it also provided precautionary criteria by predicting the future heat strain after working. For example, the resting heart rate of 110 bpm corresponds to 37.9°C (95% PI 0.6°C), but it can also indicate that rectal temperature can reach to 39.2°C after additional 20 min work. Thus, the firefighter need to rest more. On the other hand, resting heart rate of 90 bpm was acceptable level not to induce heat illness after 20 min firefighting. The models were verified under the following environmental settings: ambient temperatures within 25-32°C, wearing full firefighter's clothing and gears (9-15 kg; the helmet, hood, and gloves removed during all post-exercise rest periods) and work load of 50-80 %$\dot{V}O_{2max}$. However, it was noted that the models would significantly underestimate heat strain during recovery with cooling measures including removing turnout gear in a cool weather (~21°C). We expect that this study can help to understand Korean firefighters' heat strain, and the results could contribute to actualizing a real-time heat strain monitoring system of firefighters with the assistance of development in smart wearable products which collect heart rate.

Keyword: occupational environment, real-time heat strain monitoring system, heat index, heat-related illness, body core temperature

Student Number: 2015-30452

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List of Abbreviations

AIC	Akaike's Information Criterion
A_D	Body surface area which was calculated by Hardy and Dubois's equation (ref) (m^2)
A_D/mass	Ratio of body surface area to body mass ($m^2 \cdot kg^{-1}$)
BIC	Schwarz's Bayesian Information Criterion
BF	Body fat (%)
BMI	Body mass index
CI	Confidence interval
CTEP	Cardiac Thermal Extra Pulse
ΔT_{re}	Change in rectal temperature (°C)
eTre	Rectal temperature during exercise (°C)
F	Firefighter in Table 3.3
FF	Experimental condition that subjects wore turnout gear in Test D
HR	Heart rate (bpm)
HRC	Heart Rate Capacity
HR_{max}	Maximal heart rate collected at a maximal graded test (bpm)
HR_0	Resting heart rate (bpm)
$HR_{0corrected}$	Corrected resting heart rate (bpm)
HR_T	Heart rate during a break in work after heart rate components contributed by static exertion and muscular work have disappeared (ISO 9886, 2004) (bpm)
HRo	Cardiac cost of the work calculated by the difference of mean HR at work minus rest HR (bpm)
HRI	Heat-related illness
HRI*	Heart Rate Index in Table 2.1
HTT	Heat Tolerance Test
LoA	Limit of agreement
Marginal R^2	Coefficient of determination that explains fixed-effects variance in the mixed-effects model
M.D.	Model development in Table 3.4

N.A.	Not available
Non-F	Non-firefighter
Pseudo-R^2	Squared correlation coefficient which explains the agreement between prediction and observation
P_1	Heart rate at 1 min after exercise (bpm)
P_2	Heart rate at 2 min after exercise (bpm)
P_3	Heart rate at 3 min after exercise (bpm)
P_4	Heart rate at 4 min after exercise (bpm)
P_5	Heart rate at 5 min after exercise (bpm)
PI	Prediction interval
PPE	Personal protective equipment
R^2	Coefficient of determination
RH	Relative humidity (%)
rHR	Stabilized resting heart rate collected all rest periods (bpm)
rTre	Rectal temperature during (°C)
S	Student in Table 3.3
SCBA	Self-contained breathing apparatus
s.d.	Standard deviation
s.e.	Standard error
SI-HR	Strain Index for Heart Rate
SW	Sportswear condition in the Test D
t	Duration of a single work in Model 2 (min)
T_{110}	Rectal temperature when resting heart rate is 110 bpm (°C)
T_{120}	Rectal temperature when resting heart rate is 120 bpm (°C)
T_{130}	Rectal temperature when resting heart rate is 130 bpm (°C)
T_{air}	Air temperature (°C)
T_{or}	Oral temperature (°C)
T_{re}	Rectal temperature (°C)
T_{re}.HTT	Rectal temperature at the end of exercise during HTT, the criteria (°C)
$\overline{T}_{sk}$	Mean skin temperature (°C)
VO_{2max}	Maximal oxygen consumption (ml·min^{-1}·kg^{-1})

Chapter 1. Introduction

The early report by the World Health Organization (1969) have already documented a potential role of heart rate as a heat strain index for workers. However, despite many attempts to develop useful heat indices using heart rate, it is still a challenging issue to utilize heart rate in monitoring real-time heat strain in a working environment. ISO 9886 (2004) noted that heart rate can be used as heat indicator, but further information for application was not explained. A report published by NIOSH in 2016 on the heat exposure in the occupational environment also indicated that heart rate can be used to evaluate heat strain, but the report did not describe detailed methods including their accuracy and validity. For over half of a century, it has been widely believed that heart rate can be a heat strain indicator, and many attempts have been conducted to develop such methods. Nevertheless, it is still challenging to find a heat index or model whose validity were approved in the academia.

Today, the need for the valid method to predict heat strain by heart rate has been even increasing. Emergency workers such as firefighters have been suffering from heat-related illness (HRI). Moreover, climate change becomes another potent threat to them (Lundgren et al., 2013). At the same time, drastic development and popularization of the smart wearable technology are accelerating the actualization of real-time heat strain monitoring system. Development of a valid heat strain model using heart rate is the determinant to make it come true.

This study was started from a question on a practical way to predict heat strain by heart rate to prevent deaths and injuries during firefighters' duties. Focusing on heart rate as a primary predictor, we designed to only use well stabilized resting heart rate which can be collected at least 3 min after termination of exercise because heart rate during rest periods can be more readily and stably collected with a minimized intervention by physical work load and other emergent situations during duties. This study consists of two parts: First, nationwide survey on Korean firefighters' heat strain. Second, a development of heart rate models including finding additional individual predictors and validity tests in different conditions.

In the first part, through the nationwide survey, it was asked about the actual frequency of HRI symptoms on the line of duty to estimate the danger of heat strain of Korean firefighters because there have been limited information on detailed statistics on Korean firefighters' death and injuries. Factors which can aggravating firefighters' heat strain were also investigated.

In the second part of this study, predictive models were developed in three forms. A predictive equation of rectal temperature to resting heart rate was developed (Model 1). Another two predictive equations were about the increase in rectal temperature during exercise (Model 2) and at the end of exercise (Model 3). Then, Model 3 was used in calculating safety criteria of resting heart rate. It was hypothesized that: 1) resting heart rate can function as a valid single predictor for rectal temperature. 2) Difference in work load would not significantly affect the model validity. To augment the accuracy, individual differences causing systematic errors were analyzed. In the last part, validity tests were conducted in various conditions to suggest appropriate environments and conditions where developed models can be validly used.

By going through these research steps, it was intended to arouse social concerns regarding Korean firefighters' excessive heat strain and to suggest a better way to manage it. This study aimed to develop the methods specially for a practical purpose.

Chapter 2. Theoretical Background

2.1. Firefighters' Heat Strain

Firefighters' heat strain during duties is mainly caused by high ambient temperature and radiant heat, intensive work load, and the heavy and impermeable protective clothing (Barr et al., 2010). Ambient temperature at which firefighters have routinely exposed ranged 38°C to 66°C (Abeles et al., 1973), and the energy cost of common firefighting tasks corresponded to 55~82%VO_{2max} (Lemon & Hermiston, 1977). Typical firefighting ensemble together with PPE weights approximately 26kg (Barr et al., 2010). This clothing imposes additional physical burden on them (Dorman and Havenith, 2009) and disturbs heat dissipation by encapsulating the entire body. Under such conditions, rectal temperature can increase up to 39.0°C within 40 min in air temperature of 35°C with heavy work and full firefighters' PPE (McLellan and Selkirk, 2006). During simulated firefighting drills, rectal temperature increases from 37.4°C to 38.5°C after just three times repetition of about 6 min circuit (Kim and Lee, 2016).

However, the allowable range of body core temperature is very limited, especially for the increase, and elevation of body core temperature can cause heat-related illness (HRI). Milder forms of HRI, such as heat exhaustion and heat cramps can be occurred when the body core temperature increased more than 38.5°C, but the specific threshold temperature varies by individuals' heat tolerance. Although the damage of mild HRI is not severe, appropriate treatments should be immediately given to prevent its turn to severe forms of HRI, such as heat stroke. Dissimilar with the mild HRI, heat stroke can evoke fatal damage to the central nervous system, which can also cause deaths unless immediate and appropriate treatment is provided. In the United States, firefighters' fatalities related to heat stroke was 255 in total over a 10 year period, and the occurrence of HRI in firefighters was the second highest among various occupations over a 10 year span (Bonauto et al., 2007). Even though HRI does not directly cause irreversible injury or death, it can deteriorate their performances and be related to other disease or injuries (Razmjou and Kjellberg, 1992; Razmjou, 1996, Kales et al., 2007).

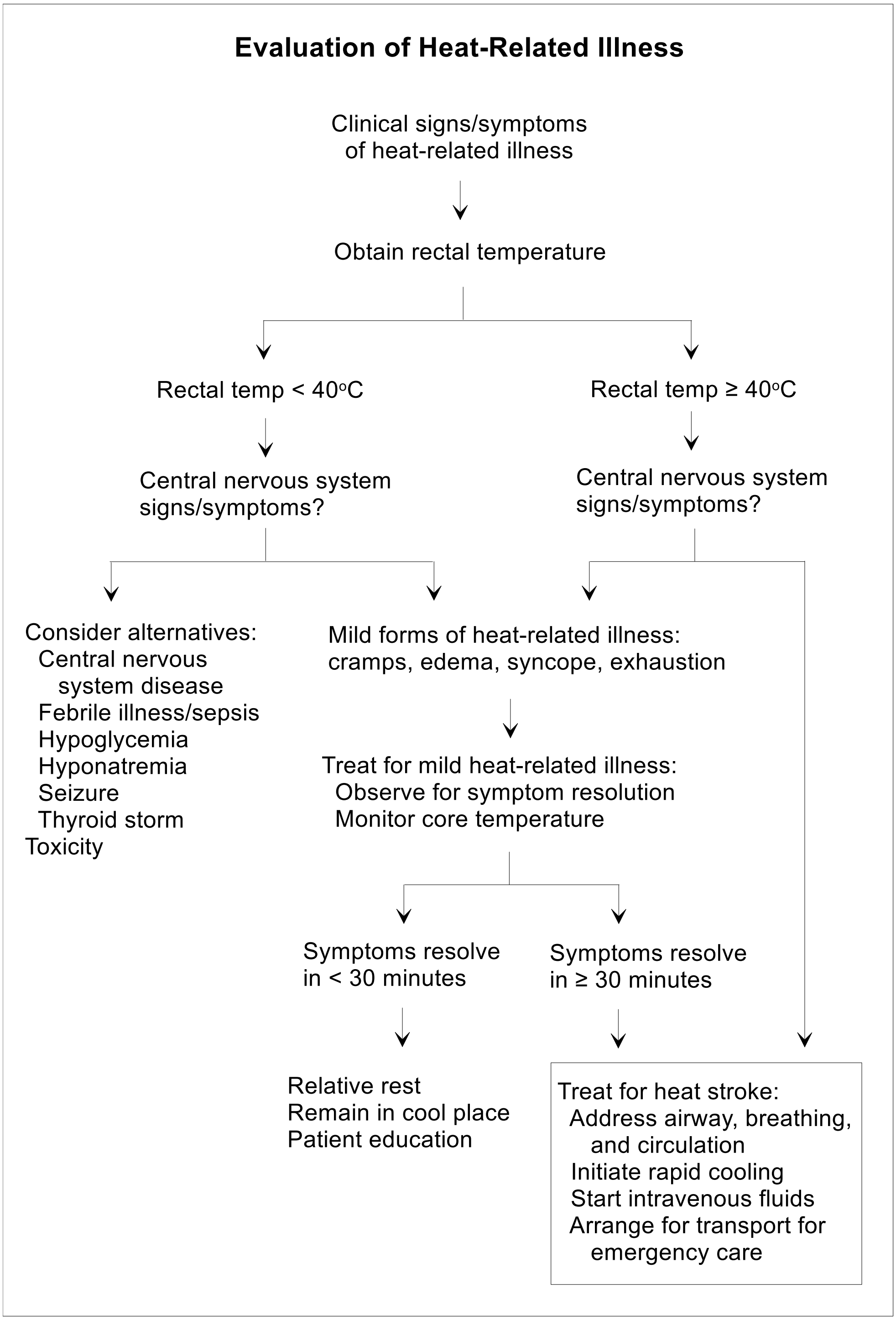

Figure 1.1. Algorithm for the initial evaluation of a patient with suspected heat-related illness (re-drawn from Becker and Stewart, 2011).

In a diagnosis of HRIs, rectal temperature is the most reliable criterion symptoms (Figure 1.1), but it can be self-noticed in an initial stage by following symptoms: dizziness, nausea, vomiting, confusion, syncope etc (Buchama and Knochel, 2002; Becker and Stewart, 2011). Because it is very difficult to immediately measure rectal temperature without assistance by medical personnel, a rapid response to these symptoms including cooling strategies can prevent HRIs from progressing to heat stroke.

However, it is not always easy to initiate appropriate and sufficient treatment right after detecting HRI symptoms in the case of firefighters. Although the limited capacity of self-contained breathing apparatus requires firefighters to come out from fire scenes every 30-60 min (Lee et al., 2015), they are often regularly obliged to re-enter fire scenes during long emergency events until completing fire suppression without sufficient rests between work bouts (Young et al., 2014).

Also, there are other difficulties in preventing HRI during firefighting. First, firefighters can experience HRI without any physiological notice because thermal sensation and perceived exertion is not always parallel with the physiological heat strain (Walker et al., 2015). This is the reason why more reliable indices to evaluate firefighters' heat strain are required. In addition, recognition of the HRI symptoms is only available after the occurrence of HRI. In this light, preventive methods should be preferentially considered than the methods after the events. Second, it is difficult to find the most appropriate method which is not only reliable, but also practical. Regarding the heat indices, it will be more described in the next session (2.2).

To prevent firefighters' HRI, efforts such as improvement of physical condition, heat-acclimatization, sufficient hydration, and proper rehabilitation should be practiced during rest periods. Incident scene rehabilitation was defined as 'an intervention to mitigate the physical, physiological, and emotional stresses of firefighting to improve performance and decrease the likelihood of on-scene injury or death (Smith et al., 2015). Rehabilitation includes active and passive cooling, rehydration, calorie and electrolyte replacement as well as medical monitoring to ensure firefighters' health condition. NFPA 1584 stated that rest and recovery time should be more than 10 min after the 1st use of self-contained breathing apparatus (SCBA) and more than 20 min after the 2nd use of SCBA. However, the minimum resting time is hard to generally used in other fire scenes because the recovery rate varied by the weather, cooling measures, hydration, and individuals. Specific duration of rest can cause inefficiency in case of cold weather and firefighters rapidly recovered, whereas it can also cause dangers of excessive heat strain in case of hot weather and firefighter who could not be sufficiently rehabilitated during the rest periods. For this reason, physiological criteria about the rest time can augment the efficiency of work cycle in the fire scenes and also help firefighters can take enough rest by suggesting individualized rest time.

2.1.2 Korean Firefighters' Heat Strain

The greatest problem regarding Korean firefighters' heat strain is that there is a lack of information. Although it was not well known to other people, one Korean firefighters died in the line of duty in 2013 after prolonged firefighting in summer. Despite this evident accident depicting extreme heat strain of Korean firefighters, we still hardly know how many times firefighters today, and in which conditions HRIs often occurred in Korea. There is no possible way to get information on firefighters' death and injuries caused by HRI on the duties. Government reports do not explain the detailed contexts on firefighters' fatalities except the brief situations and categories of the death and injuries.

Also, monitoring firefighters' heat strain and management of that have not been well implemented in Korea until now. According to Article 22 of the firefighters' health and safety management regulations in Korea, commanders should inspect firefighters' physical health condition every shift to refrain from continuing their work with health problems. However, there is no additional description about the specific way to monitor firefighters' health condition, so now it depends on a subjective way and their heat strain is often neglected from the checklist because it is not easily diagnosed by naked eyes. The fundamental problem especially regarding heat strain is that heat strain is non-visible, dissimilar with trauma. We do not know how many Korea firefighters suffer from HRI, but we only know that firefighters once died on the line of duties because of HRI in Korea.

Korea is quite hot and humid in summer. The maximum temperature recorded in 2017 was 35.4°C in Seoul and 39.1°C in Kyung-ju. Relative humidity ranges from 60 to 95%RH in July and August. Heat strain can be rapidly aggravated especially in such a hot summer season. The one death on the line of duty in 2013 was also occurred in August after the prolonged firefighting for five hours. There were complex problems in here: firefighting lasted too long, lack of cooling measures, and inspection of the health condition before re-entering the fire scene. To solve this problem of firefighter' heat strain, comprehensive approaches along with development of a simple physiological criterion about the rest times are required.

2.2. Heart Rate Responses under Heat Strain

2.2.1 Physiological Grounds of Heart Rate as a Heat Indicator

Heart rate is the speed of heart beat and expressed as the number of beats per minute (bpm). The origin of heartbeats is the sinoatrial (SA) node which generates the rhythmic pacing discharge. Without any neural or hormonal influences, the SA node pacing rate would be approximately 100 bpm. But, normal resting heart rate ranges from about 46 to 95 bpm (Spodick et al., 1992) because the parasympathetic nervous system is primarily affecting on SA node in a resting state (Klabunde, 2012). Generally, heart rate is the outcome of the combination between sympathetic and parasympathetic nervous system. Activation of the Different types of the sympathetic and parasympathetic receptors on the heart elicit different responses. On the other hand, baroreceptors are located in the aortic arch and detects the change in blood pressure. Activation of these receptors sends action potentials to the rostral ventrolateral medulla (located in the brainstem) via the autonomic nervous system. It adjusts total peripheral resistance by vasodilation through sympathetic inhibition and reduces cardiac output through parasympathetic activation (Gordan et al., 2015). Heart rate is controlled by not only the nervous system but also endocrine system. The hormones such as vasopressin, renin, angiotensin, and aldosterone contribute to water reabsorption for blood pressure regulation (Gordan et al., 2015).

Due to this physiological mechanism of heart rate, it is strongly linked to body core temperature. Generally, heart rate increases under heat stress, which is primarily driven by baroreceptor reflex to compensate for the reduction in arterial blood pressure which was resulted from cutaneous vasodilation (reduction in peripheral resistance). Such a cutaneous vasodilation is also associated with elevations in sympathetic activity and reductions of vascular conductance in the non-cutaneous tissues (Crandall, 2008). According to Crandall and González-Alonso (2010), the increase in cardiac output is primarily mediated by heart rate as stroke volume does not evidently change by such an increase in cardiac output. Heart rate can be well over 100 bpm by a passive whole body-heating with increased cardiac output up to 13 $L \cdot m^{-1}$ (Crandall, 2008). Because the peripheral resistance is mediating the response of baroreflex, thermal stimulation (e.g. passive and active cooling measures) can influence on heart rate (for more description, see the following section 2.2.2.3). Heart rate responses can also vary by various endogenic and exogenic factors, which will be more explained in the next session.

2.2.2 The Factors Affecting Heart Rate

Cardiovascular responses under heat stress can be influenced by various factors because there are numerous factors involved in the autonomic nervous system and the endocrine system. This has been recognized as the most critical obstacle to use heart rate as a valid heat indicator. Valentini and Parati (2009) categorized those factors in two groups: nonmodifiable determinants and physiologic determinants. However, there was a limitation that some between-subject factors such as blood pressure and within-subject factors such as physical activity consisted together in one group, physiologic determinants. This study will also categorize the factors in a same way: 1) within-subject factors (e.g. metabolic rate, mental stress, heat strain and ambient temperature), 2) between-subject factors (e.g. age, physical fitness, and heat tolerance). Among within-subject factors, ambient temperature was additionally included in considering that it can greatly influence on the skin temperature and thus heart rate.

2.2.2.1. Within-Subject Factors

Physical Activity

Physical activity is one of the most influential factors accompanying prominent change in heart rate. Autonomic nervous system has a critical role in regulating heart rate not only during rest periods, but also during and after exercise (Borrenson and Lambert, 2008). It has been known that the initial increase of heart rate is mainly modulated by the parasympathetic withdrawal, while the contribution of sympathetic activity drastically increases at a greater work load with parasympathetic withdrawal continuously affected (Yamamoto et al., 1985). On the other hand, during recovery after exercise, rapid decrease of heart rate is mainly caused by the parasympathetic re-activation and sympathetic withdrawal. In addition to exercise, breathing frequency and verbal activity such as talking and reading behavior also influence on heart rate variability (Bernardi et al., 2000). These responses are associated with a change in respiratory frequency.

Mental Stress

Psychological stress can significantly influence heart rate. The activation of the sympathetic nervous system may critically contribute to this response (Valentini and Parati, 2009). However, there has been long debates on the methodological agreement for the studies regarding the relationship between mental stress and the cardiovascular responses because the results have not been consistent in the different types of mental stress. For example, heart rate responses in the routine daily activities are different between healthy people and hypertensive subjects. Only hypertensive subjects showed a significant correlation between heart rate records in a doctor's visit and those in the speech test. Although in the current study, the psychological effect on heart rate was not considered as a crucial factor, while it could be regarded as a critical problem when predicting heat strain by heart rate in a working place, especially the fire scene where various psychological stressors exist. The psychological effect on heart rate in the working place should be further studied.

Heat Strain

Heat strain can significantly influence on heart rate, but there is limited literature presenting the exact models on the relationship between the heart rate and heat strain. In ISO 9886 (2004), it was documented that the change in heart rate under heat stress can be an indicator of heat strain, but the exact predictive method is not available. There have been several attempts to develop heat indices using heart rate. They will be described more in the session 2.3.

Circadian Rhythm

Heart rate is generally lower during sleeping than during daytime. Jaquet et al. (1998) reported the age difference in the cardiovascular responses when subjects were awakened and during their sleep. They documented that the difference by circadian rhythm was about 14 bpm independent of the age. Aoki et al. (2001) identified a shift of function between rectal temperature and heart rate by time of a day. They displayed approximately 0.5°C higher rectal temperature from identical heart rate in the afternoon compared to heart rate in the early morning. When considering that Korean firefighters are working in three shirts for 24 hours, the effect of circadian rhythm on heart rate can be influential factors on the accuracy of the predictive models of heat strain by heart rate.

Smoking

Many studies have reported that heart rate and blood pressure can be acutely increased by cigarette smoking (Trap-Jensen, 1988). The responses by smoking are associated with decrease in muscle sympathetic nerve activity along with blunted or impaired baroreflex function. Acute hemodynamic and neurohumoral changes can last at least for 30 min after smoking (Grassi et al., 1994).

Ambient Temperature

Ambient temperature can directly affect skin temperature (Kim and Lee, 2016a) because skin temperature serves as a feedforward signal in the thermoregulation system and the skin temperatures promptly and prominently change with the bare skin. Persistent exposure to cool or hot weather can decrease or increase body core temperature, but acute exposure to different climate can also cause acute change in skin temperature, which can also change heart rate via baroreceptor reflex modulation. In the study by Kinugasa and Hirayanagi (1999), the exposure for 20 min in the ambient temperature of 18°C and 40°C caused significant differences in heart rate, when subject wore t-shirts and trunks and rested supine. The intervention of skin temperature in heart rate can be a critical limitation in predicting heat strain by heart rate because firefighters sometimes use cooling measures during their rest periods. It can lead a decrease in skin temperature and in heart rate accordingly despite elevated core temperature. To generalize the use of the predictive models of heart rate in cooling conditions, the effect by skin temperature and application of cooling measures should be elucidated.

2.2.2.2. Between-Subject Factors

Age

Age is significantly associated with decrease in maximal heart rate and resting heart rate (Tanaka et al., 2001; Yamaguchi et al., 2005). Maximal heart rate decreases with advancing age, which mainly mediated by a reduction in the maximal cardiac output. Ageing also affects autonomic nervous activity. It can be contributed by a progressive decrease of intrinsic heart rate, which can be measured without any intervention from both autonomic nervous activities, along with a reduced β −adrenergic responsiveness (Christou and Seals, 2008). Thermoregulation under heat stress also varied by age. Age-related impairments in heat dissipation has been reported in recent study with firefighters (Kenny et al., 2015). In the study, they reported that older firefighters (54.7±2.1 years) stored 40% and 46% more heat than young firefighters in the warm/dry and warm/humid conditions, respectively. Such impaired heat dissipation can be found in the population over 40 years old (Larose et al., 2013) especially in an intensive work load (>400 W). However, impaired heat dissipation depends on individual physical fitness level (Havenith et al., 1995).

