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Influences of Swimming Caps on Thermal Responses and Performance of Swimmers

December, 2006

Graduate School of Science and Technology
Nagasaki University

Masaru MATSUNAMI
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Abbreviation

Bla : Blood Lactate Concentration
HR : Heart Rate
RPE : Rating of Perceived Exertion
Tfh : Forehead Temperature
Toc : Occipital Temperature
Th : Head Temperature
Tsk : Skin Temperature
Toral : Oral Temperature
Tty : Tympanic Temperature
Tear : Ear Temperature
Tre : Rectal Temperature
Tes : Esophageal Temperature
TSB : Thermal Sensation of Body
TSH : Thermal Sensation of Head
MC : Mesh Cap
SC : Silicon Cap
WP : Waterproof Swimming Cap
NWP : Non-waterproof Swimming Cap
WW : Warm Water
MW : Mild Water
Chapter 1

Introduction

Background

Swimming is performed submersed in water, a condition in which thermal conductivity is approximately 25 times that of air, resulting in rapid cooling of the body (Costill et al., 1967; Nielsen and Davies, 1976). However, Body temperature is raised due to the increase of water temperature and exercise intensity (Craig and Dvorak, 1966; 1968; Taimura et al., 1997). Moreover, wearing clothing has the effects of suppressing heat dissipation in water. Wet suits used in triathlons act as a thermal barrier (Wolff et al., 1985), so in water temperatures of 25 °C and above, they cause a larger increase in body temperature and skin temperature during swimming (Lowdon et al., 1992; Kerr et al., 1998).

The head area, over which a swimming cap is worn, is only 9% of the body surface area, but the head contains 15% of the entire blood flow volume (Watanuki, 1992), and has the second highest dissipation, following exercise muscle (Froese and Burton, 1957) and hence, it plays an important role in heat dissipation (Nagasaka et al., 1998; Rasch et al., 1991; Rasch and Cabanac, 1993).

Therefore, when heat production augments due to the increase of exercise time or exercise intensity, wearing a swimming cap might also influence head temperature in a similar manner to a wet suit. In particular, characteristics of waterproofs which prevent direct contact with the water could increase body temperature and discomfort during swimming, and impair swimming performance. The users of a swimming pool are extensive, and the purposes of utilization also have been diversifying. Table 1-1 demonstrated water temperature corresponding to users in consideration of influence of water temperature on the thermal and physiological responses (Japan Amateur Swimming Federation, 1987). Advisable water temperature is different corresponding to a user and hence, water temperature during recreational swimming is higher than competitive swimming. Recently, not only swimming but also aqua exercise has been instituted by frequency, and many multi-use pools maintain water temperature to be as high as 30 °C. Intense swimming training and competition in a multi-use pool raises body temperature, and then clothing enhances that influence. Especially, a waterproof swimming cap speculates the possibility that the influence is exerted on cranial thermal response and swimming performance.
Objective

The present study investigates (1) the influences of swimming caps on thermal and perceptual responses during swimming, and (2) the influences of swimming caps on thermal responses of swimmers in two water temperatures, and last (3) the influences of waterproof swimming caps on prolonged swimming performance.
Table 1-1. Advisable water temperature and swimming time in each swimmer. (Table illustrated in Japan Amateur Swimming Federation (1987) was modified a part of by Matsunami.)

<table>
<thead>
<tr>
<th></th>
<th>Advisable temperature</th>
<th>Swimming time</th>
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<tr>
<td>Infant</td>
<td>30 ± 1 °C</td>
<td>30 ~ 40 min</td>
</tr>
<tr>
<td>Children</td>
<td>28 ± 2 °C</td>
<td>40 ~ 60 min</td>
</tr>
<tr>
<td>Adults</td>
<td>28 ± 2 °C</td>
<td>40 ~ 100 min</td>
</tr>
<tr>
<td>Maternity</td>
<td>30 ± 1 °C</td>
<td>30 ~ 60 min</td>
</tr>
<tr>
<td>Competition</td>
<td>25 ~ 28 °C</td>
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Chapter 2

Physiological responses during water immersion: review

Relation between water temperature and body temperature

The temperature control of humans, homeothermal animals, is dependent on the balance between metabolic heat production and heat dissipation. The temperature of the media surrounding human body, i.e. air or water, is therefore strongly influential in the human body temperature control. Since people swim in water whose thermal conductivity is 25 times larger than that of air (Costill et al., 1967, Nielsen and Davies, 1976), the ambient temperature would have a larger effect on the temperature control in water than in air.

Thermal conductivity in water is 230W/m²·°C at the rest and 580W/m²·°C during swimming (Nadel et al., 1974), which is extremely larger than that of bicycling exercise on land (17W/m²·°C, Nielsen et al., 1969). This also indicates that the heat dissipation is larger during exercise than at the rest. There have been a number of researches conducted under various conditions of water temperature, exercise, clothes, etc., with regard to the influence of the underwater heat dissipation variance on the human body temperature control.

Back in 1955, Pugh and Edholm examined the relation between water temperature change and body temperature by measuring the temporal change in rectal temperature of channel swimmers at a water temperature of 15.8, 20.5, 21.8, 24.2, and 28.3 °C. The result clarified that the body temperature rapidly decreased at a water temperature of 24.2 °C or lower, that the lower the water temperature, the larger the decrease of the core temperature, and that the decrease of the core temperature affected the duration time of the swimming exercise.

Craig et al. (1966) studied human body temperature control at the rest in water at various temperatures from 24 to 37 °C. They found that, at a water temperature of 30 °C or lower, the core temperature (rectal temperature Tre and eardrum temperature Tear) initially increased and then decreased, while it intermittently increased at a water temperature of 36 °C or higher. The change in the core temperature was thus dependent on whether the water temperature was low or high, and the intermediate water temperature range in which body temperature does not change much in water was extremely small. Nielsen et al. (1973) performed a similar study and found that the temperature range in which ambient temperature would not affect human body temperature in water was much smaller than that in air (27-30 °C) and that body temperature increased or decreased when the water temperature was out of the range.
On the other hand, \textit{Tre} and \textit{Tear} during exercise showed different behaviors with the change in exercise intensity or water temperature (Craig, 1968). \textit{Tear} initially increased when subjects started exercise, just as observed in the measurement at the rest, irrespective of the exercise intensity. Then \textit{Tear} decreased as the exercise time passed when the exercise intensity was low at a water temperature of 32 °C or lower. When the exercise intensity was high, \textit{Tear} increased at any test temperatures, except at 24 °C (Craig, 1968). \textit{Tre} initially decreased for any exercise intensity. When the exercise intensity was low, \textit{Tre} continued decreasing at a water temperature of 32 °C or lower, but it increased in the water temperature range of 28-32 °C when the exercise intensity was high (Craig, 1968). Regarding the relation between the underwater exercise intensity and the change in body temperature, it was clarified that strong underwater exercise delayed the decrease of body temperature more significantly than light underwater exercise (McArdle \textit{et al.}, 1984b), and that the effect was stronger at higher water temperature (McArdle \textit{et al.}, 1992).

Nielsen (1976) studied the change in core temperature (\textit{Tre} and esophageal temperature \textit{Tes}) to investigate how low water temperature affected body temperature at the rest or during swimming. The result showed that the core temperature did not change when examinees stayed still in water at a water temperature of 17 °C, and that the body temperature started decreasing 15 minutes after the subjects began exercise in water of 16 °C and it decreased intermittently as long as they continued the exercise. It is thus considered that the exercise created a water convection flow and hence not only heat conduction but also heat dissipation worked as a mechanism of causing the reduction of body temperature at a low water temperature.