Physical Fitness

Regular physical training can result in a reduction of resting heart rate, whereas the maximal heart rate slightly decreases or rather remains unchanged (Borresen and Lambert, 2008). The decrease in the intrinsic heart rate is contributed predominantly by the increased parasympathetic nervous activity and slightly by the decrease in sympathetic activity (Smith et al., 1989).

Heat Tolerance

Heat tolerance is an indicator presenting the physiological adaptability to heat stress, which can be elicited by heat acclimatization/acclimation. This physiological ability can influence on overall thermoregulatory responses including heart rate, core temperature, skin temperature and sweating responses under heat stress (Rowell, 1974). Among them, heart rate is one of the parameters showing the most dramatic changes. It significantly decreases after heat adaption which is accompanied by an increased stroke volume (Rowell, 1967; Wyndham et al., 1968).

Body Morphology

Notley et al. (2016) investigated that thermoregulatory responses varied by body morphology (A_D/mass, mass-specific body surface area). With a greater A_D/mass, the forearm blood flow was greater, whereas the local sweat rates were lower. Although the study did not report heart rate responses, body morphology may be a potent factor influencing heart rate response.

2.3. Heat Indices and Models Using Heart Rate

2.3.1 Measurement of Body Core Temperature and Limitation

Body core temperature does not represent a specific anatomical location but means the temperature of inner tissues which are not vulnerably changed by circulatory adjustments and environmental effect (IUPS Thermal Commission, 2001; Taylor et al., 2014a). Measuring the temperature of the pulmonary artery is considered the best way to represent the average internal temperature of the body, but it requires very difficult instrumentation and procedures with the medical personnel, so core temperature is often measured at the rectum, oesophagus, or tympanic membrane. However, the process involved with installing those sensors also takes time and causes discomfort. For this reason, as a surrogate, oral temperature and ear-canal temperature commonly used in various settings. However, the problem is that the validity of those temperatures is significantly affected by ambient temperature (Doyle et al., 1992) and by the elevated body core temperature also negatively affect the validity and reliability of measurements (Mazerolle et al., 2011). Especially, Mazerolle et al. (2011) evaluated oral temperature as an unsuitable diagnostic tool for measuring body temperature because the accuracy and validity were lowered at the higher body core temperature. Effects by intake of fluid as well as a risk in the use of contaminated sensor in the fire scene should be additionally considered (Bernard and Kenney, 1994) for an application to firefighters' working place.

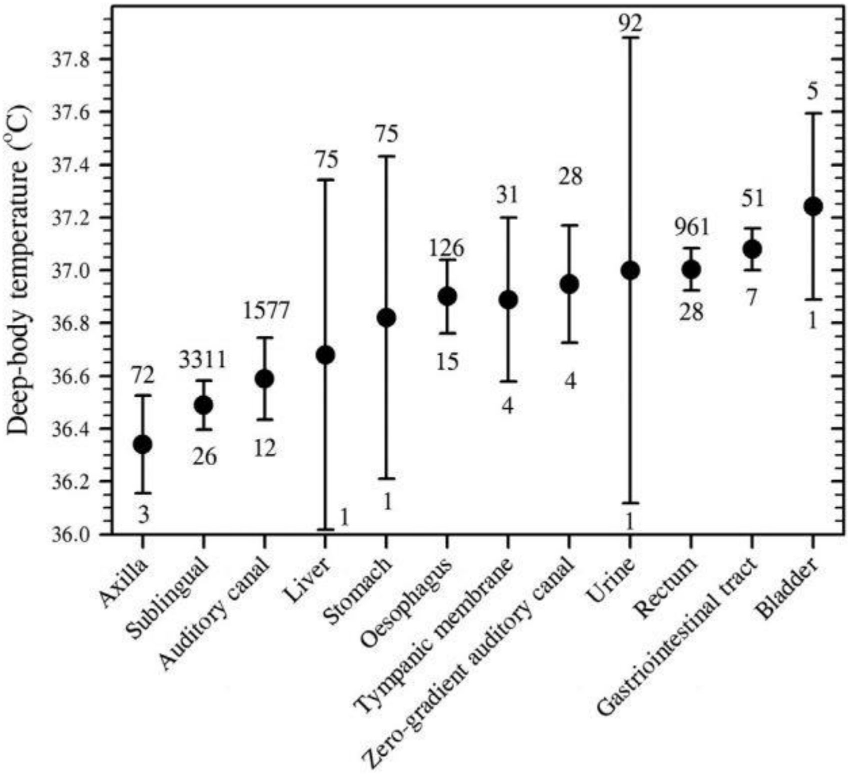

Figure 1.2. Resting body core temperature varies according to the measurement sites. Closed circle showed the means, and bars shows 95% confidence intervals for each total sample (Figure was taken from Taylor et al., 2014a).

2.3.2 Heat Indices and Thermoregulatory Models

Over 70 years, a range over 160 different climatic stress indices have been suggested and more than 100 of them are for heat stress (Havenith and Fiala, 2016). Ideal heat stress models have required to consider all aspects of heat generation of body and all pathways of heat exchange between the body and environment. These methods are accompanied by measuring various parameters such as air temperature, mean radiant temperature, vapor pressure, air velocity, metabolic rate, clothing insulation. Despite the advances in such thermal models and indices, simple climate indices such as WBGT have been still most popular in the field, since ease of use and simplicity are one of the most significant factors for practical use. The recent review paper by Havenith and Fiala (2016) sophisticatedly overviewed various types of heat indices and thermoregulatory models.

2.3.3 Heat Indices and Models Using Heart Rate

Heart rate has been utilized as an indicator of heat strain by great numbers of researchers (Table 2.1). The methods can be roughly sorted in two groups by the time and phase of the measurement: 1) methods to measure heart rate during post-exercise rest periods (Brouha, 1960; Vogt and Metz, 1981; Bernard and Kenney, 1988; Kim and Lee, 2015), 2) methods to collect heart rate during exercise or all phases including exercise periods (Givoni and Goldman, 1973; Bernard and Kenney, 1994; Buller et al., 2013; Dayal and Ramsey, 1976; Logan and Bernard, 1999).

The studies can be re-sorted in two groups by the purpose of indices and models: 1) to evaluate the general working environment focusing on heat strain by given several parameters in the working places (Givoni and Goldman, 1973; Dayal and Ramsey, 1976; Logan and Bernard, 1999), 2) to facilitate real-time monitoring of heat strain (Brouha, 1960; Vogt and Metz, 1981; Buller et al., 2013; Kim and Lee, 2015). Especially, prediction of heat strain using recovery heart rate may be more valid to measure because it can be less influenced by work intensity than measuring during exercise.

2.3.3.1. Using Heart Rate during Post-Exercise Rest Periods

The first available record using post exercise resting heart rate is known from a book written by Brouha (1960). He mentioned that an early study of post-exercise heart rate collected as a heat stress indicator was conducted at the Harvard Fatigue Laboratory by Johnson, Brouha, and Darling in the mid-1900s. Brouha wrote a monograph based on the results of a plant survey and laboratory experiments which had been conducted since 1943. In the monograph, recovery heart rates at 1 min (P_1), 2 min (P_2), and 3 min (P_3) after exercise were suggested as safety criteria to determine physiological stress, but those were containing not only both heat stress but physical aptitude: 110 bpm for P_1, 10 bpm for P_1-P_3, and 90 bpm for P_3. Since Brouha's work, various heat indices and safety criteria have been developed, and recovery heart rate has been explored as an indicator of cardiovascular health, yet Brouha's work has been still used in recent publications (Chou et al., 2011; Parsons, 2014).

However, questions about the validity of the safety criteria have also been raised. As Brouha also noticed, the first minute of recovery heart rate is easily affected by not only heat stress but also work demand which can cause 1) 110 bpm could be too low to some operations in the high work load, and 2) it was difficult to separate the effect of heat stress. Fuller and Smith (1981) reported that oral temperature would be at or below 37.5 ^{o}C with a P_1 value of 124 (95% of probability). During aluminum smelter's operations, P_1 varied according to tasks: 125 bpm after breaking and jacking, and 160 bpm after crust breaking (Logan and Bernard, 1999). Bernard and Kenney (1988) suggested a modified criterion of 120 bpm for P_1, but a question on the validity after exercises in various work load remains. Vogt and Metz (1981) suggested the CTEP (Cardiac Thermal Extra Pulse) using heart rate records at 3 to 5 min after exercise. The records displayed less influence by work load, but they added a variable of the difference in heart rate during exercise and rest. Meyer et al. (2000) showed high coefficient of determination (R^2) between CTEP and the oral temperature: R^2=0.70 (N=131). They also explained that clothing insulation and exposure time did not significantly change the relation between oral temperature and CTEP. Kim and Lee (2015) suggested that well stabilized recovery heart rate can be a single predictor of heat strain. Despite the limitation in the statistics of model development, the results showed high R^2 of 0.722 and heart rate index to determine whether to re-start working or to rest was proposed.

2.3.3.2. Using Heart Rate during Exercise or All Phases

There have been attempts to predict heat strain by heart rate during exercise in a purpose of evaluation of working environment (Fuller and Brouha, 1966; Dayal et al., 1976) and in another purpose of real-time monitoring of heat strain (Buller et al., 2013). Dayal et al. (1976) proposed 'The Heart Rate Index (HRI)' (Table 2.1), and they suggested that HRI of 110 and HRI between 0 to 100 can be a safety limit and safe area for eight hour exposures, respectively. This model and criteria could work to evaluate overall work load but did not intend to monitor the real-time heat strain.

A recent study by Buller and his colleagues (2013) suggested a useful predictive model of core temperature with successively measured heart rate by tracking heart rate with using a Kalman filter to reduce the effect of noisy observations. They reported that the estimation fell in limits of agreement (LoA) of ± 0.63 °C (Buller et al., 2013) and LoA of ± 0.48 °C (Buller et al., 2015). However, questions remain regarding the validity for subjects who are already in a hyperthermic state before tracking heart rate, because the model fits best when the initial body core temperature is given. Above all, aforementioned two studies share an identical problem that heart rate records measured during exercise holds the increase by the physical activity as well as heat strain.

Table 2.1. Summary of heat indices and model that used heart rate as a predictor for heat-stress assessment

Date	Author (s)	Index	Input HR	Description
1960	Brouha	N.A.	Recovery HR (P_1, P_2, P_3)	Criteria of no recovery were 110 bpm for P_1, 10 bpm for P_1-P_3, and 90 bpm for P_3.
1966	Fuller and Brouha	T+p index	HR measured during working phases	Prediction of HR at a given ambient temperature (T, ^{o}F), humidity (P, mmHg) and metabolic rate (MR, btuh): HR=0.029MR+0.7(T+P) for a supplement heat indicator in working environments.
1973	Givoni and Goldman	N.A.	HR during exercise	Prediction of HR by metabolic rate, clothing, air temperature, and E_{req} and E_{max}.
1976	Dayal et al.	HRI, the Heart Rate Index	HR for long-term periods (e.g. 8 hours)	HRI=[(HRe-HRc) / (HRs-HRc)]*100, where HRe is predicted equilibrium heart rate during work, HRc is HR at rest in comfortable conditions, HRs is a postulated upper limit. HRI at 110 is a safety limit and HRI between 0 to 100 is a safe area for eight hour exposures.
1981	Vogt and Metz[a]	CTEP, Cardiac Thermal Extra Pulse	Recovery HR (P_3, P_4, P_5)	Change in T_{or} =0.04+0.029·CTEP, CTEP=(P_3+P_4+P_5)/3·HRo where HRo represents the difference of mean HR at work and rest HR. CTEP lower than 20 indicates the increase in T_{or} < 1^{o}C.
1988	Bernard and Kenney[b]	N.A.	Recovery HR (P_1)	Criteria of no recovery were 120 bpm for P_1
1994	Bernard and Kenney	SI-HR, Strain Index for Heart Rate	HR during exercise	%HRC=[(HR-HRrest)/(HRmax-HRrest)]x100%. %HRC is 0 at rest and 100 at HRmax.
1999	Logan and Bernard	N.A.	Daily average HR	Acceptable limits for the average HR over 6- and 12-hour intervals below 120 bpm and 110 bpm, respectively.
2013	Buller et al.	N.A.	HR during rest and work (all phases)	Prediction of body core temperature by continuous HR records
2015	Kim and Lee	N.A.	Recovery HR after stabilization	Preliminary predictive equations of rectal temperature by HR

[a] Original paper was written in French. Description of this method in English is available in Meyer et al. (2000).

[b] The original article was not available to find. Description of this method was from Logan and Bernard (1999).

Abbreviations: HR, heart rate; T_{or}, Oral temperature; N.A., Not available,

2.4. Standards and Directives

2.4.1 ISO 9886 (2004)

This international standard provides evaluating methods of thermal strain by physiological measurements such as body core temperature, body-mass loss, and heart rate. When it comes to the assessment of thermal strain based on heart rate, this standard mainly mentions theoretical principles on the thermal components in the heart rate change, rather than suggesting specific heat indices or safety criteria. The summary of ISO 9886 in terms of heart rate is as follows:

- Heart rate change can be expressed as the sum of several components including metabolic, thermal, mental, and static exertion and error components. These components are not independent each other.
- Thermal component can be shown as heart rate minus resting values ($\Delta HR_T = HR_T - HR_0$).
- Influence of static exertion, sustained influence of exercise even after end of the exercise, on the heart rate can last for 4 min. Duration time is longer if the previous work load was much greater.
- Increase in heart rate for an increase of 1^oC in body core temperature is called thermal cardiac reactivity (beats$\cdot$min$^{-1}\cdot{}^oC^{-1}$).
- Thermal cardiac reactivity can be influenced by interindividual and intraindividual factors such as exertion mode, origin of thermal stress (exogenic and endogenic).

2.4.2 ACGIH TLV (2018)

Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs) published by Association Advancing Occupational and Environmental Health (ACGIH) provides more practical guidelines for limiting heart rate using heat strain:

- Sustained heart rate for several minutes which exceeds 180 bpm minus the individual's age in years (180 – age).
- Recovery heart rate at one minutes after a peak work effort exceeded 120 bpm.

2.4.3 NIOSH (2016)

This standard provides detailed explanation on various heat indices along with the cardiovascular responses under heat stress. It also introduces ACGIH TLVs and the safety criteria using P_1 and P_3. Table 2.2 was a part of the Table 9-1 in NIOSH (2016) which is comparing various physiologic monitoring methods.

Table 2.2. Heart rate monitoring used to prevent heat-related illness (NIOSH, 2016).

Monitoring method: Heart rate	
How assessed	• Radial pulse check: count the number of beats per minute (bpm) by feeling the pulse on the inside of the wrist • Continuous monitoring with chest strap containing a heart rate sensor
When assessed	• Before work begins and while at rest to determine baseline, then after heat exposure (e.g., minutes 1 and 3 after the work period ends) • Chest strap data can be taken over the entire work shift • Heat strain is indicated by a sustained HR>180 bpm minus the worker's age
Additional information	• Heart rate should fall rapidly, approaching the baseline once the worker is resting in a cool environment. • Heart rate will remain elevated in a worker experiencing a heat-related illness.
Limitations	• Many factors independent of heat stress can cause an increased heart rate (e.g., physical exertion, physical condition, fever from an infection, pain from an injury or heat attack, dehydration) • Medications (e.g., beta blockers) or pre-existing medical conditions (e.g., sinus bradycardia, hypothyroidism, pacemaker) can suppress heart rate. • Chest straps must be properly fitted; data loss can occur when contact with skin is lost during exertion or excessive sweating.

Chapter 2. Methods

3.1. Survey on Firefighters' Occupational Environment

3.1.1 Sample

The survey was directed towards Korean professional firefighters who have taken charge of suppressing fire or rescuing before. Firefighters in charge of only medical emergency care or office work were excluded because they are not directly exposed to excessive heat strain at fire scenes. In April 2016, printed copies of a questionnaire were distributed nationwide to 1,050 Korean professional firefighters via Fire & Disaster Headquarters. The distributed areas included the following administrative districts: Seoul, Geonggi-do, Chungchungnam-do, Junranum-do, and Gangwon-do. Of 1,050 questionnaires, 983 were collected. Among them, responses without demographic information (N=177) and those answered by firefighters who have never been responsible for suppressing fire or rescuing work (N=132) were excluded in the analysis. In the end, 674 questionnaires were used in the final analysis, and the demographic and occupational information were presented in Table 3.1. This study was approved by the Institutional Review Board of Seoul National University (IRB #E1602/001-005)

3.1.2 Questionnaire Construction

The current questionnaire was a part of an extensive questionnaire which encompassed various issues on firefighters' safety and their personal protective equipment. The series of questions related to firefighters' heat strain were placed in the initial part, and they contained five bundles of questions associated with heat-related illness and the environmental and behavioral factors related to heat strain in their work place; experiences of heat-related illness, duration time of rest and work periods, drinking habits during resting and frequencies of wearing of PPE. Also, demographic information included age, sex, possession of the certificate of emergency medical technician, and detailed information about their work periods and specific operations they have taken charge of. Prior to the survey, ten professional firefighters with more than 20 years in working experience inspected the draft. They advised on the appropriateness of questions and words used in all

Table 3.1. Demographic characteristics of the respondents.

	No.	%
Total respondents	674	100
Sex		
Male	657	97.5
Female	14	2.1
No details	3	0.4
Age (years)		
20-29	71	10.5
30-39	303	45.0
40-49	206	30.6
50 and over	88	12.9
No details	6	0.4
Duration of each job (years)		
Fire suppression		
<1	138	20.5
1-4	240	35.6
≥5	293	43.5
No details[a]	3	0.4
Emergency rescue		
<1	431	63.9
1-4	113	16.8
≥5	127	18.8
No details[a]	3	0.4
Present place of employment		
Chungchungnam-do	75	11.1
Gangwon-do	78	11.6
Geonggi-do	179	26.6
Jeonranam-do	83	12.3
Seoul	211	31.3
Others	48	7.1

[a] These answers were included in analysis because they reported the existence of fire suppressing and emergency rescuing experiences even though they did not report the detailed information of duration of each job.

questions and answers given in multiple choice questions. In a final questionnaire, 27 questions were included with 79 sub-questions (46 multiple choice questions and 33 short-answer questions). Table 3.2 showed the questions whose answer was analyzed in this study.

Table 3.2. Construction of questions in the questionnaire

No.	Questions
1	Have you ever experienced HRI symptoms or heat stroke during duties?
2	How many times have you experienced each HRI symptom and heat stroke?* HRI symptoms: headache, dizziness, sudden muscle cramps, nausea, vomiting and fainting.
3	Did you report your experience of HRI symptoms to your commander?
4	If you answered ‘no’ for the above question, what was the reason?
5	Duration time of a single work period: the average, minimum, and maximum*
6	Duration time of a total work period: the average, minimum, and maximum*
7	Duration time of a single rest period: the average, minimum, and maximum*
8	Reasons or criteria to stop working
9	Reasons or criteria to re-start working
10	Frequency to remove firefighters’ personal protective equipment (PPE) elements. PPE elements: helmet, hood, gloves, turnout jacket, turnout pants, socks, and boots

*Short-answer questions

First, to investigate the occurrence of firefighters’ HRI, a series of yes/no items regarding symptoms of HRI were elicited. Respondents also answered in short answer how frequently they experienced each symptom during a year. Symptoms of heat-related illness contained headache, sudden muscle cramps, dizziness, nausea, vomiting, and fainting (Becker and Stewart, 2011; Pryor et al., 2015). Experience of heat stroke was asked directly along with acquisition of professional certification as an emergency medical technician and self-reported level of knowledge about HRI to screen out less reliable answers about heat stroke. It was also asked whether they reported to their authority and the reasons why they did not report it. Regarding the reasons, multiple choices were given as follows: 1) it required little or no medical expenses: 2) people usually do not report it; 3) concerns of disadvantage for promotion; 4) it required a complex process; 5) troublesome; 6) it is natural to experience those symptoms at fire scenes. Participants also responded to questions about duration of rest and work period with details about the average, minimum, and maximum values. It was asked separately according to the size of the fire accident (small, medium and conflagration), because there are differences in supplies and the resting place for firefighters in case of conflagration in contrast to small/medium sized fire scenes. Also, time for duration of single work periods and total duration time were inquired separately for working hours, because their working hours tend to be divided by limited capacity of SCBA at the fire scenes.

Firefighters also responded about the frequency of taking off PPE during their rest periods; always, usually, hardly, and never taking off PPE at rest. Components of PPE included the helmet, hood, gloves, boots, bunker jacket and pants. SCBA was not included because it is obliged to be taken off for replacement or recharge during rest periods and removing SCBA is not an option for cooling body during rest. Specially, regarding the bunker jacket, another option is to just open it without totally taking it off. This was additionally considered. The entire questionnaire was added in Appendix 1.

3.1.3 Statistical Methods

Three quartiles with 95th percentiles of data about frequency of heat-related illness and duration time of rest/work periods were reported to descript data distributions. Odd ratios were calculated to quantify the influence of wearing PPE at rest on presence of HRI symptoms. In this calculation, wearing frequency of PPE was divided into two groups; people who always or usually wear PPE at rest and people who hardly or rarely wear PPE. Frequency of HRI symptoms was also analysed with odds ratios where the variables were divided into two groups: 1) 5 and less than 5 times per year, 2) more than 5 times per year. The criterion dividing the two groups was determined based on the homogeneity in the answering frequency among adjacent numbers to the median. 95% confidence interval and P-value were presented with odds ratios. In addition, Spearman's rank correlation test was used to analyse the relationship between the frequency of wearing PPE at rest and resting duration time with log transformation, and their correlation coefficients (ρ) were presented. All p-values below .05 were considered as a statistical significant level.

3.2. Development of Resting Heart Rate Models

3.2.1 Ethical Approval and Subjects

This session was composed by various sub-studies and several tests, which were all approved by the ethical review board. Test A and C were approved by the Review Board of Seoul National University (IRB #1501/001-009) and Test B was approved by the Institutional Review Board of Seoul National University (IRB# 1712/001-004). All subjects were informed of the purpose, methods, and potential risks of the experiment prior to final determination of participation, thereafter written consents were obtained. In total, thirty-one professional male firefighters and six male adult students participated in the experiments for model development (Table 3.3). The subjects were instructed to refrain from alcohol, medication, and heavy exercise for 24 hours prior to testing day. They were also refrained from any food and caffeine for 3 hours before the all tests. Although circadian rhythm affects the function between heart rate and body core temperature (Aoki et al., 2001), the test of F32C-15min and F32C-30min was carried out at 10:00-14:00, and all tests of SF28C-10min were conducted at 15:00-17:00. All subjects were free of known cardiovascular and respiratory dysfunction. They performed a maximal graded exercise test to determine maximal oxygen consumption ($\dot{V}O_{2max}$), and heart rate (HR_{max}) in a separate day prior to carrying out experimental protocols.

3.2.2 Experimental Protocol and Procedures

To develop predictive models of heart rate to body core temperature, the study went through a following procedure: 1) Develop models with some data along with correction equations for the predictors, if it is needed 2) Consider additional independent variables among individual parameters, 3) Test the validity of models using different data sets in different conditions (e.g. different exercise, clothing and ambient temperature). In the entire process of analyses, five different test data were utilized. Test B and D were conducted in a purpose of the model development and validity tests in this study, whereas the data from Test A, C, E were brought from other study to complement the insufficient sample number. Each test had a distinct protocol as shown in Table 3.4. More information on the methods of validity tests was described in the section 3.3.

Table 3.3. Anthropometric data of the participants

	Test A	Test B		Test C	Test D		Test E
Occupation	F	F	S	F	Non-F		F
Sex	Male	Male	Male	Male	Male	Female	Male
N	9	10	6	12	6	5	8
Age (years)	34±4	40±9	24±4	37±7	26±6	28±6	38±8
Height (cm)	176±5	172±4	173±3	175±5	178±8	168±5	174±5
Weight (kg)	74.5±6.6	71.5±8.8	71.4±5.2	75.8±9.1	73.8±10.0	62±9	73±10
BMI	24.5±1.8	24.2±2.6	23.9±2.0	24.6±2.4	23.3±1.8	22.0±2.0	24.2±2.6
%BF	12.5±5.0	18.5±5.2	16.7±6.3	12.5±5.7	15.6±3.8	31.2±11.4	*N.A.*
$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	46±8	45±7	41±6	45±7	52±3	44±9	51±8
HR_{max} (bpm)	186±6	187±9	187±7	188±6	199±9	193±9	191±7

Abbreviations: F, firefighters; S, students; BMI, body mass index; %BF, percent of body fat; $\dot{V}O_{2max}$, maximal oxygen consumption; HR_{max}, maximal heart rate; *N.A.*, not available.

Table 3.4. Summary of tests' protocol and the purpose of use

Test	T_{air}	Clothing	Exercise	Purpose of use (section)
A	32°C	PPE	Walking at 5.5km·h^{-1} (1% slope)	M.D.
B	28°C	PPE	Walking at 5.5 km·hr^{-1} (~5% slope)	M.D.
	40°C	Sportswear	Standard heat tolerance test (HTT)	Correction factors
	-	Sportswear	Maximal graded test[a]	Correction factors
C	32°C	PPE	Walking at 5.5km·h^{-1} (1% slope)	M.D.
D	25°C	PPE	Cycling at 50, 80, and 50%$\dot{V}O_{2max}$	Validity tests (4.2.4.1)
	21°C	PPE	Recovery after exercise	Validity tests (4.2.4.4)
	40°C	Sportswear	Cycling at 50, 80, 50%$\dot{V}O_{2max}$	Validity tests (4.2.4.3)
	21°C	Sportswear	Recovery after exercise	Validity tests (4.2.4.4)
E	21°C	PPE	Simulated firefighters' test drills	Validity tests (4.2.4.2)

[a]Maximal graded tests were conducted in all other tests as well, but in Test C, the values obtained ($\dot{V}O_{2max}$ and HR_{max}) were used as potent additional independent variables.

Abbreviations: T_{air}, air temperature; PPE, personal protective equipment; M.D. model development; $\dot{V}O_{2max}$, Maximal oxygen consumption

Test A

Data recorded in Test A was utilized in the model development. Environmental temperature and relative humidity (RH) were maintained at 32.1 ± 0.2°C and 43 ± 7 %, respectively. The experimental ensemble consisted of underwear (cotton 100%), long sleeved shirt (cotton 100%), pants (cotton 100%), socks, bunker jacket/pants (outer shell: polybenzimidazole 40%, para-aramid 60%, moisture barrier: aramides, thermal liners: aramides), hood (aramid 100%), helmet, gloves, boots, and self-contained breathing apparatus (SCBA) with an empty cylinder. The total mass of all clothing and equipment was approximately 15 kg. The face-piece of the SCBA was replaced by a respiratory mask to collect respiratory gases. Upon arrival at the laboratory, subjects drank 300 ml of water to prevent dehydration and began each trial with a 10 min initial rest in a sitting position on a stool. Thereafter, the subjects performed two 15-min bouts of walking on a treadmill (Genesis T401, HealthStream Taiwan Inc., Taiwan) with 1% slope at 5.5 $km \cdot hr^{-1}$, separated by 10 min of rest. The work load was approximately equated to 60 ± 10 % of $\dot{V}O_{2max}$. Final recovery for 20 min was followed after finishing all exercises. The helmet, hood, and gloves were removed from the body during all rest periods (initial and post-exercise rest periods and recovery). Safety criteria used to immediately terminate the test were either rectal temperature of 39.2°C or at the request of the subjects.

Test B

Test B was designed not only to examine the function of heart rate to rectal temperature but also to search for the additional individual parameters as an additional predictor. Among various individual parameters, age, body morphology such as height, weight, and the ratio of body surface area to weight (A_D/mass), physical fitness ($\dot{V}O_{2max}$ and HR_{max}), and heat tolerance were collected in this test. To obtain those values, Test B consisted of three different sub-tests: 1) an intermittent exercise test wearing turnout gear, 2) heat tolerance test, 3) maximal graded test.

The experimental schedule for each person was completed over three visits to the laboratory, which included a maximal physical capacity test, heat tolerance test (HTT), and intermittent firefighting test (IFT) in each separate day. The subjects performed a maximal graded test with modified Bruce protocol, where $\dot{V}O_{2max}$ HR_{max} were collected. Maximal exertion was defined as an inability to continue running despite encouragement and heart rate > 100% predicted maximum. In another day, they carried out standardized heat tolerance test (HTT) (Moran et al., 2007). In HTT, participants walked for 120 min on a treadmill at a pace of 5 km·h^{-1} with 2% slope (Figure 3.1B). The climatic chamber was maintained at 40°C and 40 %RH. Participants wore shorts and T-shirts, underwear, socks, and running shoes (100% cotton). 300 ml of water was provided prior to commencing exercise, and additional water intake was allowed whenever participants required it to prevent dehydration. The water bottles were stored in the climatic chamber (40°C) for more than 2 hours before being given to subjects to avoid any cooling effect by drinking cold water. Trials were immediately terminated when rectal temperature increased above 39°C or when any symptoms of HRI such as dizziness and nausea occurred. One subject re-tested HTT due to abnormally rapid increase in rectal temperature (increased up to 39°C in an hour). The subject visited the laboratory 10 weeks later, and the records from the second visit were used in the analysis.

Figure 3.1. **[Test B]** Subjects during a heat tolerance test (A) and an intermittent exercise test (B).

With at least 2 days interval from HTT, participants conducted an intermittent exercise test (Figure 3.1B). The clothing ensemble was identical with Test A. Climatic chamber was maintained at 28°C and 40%RH with negligible level of air velocity < 0.25 m·s^{-1}. After an initial 10 min rest, subjects performed three bouts of 10 min walking on a treadmill with ~5% slope at 5.5 km·hr^{-1} separated by 5 min rest at a total work load equated to 66 ± 10 %$\dot{V}O_{2max}$. The number of bouts was decided by participants if rectal temperature did not increase over 39°C. Majority of trials consisted of three exercise bouts, but two subjects completed four, whereas one subject had two exercise bouts due to dizziness. During all post-exercise rest periods, the helmet, hood, gloves, and SCBA were removed from the body. HTT was always conducted at 09:00-12:00, whereas IFT was done in the afternoon at 14:30-17:30 to avoid the effect by circadian rhythm. Every test was completed within 3 months from September to December.

Test C

Data from Test C was utilized in model development. Experimental setting was the same with Test A. The only difference was a longer exercise duration. In this test, subjects continuously walked on a treadmill for 30 min without any breaks.

3.2.3 Measurements and Calculations

Rectal temperature was measured every 5 sec using a data logger (LT-8A; Gram Corporation, Japan). The rectal probe was inserted 16 cm beyond the anal sphincter. Heart rate was also measured continuously every 5 sec using a chest belt and a data logger (RS400, Polar Electro Oy, Finland). Respiratory gases were collected from every breath and analyzed by the Quark b2 software (Quark b2, COSMED, Italy) for oxygen consumption determination. Prior to each measurement, the respirometer was calibrated using room air, a standard gas mixture (4%CO_2, 16%O_2, balance nitrogen), and a volume calibration using a 3-litre syringe. In Test A and C, %body fat was estimated by skin-fold thickness methods from 3 sites (Jackson and Pollock, 1978) whereas, in Test B, a body composition analyzer (InBody720, InBody, Korea) was used. Environmental temperature and relative humidity in the climatic chamber were measured by thermo-hygrograph (Thermo Recorder TR-72U, T&D Corporation, Japan) every minute. Body surface area was calculated according to Dubois & Dubois (1916). Then, the ratio of body surface area to body weight was obtained (A_D/mass).

3.2.4 Data Analysis

3.2.4.1 Data Sampling

First, to determine the valid time to measure stabilized resting heart rate (rHR) after rapid drop in heart rate, every 1 min heart rate during the post-exercise rest period in Test A was averaged and analyzed by one-way analyses of variance (ANOVA) with LSD *post hoc* test.

After determining the range of stabilized heart rate after exercise, mean rHR at each rest period were obtained by averaging for 3 min from 1-4 min before exercise when the duration time of rest period was 10 min (Test A and C) and by averaging for 1 min from 1-2 min before exercise in case of the test with 5 min rest (Test B). Values in the last one minute immediately before exercise were excluded because it was disturbed by preparation for the following exercise. Likewise, rectal temperature was also collected within the identical periods. ΔT_{re} was calculated by subtracting mean T_{re} for the initial 1 min immediately before starting exercise from mean T_{re} for the last 1 min at the end of exercise.

3.2.4.2 Model Development and Diagnostics

Model Development

In this study, three predictive equations were developed. The first one was an equation of rectal temperature during all resting periods (rT_{re}) with simultaneously measured rHR (Model 1). The second one was a function of increase in rectal temperature (ΔT_{re}) with two independent variables, rHR and duration of exercise (t, unit: min) (Model 2). The last one was about predicted rectal temperature at the end of exercise (eT_{re}), which was simply expressed as a sum of the function of rT_{re} and ΔT_{re} (Model 3). Because the data set included repeated measured data, the models were analyzed by a linear mixed-effects model, which was computed with *lmer* function (v. 1.1-15) in the *lme4* package using the software R (version R 3.4.2) (Bates, 2010).

To investigate any violation of the regression assumptions, normality of the data distribution was tested by Kolmogorov-Smirnov test. Residual plots were drawn to investigate whether any significant trend is shown in the distribution by changes in the independent and dependent variables.

For Model 1, a quadratic simple equation was chosen for the best fit. The independent variable was standardized prior to model fitting to deal with the 'rescaling' issue in *R*. For the Model 2, equations were developed in both linear and exponential functions. Along with linear formula, the exponential function was also analyzed because power relationship within both variables (rHR, t) was observed in the initial period of exercise. To develop the exponential formula, all dependent and independent variables were transformed to their logarithms. The representation of the population models could be:

Model 1: $rT_{re} = \mathrm{a} + \mathrm{b} \cdot rHR^2$ (eq. 3.1)

after transformation: $rT_{re} = \mathrm{a}' + \mathrm{b}' \cdot std.rHR^2$ (eq. 3.2)

Model 2A (linear formula): $\Delta T_{re} = \mathrm{c} \cdot rHR + \mathrm{d} \cdot t + \mathrm{e}$ (eq. 3.3)

Model 2B (exponential formula): $\Delta T_{re} = \mathrm{f} \cdot rHR^g \cdot t^h$ (eq. 3.4)

after *log* transformation: $\log \Delta T_{re} = \log f + \mathrm{g} \log rHR + \mathrm{h} \log t$ (eq. 3.5)

Model 3: $eT_{re} = rT_{re} + \Delta T_{re}$ (eq.3.6)

where group terms (by-subject variability) and error terms were omitted in both population models above and each alphabet, *a* to *h*, denotes population parameters. Thus, all dependent and independent variables were transformed to their logarithms to get the regression model. The transformed models were estimated using the following syntax:

Model 1: lmer (rT_{re} ~ std. rHR^2 + (std. rHR^2|ID), data I)
Model 2A (linear formula): lmer(ΔT_{re} ~ rHR + t + (1+rHR | ID) + (1 + t |ID), data II)
Model 2B (exponential formula): lmer (log ΔT_{re} ~ log rHR + log t + (1+log rHR | ID) + (1 + log t |ID), data II)

where the notation of (std.rHR^2|ID) in the Model 1 indicates that by-subject random intercept and slope for the std.rHR^2 variable are considered. Likewise, the random effects terms in Model 2A, (1+ rHR|ID) and (1+t|ID), indicate this model includes by-subject random intercepts and also random slopes for rHR and t. In the same way, in Model 2B, (1+logrHR|ID) and (1+logt|ID) indicate the random effect terms. After estimated coefficients were gathered, both Linear regression models were back-transformed to the original forms. The final formula of mixed-effects model did not include random-effects terms, but only population parameters of the intercept and slope to facilitate evaluating performance of prediction. To reduce the bias in the estimate of intercept of Model 2, a correction factor ($\frac{\hat{\sigma}^2}{2}$, $\hat{\sigma}^2$ denotes sample variance) was additionally considered (Baskerville, 2971; Mascaro et al., 2011).

Evaluation of the Model Performances

In order to report the model performance for the mixed-effects models, Marginal R^2 was calculated using *r.squaredGLMM* function in the *MuMIn* package (v. 1.40.0) in R (Nakagawa and Schielzeth, 2013). Marginal R^2 is calculated by the ratio of the fixed-effects variances to the sum of other variances, which differs from R^2 in the simple regression analysis, and it also clearly distinguished from R^2 calculated by the squared correlation between the fitted and observed values (pseudo-R^2).

Mean of the difference between observed and predicted values and its standard deviation were calculated to report mean bias with limits of agreement (LoA) in the Bland-Altman plot (Bland and Altman, 1986; Giavarina, 2015). In addition, when comparing observed and predicted values, the goodness-of-fit was reported by the pseudo-R^2 computed from linear regression analysis. RMSE (Root mean square error) was calculated as follows: RMSE $=\sqrt{\sum(y-\hat{y})^2/n}$ (eq. 3.7). To report the accuracy of the model, 95% confidence intervals (95 %CI) for estimated parameters and 95% prediction limit for predicted values were calculated.

Correction Equation of the Independent Variable, rHR

Simple linear regression analysis was utilized in a development of the correction method for lower initial resting heart rate (HR_0). At first, each subject's difference between expected rHR and observed rHR (D) was calculated as follows: $D_j = \sum_{i=1}^{n}(\hat{x}_{ij} - x_{ij})/n$ (eq. 3.8) where x_{ij} is an observed independent variable, representing rHR for the *i*th measurement of *j* subject, and $\hat{x}_{ij}$ is an expected x_{ij} for the observed rT_{re} and calculated using Model 1. In a development of the correction method, among all data sets, only V-Sim.F was excluded because in this test, stabilized rHR was not successfully collected due to many distracting factors (e.g. talking, laughing and competitive mood among firefighters). Thereafter, a trend line of the distribution of D_j to each subject's HR_0 was analyzed by data smoothing. To determine a statistical border where different type of a trend line started, an inflection points were calculated by *loess* function in R. Simple linear regression analysis was then used to get a regression equation between D_j and HR_0 under the inflection point. The final equation was suggested as $HR_{correction}$. Corrected rHR was obtained by a sum of measured rHR and $HR_{correction}$. R-3.4.2 was utilized. Data were shown as mean ± SD. Significance was accepted at $p < 0.05$.

3.2.4.3 Addition of Independent Variables

To find additional independent variables which can increase the accuracy of prediction, methods in three different approach were conducted: 1) Analysis by parameters in the individual regression line, 2) Residual analysis, 2) Stepwise multiple regression analysis.

Analysis by Parameters of in the Individual Regression Line

This method was conducted to extract morphological treats in individual regression lines: slope and T_{110}, T_{120}, and T_{130}. Slope means the coefficient of independent variable in the regression equations and T_{110}, T_{120}, and T_{130} indicate the estimated rectal temperature at rHR of 110, 120 and 130 bpm, respectively when using individual regression equation (Figure 3.2). Simple linear regression analysis was conducted to get the individual regression line. In this analysis, the data point at the initial rest was excluded, because it resulted in non-linearity of the data distribution. Pearson's correlation test was used to identify significant relationship between those analytic parameters and individual physical and physiological values including age, height, weight, A_D/mass, $\dot{V}O_{2max}$, HR_{max} and heat tolerance.

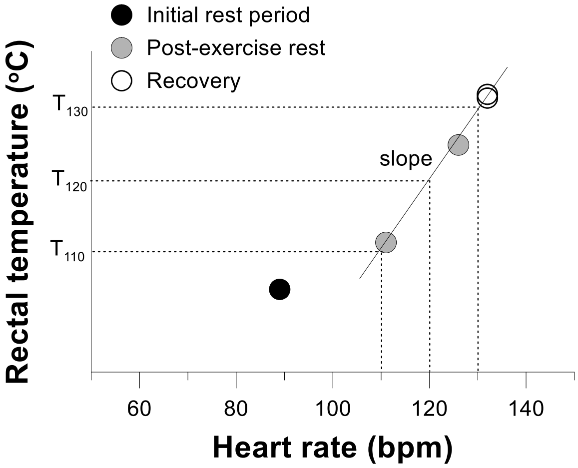

Figure 3.2. Example of analytic parameters for intermittent firefighting test in Test B; Solid line presented obtained individual regression line.

Analysis with the Residuals in Prediction

This method was conducted to examine whether any significant trend is observed in the residual distribution by each individual parameter (age, height, weight, A_D/mass, $\dot{V}O_{2max}$, HR_{max} and heat tolerance). After standardized residuals were obtained, simple linear regression analysis was conducted in case of the continuous variables, whereas one-way ANOVA was conducted for the categorical variable, heat tolerance.

Stepwise Multiple Regression Analysis

This method was conducted to obtain regression equations as well as statistically extract valid additional predictors. In this analysis, mixed-effects regression analysis was also used as used in the model development. At the first trial, all variables were included, afterwards, a variable with the minimum t-value was removed, which was repeated until the last variable remained. As criteria of each model performance, Marginal R^2, Akaike's Information Criterion (AIC), and Schwarz's Bayesian Information Criterion (BIC) were utilized. Greater Marginal R^2 and lower AIC and BIC represented better model.

3.3. Validity tests

3.3.1 Ethical Approval and Subjects

Test D was conducted in Sweden with non-firefighters, mainly university students, which was dissimilar to other data sets mostly collected with firefighters in South Korea. Eleven students were Caucasians (N=8), East Asians (N=2), and an Indian (N=1), and five among the eleven were females (Table 3.4). Test D was approved by and Regional Ethical Vetting Board in Lund in Sweden (#2017 306). On the other hand, 8 Korean firefighters participated in Test E. Test E was approved by the Institutional Review Board of Seoul National University (IRB# 1501/001-017). All subjects were informed of the purpose, methods, and potential risks of the experiment prior to final determination of participation, thereafter written consents were obtained.

3.3.2 Experimental Protocols and Procedures

Test D

This test was designed to test validity of developed models in different conditions of exercise, clothing and ambient temperature. As described in Table 3.3, data from Test D were utilized in four different analysis: 1) a validity test in different types of exercise (cycling), 2) a validity test in different clothing and ambient temperature, 3) a validity test during long-term recovery with/without cooling measures. To do this, Test D was comprised of two experimental conditions (FF: wearing turnout gear, SW: wearing sportswear).

The experimental protocol also differed from other tests, especially in terms of the type of exercise. This test consisted of three bouts of cycling at intensities of 50%, 80%, and 50%$\dot{V}O_{2max}$ in order. Each cycling bout lasted for 10 min with a pre-exercise resting period for 10 min.

In the FF and SW condition, clothing and ambient temperature during exercise protocol were different each other. In FF, subjects wore turnout gear during entire protocol. The turnout gear was the Swedish firefighter’s turnout gear RB90 consisting of outer layer (woven 77% meta-aramid, 23% para-aramid), a barrier (Teflon®, Gore-tex®), tricot fabric Rachel (100% meta-aramid, Conex®), and a lining (woven 100% para-aramid, Nomex®,). Inside the turnout gear, subjects wore long-sleeved shirts and long pants which was military innerwear (50% polyester, 28% polychlal, 22% baumwolle). The chamber was maintained at 25°C and 40%RH for one hour intermittent exercise (Figure 3.3A). In SW, subjects wore sportswear (cotton 100%), and the chamber was maintained at 40°C and 40%RH (Figure 3.3B). After the final cycling bout, the subjects recovered for an hour outside the chamber at 21°C and ~50%RH in both conditions (Figure 3.3C showed the recovery of FF condition). The order of the two tests was randomized. Each trial was conducted in the morning (09:00-12:00). Like other tests, the helmet, hoods and gloves were removed in all rest periods. Subjects were encouraged to keep breathing slowly and conversation was not allowed during all rest and recovery periods because heart rate can be influenced by breathing frequency and mentally distracting factors (Bernardi et al., 2000). More information on this study is available in Kim et al. (2017).

Figure 3.3. **[Test D]** Subjects during exercise in FF (firefighters' clothing) (A) and SW (sportswear) condition (B) and a subject during recovery in FF (C).

Test E

Test E was used to verify the validity of Model 2, prediction of the increase in rectal temperature during exercise, in the simulated firefighting tasks because the increase depends on the work load. Nine professional firefighters participated in the test, but one subject was excluded in the analysis because his initial resting heart rate without any heat strain was 115 bpm. We thought it was far beyond of normal heart rate range (Spodick et al., 1992). The test protocol was taken from Kim and Lee (2016a). This simulated firefighting test consisted of eight common firefighting tasks: carrying hose, going up and down the stairs, carrying, setting up, and withdrawing a ladder, simulated forcible entry, walking with facing radiant heat for 3 min, and pulling a victim (70 kg) (Figure 3.4). Each circuit took ~6 min and repeated three times with 5 min rest between them. The firefighters were encouraged not to run but just to keep the most appropriate rapid pace throughout the test. The subjects were not specially requested to keep calm and quiet during each rest period and allowed to talk with other firefighters and watch their performance. The firefighters removed their helmet, gloves and SCBA and took a rest in a sitting position on a stool. Due to the absence of complete relaxation during rest periods, the data was not proper to test validity of Model 1 and Model 3 but included to identify the validity of Model 2 built from restricted exercise protocols.

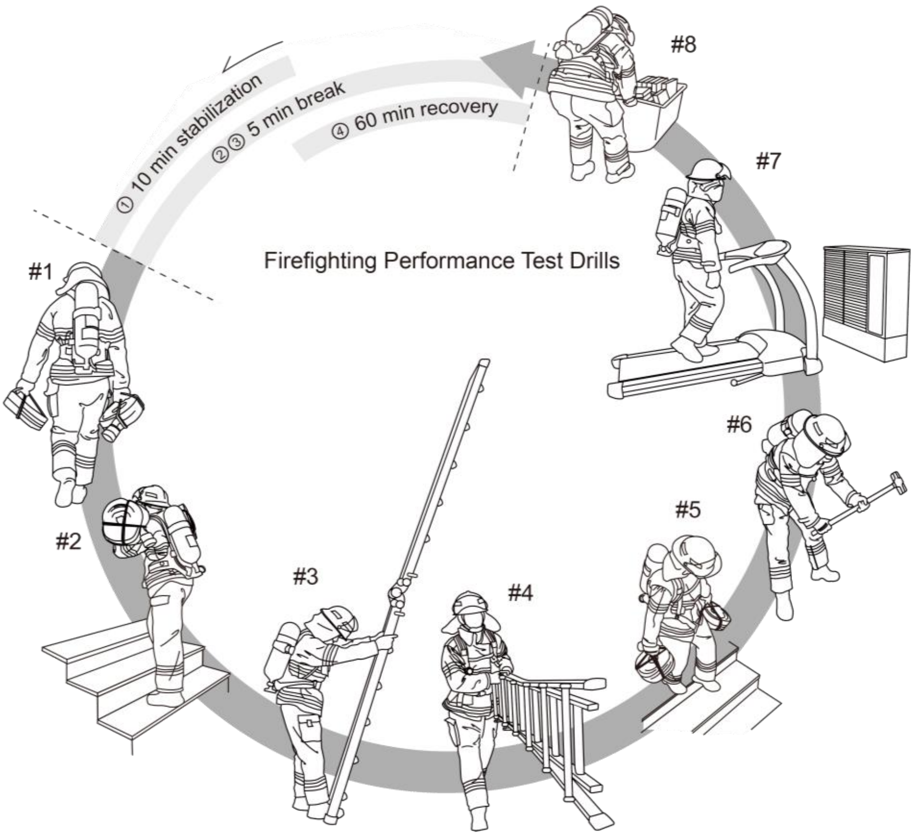

Figure 3.4. Experimental protocol (Kim and Lee, 2016a). Note: #1 Carrying hose, #2 Going up the stairs, #3 Carrying and setting up a ladder, #4 Withdrawing and carrying a ladder, #5 Going down the stairs, #6 Simulated forcible entry, #7 Walking with facing radiant heat, #8 Pulling a victim. One circuit which consists of eight tasks was repeated three times with a 5 min break after each drill. The firefighters took off a helmet, a hood, and gloves with a zipper of bunker jacket lowered.

3.3.3 Measurements

In Test D, rectal temperature was also measured every 5 sec (YSI-401, Yellow Springs Instrument, USA). The rectal probe was inserted 10 cm beyond the anal sphincter. Skin temperature was measured on the forehead, chest, forearm, hand, thigh, calf, and foot (YSI-402, Yellow Springs Instrument, USA). Mean skin temperature was calculated according to Hardy and Dubois' seven-point formula (Hardy and Dubois, 1938). Heart rate was continuously monitored every 5 sec using Polar Team2 transmitter system (Polar Team2, Polar Electro, Finland). Oxygen consumption was measured for metabolic rate assessment by an oxygen analyzer (Metamax III, Cortex Medical GmbH, Germany), which was also calibrated prior to each measurement as mentioned above. In Test E, the measurement was identical with Test A, B and C (see 3.2.2.).