In a warm water temperature environment, the difference between the environmental water temperature and human skin temperature is small (Nadel \textit{et al.}, 1974), causing only a small decrease of the body temperature (Craig, 1966; McArdle \textit{et al.}, 1984a). The change in core temperature of subjects at a certain exercise intensity increased as the water temperature increased (Nielsen, 1978; McArdle \textit{et al.}, 1984b). For moderate intensity swimming, thermal stress apparently is dependent on the exercise intensity (Houston, \textit{et al.}, 1978).

Nielsen \textit{et al.} (1976) measured body temperature change on land and in water. Subjects performed cycling exercise on land and swimming in water under two load conditions of the temperature (30 °C and 33 °C) and the exercise intensity (VO2: 1.6L/min and 2.6L/min). In the measurement of the body temperature of the subjects, it was observed that forced heat dissipation ability was higher in water than on land and that the increase of the body temperature was more suppressed in water than in air because the heat generated from the
exercise was immediately transferred from the skin to the water. Therefore, the core temperature was 0.4 °C lower in water than on land with the same exercise intensity.

Core temperature is thus maintained lower in water than on land, although a slight change in water temperature can have a large influence on body temperature. It is also considered that exercise intensity affects the change in core temperature as body temperature increases in proportion to the increase of exercise intensity, and the effect of the exercise intensity is larger at higher water temperature.

Pool water temperature is not designated in the pool sanitary criteria. However, it is considered that ideal water temperature varies depending on the purpose of users. Table 1 shows the water temperature for various users, which was suggested in view of the effect of water temperature on body temperature and other physiological effects (Japan Amateur Swimming Federation, 1987). As seen in the table, the appropriate water temperature of a pool varies from user to user. The Federation Internationale de Natation has a rule of setting the water temperature to 25 to 28 °C in competitive swimming pools, although this was not designated based on any clear scientific basis (Craig, 1983).

It is considered from the previous studies that the body temperature of swimmers decreases when the water temperature is 25 °C or lower but may increase when the water temperature is around 28 °C because of the enhancement of the exercise intensity. This may be the reason why the temperatures range of 25-28 °C was designated in the rule for competitive swimming. The temperature range was set for swimmers with swimsuits, however. When swimming with a wet suit or other clothes that prevent direct contact with the water, the change in body temperature during swimming could be large even in the designated water temperature range.
Relation between water temperature and metabolism

Metabolic responses work to maintain core temperature against environmental changes. It is said that human beings are the residents in tropical areas (Nielsen, 1978). Human metabolism becomes lowest around 30 °C on land, while oxygen consumption at the rest in water is least around 32 to 36 °C and the metabolism does not increase at 30 °C until 20 minutes pass (Craig, 1966). However, human metabolism is enhanced with the light exercise at 28 °C or lower, or with heavily exercise at 26 °C or lower (Craig, 1968).

In a low temperature environment, metabolism is enhanced to respond to the increase of heat dissipation. This is true also in water, that is, metabolism is enhanced in general to respond to the change in water temperature (Pugh and Edholm, 1965; Craig, 1966; Nielsen, 1973; Nadel et al., 1974). When air temperature decreases, human metabolism starts being enhanced at a certain temperature. This temperature is called lower critical ambient temperature and is about 26-28 °C for the naked body on land and 33 °C in water (Nakayama, 1981). The enhancement of metabolism in the decrease of ambient temperature is mainly due to the heat produced by the body shivering.

Nielsen (1978) studied the relation between metabolism and water temperature or body temperature using four water temperature conditions (14, 16, 18, and 20 °C). The result indicated that oxygen intake increased as the water temperature decreased. The oxygen intake increased by 0.5L due to “shivering” during either at the rest or swimming at a speed of 0.4m/s. During swimming at a speed 0.5m/s and a water temperature of 16 °C, the core temperature continued decreasing linearly but VO₂ increased and reached a steady state. On the other hand, during the rest at a water temperature of 17 °C the core temperature did not change much, although the oxygen intake increased by about 1.0L, not that much as during swimming, due to “shivering”.

Holmmar et al. (1974) conducted similar studies of 20-minute swimming with 50%VO2max under three water temperature conditions (18, 26 and 34 °C) and found that oxygen intake was high at the low temperature (18 °C) and the amount of VO₂ increased in proportion to the decrease of esophageal temperature (Teş). Thus, metabolism is enhanced in inverse proportion to the decrease of water temperature during either exercise or the rest.

The relation between body temperature change and metabolism is different depending on whether during exercise or the rest. During exercise, metabolism is enhanced but core temperature decreases (Nielsen, 1976). Core temperature also decreases when leaving the water (Craig, 1983). This is because skin blood flow or peripheral blood flow increases and the cold surface blood flows into the deep parts of the body. It is hence considered that the
decrease of body temperature during exercise is caused by the following process. Blood vessels constricted to block the external influence and keep core temperature are dilated by the exercise, and cold blood near the skin surface flows deeply into the body and decreases the core temperature as a consequence.

Metabolism is enhanced by shivering, which is a response under low water temperature environments. However, “shivering” is not very effective as a heat production method to maintain heat equilibrium. Exercise is the only method of maintaining heat equilibrium in water (Craig, 1983). Craig et al. (1968) clarified that the heart rate increased at a water temperature of 30 °C or higher when the exercise intensity was low, or at a water temperature of 24 °C or higher when the exercise intensity was high. The fact that body temperature decreased during exercise in a low water temperature environment irrespective of the enhancement of metabolism (Nielsen, 1976) could be due to low exercise intensity. Lowdon et al. (1992) found that heat production increased as the exercise intensity became higher and hard physical activities contributed to maintaining core temperature under cold temperature stresses. Also, Pugh and Edholm (1955) showed that the increase of exercise amount enhances metabolism and eventually suppresses the decrease of body temperature during the exercise. Therefore, we consider that the decrease of body temperature in a low temperature environment could be suppressed by enhancing exercise intensity and increasing body activities.

In a warm water temperature environment, on the other hand, metabolism is enhanced when the ambient temperature exceeds the upper critical ambient temperature (Nakayama, 1981). Also in the hot environment, heat storage increases body temperature and metabolism is enhanced to respond to it according to van’t Hoff’s Law (Nakayama, 1981). When people stay still for an hour in water with a temperature of 37 °C, VO₂ significantly increases compared to the level of staying on land (Craig, 1966). When people do exercise in water, VO₂ increases by 150% from the level of the rest if the exercise intensity is low, and by 240% if the intensity is high (Craig, 1968).
Influence of underwater clothes on heat dissipation and body temperature change

One of the differences between air and water can be found in their heat conductivity, and another is the effect of wearing clothes on the heat conductivity. In water, clothes significantly decrease the heat conductivity. Tipton (1989) reported that clothes suppress cold-induced shock response in water, and hence wearing clothes in water has a large heat-storage effect. A 6mm-thick Neoprene wet suit decreases the heat transfer efficiency ($F_{e1\cdot w}$) down to 2-9% of the value for the naked body (Nakayama, 1981), and the heat conductivity ($h_w \cdot F_{e1\cdot w}$) to 8-9kcal/m$^2$/h almost irrespective of the value of convection heat conductivity ($h_w$) (Nakayama, 1981). According to Marcus and Richards (1978), wearing multiple layers of clothes suppresses the decrease of skin temperature or core temperature in a low temperature environment, and covering the trunk and four limbs with layers of clothes suppresses the temperature depression of each part. Wolff et al. (1985) studied the influence of a diver’s wet suit on heat exchange and found its thermal insulation effect whereby water stagnation between wet suit and skin halves heat dissipation. There are also other reports that a diver’s gloves and boots increase skin temperature and that wearing gloves and boots reduces the gradient between core temperature and surface temperature and enhances heat dissipation (Choi et al., 1988; Park et al., 1992). There are several reasons for this. At first, blocking the skin from water forcedly prevents heat removal and suppresses the decrease of skin temperature. Secondly, cold stimulation suppresses vascular constriction and increases blood flow, resulting in the enhancement of heat dissipation. Thirdly, clothes prevent heat dissipation and work for heat storage, which increase skin temperature. Accordingly, the human body can maintain thermal balance in water at lower water temperature when wearing clothes than when naked. However, in the temperature range where the naked body is thermally balanced, doing exercise with clothes could upset the balance and increase the body temperature.