3.3.4 Data Analysis

In the validity tests, repeated measures ANOVA with paired t-test was conducted to compare rectal temperature, mean skin temperature, heart rate and mean arterial pressure in two conditions. Regression analysis was also conducted to verify the significant effect of group term. The group term was given by a dummy variable to distinguish two conditions. Lastly, residual plots were drawn by box-whisker plots to clearly show the distribution of residuals by phases. There, significant bias of the residuals was confirmed by one-sample t-test, comparing with 0.

Chapter 4. Results and Discussion

4.1. Korean Firefighters' Heat Strain

4.1.1 Frequency of Heat-Related Illness

74.8% of firefighters out of 646 responded they have experienced at least one of the HRI symptoms asked. HRI symptom experienced by the largest number of firefighters was dizziness. More than half of firefighters experienced dizziness during firefighting (56.6%) (Table 4.1). Headache (48.8%), nausea (47.5%), and sudden muscle cramps (45.7%) were also reported by nearly half of firefighters. Confusion was experienced by one third of respondents (33.2%), 22.8% of participants experienced vomiting, and 20 firefighters (3.1%) fainted in the work place (Table 4.1). The medians of frequency in those symptoms were 4 times in headache, 3 times in sudden muscle cramps, dizziness, confusion, and nausea, 2 times in vomiting, and once in fainting in a year. There were great variances in distribution: Upper 5% of firefighters answered that they experienced 30-50 times of headache, sudden muscle cramps, dizziness, confusion, and nausea and 18 times of vomiting (Table 4.1). Eight firefighters answered that they experienced heat stroke during firefighting among 129 firefighters, which was 6.2% of the sample. Median of the experience frequency of heat stroke was 2.75 (Table 4.1).

Among firefighters who answered they have experienced HRI symptoms, the majority of firefighters (98.5%) answered they did not report it to the authority. The main reason was that they thought it was just a natural phenomenon in the fire scenes (44.1%), which they should endure. 16.9% of firefighters answered that not-reporting their heat-related illness is a conventional behaviour. That is, other colleagues do not report it as well, and it made them to be passive to report it. There were other reasons of complexity in process (12.3%) and troublesome (11.7%). 9.9% of participants explained the reason as little or no medical expense and 5.5% of firefighters were concerned about the potential of disadvantage for promotion. There were also other responses such as shame on their own physical capacity. Few firefighters answered that they do not report it, because they knew that those symptoms usually disappeared shortly.

Table 4.1. Experience frequency of symptoms of heat-related illness (HRI)

HRI symptoms and HRI	No. of Respon-dents	Number of experienced firefighters		Frequency of experience per year [a]				
				Percentiles				
		N	%	N	25th	50th	75th	95th
HRI symptoms								
Dizziness	669	379	56.6	373	2	3	10	44
Headache	667	326	48.8	320	2	4	10	35.95
Nausea	667	317	47.5	313	2	3	10	50
Sudden muscle cramps	665	304	45.7	303	1.5	3	10	30
Confusion	665	221	33.2	215	2	3	10	42
Vomiting	661	151	22.8	147	1	2	5	18
Fainting	654	20	3.1	19	1	1	2	-
HRI								
Heat stroke	129 [b]	8	6.2	8	1	2.75	5	-
Any HRI symptoms experienced at least once	670	501	74.8	-	-	-	-	-

[a] Responses from firefighters who experienced each symptom of HRI were included

[b] Two criteria were used in screening of respondents. Acquisition of a certificate of emergency medical technician and high score in self-evaluated knowledge about heat-related illness (1, I know it very well; 2, I know it well). Firefighters who fulfill both criteria were included.

Official records regarding Korean firefighters' heat-related illness was the death in the line of duty, which was separately reported in the news articles. The most recent case was one death in 2012. The cause of his death was heat exhaustion. It was known that his duty was prolonged more than 5 hours in summer. However, there was lack of additional records of other HRI cases during firefighters' duties.

The current result clearly revealed that Korean firefighters still routinely experience HRI symptoms and the fatalities officially reported were just a tiny fraction. In addition, there was a great difference in the severity of the problem. Specifically, when it comes to the nausea, 5% of firefighters experienced at least 50 times in a year. When we consider that Korean firefighters have 3 shifts system in their working hours, and the incidence of heat-related illness is concentrated during summer, 5% of firefighters experience nausea in almost every working days during summer. With an assumption that the number of cases of nausea is equivalent with the number of cases of HRI, when extrapolated to the total population of firefighters in Korea who have experiences of suppressing and rescuing work is currently 32,372 among 40,406 (80%) except special employment for emergency medical services, it can be calculated that 15,182 firefighters suffer from HRI more than 2 times every year and 3796 firefighters suffer HRI more than 10 times every year.

This calculation is not even close to previously reported frequency of HRI of firefighters (Bonauto et al., 2007), although little information about firefighters' HRI is available to precisely compare it with previous studies. Indeed, most of studies and reports have been dealt with the number of fatalities rather than accounting for mild HRI such as heat exhaustion and heat cramps. Exceptionally, there are few studies which included heat-related illness. Bonauto et al. (2007) documented the frequency of occupational HRI cases including the mild forms by analysing data of compensation insurance claims in Washington State for 11 years from 1995 to 2005. According to their results, firefighter was the second highest ranked occupation in terms of the frequency of HRI claims by showing 39 claims (8.2%) among the 480 HRI claims. In other words, only 3.5 cases were claimed every year in Washington State. This is incomparably smaller than the frequency of HRI in Korean firefighters.

This huge discrepancy in the HRI occurrence clearly presents a critical role of methodology to collect HRI cases when we examine HRI cases, especially of firefighters. In the study by Bonauto et al. (2007), mild HRI symptoms such as headache and dizziness could be disregarded because they can disappear without medical treatment in case of an appropriate treatment provided. Bonauto et al. (2007) also expressed concerns about unreported or unrecognized cases of HRI. On the other hand, the current study utilized self-reported frequency of previously identified HRI symptoms from dizziness to fainting to count expansive HRI cases which have not been recognized or not reported. This method was also utilized by Fleischer et al. (2013) when they reported HRI cases in farm-workers. The authors explained that the greatest benefit of self-reports about HRI cases was that it could overcome the problem of underestimation which can be caused by difficulty to clinically diagnosis HRI and the passive attitude of subjects for the medical care.

According to Article 22 of the Health and Safety Management Regulations of the Fire Service in South Korea, a commander should inspect each firefighter's physical health condition prior to every shift to prevent any injuries. Also, the commander should offer proper aids including a cessation of the duty in case of any inappropriate health condition found. However, the problem of heat strain existed in that it is hardly noticeable by naked eyes unless it is self-reported. However, the current study found that most of firefighters (98.5%) did not report their experiences of HRI symptoms to the commander and authority. This passive attitude to announce their heat strain can increase the risk of not only heat-related illness but other injuries as well because heat exhaustion is postulated to have the function of alarming the person about increased body core temperature by a central mechanism that protects the body from severe damage. Early recognition of the HRI symptoms and appropriate treatment can lead them to cool down their body. Ignoring the first signal of excessive heat strain can result in the severe heat-related illness. It can also negatively impact on the accuracy of performance and ability to safely complete their duty in the fire scene (Razmjou, 1996). More attention and efforts in recognition and prevention of firefighters' heat illness are required.

In following sections in this chapter, further investigations on Korean firefighters' working conditions will be discussed, focusing on several potent factors which can be strongly associated with accumulated heat strain and occurrence of heat-related illness.

4.1.2 Duration Time of Work and Rest Period

Heat strain increased during work periods and it can decrease during rests, thus the work-rest cycle is a critical factor determining firefighters' heat strain in the working place. In this study, respondents answered that the median duration time of average rest period was 10 min, but the median of the minimum rest time was 5 min in a small to medium fire accidents (Figure 4.2). On the other hand, median of the work duration time was 40 min for a single work and 65 min for a total operation. Respondents also answered that the work can lasted at most for 60 min in a single operation and 140 min in a total operation if the operation is prolonged. However, there were great variances in distribution. 5% of respondents reported that the maximum duration time of a single work period was 300 min, while 720 min for the total work period.

Table 4.2. Korean firefighters' duration time of rest and work period in the small-to-medium fire scenes)

	N	Percentiles (unit: min)			
		25^{th}	50^{th}	75^{th}	95^{th}
Single rest period					
Average	599	7	10	15	30
Minimum	626	5	5	10	20
Maximum	625	10	20	29.5	50
Single work period					
Average	611	30	40	60	120
Minimum	644	10	20	30	60
Maximum	643	50	60	120	300
Total work period					
Average	579	50	65	120	240
Minimum	608	20	30	60	115.5
Maximum	607	90	140	240	720

In case of conflagration, median of a single work duration was 1.8 times greater than those in smaller fire scenes, but the duration time of rests did not increase proportionally (Table 4.3). Median of the average rest time was 15 min, which was 1.5 times longer than the time of the smaller scenes. Median of the maximal rest time was 20 min, which was identical with the time in the smaller scenes (1.0 times). Unproportioned increase in rest time was also presented in the 75^{th} and 95^{th} percentiles of the rest and work duration times. In the conflagration, upper 5% of the duration time of single and total work period was 274.5 min and 628.5 min, in an average, respectively. On the other hand, the maximally prolonged duration time of each work period was 500 min (8.3 hours) and 1440 min (24 hours).

Table 4.3. Korean firefighters' duration of rest and work in conflagration[a]

	N	Percentiles (unit: min)			
		25th	50th	75th	95th
Single rest period					
Average	585	10 (1.4)	15 (1.5)	21 (1.4)	45 (1.5)
Minimum	614	5 (1.0)	10 (2.0)	15 (1.5)	30 (1.5)
Maximum	614	15 (1.5)	20 (1.0)	30 (1.0)	60 (1.2)
Single work period					
Average	590	40 (1.3)	70 (1.8)	120 (2.0)	274.5 (2.3)
Minimum	621	30 (3.0)	40 (2.0)	60 (2.0)	180 (3.0)
Maximum	620	60 (1.2)	120 (2.0)	240 (2.0)	500 (1.7)
Total work period					
Average	560	88.5 (1.8)	141.5 (2.2)	240 (2.0)	628.5 (2.6)
Minimum	589	50 (2.5)	70 (2.3)	120 (2.0)	300 (2.6)
Maximum	589	140 (1.6)	260 (1.9)	480 (1.0)	1440 (2.0)

[a] Values in parentheses indicate the ratio of values in conflagration compared with those in small-to-medium sized fire accident.

In a small-to-medium sized fire accidents, the biggest reason to stop working was out of air in self-contained breathing apparatus (74%). Contribution by the commands to stop working (40%) and physical exertion (36%) was also substantial (Figure 4.1). On the other hand, only 12% of firefighters said that symptoms of HRI plays a role to stop working. The answers were not different by the size of fire accidents. When the opposite occasion was asked about what contributes to the decision of re-starting firefighting, more than half of firefighters answered that they feel psychological burden during rest periods which led them to begin to work again. It was followed by commands to re-start working (41%) and self-identified physical restoration (41%). Interestingly, 21% of firefighters answered that they stop to rest because of the pressure by the public. In conflagration, the frequency of the commands to re-start working was greater than in small-to-medium sized fire accidents, but there was no difference in the entire rank of the answers.

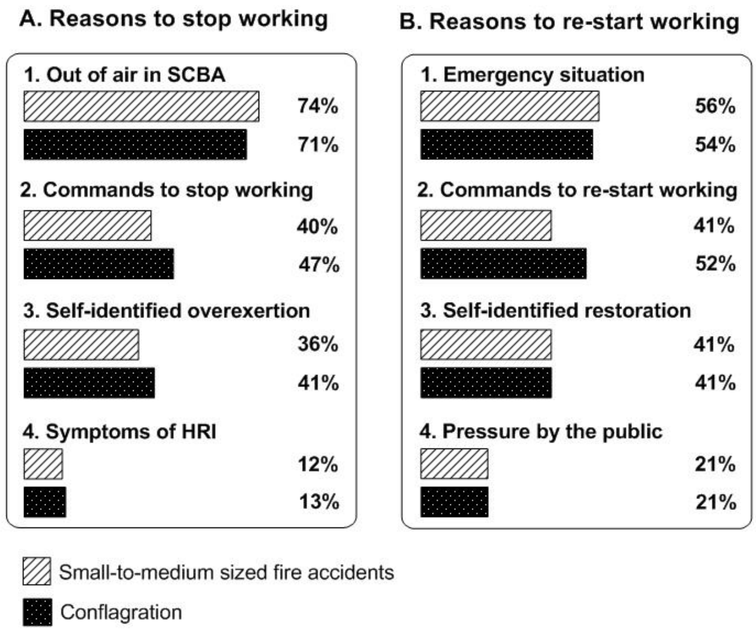

Figure 4.1. Reasons to stop and re-start working in small-to-medium sized fire accidents and conflagration.

4.1.3 Actual Practices to Reduce Heat Strain

When asked to firefighters about cooling measures currently used in the working place, the most common response was 'taking off the protective clothing or opening it' (Table 4.4). However, when more specifically asked by each protective clothing element, it was revealed that removed protective clothing was restricted to a helmet, hood, and gloves (Figure 4.2). Majority of firefighters hardly take off their turnout gear and boots in the working place even during rest periods (93.8%, bunker pants; 88.9%, boots; 61.4%, bunker jacket). Among the responses about cooling practices, the most efficient methods to remove heat (e.g. emersion in cold water, fan cooling) were rarely chosen, except the spraying water on the face and body which was exceptionally used by approximately half of firefighters among active cooling measures. The outcome clearly pointed out that the current Korean firefighters have not efficiently removed their heat strain during their rest time. In addition, the most commonly used method, removing protective clothing, was very limited to the elements which cover local parts, not overall of the body.

Table 4.4. Cooling measures in the working place (N=669).

Rank	Answers	Frequency
1	**Taking off the protective clothing or just opening it**	**72%**
2	Spraying water on their face and body	52%
3	Resting in a shade	44%
4	Drinking cold water	32%
5	Sitting in a car with an air-conditioning system turned on	6%
6	Fan cooling	3%
7	Emerging the hands and feet in cold water	1%

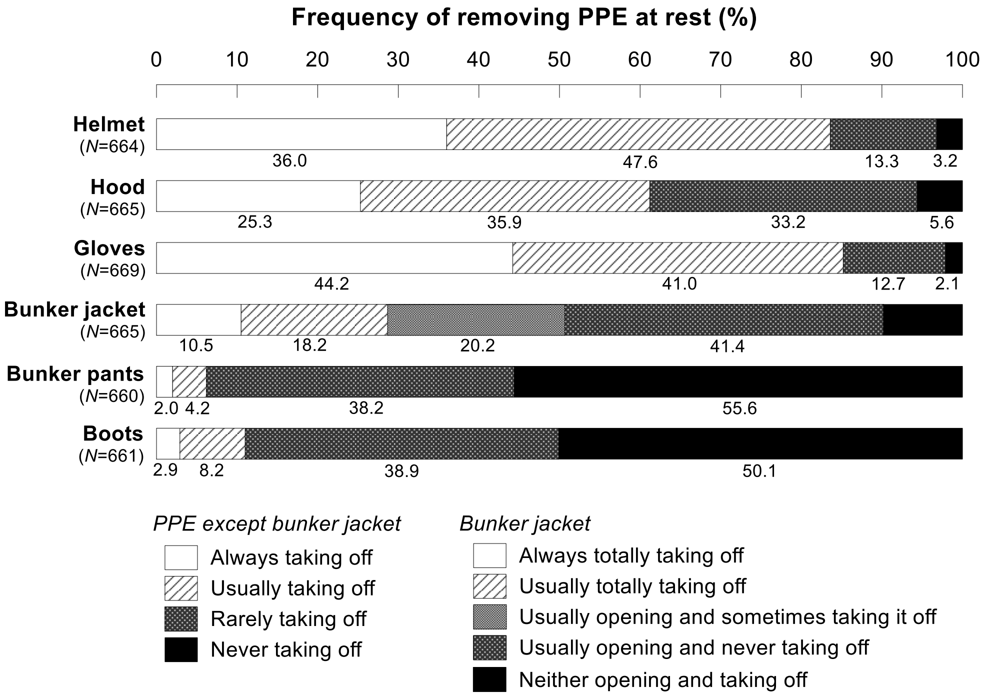

Figure 4.2. Frequency of removing firefighters' personal protective equipment (PPE) during rest period.

When a correlation between the frequency of removing protective clothing with the duration of rest periods was analyzed by Spearman's rank correlation, firefighters with longer resting time removed their protective clothing elements more frequently, except the helmet and gloves: a hood (r = 0.158, p < 0.001); a bunker jacket ($r = 0.200$, $p < 0.001$); bunker pants ($r = 0.136$, $p = 0.001$); boots ($r = 0.182$, $p < 0.001$). Correlation coefficients between removing gloves and the resting time was 0.080 ($p = 0.051$). This outcome demonstrated that the "dress down" methods to cool down the body are a matter of rest time. NFPA 1584 (2015) recommends firefighters take a rest at least 10 min to 20 min, but the median value for the average rest time in the small-to-medium fire was 10 min. Even 25% of respondents answered that they rest on average less than 7 min, which is not enough time for removing PPE, except the helmet. In addition, don/doff-friendly design is another issue here. Especially, when PPE is soaked by sweating or water from fire hoses, removing them gets far harder than before. Kim et al. (2016) documented significantly extended time to don/doff wet gloves than dry ones, and 9 gloves among 13 made in US, Europe, Japan, and Korea displayed problems of separated lining from the outer layer and coming off with the hands, which hindered firefighters successfully wearing them within a short time. Although it was not significant, there was still a weak correlation between rest time and doffing gloves ($r = .080$, $p = .051$).

Lastly, presences of HRI symptoms were statistically significantly greater in firefighters who usually wear PPE when resting versus firefighters who always/usually remove PPE: dizziness (gloves: OR 1.95, 95% CI [1.23-3.09]); nausea (helmet: OR 2.01, 95% CI [1.31-3.07]); vomiting (helmet: OR 2.16, 95% CI [1.38-3.37]; gloves: OR 1.64, 95% CI [1.02-2.64]); confusion (helmet: OR 2.07, 95% CI [1.36-3.15]; gloves: OR 2.41, 95% CI [1.02-2.64]); sudden muscle cramps (helmet: OR 1.67, 95% CI [1.10-2.54]) (Table 4.5). Categorized experience frequencies also showed statistically significant increases when compared with wearing frequency of PPE during rest: dizziness (helmet: OR 2.62, 95% CI [1.53-4.49]); nausea (helmet: OR 2.02, 95% CI [1.14-3.57]; hood: OR 1.85, 95% CI [1.12-3.05]; gloves: OR 1.90, 95% CI [1.03-3.50]; boots: OR 2.44 [0.98-6.04]); confusion (gloves: OR 2.09, 95% CI [1.07-4.08]; bunker jacket: OR 2.26, 95% CI [1.06-4.84]). These results imply the significant role of removing protective clothing during rests in firefighters' physiological recovery. Theoretically, with a smaller cover area of protective clothing, heat dissipation can be more promoted. For this reason, guidelines for U.S. firefighters' rehabilitation urges firefighters to dress down by taking off their bunker coats, helmets, hoods, and opening the bunker pants as well

(NFPA 1584, 2015). In addition, although the boots were not usually removed by approximately 90% of firefighters, removing boots can effectively dissipate heat strain from the body, since the feet behave as remarkable radiators and evaporators, as well as the hands, with a great surface area to mass ratio (~3 times larger than that of the body) (Taylor et al., 2014b).

Table 4.5. Odds ratio of symptoms of heat-related illness (HRI) according to the frequency of taking off PPE

HRI symptoms / Wearing PPE	Presence of HRI symptoms			Frequency of HRI symptoms (more or less than 5 times/yr)[a]		
	OR	CI 95%	*p*	OR	CI 95%	*p*
Dizziness						
Wearing helmet at rest	1.48	0.97-2.27	.070	2.62	1.53-4.49	<.001
Wearing gloves at rest	1.95	1.23-3.09	.004	1.51	0.87-2.60	.142
Nausea						
Wearing helmet at rest	2.01	1.31-3.07	.001	2.02	1.14-3.57	.014
Wearing hood at rest	1.06	0.77-1.45	.727	1.85	1.12-3.05	.015
Wearing gloves at rest	1.51	0.98-2.32	.062	1.90	1.03-3.50	.037
Wearing boots at rest	0.69	0.42-1.13	.142	2.44	0.98-6.04	.048
Sudden muscle cramps						
Wearing helmet at rest	1.67	1.10-2.54	.015	1.80	0.99-3.26	.052
Confusion						
Wearing helmet at rest	2.07	1.36-3.15	.001	1.90	0.97-3.74	.060
Wearing gloves at rest	2.41	1.56-3.71	<.001	2.09	1.07-4.08	.030
Wearing bunker jacket at rest	1.14	0.79-1.64	.478	2.26	1.06-4.84	.033
Vomiting						
Wearing helmet at rest	2.16	1.38-3.37	.001	1.43	0.56-3.64	.453
Wearing gloves at rest	1.64	1.02-2.64	.040	2.47	0.97-6.30	.053

[a] Experience frequency of symptoms of heat-related illness and heat stroke was categorized in two groups: more than 5 times per year (5 was not included) and less than 5 times (5 was included)

Frequency of wearing PPE during rest period was categorized in two groups: group of never/rarely taking off PPE and another group of always/usually taking off

Abbreviations: HRI, heat-related illness; OR, odds ratio; CI 95%, 95% confidence interval.

In the current survey, several firefighters gave the extra answer that they prefer a state of readiness, because they do not know when they should re-enter fire scenes. Guaranteed sufficient rest time is needed along with improved PPE which can be easily donned/doffed even in the wet condition. Also, Additional cooling methods should be promoted to firefighters to efficiently remove firefighters heat strain during the restricted rest periods. In addition, the crucial role of removing helmet and gloves can still be valid in the working place where neither sufficient resting time or rehabilitation strategies are given to firefighters. Also, removing PPE is required to be promoted to firefighters, so that they recognize its critical contribution to their heat strain.

4.1.4 Summary

In this chapter, it was revealed that firefighters routinely experienced mild HRI symptoms and the fatalities were just a tiny fraction. It is also emphasized that attention should be given on the significant role of more active cooling measures as well as taking off protective clothing during rest. However, when considering that firefighters often re-start firefighting because of the emergent situation and that commonly firefighters use self-identified physical restoration as a criterion to start working, just repetition of the needs for cooling measures cannot be an ultimate solution for the current Korean firefighters. To monitor firefighters' heat strain prior to re-start the duty and to verify whether firefighters are sufficiently recovered or not, question remains about the way to evaluate heat strain with a very simple instruction.

4.2. Development of Resting Heart Rate Model

4.2.1 Rectal Temperature and Heart Rate

Time courses of the rectal temperature and heart rate presented in Figure 4.3. Heart rate was drastically decreased immediately after each exercise was ended, thereafter it settled down to a plateau during the post-exercise rest period at greater values than the previous rest periods (Figure 4.3A and C). The plateau was obtained at least 2 min after cessation of exercise in both post-exercise rest periods (Figure 4.4B and D).