There are some studies regarding the influence of swimwear on body temperature control during swimming (Lowdon et al., 1992; Trappe et al., 1995; Kerr et al., 1998; Taimura et al., 2006). Kerr et al. (1998) examined the influence and reported that the increase of skin temperature and body temperature was higher respectively by 4 and 1.6 °C after 30-minute swimming with a wet suit, than with a swimsuit. The influence of wearing a wet suit on the body temperature change during swimming was dependent on water temperature (Lowdon et al., 1992; Trappe et al., 1995). Trappe et al. (1995) found that the elevation of skin temperature during swimming with a wet suit worked to suppress the increase of core temperature if the water temperature was relatively high. However, another report indicated
that core temperature was elevated if water temperature was high (29.5 °C) (Lowdon et al., 1992). It was also clarified that wearing a swimsuit with a wet-suit like shape had a large influence on the skin temperature or the thermal sensation during swimming if the water temperature was relatively high (30.2 °C) (Taimura et al., 2006). These results suggest that wearing swim clothes suppresses heat dissipation and affects the change in body temperature during exercise and that the effect is larger at a higher water temperature.

The head area occupies about 9% of the entire body area and is much smaller than the trunk that wears the swimsuit, while approximately 15% of all circulating blood volume flows inside the head at any body activity level (Watanuki, 1992). The heat dissipation ability of the head is higher than any other body parts except working muscle (Froese and Burton, 1957), and hence some types of swim caps that swimmers wear may have an influence on the temperature change in the head during exercise. Waterproof swimming caps, whose heat conductivity is about 1.35W/m²·°C, are expected to prevent contact with the water and to conserve heat generated during exercise, just as a wet suit does, since swimwear can change the heat dissipation rate (Nadel et al., 1974).
Relation between body temperature and exercise performance

Heat production is enhanced by muscle activity during exercise and is directly related to the exercise intensity, by increasing in proportion to the intensity. The prolonged exercise at a high ambient temperature, tend to reach the fatigue threshold earlier than exercise in a cool environment (Parkin et al., 1999; Faiti et al., 2001). Exercise performance decreases as body temperature increases irrespective of the exercise intensity or method of exercise (Morris et al., 1998; Suzuki et al., 1980; Hirata et al., 1987).

Willingness or motivation of doing exercises is depressed with the increase of body temperature (Gonzalez-Alonso et al., 1999). In hyperthermia, where body temperature overly increases, the central nervous system depresses the willingness for doing exercise (Swaka, 1992). Nybo et al. (2001a) found that the reduction of exercise performance in the maximum isometric muscle activity in hyperthermia was caused by fatigue of the central nervous system and the depression of exercise performance in a hot environment was associated with the alterations in cerebral activity. Moreover, perceptual fatigue can be related to the depression of exercise performance in a hot environment, as it was observed that the rating of perceived exertion (RPE) was linked to EEG, a measure of core temperature or cerebral activity (Nybo et al., 2001b).

It was also shown that the increase of muscle temperature due to exercise or thermal load enhanced the consumption of glycogen in a submaximal exercise (Starkie et al., 1999) and that the increase of muscle temperature in a high intensity exercise enhanced carbohydrate consumption during the exercise and increased the lactic acid concentration in the muscle (Febbario et al., 1996). Another cause for the reduction of exercise performance in a hot environment is the process whereby the body adjustment function of suppressing body temperature elevation reduces blood volume in skeletal muscles (Gonzalez-Alonso et al., 1999; Tucker et al., 2004) and hence restricts the muscle activity (Tucker et al., 2004).

Water has an extremely narrow range of physiologically neutral temperature, and it is hence considered that water can prevent the human body from becoming too hot. However, the body temperature adjustment response in water is different from that on land. Moreover, exercise performance is affected by the elevation of body temperature due to water temperature change, increase of exercise intensity, or wearing clothes. Nielsen (1978) showed that it was difficult to swim for a long time at 32 °C or higher, and that swimming at 34 °C or higher increased body temperature and reached a dangerous level in about 30 minutes.

Mougios et al. (1993) investigated the influence of water temperature on swimming with maximal or sub-maximum intensity under three water temperature conditions (20, 26, and
32 °C), and found that the swimming performance, heart rate, and serum lactate concentration in the maximal swimming was highest at a high water temperature of 32 °C and lowest at a low water temperature of 20 °C. On the other hand, since the water temperature was relevant only to the heart rate in the long-distance maximal swimming, the water temperature had an influence on the performance of short-time maximal swimming. Lowdon et al. (1992) studied the influence of water temperature and clothes on prolonged maximal swimming (1500m), and found that the swimming performance was not affected by the water temperature but changed depending on the type of clothes at any water temperature.

Therefore, in a warm water temperature environment, the environmental condition can benefit the performance of short-time swimming with high exercise intensity, but may have a negative effect on the performance of long-time swimming with high exercise intensity. Furthermore, the material or shape of the swimming cap or clothes can have an influence on the swimming performance.
Chapter 3

Thermal responses of head in swimmers wearing waterproof swimming caps

Introduction

Swimming caps comprise waterproof and non-waterproof types. However, waterproof caps prevent direct contact with, and thus resistance to water, this type is worn exclusively during competitive swimming.

Swimmers are exposed to water where heat conductivity is 25-fold higher than that on land (Nadel et al., 1974) and thus the body can be easily cooled (Costill et al., 1967). However, body temperature actually rises as the water temperature and exercise intensity increase while swimming (Taimura et al., 1997).

Lowdown et al. (1992) reported that the swimsuit fabric lessens the decrease in body temperature during swimming. Furthermore, wet suits such as those used in triathlons act as a thermal barrier (Wolff et al., 1985), so in water temperatures of 25°C and above, they cause a larger increase in core and skin temperature than swimsuits (Kerr et al., 1998). Thus, wet suits impact heat dissipation while swimming, despite the absence of direct contact with the water.

The head plays an important role in the occurrence of exercise-induced hyperthermia (Rasch et al., 1991). Rasch and Cabanac (1993) have shown that wearing headgear such as caps or headbands during exercise restrains heat loss from the head and thus the temperature of the head increases. Waterproof swimming caps might also influence head temperature in a similar manner to wet suits.

Therefore, the present study investigates thermal responses of the head in swimmers wearing waterproof swimming caps.
Methods

**Subjects.** Six trained competitive female swimmers volunteered to participate in this investigation. All of the swimmers had at least 4 years of competitive experience and regularly participated in 10 training sessions per week. We confirmed that all of the subjects were between the early- and mid-follicular phases of the menstrual cycle to avoid elevations in basal body temperature associated with the luteal phase (Pivarink *et al.*, 1992; Shfeeld-Mooore *et al.*, 1997). Each subject were informed of the aims, possible risks, and benefits of this investigation both verbally and in writing prior to their signing an informed consent document. Table 3-1 shows the characteristics of the subjects.

**Testing protocol.** The swimmers were tested in a 25 m indoor swimming pool at a water temperature of 29.7 °C and room temperature of 26.0 °C. The water temperature throughout testing was the same as that to which the swimmers were usually exposed while training. A waterproof temperature sensor (3650, HIOKI, JAPAN) was taped onto the forehead of each swimmer with a transparent dressing (Tegaterm™, 3M Health Carest. Paul, MN) and covered with a swimming cap. Another temperature sensor on the back region of the scalp was also covered with the cap to determine the temperature of the occipital region while swimming. Oral (Toral) and tympanic (Tty) temperatures were determined before and after the test using a waterproof electronic thermometer (C102, Termo, JAPAN) and an infrared tympanic membrane thermometer (FirstTemp Ginius 3000A, Sherwood Medical Co., St. Louis, MO), respectively. To minimize the temperature influence from outside the mouth, a sublingual thermometer was placed far back under the tongue and Toral was determined for three minutes.

The subjects were instructed to swim 2,000 meters at maximal effort using the front crawl and then forehead skin (Tf/h) and occipital (Toe) temperatures were measured every five minutes. Upon completion of the test, the swimmers were asked immediately to numerically gauge localized thermal sensations of head (TSH) and body (TSB) using The Thermal Sensation Scale (from 0, unbearably cold to 8, unbearably hot) described by Shfeeld-Mooore *et al.* (1997) In accordance with this approach, the swimmers were first asked to perceptually gauge TSB, and then to gauge TSH in relation to TSB.

**Statistical analysis.** The results are presented as means ± SE. A paired t-test determined the significance of the temperatures (forehead, occipital, oral and tympanic), TSB and TSH before and after the swimming trial. The level of significance was established at *P*<0.05.
Results

Figure 3-1 shows the changes in $T_{fh}$ and $T_{oc}$ temperatures while swimming and after recovery. $T_{fh}$ declined during the initial five minutes, and then increased until the end of the trial. $T_{oc}$ also began to increase from five minutes after starting the swim, in the same manner as $T_{fh}$. The actual $T_{fh}$ and $T_{oc}$ values are presented in Table 2.

Figure 3-2 shows the changes in $T_{fh}$ and $T_{oc}$ before and after swimming. The post-swim $T_{fh}$ was not significantly increased compared with the pre-swim temperature ($-0.33 \pm 0.21 \, ^{\circ}C$, $P>0.05$), whereas the elevation in $T_{oc}$ was significant ($1.58 \pm 0.45 \, ^{\circ}C$, $P<0.05$).

Figure 3-3 shows the mean temperatures of $T_{ty}$ and $T_{oral}$ before and after swimming. Though $T_{ty}$ ($0.35 \pm 0.11 \, ^{\circ}C$, $P<0.05$) was significantly elevated after swimming, $T_{oral}$ ($0.03 \pm 0.17 \, ^{\circ}C$, $P>0.05$) was not obviously changed. The relationship between $T_{ty}$ and $T_{oral}$ before and after swimming shows that $T_{ty}$ was significantly higher than $T_{oral}$ (pre, $0.58 \pm 0.22 \, ^{\circ}C$ vs. post, $0.90 \pm 0.43 \, ^{\circ}C$; $P<0.05$).

Figure 3-4 shows the thermal sensation level of the TSH and the TSB after swimming. TSH ($6.4 \pm 0.4$) and TSB ($5.5 \pm 0.5$) exceeded the sensation scale of "5 - warm." However, the value of TSH was much higher than that of TSB, and the difference between them was significant ($P<0.05$).
Discussion

The present study examined the thermal responses of the head covered with a waterproof cap while swimming. Human head sweats more than any other part of the body during rest (Cabanac, 1993), so the capacity for heat loss due to evaporation is the highest on the head with the exception of the working muscle (Froese and Burton, 1957). The skin temperature of the truncus exposed directly to the water during swimming is 0.5 °C higher than the water temperature (Trappe et al., 1995). Therefore, the head temperature while swimming without a cap is 30.2 °C. Furthermore, the fall in skin temperature is stable while swimming (Trappe et al., 1995). Tfh in this study declined during the first five minutes of swimming and Toc was almost identical to the water temperature. However, both temperatures gradually increased during the remainder of the swim (Figure 3-1). The Tfh value while swimming was approximately 3 °C higher than the water temperature. Kerr et al. (1998) have shown that skin temperature differs by 4 °C when swimming wearing a wet suit as opposed to a swimsuit. Therefore, the temperature elevation in the heads of swimmers wearing waterproof caps is probably due to restrained heat loss caused by the lack of direct contact with the water in the same manner as a wet suit. Moreover, the influences of the waterproof swimming cap probably increased 10 minutes after the trial started and the warm water temperature (29 °C) might also have enhanced the influence of the waterproof swimming cap.

The influence of swimming caps on the core temperature was examined in terms of body and head temperature. Core temperature has been estimated from rectal and esophageal temperatures. However, we determined the Toral and Tty, which both influence the surface temperature of the cranium (McCaffrey et al., 1975). Tty indicates core temperature as a substitute for rectal temperature (Craig, 1983), and it is also an effective indicator of the intracranial temperature (Cabanac, 1993; Nagasaka et al., 1998; Rasch et al., 1991). Tty is higher than either the esophageal (Tes) or rectal temperature before bathing or exercise (Cabanac and Caputa, 1979; Rasch and Cabanac, 1993). Furthermore, several investigations (Cabanac and Caputa, 1979; Cabanac, 1993, 1998; Nadel et al., 1974; Rasch et al., 1991; Rasch and Cabanac, 1993) have shown that the elevation of Tty is restrained compared with that of Tes at the time of exercise-induced hyperthermia, so the relationship between Tes and Tty becomes contrary during exercise compared with that before. However, Rasch and Cabanac (1993) have shown that wearing headgear lessens heat loss from the head, thus reducing the efficacy of cephalic cooling, because no significant difference has been observed between Tes and Tty while cycling with headgear. In the present study, Tty was significantly higher than Toral before exercise and the difference became more obvious after swimming.
The elevation of $T_{ty}$ after swimming was considered to be due to the waterproof nature of the swimming cap on intracranial thermal responses during exercise.

The post-exercise thermal sensation scale showed that the TSH value was significantly higher than the TSB. This finding indicates that heat is perceptually difficult to lose while wearing a waterproof swimming cap. Thus, the head is more stressed by heat than the body while wearing a waterproof swimming cap.