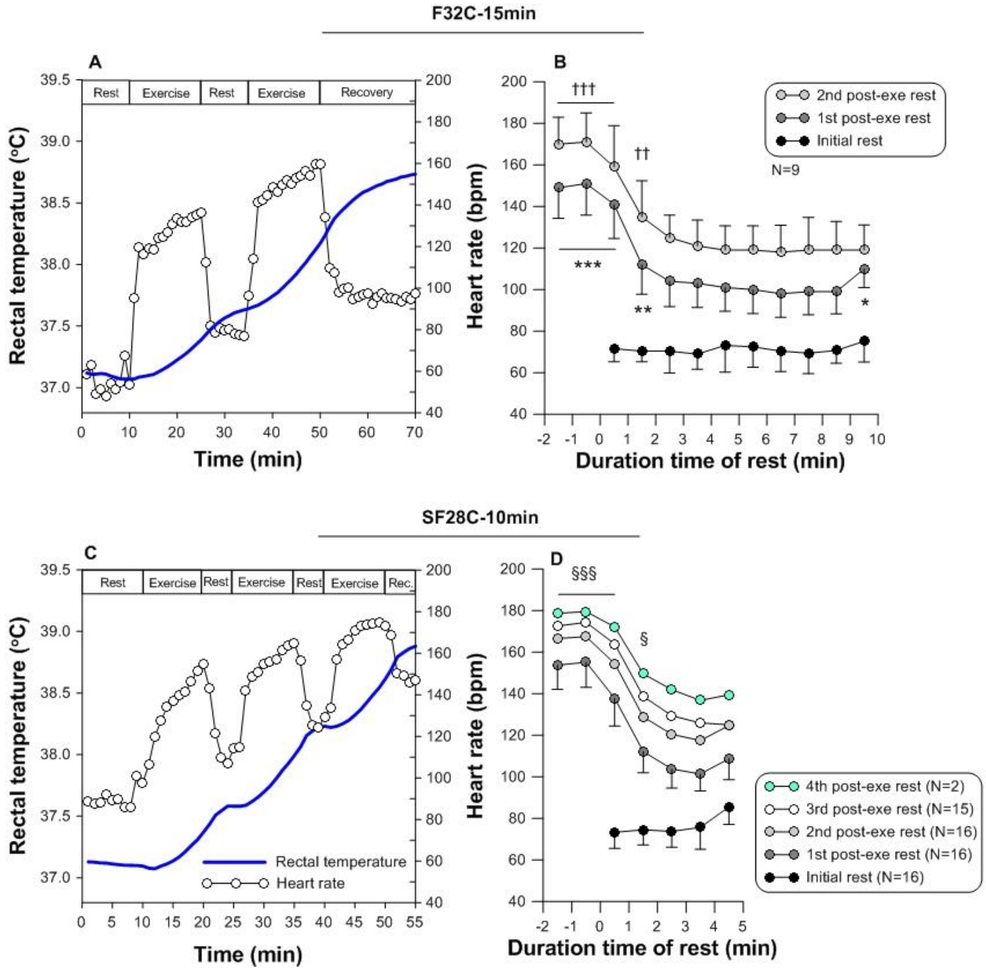

Figure 4.3. Examples of paralleled increases in resting heart rate and rectal temperature in Test A and B (A, C) and changes in heart rate during initial and post-

exercise rest periods (B, D). Data in figure A and C were taken from one male firefighter in 30 years of age and one male student in 21 years of age, respectively. In figure B, * and † indicate significant differences from the values from 6 min to 7 min in the 1st and 2nd post-exercise rest periods, respectively ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{††}p < 0.01$, $^{†††}p < 0.001$). In figure D, § indicates significant differences from the values at 3-4 min in the 1st, 2nd, and 3rd post-exercise rest periods ($^{§}\ p < 0.05$, $^{§§§}\ p < 0.001$).

4.2.2 Model Development

Based on the observations from the Test A, B, and C, Model 1 was computed with mixed-effects model. The coefficients obtained as shown in Table 4.6. The intercept and slope were both significant. Based on them, the formula was re-transformed, and the final formula was obtained as follows:

$$\text{Model 1: } rTre = 36.36 + 1.3 \times 10^{-4} \times rHR^2 \quad \text{(eq.4.1)}$$

In this equation, the independent variable, rHR. was restricted in the range of 50 $\leq$ rHR $\leq$ 140. Marginal R^2 and 95 % prediction limit were calculated as 0.800 and 0.61°C, respectively (Figure 4.4A). RMSE was 0.308 and the mean bias with LoA was 0.01 ± 0.61 in the Bland Altman plot (Figure 4.4B).

Table 4.6. Un-transformed parameter details of Model 1

Coefficients	Estimate	s.e.	*t* value
a'	37.8603	0.0492	848.51***
b'	0.6379	0.0275	23.75***

Abbreviations: s.e. standard error of the estimated parameters; *t* value, *t*-test value, ***p<0.001

Table 4.7. Un-transformed parameter details of Model 2B

Model 2B	Estimate	s.e.	*t* value
log f	-11.8175	1.1877	-9.950***
g	1.5765	0.2328	6.772***
h	1.5094	0.0918	16.450***

Abbreviations: s.e. standard error of the estimated parameters; *t* value, *t*-test value, *P<0.001

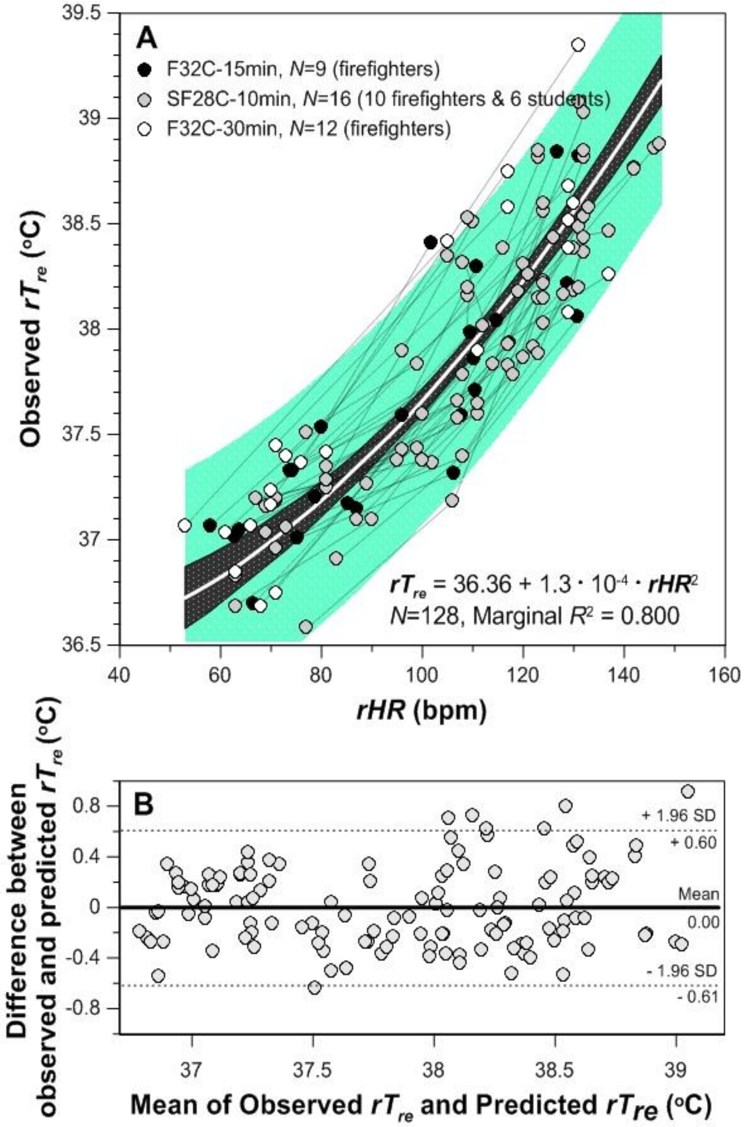

Figure 4.4. [Model 1] Regression line of rectal temperature during rest periods (rT_{re}) predicted by resting heart rate (rHR)(A) and its Bland Altman plot (B). A: This graph displays observed data points from three separate experiments. The fit is shown in center line with the 95% confidence intervals (in dark grey area) and the 95% prediction intervals (in green or light grey area) around the fit.

Model 2 was computed in both linear formula (Model 2A) and exponential formula (Model 2B) via log transformation. A linear formula of Model 2 was computed as follows:

$$\text{Model 2A: } \Delta T_{re} = -0.71854 + 0.00535 \cdot \mathrm{rHR} + 0.05173 \cdot \mathrm{t} \qquad \text{(eq.4.2)}$$

Model 2A showed marginal R^2 of 0.865, and pseudo-R^2 was 0.857 (Figure 4.5A). In the Bland Altman plot, mean difference was – 0.01 with 0.24 of LoA.

In terms of Model 2B, estimated parameters were obtained as shown in Table 4.7. The *t* values in Table 4.7 present that all regression coefficients are significantly different from zero. The final equation of Model 2B after re-transformation was developed as follows:

$$\text{Model 2B: } \Delta T_{re} = 8 \times 10^{-6} \times rHR^{1.6} \times t^{1.5} \qquad \text{(eq.4.3)}$$

Because the data set only held *t* at most 30 (min), there should be extrapolation regarding $t > 30$ in Model 2A and 2B. This exponential model (Model 2B) showed slightly worse performance than the linear model (Model 2A): Marginal R^2 of Model 2B was 0.756, while the goodness of fit between observation and prediction was argued as R^2 of 0.811 (Figure 4.5B). In the Bland Altman plot, mean difference was – 0.04 with 0.28 of LoA. Tendency of heteroscedasticity was presented in the Bland Altman plot (Figure 4.6A), but it was disappeared after replacing the absolute values with the percent of differences (Figure 4.6B).

Lastly, the Model 3 was simply generated by sum of rT_{re} and ΔT_{re}. When it was a sum of Model 1 and 2A, it was called Model 3A, whereas a sum of Model 1 and 2B was called Model 3B. 95% PI of Model 3A was 0.55 °C. In the Bland Altman plot, the mean bias was – 0.06 with ± 0.52 of LoA, and RMSE was 0.270. On the other hand, Model 3B yielded that the 95% prediction limit was 0.61°C. The mean bias in the Bland Altman plot was – 0.09 with ± 0.58 of LoA and RMSE was 0.288.

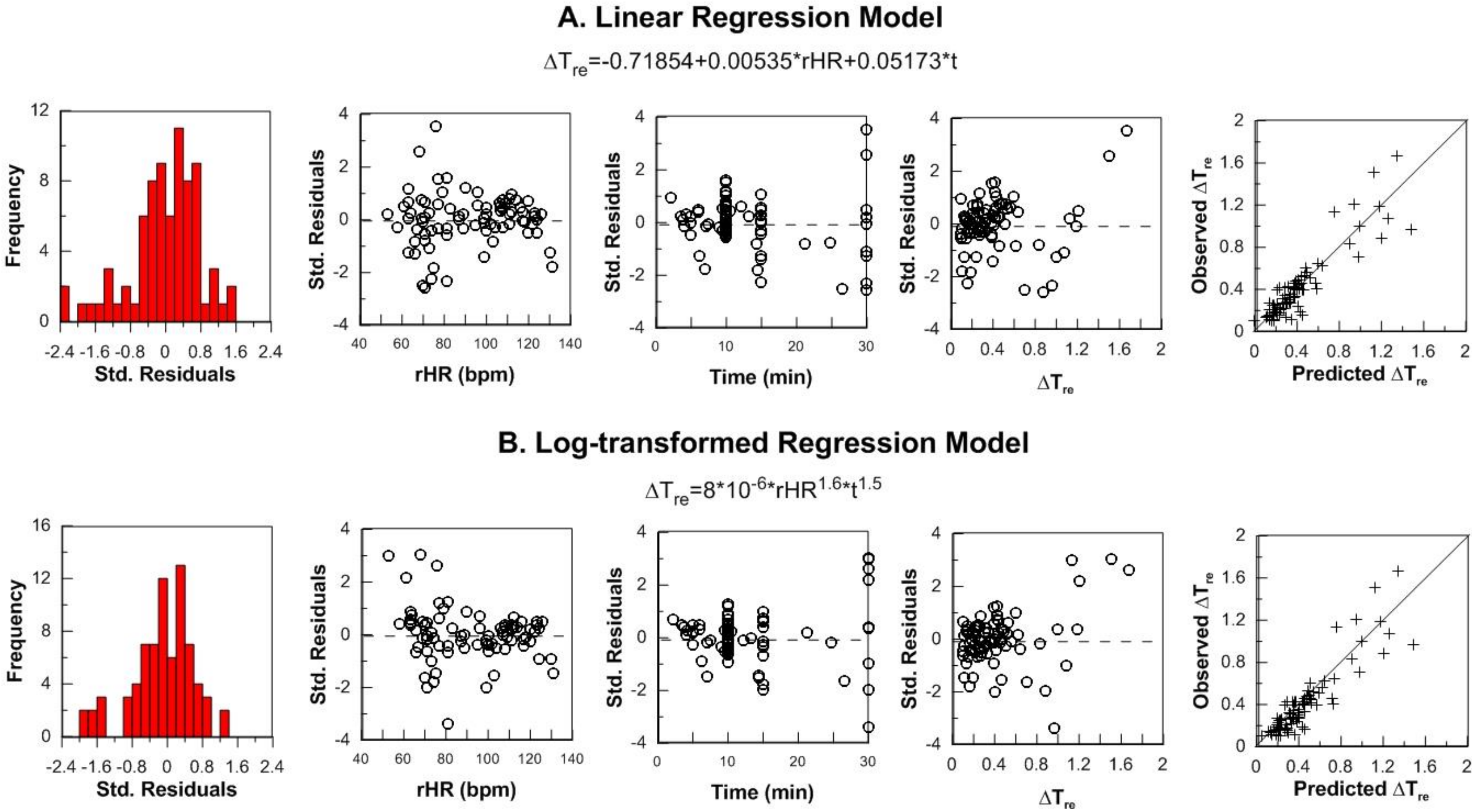

Figure 4.5. [Model 2] Residual analyses about Model 2 in a linear formula (A) and a logarithmic formula (B) and the goodness of fit plot presenting observations and predictions.

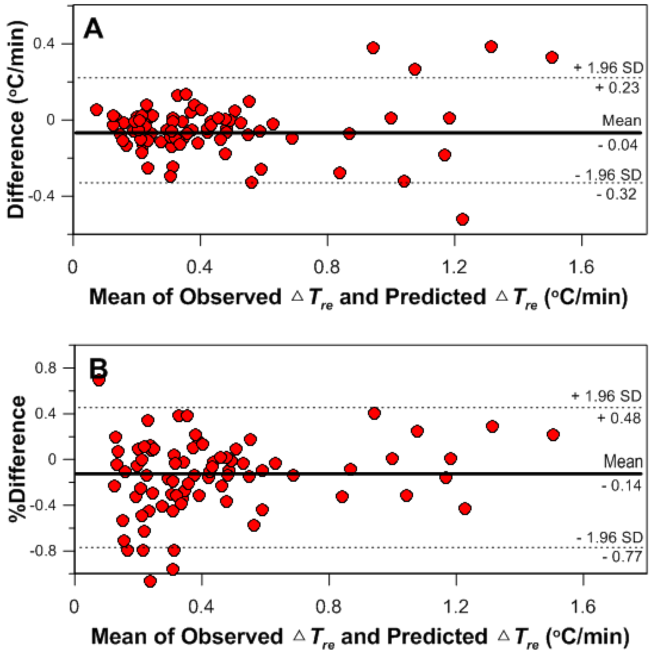

Figure 4.6. [Model 2B] Bland Altman plot with absolute values in a y-axis (A) and relative values in a y-axis (B).

Byrne and Lim (2007) suggested 0.4°C for the acceptable criteria for that, while in this study, 95%PIs in Model 1 and 3A were 0.61°C and 0.55°C respectively. When comparing the acceptable criteria by Byrne and Lim (2007), it would be difficult to say that rHR is the complete surrogate of the body core temperature. However, when considering that this model is developed not for an representatives of body core temperature, but supplementary indicators of heat strain for a practical use, it is comparable with other practical models of body core temperature (Buller et al., 2013; Buller et al., 2015; Laxminarayan et al., 2018).

Overall, the models developed in. the current study showed better performances than the models by Buller et al. (2013) and Laxminarayan et al. (2018) when compared with the overall LoA and RMSE, respectively. In particular, Laxminarayan et al. (2018) recently developed individual predictive models of body core temperature using five independent variables including skin temperature, heart rate, physical activity and two environmental variables (ambient temperature and relative humidity) and yielded overall average RMSE of 0.33. In the current models, RMSE was 0.308, 0.270, and 0.288 for Model 1, 3A, and 3B, and the models have superiority of practicality in these models have advantages that the models were mainly operated by single predictor, rHR.

On the other hand, individual differences still remain as the obstacles to overcome. In this study, among various individual differences, initial resting heart rate was especially analyzed to explain individual differences in heart rate responses. In order to investigate significant difference in predictive validity of Model 1, the distribution of each subject's difference between expected rHR and observed rHR (D) by initial resting heart rate was examined. The result was shown in Figure 4.7. A trend line in Figure 4.7A showed that D increased as the initial resting heart rate decreased, which means that with lower initial resting heart rate, underestimation can be more substantial. To identify a valid range of initial resting heart rate to compute linear regression analysis, a local polynomial regression fitting was conducted using *loess* function in R. The outcome presented that the early inflection point was HR_0 = 64.11. Thus, a linear regression analysis has completed with the data points with HR_0 below 64.11. The computed regression line between was significant (R^2=0.401, p<0.05). $HR_{correction}$ was suggested as follows:

$$HR_{correction} = -1.56 \times HR_0 + 97.24 \text{ (if } HR_0 < 63 \text{ bpm)} \quad \text{(eq.4.4)}$$

When HR_0 equals 62.3, $HR_{correction}$ becomes 0. Thus, this equation was suggested to be used of HR_0 only below 62.3, which approximately equates to 63. Corrected rHR was suggested as a sum of rHR and $HR_{correction}$.

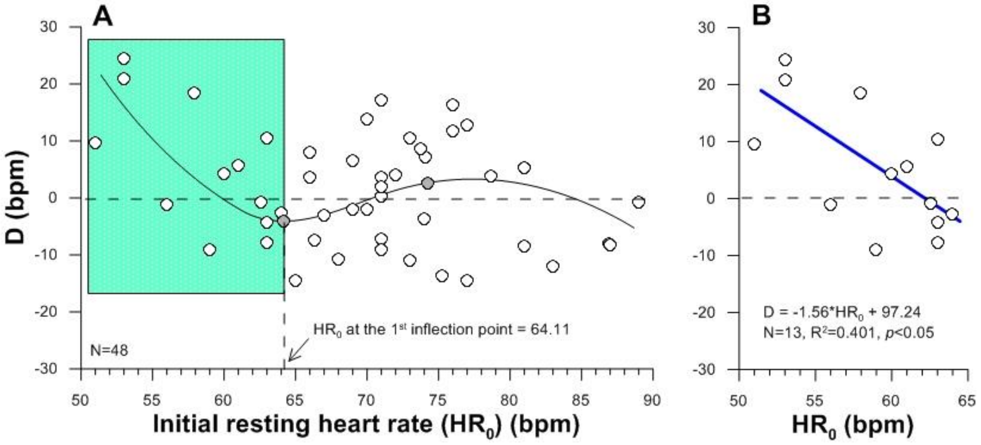

Figure 4.7. [Model 1] Each subject's difference between expected rHR and observed rHR (D) by initial resting heart rate (HR_0) in Model 1. In Figure A, the line shows a trend of the distribution and two dots on the line are inflection points. In Figure B, the bold line shows a regression line between D and HR_0 below 64.11 bpm.

With corrected rHR, Model 1 and Model 2 were re-computed. A small range of estimated coefficients were modified, yet they did not escape the bounds of a 95 %CI for the previous outcomes. Thus, the final re-transformed predictive equations were not further modified. With rHR corrected, the models' performances were improved presenting increased R^2 between observed and predicted values along with decreased RMSE and LoA (Table 4.8). This correction is also important because lower HR_0 can lead significant underestimation of rectal temperature which is more dangerous than overestimation in a safety point of view. Using a developed correction equation, resting heart rate of a subject whose initial resting heart rate was 52 bpm was modified to 68 bpm.

Still, it can be debated on which variables are the most aapropriate between heart rate and the increase in heart rate due to heat strain (ΔHR_T) (ISO 9886, 2004). In the current study, the distribution between initial resting heart rate and the difference between expected and observed rHR was analyzed, but it hardly showed an overall trend, but a drastic skewness for lower initial resting heart rate (Figure 4.5A). Based on this trend, this model just utilized initial resting heart rate values for correction rather than ΔHR_T.

Table 4.8. Model performances with/without correction of resting heart rate

	Model 1 [rT_{re}]		Model 2A [ΔT_{re}]		Model 2B [ΔT_{re}]		Model 3A [eT_{re}]		Model 3B [eT_{re}]	
	Without correction	*With correction*	*Without correction*	*With correction*	*Without correction*	*With correction*	*Without correction*	*With correction*	*Without correction*	*With correction*
Model development data: Test A, B, and C										
Pseudo-R^2	0.782	0.789	0.857	0.857	0.857	0.839	0.705	0.723	0.676	0.716
RMSE	0.308	0.297	0.125	0.125	0.147	0.140	0.278	0.270	0.306	0.288
Mean bias ± LoA	0.01±0.63	-0.01±0.58	-0.01±0.24	-0.01±0.24	-0.04±0.28	-0.01±0.26	-0.06±0.54	-0.06±0.52	-0.09±0.58	-0.10±0.53
95% PI	0.61	0.59	-	-	-	-	0.55	0.54	0.61	0.58
Validity test data: Test D										
Pseudo-R^2	0.638	0.670	0.037	0.050	0.026	0.037	0.586	0.638	0.577	0.634
RMSE	0.330	0.309	0.227	0.218	0.228	0.227	0.359	0.318	0.356	0.339
Mean bias ± LoA	0.07±0.64	-0.04±0.61	0.05±0.44	0.02±0.43	-0.02±0.45	-0.04±0.44	0.09±0.69	-0.04±0.63	0.03±0.71	-0.10±0.65

Pseudo-R^2 is obtained from the simple regression analysis between observed and predicted values.
Abbreviations: rT_{re}, rectal temperature during rest periods; ΔT_{re}, increase in rectal temperature; eT_{re}, rectal temperature at the end of exercise; RMSE, Root mean square error;, LoA. Limit of Agreement; 95% PI, 95% prediction interval.

Table 4.9. Resting heart rate (rHR) and the corresponding rectal temperature at rest (rT_{re}) and anticipated rectal temperature at the end of exercise (eT_{re}) lasted for 20 or 30 min (Unit: ^oC)

rHR[a] (bpm)	Predicted rT_{re} (lower 95%PI, upper 95%PI)	Predicted eT_{re} after t min (lower 95%PI, upper 95%PI)	
		t = 20	t = 30
60	36.8 (36.2, 37.4)	37.3 (36.7, 37.9)	37.7 (37.1, 38.3)
70	37.0 (36.4, 37.6)	37.6 (37.0, 38.2)	38.2 (37.6, 38.8)
80	37.2 (36.6, 37.8)	38.0 (37.4, 38.6)	38.6 (38.0,39.2)
90	37.4 (36.8, 38.2)	38.4 (37.8, 39.0)	39.2 (38.6, 39.8)
100	37.7 (37.1, 38.3)	38.8 (38.2, 39.4)	39.7 (39.1, 40.3)
110	37.9 (37.3, 38.5)	39.2 (38.6, 39.8)	40.3 (39.7, 40.9)
120	38.2 (37.6, 38.8)	39.7 (39.1, 40.3)	
130	38.5 (37.9, 39.1)	40.2 (39.6, 40.8)	
140	38.9 (38.3, 39.5)		
150	39.3 (38.7, 39.9)		

[a] If initial resting heart rate (HR_0) is lower than 63 bpm, $HR_{correction}$ should be added in measured rHR using following equation: $HR_{correction} = -1.56 \times HR_0 + 97.236$ (eq.4.3)

Abbreviations: rHR, stabilized recovery heart rate; rT_{re}, rectal temperature at rest; eT_{re}, rectal temperature during exercise; t, duration time of working (or exercise); PI, prediction interval

Based on the developed models with rHR corrected, predicted rT_{re} and eT_{re} were calculated with varied rHR and t. Based on the calculation, Table 4.9 was suggested to simply show the interpretation of resting heart rate as a heat indicator. For example, we can estimate that firefighters' rTre is 37.7℃ (95 %PI, 37.1 to 38.3) when their rHR is 100 bpm. However, T_{re} can increase up to 38.8℃ (95 %PI, 38.2 to 39.4), if the firefighter works for 20 min. These results can be rather rigorous criterion, since it was developed based on intensive work load. It is expected that this limit could be a practical guidance for firefighters to judge whether to begin work again or to rest more in the repetitive and prolonged firefighting.

Table 4.10. Anthropometric data for all participants

	Middle-aged firefighters (N=5)	Younger firefighters (N=5)	Young adult students (N=6)	*p*
Age (years)	48 ± 3	31 ± 4	24 ± 4	.002
Height (cm)	172 ± 3	171 ± 2	173 ± 3	.819
Weight (kg)	73.5 ± 11.4	69.4 ± 5.7	71.4 ± 5.2	.841
Body mass index (BMI)	24.7 ± 2.9	23.7 ± 2.4	23.9 ± 2.0	.761
% Body fat	19.8 ± 5.3	17.2 ± 5.4	16.7 ± 6.3	.601
Lean body mass (kg)	58.8 ± 7.6	57.2 ± 2.9	59.3 ± 4.4	.833
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	41.4 ± 3.3	48.5 ± 8.7	41.0 ± 5.7	.257
HR_{max} (bpm)	186 ± 12	188 ± 7	187 ± 7	.915

p-value was obtained by Kruskal-Wallis test.

Abbreviations: % Body fat, percent of body fat; $\dot{V}O_{2max}$, maximal oxygen consumption; HR_{max}, maximal heart rate.

4.2.3. Addition of Independent Variables

4.2.3.1. Analysis by Parameters of the individual regression line

Test B was conducted with subjects in three groups (middle-aged firefighters, young firefighters and young adult students) to identify significant factors affecting

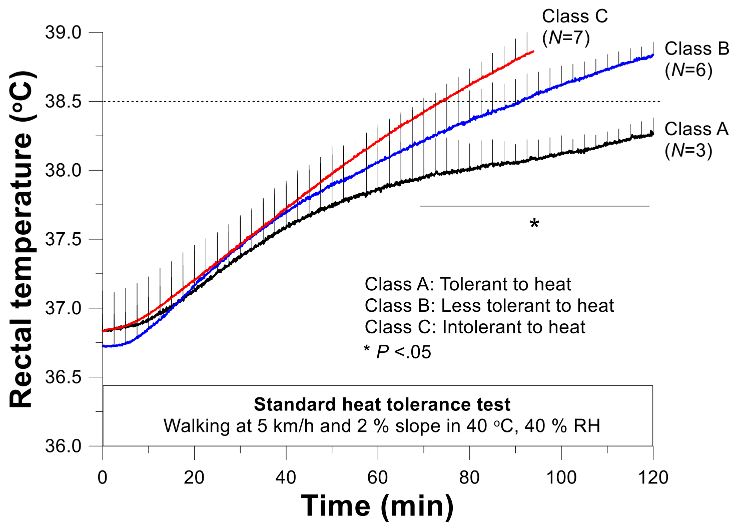

Figure 4.8. Time courses of rectal temperature during heat tolerance test (HTT): The subjects were classified in three classes according to the physiological parameters at the end of the test.

interindividual variations in a function of rectal temperature to resting heart rate among various individual physical and physiological parameters. Statistically, there was no significant group difference of those variables except the age (Table 4.10).

Each subject's rectal temperature and heart rate during HTT were analyzed. As a result, subjects were divided in three groups as follows (Figure 4.8): three in group A (tolerant to heat), six in group B (less tolerant to heat), and seven in group C (intolerant to heat) (Table 4.11). Among five young firefighters, three of them were classified in group A, while two were belonged to group C. The subjects who was classified in group A were all young firefighters, and none of the older firefighters were sorted to group A. Three older firefighters were sorted to group B, and two were group C. None of the young students were belonged to group A. Half of the

Table 4.11. Classification of the heat tolerance

Group	Subject's No.	Age (years)	Duration time (min) [a]	$T_{re, HTT}$ (°C)	HR_{HTT} (bpm)	Classification[c]		
						A	B	C
Middle-aged firefighters	1	48	108	39.00	173			X
	2	46	Completed	38.85	149		X	
	3	46	Completed	38.91	167		X	
	4	53	Completed	38.85	139		X	
	5	48	94	39.00	169			X
Young firefighters	6	33	105	39.00	151			X
	7	36	Completed	38.17	131	X		
	8	27	96	39.00	162			X
	9	34	Completed	38.37	117	X		
	10	27	Completed	38.28	131	X		
Young adult students	11	29	Completed	38.68	143		X	
	12	20	113	38.75 [b]	154			X
	13	26	98	39.00	140			X
	14	26	Completed	38.94	159		X	
	15	21	Completed	38.81	150		X	
	16	21	103	39.00	158			X

[a] 'Completed' means subjects finished 120 min walking with T_{re} lower than 39°C.
[b] Subject No.12 discontinued the HTT before T_{re} approach at 39°C because of dizziness.
[c] Heat tolerance was classified: A, $T_{re, HTT} < 38.5$°C with $HR_{HTT} < 150$ bpm. B, $38.5°C < T_{re, HTT} < 39°C$. C, Incompleted HTT.
Abbreviations: $T_{re, HTT}$, rectal temperature at the end of exercise during HTT; HR_{HTT}, heart rate at the end of exercise during HTT

young adult students were in group B, and the others were in group C. When recruiting subjects, firefighters were postulated as a heat-acclimatized subjects and students were thought as subjects not acclimatized to heat. However, this result did not agree to the simple classification of heat tolerance by occupations.

When theses individual variables were analyzed in terms of association with the slope and T_{110}, T_{120}, and T_{130}, the results presented no significant effect by any other individual factors but by HR_{max} with T_{110}, T_{120}, and T_{130} (Table 4.12, Figure 4.9A, T_{110}: r = - 0.686, T_{120}: r = - 0.687, T_{130}: r = - 0.662), but no significant relation was found with the slope (Table 4.12). Heat tolerance showed no significant effect on T_{120}(Figure 4.9B). Figure 4.10 showed the individual data of rectal temperature and resting heart rate for all subjects of the Test B, especially showing T_{120}. This result suggested the possibility that HR_{max} may work as an additional independent variable to improve predictive equations of core temperature by resting heart rate among various individual physical and physiological parameters.

Table 4.12. Correlation coefficients (r) between individual factors and indicators of regression line between heart rate to rectal temperature

	Age	Height	Weight	A_D/mass	VO_{2max}	HR_{max}	*Est.* HR_{max}	Heat tolerance
Slope	.097	.193	- .134	- .230	.118	- .181	- .094	*N.A.*
	(.721)	(.474)	(.620)	(.391)	(.663)	(.536)	(.729)	
T_{110}	.071	- .200	- .292	- .233	- .022	- .686 **	- .064	*N.A.*
	(.795)	(.459)	(.273)	(.385)	(.935)	(.007)	(.814)	
T_{120}	.090	- .140	- .307	- .276	.012	- .687 **	- .084	*N.A.*
	(.739)	(.606)	(.247)	(.301)	(.965)	(.007)	(.758)	
T_{130}	.102	- .079	- .301	- .296	.035	- .662 *	- .095	*N.A.*
	(.707)	(.772)	(.257)	(.266)	(.899)	(.010)	(.726)	

Abbreviation: A_D/mass, the ratio of body surface area to body mass. VO_{2max}, maximal oxygen consumption. HR_{max}, maximal heart rate. Est. HR_{max}, estimated maximal heart rate by age, V.A., not available.

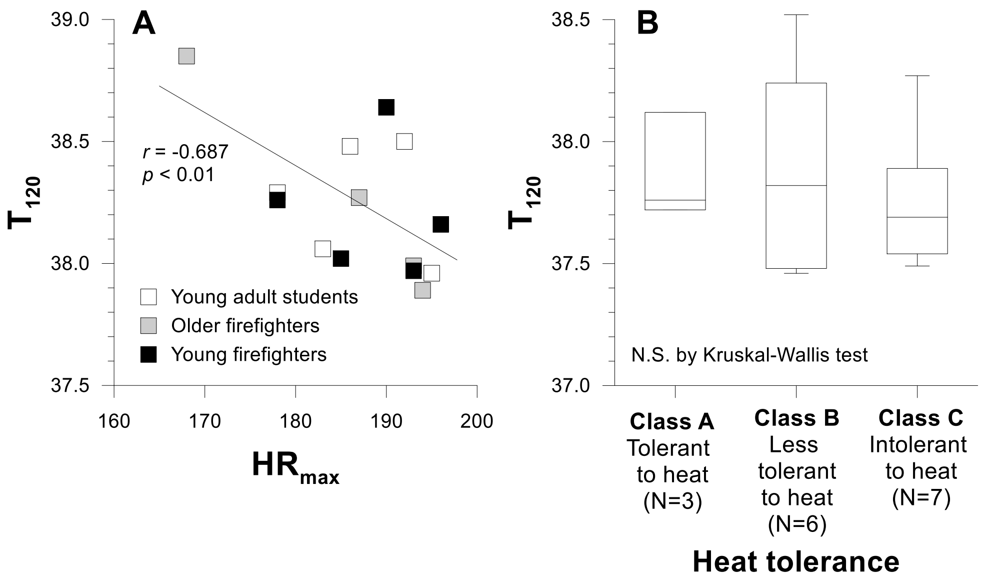

Figure 4.9. Significant correlation between maximal heart rate (HR_{max}) and T_{120} (A) and the difference in T_{120} by heat tolerance (B); T120 indicates rectal temperature corresponds to resting heart rate of 120 bpm.

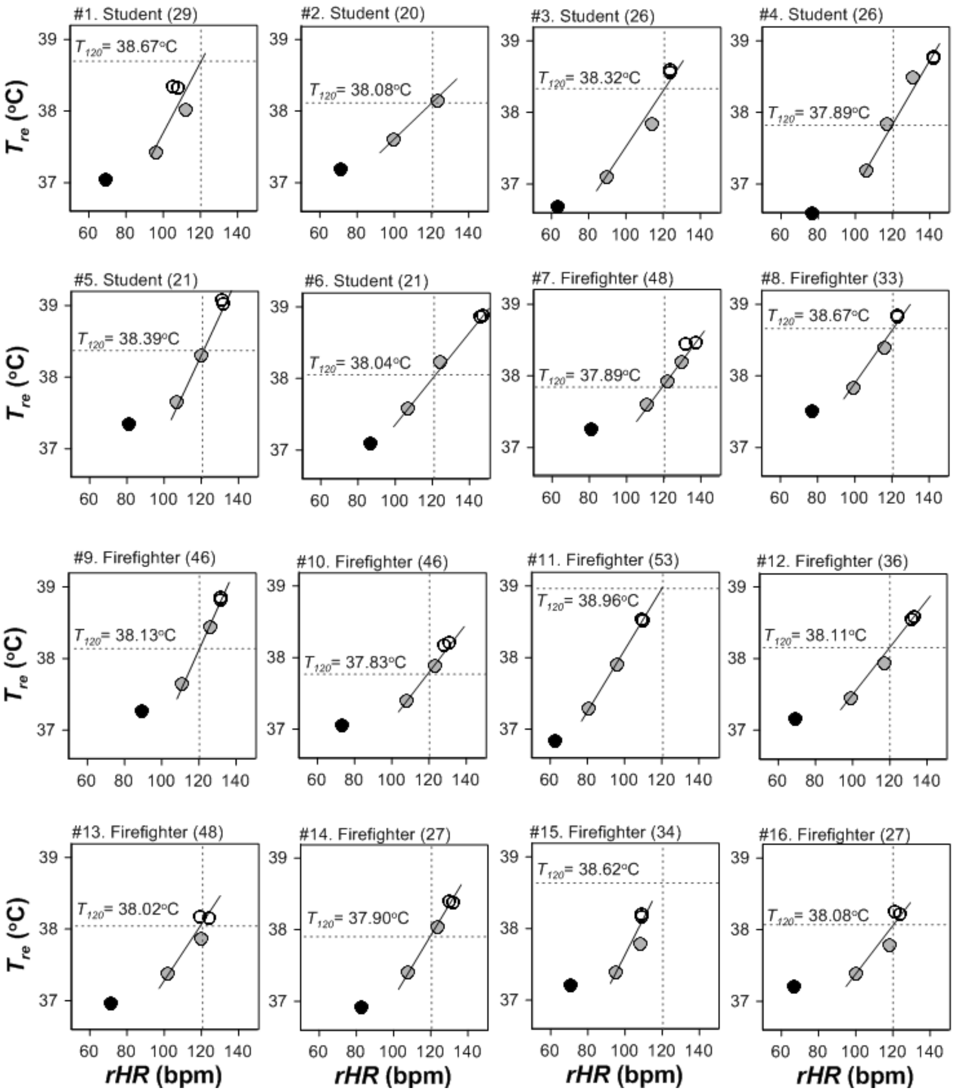

Figure 4.10. All data of the function of rectal temperature and resting heart rate of 16 subjects in Test B. T_{120} is rectal temperature when resting heart rate is 120 bpm.

The individual variables are inter-related each other. For example, HR_{max} is known to decrease by ageing (Tanaka et al., 2001). However, in this study, the other variables but age were all controlled no to differ by groups. In a scatter plot between HR_{max} and T120 (Figure 4.9A), there is an influential point who had very different HR_{max} from other data, which could exaggerate the significance of correlation. To reduce the contribution of the influential point, additional two data points which measured in Test D were added. They rather reinforced the correlation with a higher correlation coefficient (r = - 0.727, p = 0.001). Age-predicted maximal heart rate is often used as a surrogate of maximal heart rate because of its ease of use. However, this result did not find that age-predicted HR_{max} can replace HR_{max} which can be measured by a maximal graded test.

4.2.3.2. Analysis of Residuals in Prediction

When the residual distributions were obtained by each individual variable, there was no individual variable which showed significant R^2 with the residuals but only HR_{max} presented a significant negative correlation coefficient (r= -0.203, p=0.032, Figure 4.11). This implied that underestimation of predicted rectal temperature can be associated with lower HR_{max}, which were paralleled with the result from Analysis by parameters of in the individual regression line (Table 4.11).

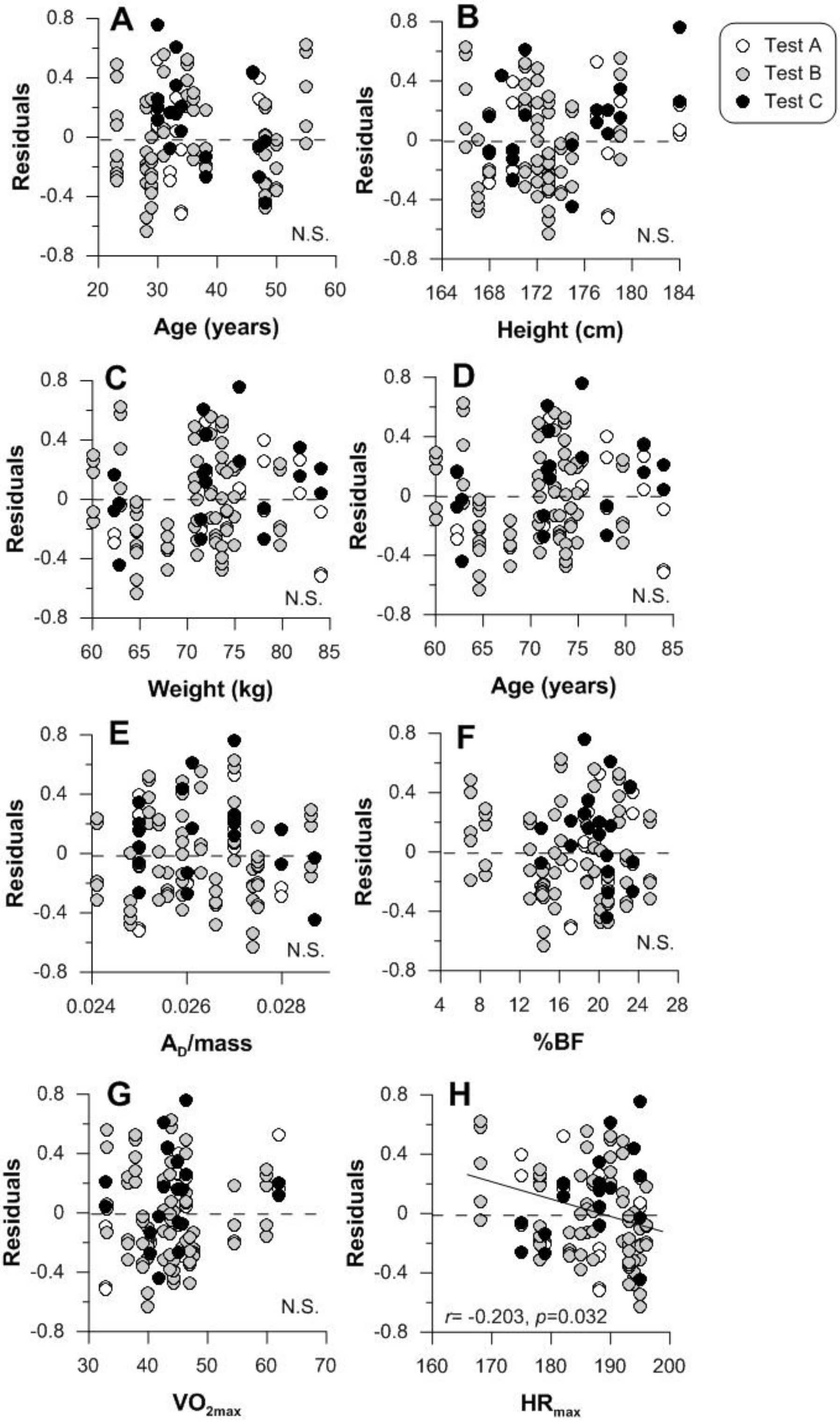

Figure 4.11. Residual distributions by the individual variables.

4.2.3.3. Multiple Regression Analysis

However, when the mixed-effects regression model was re-computed with all other individual variables, the estimated parameter of HR_{max} was the least significant (estimated parameter = -0.0006, t value =-0.172, p>0.05). This result was in discord with the results from above two analyses. The reason on this discrepancy should be investigated.

The regression model with three additional predictors, weight, A_D/mass, and VO_{2max}, was evaluated as another good model (Model 1.5 in Table 4.13) when Marginal R^2 was the criteria of model determination. Marginal R^2 represent the fixed-effects variance among all variances, and Marginal R^2 in the Model 1.5 was well maintained despite of reduction in the number of independent variables (compared with Model 1.4) and enough high than the further reduced model (Model 1.6).

However, Model 1.5 had a problem of strong collinearity between weight and A_D/mass (r = -0.814). To resolve it, Model 1.9 and Model 1.10 were additionally computed and compared (Table 4.13). Model performance of Model 1.9 was better than that of Model 1.10 specially on the AIC and BIC (smaller AIC and BIC are preferred, and they usually agree each other). However, when comparing the model 1.9 with model 1.8 (null model), AIC and BIC were still greater, which implied that the benefit from an increase in the number of predictors in Model 1.9 was not prominently greater. In this context, following regression formula could be optionally used as an alternative of Model 1, but the Model 1 is still the best model when considering the benefit of simplicity.

Alternative model of Model 1:

$$\text{rHR} = 34.023 + 0.02762 rHR^2 + 0.00783 Weight + 0.0093 \dot{V}O_{2max} \quad \text{(eq. 4.5)}$$

(Marginal R^2 = 0.816)

Table 4.13. **[Model 1]** Comparison of the model performances in a stepwise multiple regression (111 observations, N=37)

Models		Independent variables[a]								Marginal R^2	AIC	BIC
		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8			
Stepwise multiple regression	Model 1.1	rHR	Weight	A_D/mass	VO_{2max}	%BF	Age	Height	HR_{max}	0.815	24.1	56.6
	Model 1.2	rHR	Weight	A_D/mass	VO_{2max}	%BF	Age	Height		0.814	22.1	51.9
	Model 1.3	rHR	Weight	A_D/mass	VO_{2max}	%BF	Age			0.812	20.2	47.3
	Model 1.4	rHR	Weight	A_D/mass	VO_{2max}	%BF				0.814	18.9	43.3
	Model 1.5	rHR	Weight	A_D/mass	VO_{2max}					0.814	18.9	43.3
	Model 1.6	rHR	Weight	A_D/mass						0.808	18.4	40.1
	Model 1.7	rHR	Weight							0.809	18.3	37.3
	Model 1.8	rHR								0.809	16.9	33.2
After removing collinearity	Model 1.9	rHR	Weight	VO_{2max}						0.816	17.6	39.3
	Model 1.10	rHR	A_D/mass	VO_{2max}						0.815	18.8	40.5

[a]All variables were normalized before the regression analysis in order to overcome the rescaling issue in R.

Abbreviations: rHR, resting heart rate; A_D/mass, a ratio of body surface area to body mass; VO_{2max}, maximal oxygen consumption; %BF, percentage of body fat; HR_{max}, maximal heart rate; AIC, Akaike's Information Criterion; BIC, Schwarz's Bayesian Information Criterion; logLik, log-likelihood.

4.3. Validity tests

4.3.1. Different Type of Exercise and Work Load [Test D]

Validity of the models in the different type of exercise (walking on a treadmill and cycling) and different work load were examined with data from Test D. Overall, these data presented the best agreement with Model 1 showing no significant bias in all phases (Figure 4.12A) with pseudo-R^2 of 0.670 between observation and prediction (Figure 4.13A). On the other hand, there was a poor agreement with Model 2B (R^2=0.037, p=0.294, Figure 4.13B). There were also statistically negative biases in the 1st and 3rd exercise phases when exercise was done at 50 %$\dot{V}O_{2max}$ (Figure 4.12B, 1st exercise: -0.12, 95 %CI [-0.20, -0.04], p=0.008; 3rd exercise: -0.23, 9 5%CI [-0.32, -0.14], p=0.001), and statistically positive bias in the 2nd exercise phase when the exercise was done at 80 %$\dot{V}O_{2max}$ (Figure 4.12B, 0.20, 95 %CI [0.09, 0.31], p=0.003). Such results demonstrated that Model 1 would be valid irrespective of the previous exercise intensity, but Model 2B would overestimate ΔT_{re} at the lighter exercise intensity and underestimate ΔT_{re} with work load over 65 %$\dot{V}O_{2max}$. The magnitudes of overestimation and underestimation in the V-SF25C-10min were approximately -0.02 and 0.02 °C·min^{-1}, respectively.

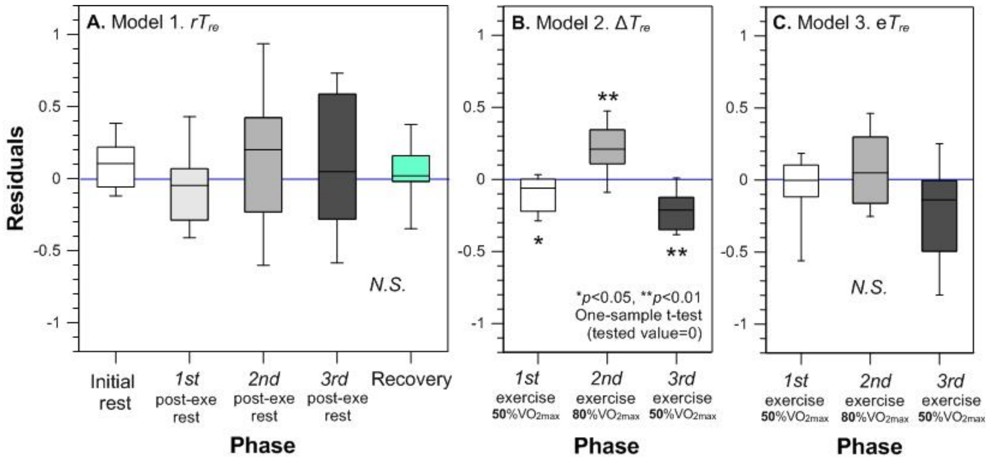

Figure 4.12. **[Model 1, 2B, and 3B]** Residuals in each model by phases (A: Model 1, B: Model 2B, C: Model 3B): There was no significant bias by phases in the Model 1 and 3B, but significant underestimation and overestimation were found in the Model 2B.

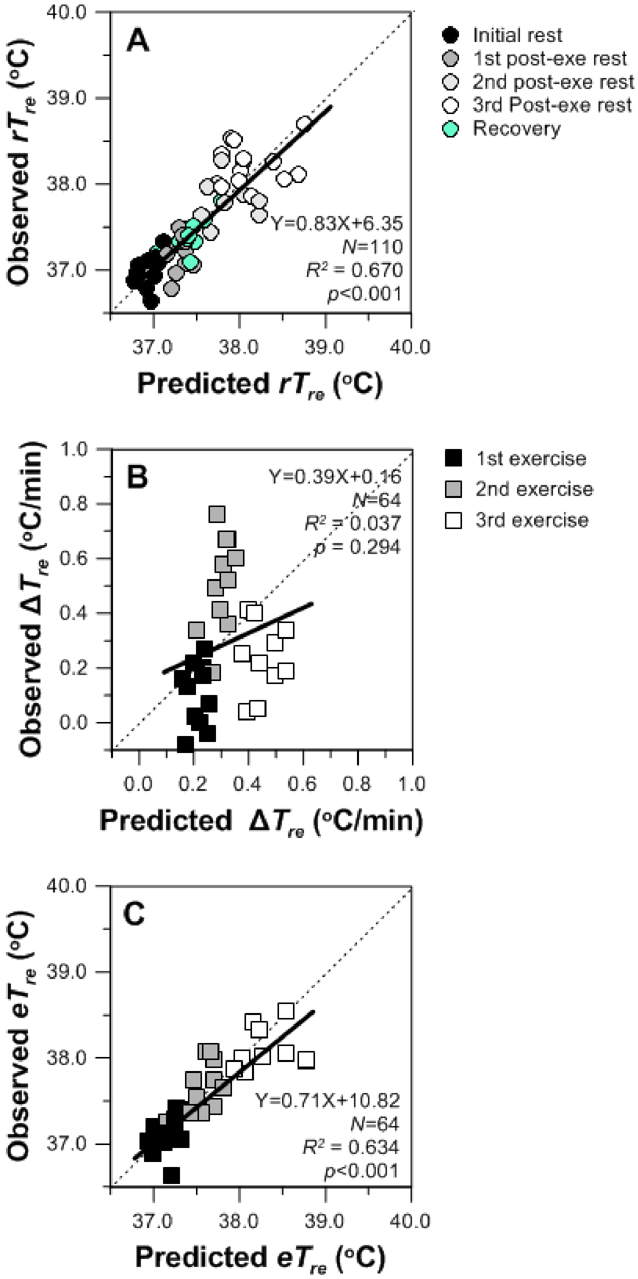

Figure 4.13. [Model 1, 2B, 3B] Validity tests about Model 1 [rT_{re}, rectal temperature during rest and recovery periods], Model 2B [ΔT_{re}, increase in rectal temperature], and Model 3B [eT_{re}, rectal temperature at the end of exercise] with data from Test D (intermittent cycling tests at exercise intensities of 50, 80, and 50 %$\dot{V}O_{2max}$ with 10 min post-exercise periods).