In conclusion, waterproof caps raised the head temperature ($T_{fh}$, $T_{oc}$ and $T_{ty}$) while swimming. Therefore, waterproof swimming caps obstruct heat dissipation, and act as a thermal barrier like wet suits. Consequently, the head might become stressed by heat during exercise. Additionally, the influence of waterproof swimming caps should increase due to increasing swimming duration and distance. Swimmers should understand the features of waterproof swimming caps and wear them in consideration of the swimming duration and distance.
Table 3-1. Physical characteristics of the subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>%Fat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y. K</td>
<td>17</td>
<td>155.2</td>
<td>54.1</td>
<td>25.2</td>
</tr>
<tr>
<td>N. M</td>
<td>15</td>
<td>151.5</td>
<td>51.5</td>
<td>25.3</td>
</tr>
<tr>
<td>S. M</td>
<td>16</td>
<td>153.5</td>
<td>50.4</td>
<td>27.4</td>
</tr>
<tr>
<td>H. T</td>
<td>18</td>
<td>161.7</td>
<td>62.6</td>
<td>27.6</td>
</tr>
<tr>
<td>I. N</td>
<td>19</td>
<td>163.5</td>
<td>65.6</td>
<td>28.0</td>
</tr>
<tr>
<td>K. R</td>
<td>18</td>
<td>155.0</td>
<td>48.9</td>
<td>22.5</td>
</tr>
<tr>
<td>Mean</td>
<td>17.2</td>
<td>156.7</td>
<td>55.5</td>
<td>26.0</td>
</tr>
<tr>
<td>SE</td>
<td>0.6</td>
<td>1.9</td>
<td>2.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Table 3-2. Forehead and occipital temperature responses during swimming.

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>5min</th>
<th>10min</th>
<th>15min</th>
<th>20min</th>
<th>25min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead temp. (°C)</td>
<td>34.08</td>
<td>32.17</td>
<td>33.33</td>
<td>33.50</td>
<td>33.67</td>
<td>33.58</td>
</tr>
<tr>
<td></td>
<td>± 0.15</td>
<td>± 0.11</td>
<td>± 0.28</td>
<td>± 0.32</td>
<td>± 0.37</td>
<td>± 0.34</td>
</tr>
<tr>
<td>Occipital temp. (°C)</td>
<td>30.42</td>
<td>30.42</td>
<td>31.50</td>
<td>31.83</td>
<td>31.83</td>
<td>32.08</td>
</tr>
<tr>
<td></td>
<td>± 0.30</td>
<td>± 0.24</td>
<td>± 0.24</td>
<td>± 0.49</td>
<td>± 0.44</td>
<td>± 0.47</td>
</tr>
<tr>
<td>Head temp. without cap (predict) (°C)</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
</tr>
</tbody>
</table>

Head temperature without cap was estimated as 0.5 °C above the water temperature based on the data from Trappe et al. Thermal responses to swimming in three water temperature: influence of a wet suit. Med. Sci. Sport Exer. 27. 1014-1021, 1995. Values are means and SE.
Figure 3-1. Temporal changes in mean forehead (○) and occipital (▲) temperature during a 2000 m swim. Values are means and SE. * Significant difference compared with beginning of swim (0 minutes), $P<0.05$. 
Figure 3-2. Change in forehead and occipital temperature before and after a 2000 m swim. Values are means and SE. *Significant difference compared with before swimming, $P<0.05$. 
Figure 3-3. Tympanic temperature (○) and oral temperature (▲) changes before and after a 2000 m swim. Values are means and SE. * Significant difference from tympanic temperature before swim ($P<0.05$). # Significant difference from oral temperature ($P<0.05$).
Figure 3-4. Perceived thermal sensation of the body (TSB) and head (TSH) after a 2000 m swim. Thermal sensation was scaled; from 0: Unbearably cold to 8: Unbearably hot. Values are means and SE. * Significant difference from TSB, $P<0.05$. 
Chapter 4

Effects of swim caps on thermal responses during swimming

Introduction

There are two kinds of swimming caps - a waterproof type and a non-waterproof type. Waterproof swimming caps are used exclusively in a swimming race because of their reduced water resistance in comparison with the non-waterproof caps. Because the body is cooled down easily by water temperature (Costill et al., 1967), their research focused on the hypothermia due to water temperature rather than exercise-induced elevation of body temperature. The researches showed that the material and type of swimsuit and water temperature affect the elevation of body temperature during swimming (Kerr et al., 1988; Lowdon et al., 1992; Taimura et al., 2006). The head, over which a swim cap is worn, shows a more remarkable heat loss capacity than any other region of the body, except working muscle body (Froese and Burton, 1957), and plays an important role in heat dissipation (Nagasaka et al., 1998; Rasch et al., 1991; Rasch and Cabanac, 1993). Rasch and Cabanac (1993) showed that wearing headgear such as caps or headbands during exercise restrains heat loss from the head and thus the temperature of the head increases. Therefore, when a swimming cap is worn, during long hyperintensity, the swimmer's head sometimes becomes hot. Matsunami et al. (2001) reported that waterproof caps gave subjects heat stress more in the head than in the body while swimming. Waterproof swimming caps obstruct cranial heat dissipation by restraining water contact, which probably leads to elevation of the cranial temperature during swimming.

This study examines the affect of waterproof and non-waterproof swimming caps on cranial thermoregulation during swimming.
Methods

Subjects
Ten male well-trained competitive swimmers volunteered to participate in this investigation. Each subject was informed of the aims, possible risks, and benefits of this investigation both verbally and in writing prior to their signing an informed consent document in accordance with the guidelines established by the Declaration of Helsinki. The subjects' characteristics are presented in Table 4-1.

Measurements

1. Head temperature
A waterproof temperature sensor (3650, HIOKI, JAPAN) was taped onto the forehead of each swimmer with a transparent dressing (TegatermTM, 3M Health Care, St. Paul, MN) underneath a swimming cap. Another temperature sensor was placed in the occipital region also covered by the swimming cap to determine the occipital temperature during swimming. Forehead skin temperature (T_{fh}) and occipital temperature (T_{oc}) were measured every one minute.

2. Core temperature
Oral temperature (T_{oral}) and tympanic temperature (T_{ty}) were determined before and after the exercise by a waterproof thermorecorder (RT-30S, Espec, JAPAN) and an infrared tympanic membrane thermometer (FirstTemp Ginius 3000A, Sherwood Medical Co., St. Louis, MO), respectively. To minimize temperature influence from outside the mouth, an oral thermometer was placed far back under the tongue.

3. Heart Rate
The subjects attached heart rate monitors (S610, POLAR, Finland). Heart rates (HR) were recorded at 15-second intervals.

4. RPE (Rate of perceived exertion) and thermal sensation
Upon the completion of 20 minute swimming, the subjects were asked immediately to numerically gauge their perceptions of overall effort (RPE) and localized heat sensations of head (TSH) and body (TSB) on The Thermal Sensation Scale (from 0, unbearably cold to 8, unbearably hot) described by Shefeeld-Moore et al. (1997). They were asked to perceptually gauge TSB first, and then to gauge TSH in relation to TSB.
**Procedure**

The swimming test was performed in an indoor 25m swimming pool at the water temperature $28.8 \pm 0.4 \, ^\circ C$ and the room temperature $28.7 \pm 1.4 \, ^\circ C$ (RH: $67.5 \pm 6.4\%$). Subjects swam front crawl stroke for 20 minutes at sub-maximal effort; they wore either of two types of swimming caps: waterproof silicone swimming caps (SC) or non-waterproof meshed swimming caps (MC). The subjects were instructed to avoid final spurt was avoided and they maintained the sub-maximal pace throughout a trial. Upon the completion of each trial, TSB, TSH and RPE were measured afterward T oral and T ty were measured. Each trial was held with an interval of at least 24 hours after the previous trial.

**Statistical analysis**

The results were presented as means ± SE. Two-way ANOVA with repeated measure was used to evaluate changes in temperature. Post-hoc comparisons were conducted with Fisher’s PLSD test. Student’s t test for paired samples was used to determine the significance of HR, RPE, TSB and TSH on completion of 20-minute swimming. The acceptable level of significance was set at $P<0.05$. 
Results

Table 4-2 presents a swimming distance, HR and RPE at each trial. A swimming distance, HR, RPE obtained in each trial was 1672.2 ± 83.9m, 176.1 ± 9.9 bpm, 15.4 ± 2.8 in SC trial and 1681.3 ± 74.9m, 176.6 ± 10.5 bpm, 15.4 ± 2.0 in MC trial. There was no significant difference between the SC and the MC in any variable, which showed that exercise intensity in each trial was almost the same.