4.3.2. Simulated Firefighting Test [Test E]

On the other hand, another validity test with simulated firefighting test drills (Test E) presented the best agreement with Model 2B with no meaningful bias observed (Figure 4.13B, slope of a fitted line 0.78, 95 %CI [0.32, 1.24]). However, it showed a significant bias with Model 1 and Model 3B (Model 1: Figure 4.14A, slope 0.54, 95 %CI [0.34, 0.74]; Model 3B: Figure 4.14C, slope 0.52, 95 %CI [0.33, 0.70]).

Poor agreement of Model 1 and 3B with data of Test E was expected because firefighters did not achieve psychological relaxation during the rest periods. They did talk with other firefighters and watched their performance. Talking can interrupt the respiratory frequency and the observation of other firefighters' performance can evoke competition rather than relaxation. Quantitative evaluation on the effect by psychological intervention was not involved in the current study. However, it should be required in the further study to find out the validity of this model in the working place. Control in breathing frequency without any talking and watching other scenes may work to minimize the psychological variance of heart rate (Bernardi et al., 2000)

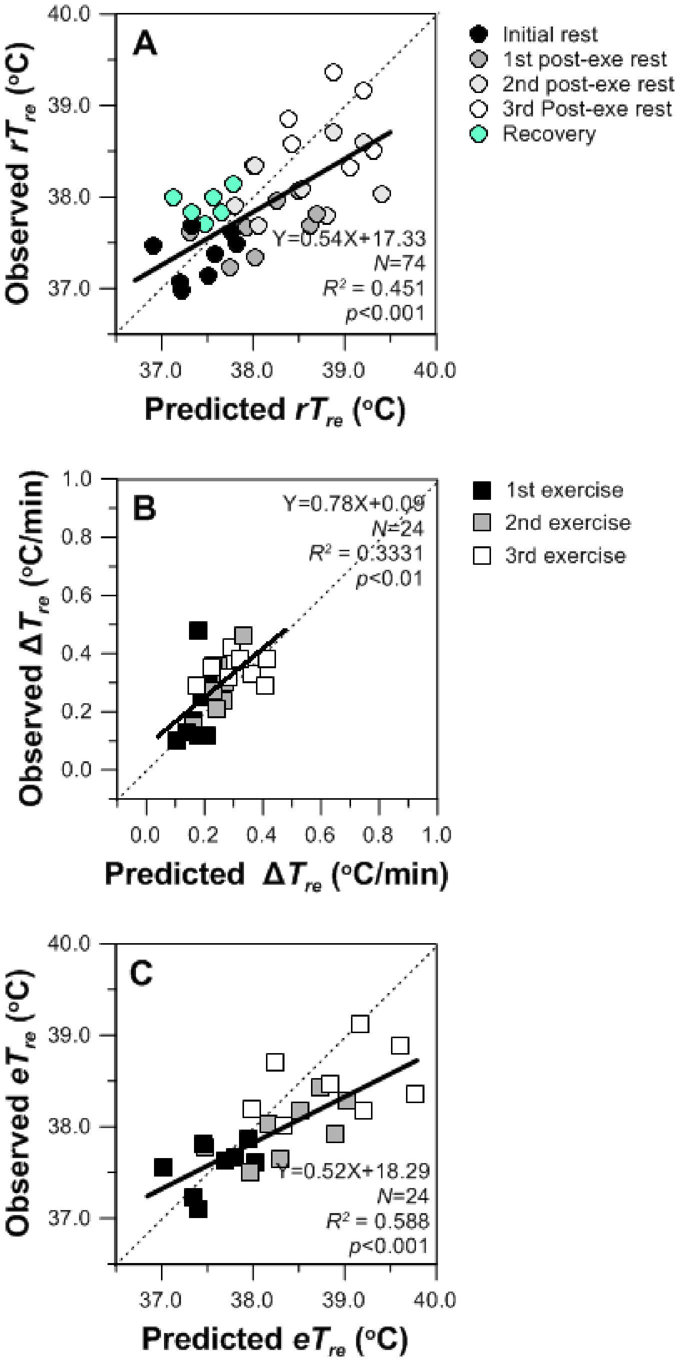

Figure 4.14. [Model 1, 2B, and 3B] Validity tests about Model 1 [rT_{re}, rectal temperature during rest and recovery periods], Model 2B [ΔT_{re}, increase in rectal temperature], and Model 3B [eT_{re}, rectal temperature at the end of exercise] with data from Test E (simulated firefighting test drills where subjects repeated a circuit which consisted of eight tasks three times with 5 min post-exercise rest periods).

4.3.3. Different Clothing during Heat Exposure [Test D]

To investigate significant difference in predictive validity of Model, the difference between FF (turnout gear) and SW (sportswear) was investigated during the intermittent exercise protocol (first one hour in the 2 hours protocol).

Skin temperature displayed significant difference between two groups (p<0.001, Figure 4.15). SW had greater skin temperature than FF, which would be affected by the higher ambient temperature (SW: 40°C, FF: 25°C): Differences was -2.15°C during initial rest and -1.24°C during 2nd post-exercise rest.

In both conditions, rectal temperature and heart rate gradually increased during the rest periods. Despite of the higher skin temperature, there was no difference in both rectal temperature and heat rate (Figure 4.16, p > 0.05). In this condition, it was possible to compare the differences by skin temperature, which can be caused by clothing insulation, while the heat strain level was controlled.

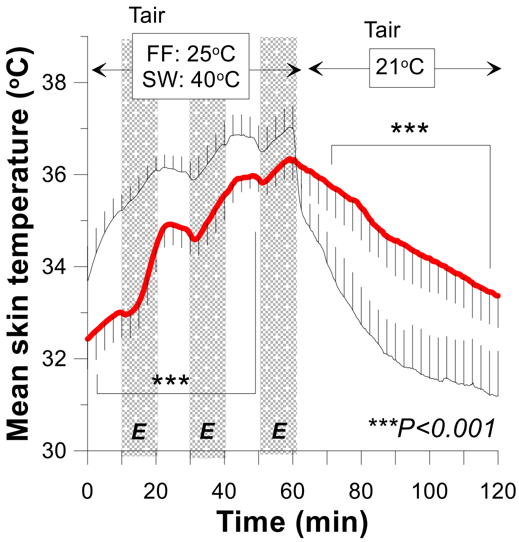

Figure 4.15. Skin temperature during entire period of Test D. An intermittent exercise was carried out for the initial one hour; a bold line is FF (turnout gear) and a thin line is SW (sportswear) (N=11).

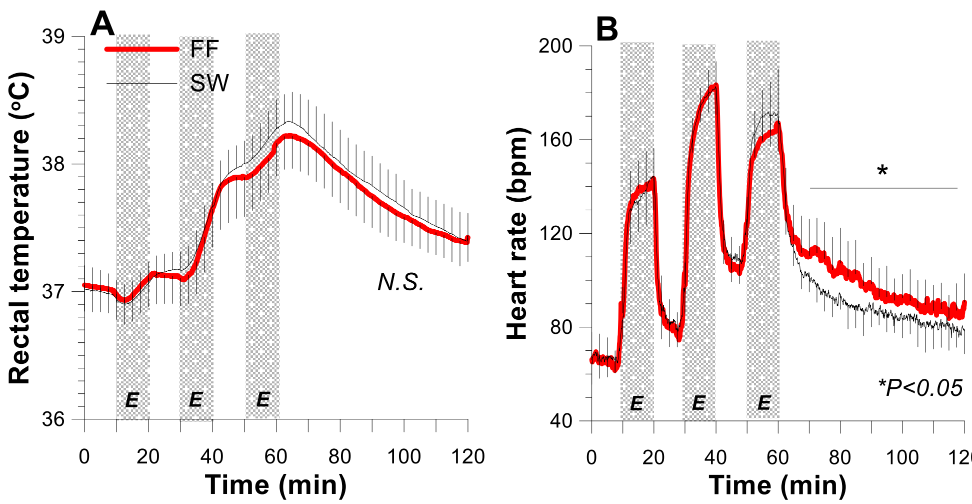

Figure 4.16. Rectal temperature (A) and heart rate (B) during Test D, and initial one hour represents the period of an intermittent exercise protocol. There was no difference in both during entire protocol (N=11).

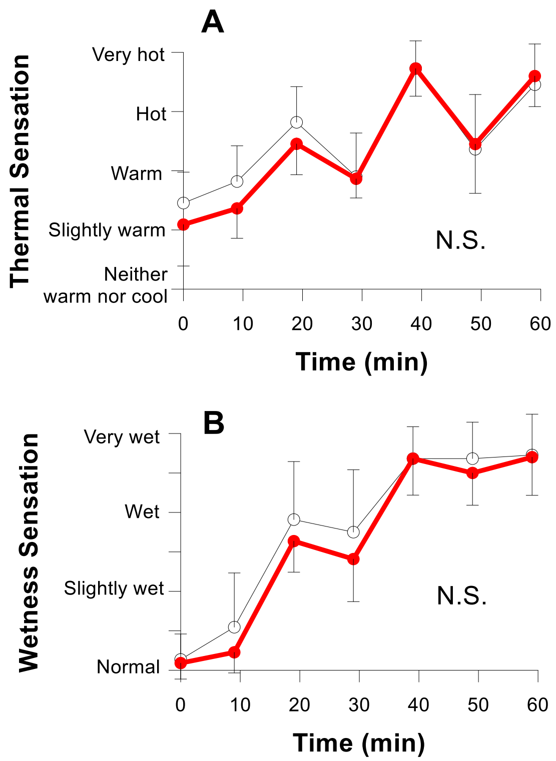

Figure 4.16. Thermal sensation (A) and wetness sensation (B) during heat exposure: bold line and thin line indicate sportswear and turnout gear condition, respectively.

When the relation between heart rate and rectal temperature was drawn by conditions, no difference was found in the distribution (Figure 4.17).

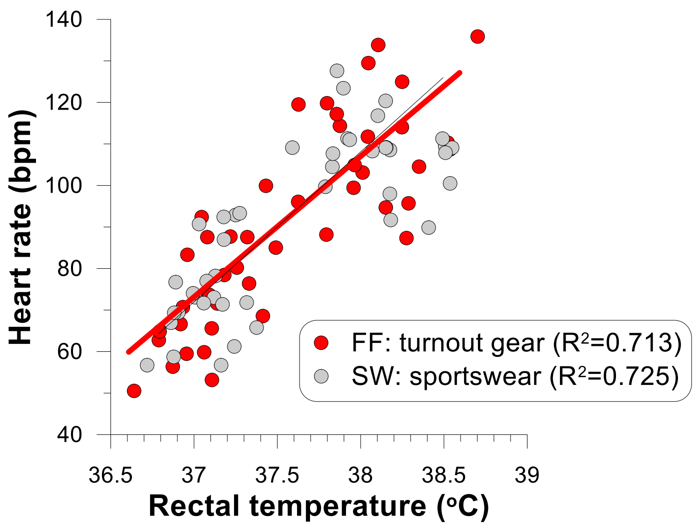

Figure 4.17. Relationship between rectal temperature and heart rate in two conditions. Linear line indicates the regression line. There was no skewness or shift by two conditions.

Additional regression analysis was computed to identify statistical difference in two regression line. The group term is given by a dummy variable to explain the experimental conditions. Results showed no significant t-value on the group term, which implied that the regression lines in both conditions are statistically identical (Table 4.14).

Table 4.14. Estimated coefficients in the regression analysis during heat exposure

	Estimate	s.e.	t-value	*p*-value
Intercept	-1083.314	84.643	-12.799	***
T_{re}	31.250	2.252	13.875	***
Group*	1.959	2.531	0.774	N.S.

*Group term was given by a dummy variable.

Abbreviations: T_{re}, rectal temperature; s.e. standard error of the estimated parameters; *t* value, *t*-test value; *p* value, *p*-test value

To sum up the result in this sub-session, when considering the model development was based on the data where subjects wore turnout gear in 28 to 32°C of ambient temperature, First, this study expanded the ambient temperature at which models can be used. Second, this study suggested the application onto sportswear condition in the hot weather could be possible. In this study, the independent effect of skin temperature on the validity of prediction was identified under the identical level of the rectal temperature. The difference of mean skin temperature was about 2°C, which was caused by the different clothing insulation from protective clothing.

4.3.4. During Long-Term Recovery with/without Turnout Gear [Test D]

The last validity test was conducted, focusing on the long-term recovery period and the effect by passive cooling (in other words, removing turnout gear) using the data from Test D. The only difference in two conditions during recovery period was the clothing. Ambient temperature was maintained at 21°C, identically, but subjects wore turnout gear and sportswear in FF and SW, respectively (Figure 3.3). The hypothesis was that the heart rate would be lower in SW because of the reduced skin temperature accompanied by reduction of blood pressure. The results partially agreed it.

First, mean skin temperature was significantly different in two conditions during recovery (Figure 4.15). The difference was about 1.35°C at the first 10 min and 2.57°C at the 40 min at recovery without any difference in the rectal temperature. Heart rate had a similar tendency with mean skin temperature showing significant difference during all recovery period except the first 10 min (Figure 4.16B), which was not accompanied by different in blood pressure (Figure 4.19).

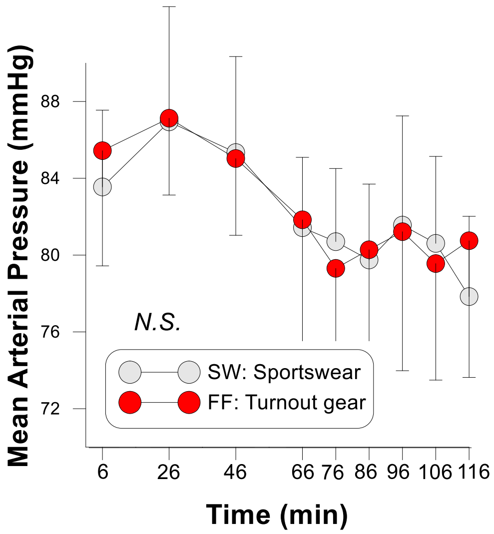

Figure 4.19. Mean arterial pressures (MAP) in two conditions.

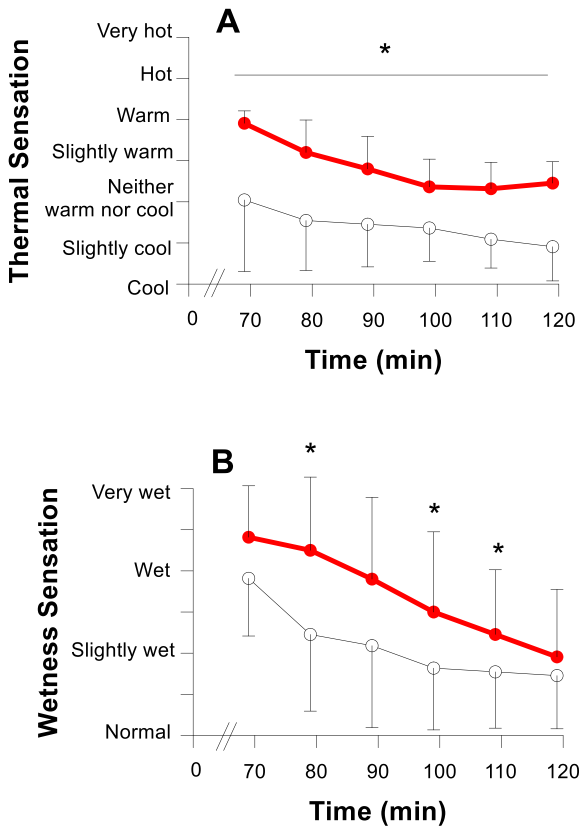

Figure 4.20. Thermal sensation (A) and wetness sensation (B) during recovery: red and bold line indicates sportswear condition, and thin line indicates turnout gear condition.

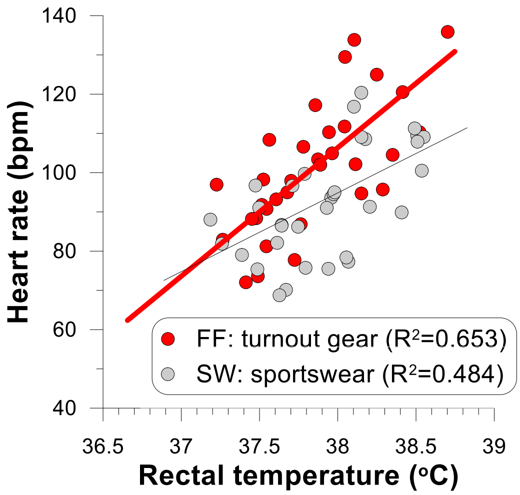

Figure 4.21. Relationship between rectal temperature and heart rate during recovery. Significant skewness of regression line was observed in SW condition.

Table 4.15. Estimated coefficients in the regression analysis during recovery

	Estimate	s.e.	t-value	*p*-value
Intercept	-1029.150	61.846	-16.64	***
T_{re}	29.846	1.636	18.25	***
Group*	-10.873	1.061	-10.25	***

*Group term was given by a dummy variable.

Abbreviations: T_{re}, rectal temperature; s.e. standard error of the estimated parameters; *t* value, *t*-test value; *p* value, *p*-test value

When the distribution of heart rate and rectal temperature was drawn in a scatter plot (Figure 4.21), the regression line of SW condition was substantially skewed when compared with the line of FF. To identify the statistical difference between two lines, additional regression analysis was computed. Results showed significant t-value on the group term, which implied that the regression lines in both conditions are statistically different (Table 4.15).

When the heart rate in SW condition was used as an input value of Model 1, significant residuals were observed during entire recovery period as shown in

Figure 4.22. This was very different with FF condition which showed no significant during recovery (Figure 4.23). The following box-whisker plot showed the distribution in residuals of Model 1. The most prominent bias was occurred during initial 30 min of recovery. Discrepancy in the mean skin temperature was getting greater during initial 30 min and maintained until the end of recovery, but the heart rate along with predictive bias was showed a tendency of reduction during recovery.

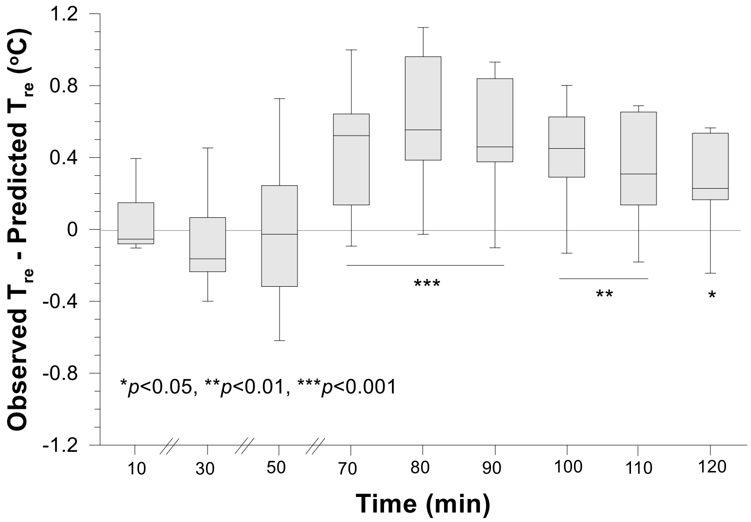

Figure 4.22. Residuals distribution of Model 1 in SW condition

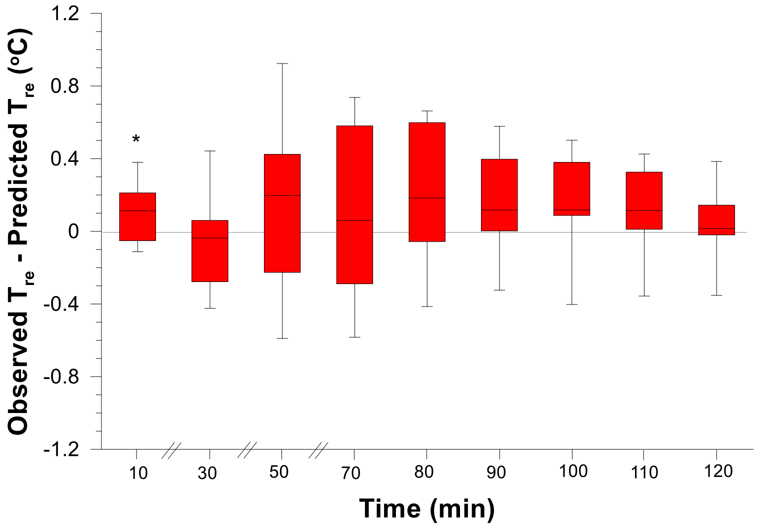

Figure 4.23. Residuals distribution of Model 1 in FF condition

This result delivered critical implications on the use of heat indices and models which used heart rate as a main predictor. First, heat indices and models which used heart rate as a main predictor can underestimate heat strain when cooling methods are implemented. Firefighters are often encouraged to utilize cooling measures during their recovery. Here, cooling measures compass passive methods such as removing turnout gear and staying in a cool area and very active methods such as to immerging hands and feet in the cold water and fan cooling. These measures were helpful to remove heat strain more efficiently during limited rest time, but it did underestimate rectal temperature approximately 0.5°C when the mean skin temperature was reduced ~2°C. When firefighters recovered, maintaining turnout gear on their body, there was no significant decrease in heart rate despite the cool environment (21°C).

4.2.6. Summary

Three models of rectal temperature by resting heart rate were derived in this chapter. Along with correction factor, additional predictors were explored, and validity tests were conducted in various conditions.

First, the models developed had the following features: 1) heart rate should be measured during resting periods with accompanying mental and physical relaxation, 2) an interval of at least 2 min after the cessation of exercise to remove the effect of physical exertion, 3) use of averaged heart rate at least for 1 min, 4) 95% of prediction located in the range of ±0.6°C, 4) Correction for the lower initial resting heart rate can be applied to prevent significant underestimation of the rectal temperature. 5) Optionally, weight and $\dot{V}O_{2max}$ could be added as an additional predictor using eq. 4.5. The valid performance of the models was confirmed in following conditions:

- Ambient temperature: 21-32°C while wearing turnout gear during the rest in a duration of 5 to 60 min (also valid at 40°C while wearing sportswear)
- Clothing: Full firefighters' personal protective equipment were equipped during exercise, but the helmet, hoods, and gloves were removed during rest.

- Participants: healthy individuals without any known diseases in wide range of age (17-53 years), race (Caucasians, and Indian, and many Asians), sex (5 females in Test D), physical fitness (32-60 %$\dot{V}O_{2max}$), and heat tolerance.
- Work load: Model 1 was validated in the work load between 50-80 %$\dot{V}O_{2max}$, while resting heart rate limit was validated in the work load at ~ 65 %$\dot{V}O_{2max}$ and simulated firefighting task drills.

By a series of validity tests, special caution of the model application was suggested as follows:

- During recovery when cooling measures including removing turnout gear are implemented (Removing local equipment is not influential)
- When psychological tension exists. Controlling breathing frequency and short meditation may work to reduce psychological effect on heart rate, but further studies are needed.

Chapter 5. Conclusions

This study explored the possibility that heart rate could be used as a single predictor of heat strain and the results yielded that well stabilized heart rate which was only collected with physical and psychological relaxation can be significantly predict body core temperature. These models can be easily adapted to current smart wearable devices which collect heart rate. With assistance of proper applications or software, it will be able to provide an easy way to inspect firefighters' heat strain during their rest periods not to exceed their physiological limitation.

This study also investigated Korean firefighters' heat strain in the first part and clearly demonstrated that the fatality of firefighters that is usually known to people is a just tiny fraction when it is compared with the actual occurrence of HRI during duties. This study finally suggested a practical guidance to judge whether to begin work again or to rest more in the repetitive and prolonged firefighting based on developed models. Advantages of this method were: 1) it is a precautionary measure to distinguish firefighters in danger of heat-related illness, 2) the instrumentation is simple. Detailed instructions on the way to predict heat strain by heat rate was additionally described in the Appendix 2. Several implications can be separately given to Korean Fire Department, firefighters, and the society and citizens:

Korean Fire Department

- Educate firefighters especially on the danger of accumulated heat strain and appropriate rehabilitation procedures to prevent heat-related illness.
- Improve safety management system (e.g. ensure the minimum duration of rest and inspect each firefighter's health during every rest)
- Periodically publish reports on all incidents and HRI cases during duties including the causes and their preventive measures.

Firefighters

- Always doubt self-identified restorations

- Practice active cooling measures during rest (if it is not feasible, taking off protective clothing is better than keeping encapsulated by it)

Society and the Citizen

- Understand that firefighters cannot keep working without rest and respect firefighters' rest periods (do not impose firefighters to re-work)

In addition, the current standards on the physiological monitoring of heat strain (ISO 9886; ACGIH, 2018; NIOSH, 2016) do not explain about the appropriate and inappropriate conditions when the heart rate can be validly used as a heat indicator. For a correct use, environmental condition and instruction should be more clearly provided (e.g. lower validity during cooling measures).

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Appendix 1.

Questionnaire (in Korean)

관할		No.	

2016 소방안전 및 119구조·구급기술연구개발사업

소방공무원의 돌발 고위험 상황 · 화상 · 열질환 경험 실태 및 소방활동 개인보호장비 개선 방향 연구

연구주관기관: 서울대학교 (연구책임자: 교수 이주영)

설 문 지

※ 본 설문조사는 전국 시도 소방공무원 가운데
화재진압과 구조 경력이 있는 소방공무원에 한해 참여하실 수 있습니다.

○ 귀하는 소방공무원으로서 화재진압 혹은 구조 경력이 있으십니까?	□ 있다 (→ 설문조사 진행). □ 없다 (→ 설문조사 중단).

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동 의 서

이 연구는 자발적으로 참여 의사를 밝히신 분에 한하여 수행될 것이며, 귀하께서는 참여 의사를 결정하기 전에 본 연구가 왜 수행되는지 그리고 연구의 내용이 무엇과 관련이 있는지 이해하는 것이 중요합니다. 다음 내용을 신중히 읽어보신 후 참여 의사를 밝혀 주시길 바랍니다. 답해주신 모든 내용은 『통계법』 제 33조에 따라 비밀이 보장됩니다.

연구 목적 및 과정

본 연구는 2016년 한국 ' 국민안전처 소방안전 및 119구조·구급기술연구개발사업'의 '소방활동 개인보호장비의 성능한계분석 및 안전성 평가기법 연구'의 일환으로, 화재진압·구조를 담당하는 소방관이 화재 현장에서 서열 부담을 가중시키는 환경 요인, 그리고 경험하는 화상, 돌발 고위험 상황에 대한 문항으로 구성되어 있습니다. 특히 서열 부담을 가중시키는 작업 환경 요인에 대해서는 화재 현장에서의 휴식의 실태(시간, 휴식의 기준, 음수 공급, 개인보호구 탈의 여부)에 대한 구체적인 질문이 있을 것이며, 뒤이어 귀하의 돌발 고위험 상황과 화상 경험(화상 부위, 정도, 개인보호구 착용 여부와 손상 여부)에 대해서 구체적으로 여쭤볼 것입니다. 설문지는 총 네 가지 파트, 57개의 객관식 또는 주관식 문항으로 구성되어 있으며, 약 30분이 소요될 것입니다.

연구 참여에 대한 위험과 이익

본 설문조사는 화재 현장에서의 귀하의 화상 경험과, 화재 현장에서의 휴식 환경에 대한 문항들로 구성되어 있으며, 귀하를 특정 지을 수 있는 어떠한 개인정보를 요구하고 있지 않습니다. 귀하의 설문조사 참여는 소방관의 화상에 대한 국내 실태를 조사하고, 향후 화상으로부터 소방관을 보호할 수 있는 개인보호구의 개발, 제도적 기반의 마련에 도움이 될 것이며, 서열 부담을 경감할 수 있는 적절한 휴식에 대한 제도적 노력의 밑거름이 될 것입니다.

연구 보상 및 기타 문의

귀하는 설문에 참여하는 도중 연구 참여에 대한 동의를 철회하고 설문을 중단할 권리가 있습니다. 본 연구에 대해 질문이 있거나 설문 중간에 문제가 생길 시 다음연구 담당자에게 연락하십시오 (김시연, 02-880-8744, 010-2820-7047). 만일 어느 때라도 연구 참여자로서 귀하의 권리에 대한 질문이 있다면 서울대학교 생명윤리심의위원회에 연락하십시오.

서울대학교 생명윤리심의위원회 (SNUIRB) 전화번호 : 02-880-5153

※ 본 설문조사 참여에 대한 동의 여부를 표시해 주세요.

○ 본인은 연구의 목적과 설문조사 내용을 이해하였으며, 자발적으로 이 설문조사에 참여하는 것에 동의합니다.	□ 동의함 □ 동의하지 않음

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Part A. 화재 현장에서의 서열부담

가. 더위로 인한 신체 이상 증상

1. 귀하는 화재현장에서 작업 중에 아래와 같은 증상을 경험하신 적이 있습니까? 있다면 얼마나 자주 경험하셨습니까?

1-1. 피로	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-2. 현기증	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-3. 근육경련	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-4. 메스꺼움	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-5. 극심한 갈증	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-6. 두통	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-7. 사지에 힘이 빠짐	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-8. 정신이 혼란스러움	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-9. 구토	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-10. 실신	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음
1-11. 더위 먹음	① 경험 있음 (평균 연 ______ 회) ② 경험한 적 없음

2. 귀하는 화재 현장에서 더위와 관련하여 아래와 같은 증상을 경험한 적이 있습니까? 경험하셨다면, 얼마나 자주 경험하셨습니까?

2-1. 열사병	① 경험 있음 (**평균 연 ______ 회**) ② 경험한 적 없음
2-2. 열경련	① 경험 있음 (**평균 연 ______ 회**) ② 경험한 적 없음
2-3. 열피로	① 경험 있음 (**평균 연 ______ 회**) ② 경험한 적 없음
2-4. 기타: ____________	① 경험 있음 (**평균 연 ______ 회**) ② 경험한 적 없음

3. 귀하는 더위로 인한 신체 이상 증상에 대한 경험을 본부에 보고하였습니까?

① 보고했다 (→ 5번 문항으로 이동)　② 보고하지 않았다

4. 귀하는 왜 더위로 인한 이상 증상에 대한 경험을 본부에 보고하지 않았습니까? (복수응답 가능)

① 치료비 부담이 적거나 없었기 때문에
② 본부에 보고를 하지 않는 전반적인 분위기 때문에
③ 공상처리를 하면 인사평가에 불이익이 있을 수도 있기 때문에
④ 절차가 복잡하거나 오래 걸리기 때문에
⑤ 귀찮아서
⑥ 화재현장에서 위와 같은 증상을 겪는 것은 당연하기 때문에
⑦ 기타 : ____

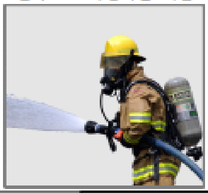
5. 귀하는 열질환(열사병·열경련·열피로 등) 종류와 증상에 대해서 알고 계십니까?

① 잘 알고 있다　② 알고 있다　③ 조금 알고 있다　④ 거의 아는 바가 없다　⑤ 모른다

나. 작업 패턴

6. 장시간의 소형/중형 화재 상황에서 작업이 종결될 때까지의 총 작업시간과, 그 동안의 1회 작업 시간과 1회 휴식 시간의 최소, 최대, 평균값을 빈칸에 적어주세요.

<소형/중형 화재 상황>

1회 작업 시간		1회 휴식 시간	
휴식 없이 화재현장에서 연속으로 작업하는 시간		공기통 교체, 음수 시간 포함	
			
최소	분	**최소**	분
최대	분	**최대**	분
평균	분	**평균**	분

총 작업시간	
(모든 단위작업 + 휴식)	
	
최소	시간 분
최대	시간 분
평균	시간 분

7. **장시간의 소형/중형 화재 상황**에서 언제 **작업을 중단하고 휴식을 시작**합니까? (복수선택 가능)

① 호흡기 보호구의 충전된 공기가 바닥나고 있다는 경보음이 들릴 때

② 할당된 1회 작업 시간을 모두 채웠을 때

③ 지휘본부로부터 작업을 중단하라는 지시가 있었을 때

④ 어지러움, 메스거림, 다리 풀림 등 신체 이상 징후가 느껴질 때

⑤ 체력적으로 너무 힘들 때

⑥ 기타 : ____________________

8. **장시간의 소형/중형 화재 상황**에서 **휴식을 끝내고 다시 작업을 시작**하는 시점은 언제입니까? (복수 선택 가능)

① 정해진 중간 휴식 시간을 모두 채웠을 때 (휴식 시간: ________분)

② 충분히 쉰 것 같아 다시 작업이 가능하다고 스스로 느낄 때

③ 지휘본부로부터 다시 작업을 시작하라는 지시가 있을 때

④ 시민들의 시선이 있어서 쉬는 것이 눈치 보이는 경우에

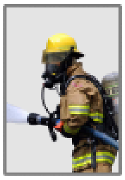
⑤ 쉴 여유가 없이 빨리 다시 작업을 시작해야할 때

⑥ 기타 : ____________________

9. 대형 화재 현장에서 작업이 종결될 때까지의 총 작업시간과, 그 동안의 1회 작업 시간과 1회 휴식 시간의 최소, 최대, 평균값을 빈칸에 적어주세요.

<대형 화재 상황>

1회 작업 시간		1회 휴식 시간	
휴식 없이 화재현장에서 연속으로 작업하는 시간 		공기통 교체, 음수 시간 포함 	
최소	*분*	**최소**	*분*
최대	*분*	**최대**	*분*
평균	*분*	**평균**	*분*

총 작업시간	
(모든 단위작업 + 휴식)  + 	
최소	*시간* *분*
최대	*시간* *분*
평균	*시간* *분*

10. **대형 화재 현장**에서 ***작업*을 중단하고 *휴식*을 시작**하는 시점은 언제입니까? (복수선택 가능)

① 호흡기 보호구의 충전된 공기가 바닥나고 있다는 경보음이 들릴 때

② 할당된 1회 작업 시간을 모두 채웠을 때

③ 지휘본부로부터 작업을 중단하라는 지시가 있었을 때

④ 어지러움, 메슥거림, 다리 풀림 등 신체 이상 징후가 느껴질 때

⑤ 체력적으로 너무 힘들 때

⑥ 기타 : ______________________________

11. **대형 화재 현장**에서 **휴식을 중단하고 다시 작업을 시작**하는 시점은 언제입니까? (복수선택 가능)

① 정해진 중간 휴식 시간을 모두 채웠을 때 (휴식 시간: ________ 분)

② 충분히 쉰 것 같아 다시 작업이 가능하다고 스스로 느낄 때

③ 지휘본부로부터 다시 작업을 시작하라는 지시가 있을 때

④ 시민들의 시선이 있어서 쉬는 것이 눈치 보이는 경우에

⑤ 쉴 여유가 없이 빨리 다시 작업을 시작해야할 때

⑥ 기타 : ______________________________

12. **화재 현장**에서 여름과 겨울의 1회 작업시간(작업 시작 후 휴식 전)에 차이가 있습니까?

① 차이가 없다 ② 겨울에 작업 시간이 더 길다 ③ 여름에 작업 시간이 더 길다

④ 기타 : ______________________________

13. **화재 현장**에서 여름과 겨울의 1회 휴식 시간(휴식 시작 후 작업 시작 전)에 차이가 있습니까?

① 차이가 없다 ② 겨울에 휴식 시간이 더 길다 ③ 여름에 휴식 시간이 더 길다

④ 기타 : ______________________________

14. **화재 현장**에서의 작업 시간과 휴식 시간 시스템의 개선이 필요하다고 생각하십니까?

① 반드시 개선되어야 한다

② 개선이 필요한 것 같다

③ 필요하지 않다 (지금의 작업 시간과 휴식 시간 시스템이면 충분하다)

④ 기타 : ______________________________________

15. 국내에는 충분한 휴식에 대한 기준이 없습니다. 이에 소방관의 휴식이 충분하였는지, 즉, **작업 중 상승했던 체온이 하강하여 다시 작업을 하여도 괜찮은 수준에 도달하였는지를 심장박동수(심박수)로 판단하는 연구**가 진행되고 있습니다. 연구가 완료될 경우, 심박수를 이용하여 자신의 열 부담 수준을 확인하고 이에 따라 휴식/작업을 선택할 수 있습니다. 이러한 기준이 마련되는 것에 대해 어떻게 생각하십니까?

① 꼭 필요하다 ② 필요한 편이다 ③ 모르겠다 ④ 필요하지 않은 것 같다 ⑤ 전혀 필요하지 않다

16. **작업과 휴식 시간의 개선 방향**에 대한 의견을 자유롭게 적어주세요.

다. 화재 현장에서 휴식 환경

17. 휴식 시 **물**(음료수 포함)을 **평균적으로 얼마나 많이** 드십니까?

① 갈증이 충분히 해소될 정도로 마신다 (음수량: 약 ml)

② 갈증이 심한 경우에만 최소한의 양의 물을 마신다 (음수량: 약 ml)

③ 물을 거의 마시지 않는다 (음수량: 약 ml)

④ 기타 : ______________________________

18. 화재 현장에서 **소방관이 마시는 물**(음료수 포함)은 어떻게 조달됩니까? (복수 선택 가능)

① 소방차에 음수용 물이 충분히 비치되어 있다

② 소화용 물을 그냥 마신다

③ 현장에 있는 마트나 편의점에서 직접 구입하여 마신다

④ 자신이 마실 물을 직접 개인 물통에 가지고 다닌다

⑤ 현장에서 시민들에게 요청하거나 혹은 시민들이 직접 갖다 주는 물을 주로 마신다

⑥ 기타 : ______________________________

19. 화재 현장에서 중간 휴식 시 더위를 식히기 위해 어떤 방법을 사용하십니까? (복수 선택 가능)

① 몸과 얼굴에 물을 뿌린다

② 차가운 물(음료수 포함) 또는 얼음 물을 마신다

③ 선풍기 (팬) 앞에서 바람을 쐰다

④ 발 또는 손을 찬 물에 담근다.

⑤ 방화복 또는 개인보호구를 벗거나 지퍼를 열어둔다

⑥ 그늘에서 쉰다

⑦ 차 안에서 에어컨을 켜놓은 채 쉰다.

⑧ 기타 : ______________________________

[20~27] 화재 현장에서 **작업 중간에 휴식을 취할 때** 개인보호구를 벗는지, 벗지 않는다면 이유가 무엇입니까?

헬멧	20-1. 휴식 중 탈모 여부	① 항상 벗음 (→ 21-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	20-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________
방화두건	21-1. 휴식 중 탈의여부	① 항상 벗음 (→ 22-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	21-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________
보호장갑	22-1. 휴식 중 탈의여부	① 항상 벗음 (→ 23-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	22-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________
방화복 상의	23-1. 휴식 중 탈의여부	① 항상 완전히 벗음 (→ 24-1으로 이동) ② 대체로 완전히 벗는 편, 가끔 지퍼만 내림 ③ 대체로 지퍼만 내리고, 가끔 완전히 벗음 ④ 대체로 지퍼만 내리고 완전히 벗지는 않음 ⑤ 항상 지퍼를 내리지도, 벗지도 않음
	23-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________

방화복 내 상의 (기동복 또는 활동복)	**24-1. 휴식 중 탈의여부**	① 항상 벗음 (→ 25-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	24-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________
방화복 하의	**25-1. 휴식 중 탈의여부**	① 항상 벗음 (→ 26-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	25-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________
보호장화	**26-1. 휴식 중 탈의여부**	① 항상 벗음 (→ 27-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	26-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________
양말	**27-1. 휴식 중 탈의여부**	① 항상 벗음 (→ 28-1으로 이동) ② 벗는 편 ③ 벗지 않는 편 ④ 항상 벗지 않음
	27-2. 휴식 중 벗지 않는 이유	① 다시 입기가 어려워서 ② 주위 시선 때문에 ③ 벗을 필요가 없어서 ④ 기타 : ________________

Appendix 2.

Instruction of Resting Heart Rate Criteria

(for firefighters)

Preparation

- After cessation of work, remove SCBA, helmet, hoods, gloves (But, turnout gear is preferred to wear. Cooling practices is postponed until measurement of heart rate is completed)
- Use this method in an ambient temperature at a range of 21-32^{o}C
- Sit down and lean your back somewhere at least for 3 min.
- Move to an isolated or quiet place than noisy and busy place
- Try to breath slow and to achieve physical and physiologically relaxation

Measurement of Heart Rate

- Refrain talking or watching the fire scene
- Keep breathing slowly
- Record heart rate for 1 min after at least 3 min rest.

Resting Heart Rate Criteria

Heart rate *(bpm)*	Predicted rectal temperature (range of 95% possibility)	If you work again for 20 or 30 min, your rectal temperature will increase up to…	
		20 min	30 min
60	36.8 (36.2, 37.4)	37.3 (36.7, 37.9)	37.7 (37.1, 38.3)
70	37.0 (36.4, 37.6)	37.6 (37.0, 38.2)	38.2 (37.6, 38.8)
80	37.2 (36.6, 37.8)	38.0 (37.4, 38.6)	38.6 (38.0,39.2)
90	37.4 (36.8, 38.2)	38.4 (37.8, 39.0)	39.2 (38.6, 39.8)
100	37.7 (37.1, 38.3)	38.8 (38.2, 39.4)	39.7 (39.1, 40.3)
110	37.9 (37.3, 38.5)	39.2 (38.6, 39.8)	40.3 (39.7, 40.9)
120	38.2 (37.6, 38.8)	39.7 (39.1, 40.3)	
130	38.5 (37.9, 39.1)	40.2 (39.6, 40.8)	
140	38.9 (38.3, 39.5)		
150	39.3 (38.7, 39.9)		

Interpretation of the Resting Heart Rate Criteria

- If your resting heart rate (HR_0) before starting firefighting is less than 63 bpm, please calculate $HR_{correction}$ using following equation and add to your heart rate value: $HR_{correction} = -1.56 \cdot HR_0 + 97.24$

- Example I: $HR_{correction}$ of firefighter whose resting heart rate was 50 bpm is 19 bpm. When his resting heart rate after firefighting is 100 bpm, rectal temperature in the second column corresponded to heart rate of 120 bpm should be considered.
- Example II: firefighters with resting heart rate of 110 bpm should rest more so that there is less concern of heat-related illness after 20 min firefighting

People not supposed to use this method

- Age: younger than 17 or older than 53 years
- Diseases: any known diseases which can affect heart rate response
- Drinking and smoking

초 록

본 연구는 한국 소방관의 서열부담 문제의 심각성을 재고하고 소방관의 장시간 작업 중 열질환을 예방하기 위해 소방관의 서열부담을 실시간으로 예측하는 간단한 생리적 모델을 개발하는 것을 목표로 하였다. 개발된 예측 모델이 실제 소방작업환경에서 실용적으로 사용될 수 있도록 서열부담의 예측변수로서, 스마트 웨어러블 디바이스 기기의 상용화로 인해 보편화된 생리적 측정변수인 심박수를 단일 변수로 활용하였다. 본 연구는 크게 세 가지 하위 연구로 구성되었다. 첫 번째 연구에서는 현재 소방관의 열질환 경험 실태를 조사하고 작업환경에서 서열부담을 더욱 악화시키는 환경적 요인을 탐색하였다. 두 번째 연구에서는 안정 시 심박수(stabilized resting heart rate)를 이용한 직장온의 예측식을 개발하였다. 안정된 휴식 심박수는 소방관이 의자에 앉아서 쉬는 기간에 측정하였으며, 운동 직후 3분간의 심박수 데이터는 이전 운동의 영향을 받는 다고 판단하여 분석에서 제외하였다. 마지막으로 다른 운동 조건, 의복 조건, 온열환경 조건에서의 타당도 평가를 통해, 예측 모델을 사용하기에 적합한 환경을 제한하고 예측 모델 사용방법을 구체적으로 제안하였다.

첫 번째, 한국 소방관을 대상으로 전국규모의 설문조사를 시행하였다(N=674). 그 결과 소방관들이 열질환 증상을 빈번하게 경험하는 것을 확인하였으며 74.8%의 소방관이 열질환 증상을 적어도 한 번 경험했고 각 열질환증상의 경험이 있다고 응답한 소방관의 5%는 근경련, 두통 등의 열질환 증상을 1년에 30회 이상, 어지러움증은 40회 이상, 메스꺼움은 50회 이상 경험하는 것을 확인하였다. 그럼에도 불구하고 98.5%의 소방관은 이러한 열질환 증상 경험을 상부에 보고하지 않으며, 그 이유로는 항상 그래왔기 때문이라고 응답하였다. 소방관의 서열부담은 짧은 휴식 시간과 휴식 중 충분하지 않는 냉각 처치로 인해 악화되는 것으로 나타났으며, 소방관들의 짧은 휴식시간의 이유로 다음의 두 가지가 제안되었다. 1) 다시 일을 시작해야하는 긴급한 상황이 있기 때문에, 2) 서열부담이 충분히 제거되지 않은 경우에도 스스로 판단했을 때 충분히 회복되었다고 느끼는 경우가 있기 때문에. 이에 다음의 연구단계에서 소방관의 자각적 회복을 대체하는 객관적이면서 생리적인 서열부담 모니터링 방법을 제안하고자 하였다.

두 번째 단계에서 안정화된 휴식 심박수를 이용하여 직장온을 예측하였으며, 운동 종료 최소 3분 이후에 측정되었고 신체적인 심리적인 이완상태에서 측정된 심박수를 안정화된 상태로 정의하였다. 본 연구에서는 총 세 가지 모델이 제안되었다. Model 1은 안정화된 휴식 심박수로 동시간대 직장온을 예측하고자 하였으며, Model 2는

운동 전 휴식 심박수(rHR)와 운동지속시간(t)을 이용하여 운동 중 직장온의 증가량을 예측하고자 개발되었고, 마지막으로 Model 3은 Model 1과 Model 2의 합으로 안정화된 심박수로 운동지속 시간을 통해 운동 종료 시 직장온을 예측하고자 하였다.

Model 1: $rT_{re} = 36.36 + 1.3 \times 10^{-4} \times rHR^2$ (Marginal R^2=0.8, 95% PI: 0.61°C)

Model 2A: $\Delta T_{re} == -0.71854 + 0.00535 \cdot rHR + 0.05173 \cdot t$ (Marginal R^2=0.865)

Model 3A: $eT_{re} = rT_{re} + \Delta T_{re}$ (Pseudo-R^2=0.716, 95% PI: 0.54°C)

이러한 모델을 기반으로 소방작업 시 열질환을 예방할 수 있는 휴식 심박수를 제안되었다. 예를 들면, 휴식 심박수가 110 bpm인 경우 예측된 직장온은 37.9°C이지만, 그러한 상태에서 20분의 소방작업을 추가로 진행할 경우에 직장온이 39.2°C까지 상승할 수 있으며 이는 열질환의 위험을 증가시키므로 휴식 심박수가 90 bpm 이하가 될 때까지 추가 휴식을 제안할 수 있을 것이다.

본 연구에서 제안한 모델은 25−32°C의 환경에서 9−15kg의 소방복을 입은 상태에서 50−80%VO_{2max}의 운동강도에서 타당도가 검증되었다. 또한 21°C 의 환경온도에서 방화복을 탈의하였을 때, 혹은 평균피부온을 약 2°C 하락시키는 냉각조치를 취하고 있을 때 심박수는 동일한 직장온에 대해 유의하게 낮아지므로 본 예측모델을 적용하였을 때 실제 직장온보다 낮게 예측하는 문제가 발생할 수 있음을 확인하였다. 본 연구논문은 소방관 등 서열부담이 극심한 작업자들의 작업환경에서 열질환을 예방할 수 있는 실용적인 서엶부담 모니터링 시스템의 개발에 도움이 될 수 있을 것이다.

주요어: 작업환경, 실시간 서열부담 모니터링 시스템, 서열지표, 열질환, 심부온