Figure 4-1 and 4-2 illustrates the forehead skin temperature ($T_{fh}$) and the occipital temperature ($T_{oc}$) through 20-minute trials with SC and MC. $T_{fh}$ of both trials declined during the first five minutes and afterwards elevated until the end of the trials. Although $T_{oc}$ in SC declined by the 5-minute point of swimming, it shifted to slow elevation at the 10-minute point. On the other hand, $T_{oc}$ in MC trials dropped to the water temperature (28.90 ± 0.39 °C) level immediately after the swim started, and then stabilized at that level through the trials. $T_{fh}$ and $T_{oc}$ during swimming were significantly higher in the SC than in the MC trial ($P<0.05$). The post trial $T_{fh}$ and $T_{oc}$ were 33.70 ± 0.82 °C and 30.85±1.18 °C in the SC and 32.45 ± 0.69 °C and 28.95 ± 0.55 °C in the MC.

Figure 4-3 illustrates changes in the $T_{oral}$ and $T_{ty}$ before and after trials in SC and MC. The $T_{oral}$ and $T_{ty}$ obtained at completion of swimming was 36.77 ± 0.41 °C and 37.49 ± 0.39 °C in the trial with SC, and 36.89 ± 0.54 °C and 37.43 ± 0.27 °C in the trial with MC. There were no significantly differences in core temperatures between SC and MC condition after the trials. However, in the MC trial, $T_{ty}$ significantly decreased (-0.32 ± 0.09 °C, $P<0.05$).

Figure 4-4 illustrates thermal sensation levels on the head (TSH) and body (TSB) after SC and MC trials. The types of material of swimming caps did not affect TSB (6.0 ± 0.6 in SC and 5.8 ± 0.4 in MC), but TSH was higher in SC (6.7 ± 0.8) condition than MC condition (5.6 ± 0.8) ($P<0.05$).
Discussion

The purpose of this study was to examine the influence of swim caps on thermal responses during swimming. There was no significant difference in a swimming distance, HR, RPE obtained in the trial with SC and MC, which showed that exercise intensity in each trial was almost the same.

$T_{fh}$ and $T_{oc}$ throughout swimming were significantly higher in the SC than in the MC trials ($P<0.05$). $T_{fh}$ of both trials declined during the first five minutes and afterwards elevated until the end of the trials. Although $T_{oc}$ in SC declined by the 5-minute point of swimming, it shifted to slow elevation. On the other hand, $T_{oc}$ in the MC trials dropped to the water temperature level immediately after the swim started, and then stabilized at that level through the trials.

The skin temperature while swimming in the water temperature of 25.6 °C wearing a wet suit was higher 3.21 °C or 4.0 °C than that of wearing a swim suit (Trappe et al., 1995; Kerr et al., 1998). Lowdon et al. (1992) reported that skin temperature increased with 2.38 °C in comparison with a swim suit during maximal swimming wearing a wet suit in the pool of 29.5 °C. In this study, the increase of $T_{fh}$ and $T_{oc}$ after swimming was higher by 1.25 °C and 1.90°C in SC than in MC condition, respectively. On the other hand, when wearing a swim suit, the skin temperature is 0.5 °C higher than the water temperature and remains constant throughout the swim (Trappe et al., 1995). It depends on whether a water temperature condition is different that $T_{fh}$ and $T_{oc}$ observed while swimming with the SC was higher than the results of wet suit. Because of the water temperature (28.8 °C) in this study was higher than that (25.6°C) established by the previous study by Trappe. Therefore, waterproof swimming caps raises cranialis surface temperature in accordance with the progress of the exercise temporal during sub-maximal swimming in relatively warm water and then act as a thermal barrier like wet suits. In triathlons, wearing a wet suit is regulated by relationship with the water temperature (Chatard et al., 1995). Waterproof swimming caps are used exclusively in swimming races because of their reduced water resistance in comparison with the non-waterproof cap. However, because waterproof swimming caps promote the elevation of cranialis surface temperature, swimmers should choose a swimming cap in consideration of pool condition; especially, in a long-distance event (800m or 1500m).

$T_{oral}$ did not differ before and after each trial. However, changes in $T_{ty}$ were significantly lower with MC compared with SC ($P<0.05$). $T_{ty}$ indicates core temperature as a substitute for rectal temperature (Cabanac, 1993), and it is also an effective indicator of the intracranial temperature (Cabanac, 1993; Nagasaka et al., 1998; Rasch et al., 1993). $T_{ty}$ is higher than
either the esophageal or rectal temperature before bathing or exercise (Cabanac and Caputa, 1979; Rasch and Cabanac, 1993). In this study, Tty before swimming indicated a higher temperature than Toral in both SC and MC conditions.

Furthermore, the elevation of Tty during exercise is restrained compared with that of Tes at the time of exercise-induced hyperthermia, so the relationship between Tes and Tty becomes contrary during exercise compared with that before (Rasch and Cabanac, 1993). However, wearing headgear lessens heat loss from the head, thus reducing the efficacy of cephalic cooling, because of headgear obstructs evaporation during cycling exercise (Rasch and Cabanac, 1993). In the present study, the results of Toral indicated that swimming trials may not have performed so intensively as to increase core temperature. Tty during swimming was decreased significantly in MC. In air, conductive heat loss is so small that it is usually ignored, but in water this route is very important (Craig, 1983). The decrease of Tty observed in MC trials might be due to cooling by conduction in water. On the contrary, Tty did not decrease in SC trials, which suggested that waterproof nature have an influence on the cranialis thermal responses during swimming.

Lowdon et al. (1992) showed that perceived comfort rating was higher with a wet suit than with a swimsuit, when subjects swam maximal 1500m. There were significant differences in TSH between SC and MC trials. Furthermore, TSH was significantly higher than TSB when wearing a waterproof swimming cap. These results explain that wearing waterproof swimming cap gives the head large thermal stress. It is suggested that thermal stress elevates cranial surface temperature.

Recently, there are many physically disabled people who have swimming training for competition. They have performed prolonged and high intensive swimming training. However, spinal cord injured athletes have a functional disorder in body temperature regulation and can not maintain the heat balance (Ishi et al., 1994). In the water, the increase of body temperature attenuates by conductive heat dissipation in comparison with on land. Waterproof swimming caps might impair conductive heat dissipation in prolonged training and competition, so it is desirable for swimmers to select their swimming caps with water temperature in mind in order to avoid heat injury.
Table 4-1. Physical characteristics of the subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>%Fat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>20.3</td>
<td>174.1</td>
<td>66.2</td>
<td>18.4</td>
</tr>
<tr>
<td>SD</td>
<td>1.3</td>
<td>6.3</td>
<td>6.3</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Table 4-2. Swimming distance, heart rate and RPE for 20 minutes swims.

<table>
<thead>
<tr>
<th></th>
<th>Silicon cap (SC)</th>
<th>Mesh cap (MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swimming distance (m)</td>
<td>1672.2 ± 83.9</td>
<td>1681.3 ± 74.9</td>
</tr>
<tr>
<td>Heart Rate (bpm)</td>
<td>176.1 ± 9.9</td>
<td>176.6 ± 10.5</td>
</tr>
<tr>
<td>RPE</td>
<td>15.4 ± 2.8</td>
<td>15.4 ± 2.0</td>
</tr>
</tbody>
</table>

Note: no significant differences between silicon and mesh cap.
Figure 4-1. Change in forehead skin temperature during swimming with silicon cap (SC) and mesh cap (MC). * $P<0.05$ from MC
Figure 4-2. Change in occipital temperature during swimming with silicon cap (SC) and mesh cap (MC). * $P<0.05$ from MC
Figure 4-3. Changes in oral temperature (Toral) and tympanic temperature (Tty) before and following 20 minutes swims with silicon (SC) and mesh cap (MC). * $P<0.05$ from before swimming
Figure 4-4. Perceived thermal sensation of the body (TSB) and head (TSH) (Scale= 0 - 8) following 20 minutes swim. * $P < 0.05$ from MC ; # $P < 0.05$ from TSB
Chapter 5

Influences of swimming caps on thermal responses of swimmers in two water temperatures

Introduction

Since water has 25-fold more thermal conductivity than air, swimming reduces the body temperature with comparative ease (Costill et al., 1967). However, the influence of swimming on body temperature differs with the water temperature. When the water temperature is high, the core temperature while exercise becomes higher than in a lower water temperature (Craig, 1968; Nielsen, 1978; McArdel et al., 1984b). In addition, wearing a wet suit increases the body temperature while swimming more than a swimsuit because the wet suit blocks direct contact between the body and water (Lowdon et al., 1992; Trappe et al., 1995; Kerr et al., 1998). Wearing headgears such as caps or headbands during exercise restrains heat loss from the head and thus the temperature of the head increases (Rasch and Cabanac, 1993). Waterproof swimming caps are composed of latex or silicon and prevent direct contact between water and the head. Matsunami et al. (2005) reported that waterproof swimming caps act as a thermal barrier. Since waterproof caps increase the temperature of the head more than non-waterproof caps, swimmers feel the heat more in the head than in the body while swimming (Matsunami and Taimura, 2003). The FACILITY RULES (FR 2.11) of the Federation Internationale de Natation (FINA) state that the water temperature of a swimming pool for competition should be between 25 and 28 °C. The water temperature of indoor swimming pools is relatively stable whereas that of outdoor pools is due to the influences of weather and the air temperature. Thus, pool temperatures might come close to the prescribed upper or lower limits depending upon environmental conditions. Furthermore, many multi-use pools (those used for training, competitive, recreational, learn-to-swim, and disabled swimming) require water temperatures to be in excess of 30 °C. Thus, the upper limit temperature, while accommodating FINA rules, could be less than that of water in which swimmers perform serious training. Any revealed effect might be further heightened in such elevated conditions that at least are common in Japan.

Therefore, wearing a waterproof swimming cap is considered to differently affect the temperature of the head and thermal sensation depending on the water temperature. This study examined the thermal and perceptual effects of wearing swimming two types of caps while
swimming in different water temperatures.
Methods

Subjects. Fourteen competitive male swimmers (age, 20.1 ± 0.9 y; weight, 69.4 ± 6.7 kg; %Fat, 19.2 ± 2.9%, 400m swim time, 4:12.3 ± 7.9 sec) volunteered to participate in this investigation. All of them had at least 4 years of competitive experience and trained 10 times per week. The swimmers were separated into groups wearing either waterproof (WP) or non-waterproof (NWP) swimming caps. There was no significant difference in height, weights, %Fat and swimming time between the groups. The local institutional review board approved the study. Each subjects was informed of the aims, possible risks, and benefits of this investigation both verbally and in writing prior to their signing an informed consent document in accordance with the guidelines established by the Declaration of Helsinki.

Water temperature and ambient conditions. Water temperature and ambient conditions: Trials proceeded in an indoor 25 m swimming pool at two water temperatures (26.1 ± 0.1 °C and 29.1 ± 0.1 °C). These temperatures were maintained as closely as possible to the upper and lower limits (25~28 °C) established by the FINA FACILITIES RULES (FR 2.11). The air temperature and relative humidity in the pool area were 27.0 ± 0.5 °C and 52.1 ± 3.3%, respectively.

Testing protocol. Throughout the study, the subjects maintained their normal dietary habits and sleep patterns, and refrained from vigorous exercise and alcohol consumption during the 24 h preceding each trial. All tests were performed at approximately the same time of day to minimize the influence of circadian rhythm variation in internal body temperatures. After voiding and before the swim trials, the subjects were weighed (UC-321; A & D Inc., JAPAN) and fitted with a waterproof temperature sensor (3650, HIOKI, JAPAN) and heart rate monitor (S610, POLAR, Finland). Waterproof temperature sensors were placed on the forehead, chest, upper arm, thigh and calf with a transparent dressing (TegatermTM, 3M Health Care, St. Paul, MN), and on the occipital region between the scalp and the cap. Both oral (Toral) and tympanic (Tty) temperatures were determined using a waterproof thermorecorder (RT-30S, Espec, JAPAN) and an infrared tympanic membrane thermometer (FirstTemp Ginius 3000A, Sherwood Medical Co., St. Louis, MO) before and after the trials. To minimize temperature influences from outside the mouth, a sublingual thermometer was placed far back under the tongue and Toral was determined after three minutes. The Tty was determined 3 times and the mean was recorded. After pre-trial temperatures were recorded, the subjects started a 20-minute swim at sub-maximal effort (80% of their 400 m best time)
wearing either the waterproof or non-waterproof cap in each water temperature. A final spurt was avoided and the swimmers maintained the sub-maximal pace throughout the trial.

Upon completion of the 20-minute swim, the subjects immediately gauged their perceived exertion (RPE), as well as localized thermal sensations of the head (TSH) and body (TSB) using the Thermal Sensation Scale (from 8: Unbearably hot through 4: Neutral (comfortable) to 0: Unbearably cold) described by Shefeeld-Moore et al. (1997).

**Statistical analysis.** A two-way ANOVA with repeated measures was performed to evaluate changes in temperature. *Post-hoc* comparisons were conducted using Fisher’s PLSD test. Student’s *t* test for paired samples determined the effects of HR, RPE, TSB and TSH upon the completing the 20-minute swim. The level of significance was set at *P*<0.05.
Results

Swimming trial

Table 5-1 presents swimming distance, HR and RPE at each trial. Swimming speed which calculated from obtained distance in WP and NWP trial was 77.9~78.6 and 77.8~78.6% of 400m best record respectively. None of these variables significantly differed between the water temperature and cap conditions.

Temperature

Figure 5-1 shows mean skin temperature ($T_{sk}$) calculated according to the equation of Ramanthan (1968). The changes in $T_{sk}$ during the WW and MW trials were similar for both types of caps and $T_{sk}$ did not differ significantly between the caps. Moreover, $T_{sk}$ was significantly higher ($P<0.05$) for WW (WP: -1.43±0.34 °C, NWP: -1.59±0.20 °C) than MW (WP: -3.84 ± 0.36 °C, NWP: -3.75 ± 0.27 °C) regardless of the type of cap. The lowest $T_{sk}$ during the swim was 31.22 and 28.89°C in WW and MW, respectively. These temperatures were about 2 °C higher than the water temperature.

Figure 5-2 shows that the head temperatures ($T_{h}$) during the WP and the NWP trials in WW and MW declined and then increased. However, the $T_{h}$ during the WP and NWP trials decreased by 0.46 ± 0.18 and 1.79 ± 0.32 °C, respectively in WW and by 2.79 ± 0.40 and 4.11 ± 0.33 °C in MW, respectively. The $T_{h}$ in the WW was significantly higher than that in the MW regardless of the type of cap ($P<0.05$). Although the head temperature during the NWP trial in WW and during the WP and the NWP trials in MW significantly decreased ($P<0.05$), the decrease during the WP trial in WW was not significant. After the $T_{h}$ declined, the increase during the WP trial was high compared with the NWP trial, and at the end of the swim, the $T_{h}$ of the swimmers wearing the WP was significantly higher than that of those wearing the NWP in WW (1.32 °C, $P<0.05$) and MW (1.32 °C, $P<0.05$). The lowest $T_{h}$ during the swim was 31.86 °C (WP) and 30.46 °C (NWP) in WW and 29.04 °C (WP) and 27.64 °C (NWP) in MW. The $T_{h}$ in both water temperatures was higher with the WP than with the NWP at approximately 3 °C and 1.5 °C respectively, above the water temperature.

Figure 5-3 shows the Tympanic ($T_{ty}$) and oral ($T_{oral}$) temperatures before and after the swim. Although the $T_{ty}$ in all trials became significantly decreased ($P<0.05$) (-0.41 ± 0.13 °C with WP, -0.53 ± 0.12 °C with NWP in WW; -0.77 ± 0.15 °C with WP, 0.77 ± 0.15 °C with NWP in MW), the decrease in the $T_{ty}$ in WW was significantly lower than that in the MW while wearing both types of caps ($P<0.05$). $T_{oral}$ did not significantly differ between
the swimming caps and the water temperature.

**Thermal sensation**

Figure 5-4 shows the thermal sensation levels of the head (TSH) and body (TSB) immediately after the trials. The TSB did not significantly differ between the caps in each water temperature, but the TSB in WW (WP: 6.21 ± 0.42, NWP: 6.36 ± 0.28) was significantly higher than that of the MW (WP: 5.27 ± 0.52, NWP: 5.27 ± 0.33) for both caps. Although the TSH did not significantly differ between WP (5.86 ± 0.28) and NWP (5.57 ± 0.35) caps in MW, the TSH of the WP cap (7.21 ± 0.18) in the WW was significantly than that of the NWP cap (6.36 ± 0.18) (P<0.05). The TSH for the WP cap significantly differed between WW and MW (P<0.05), whereas that of the NWP cap did not.
**Discussion**

The present study compared the effects of waterproof and non-waterproof swimming caps on head temperature and sensation at different water temperatures.

The $T_{sk}$ was significantly higher in WW than in MW ($P<0.05$), but at each water temperature, $T_{sk}$ did not differ significantly between each type of cap. One study of $T_{sk}$ measured at intervals has shown that the skin temperature while swimming is 0.5 °C higher than the water temperature and remains constant throughout the swim (Trappe *et al*., 1995). The differences of significant $T_{sk}$ observed in the between WW and MW trial, therefore, depends on the influence of the water temperature. We found here that the lowest skin temperature was 2 °C higher than either of the water temperatures (WW, 31.22 °C; MW, 28.96 °C). In addition, $T_{sk}$ significantly increased ($P<0.05$) both at WW and MW while swimming. The increase in $T_{sk}$ was significantly greater in WW (1.06 °C) than in MW (0.60 °C) ($P<0.05$), probably because the water temperatures in this study were higher (26.0 °C and 29.1 °C) than those (25.6 °C) used by previous study (Trappe *et al*., 1995). In case of the water temperature is high, the body temperature increases while swimming (Taimura *et al*., 1997). In other study, the core and skin temperature after 1500m swimming at 29.5 °C is higher than that while swimming at 17.0 °C and 21.3 °C (Lowdon *et al*., 1992). The significant higher $T_{sk}$ observed during WW trial was attributable to a decrease in the temperature gradient between the skin and water temperatures.

The head surface temperature of swimmers wearing NWP caps immediately decreased like the $T_{sk}$ after starting to swim. The $T_h$ of swimmers wearing WP caps gently decreased both in WW and MW. At each water temperature, $T_{sk}$ did not significantly differ between the types of cap but $T_h$ significantly differed over the duration of the swim. Particularly in WW, the WP cap kept the increasing $T_h$ to the level at the start of the swim and the decrease before and after the swim was the smallest. Froese and Burton (1957) reported that the head has greater heat dissipation capability than any other physical region, excluding active muscles. The present study found that the head temperature at each water temperature significantly differed between the types of swimming cap whereas the skin temperature of the surface layers of skeletal muscles (upper arm, chest, thigh and calf) used for swimming did not.

The bicycle-racing helmets limit the area for heat exchange between the forehead and external environment (John and Dawson, 1989). Therefore, a waterproof swimming cap covering the head might minimize heat exchange by conduction, a major means of heat exchange under water (McMurray and Horvath, 1979; Craig, 1983). This indicates that waterproof swimming caps exert thermal insulation effects like wet suits that suppress heat.
dissipation. In addition, the \( Th \) increase observed during the latter half of swimming indicate that waterproof swimming cap in MW indicated that waterproof swimming cap enhance influences of head temperature during extended swims regardless water temperature. In the triathlons, wearing of wet suits are not permitted at water temperatures of 21 or 24 °C or higher, depending on the distance of the swim (Chatard et al., 1995). Furthermore, it was indicated that insulating cap be worn in events in water temperature below 24 °C (Lowdon et al., 1992). Conversely, wearing of clothes that interrupt out heat dissipation is not desirable, when water temperature is warm. Therefore, it is desirable for the swimmers to be careful of the wearing of swimming caps in according to the water temperature.

In many studies, rectal, esophageal, or oral temperature is measured as the core temperature. However, prior studies have indicated that the tympanic temperature accurately indicates changes in temperature (Voltaire et al., 2003) is reliable if environmental conditions are constant (Masterson and Wacker, 1999) can represent core temperature (Jakobsson et al., 1992) and serves as a good index of brain temperature (Power and Howley, 1997). Because they are easy to measure in a sanitary manner while swimming, we used tympanic and oral temperatures as indicators of core temperature.

\( Toral \) after the trial did not significantly differ irrespective of the type of swimming cap or water temperature. This indicated that the strength of the movement while swimming was similar regardless of conditions in terms of body temperature, length of swim, heart rate and rating of perceived exertion (Table 5-1).

In both WW and MW, \( Tty \) significantly decreased before and after swimming. \( Tty \) below the core temperature after swimming is attributable to heat dispersion by conduction if the environmental temperature (water temperature or air temperature) is below 37 °C (Arnett, 2002). \( Toral \) did not significantly differ between the tested water temperatures after swimming. The significant difference in \( Tty \) between water temperatures endorses the previous finding (Nielsen, 1988) that \( Tty \) is affected by environmental temperature.

The significant difference in \( Th \) between types of swimming caps indicates that a waterproof cap suppresses heat dissipation by conduction and subsequently alters \( Tty \). WW and WP suppressed the decrease in \( Tty \) and the difference in the decrease was not significant. Since \( Toral \) did not significantly differ between swimming caps, swimming velocity or duration might have not been sufficient to allow the waterproof swimming cap to generate an obvious difference in core temperature. However, the increase in \( Th \) induced by the waterproof cap indicated that heat exchange produced by conduction was suppressed. Compared with the non-waterproof type, a waterproof cap might have more potential to increase the tympanic temperature as the water temperature increases, the temperature
gradient with $T_{ty}$ decreases, the swimming velocity increases, and as an extended period of swimming increases heat generation.

The $T_{sk}$ significantly differed between water temperatures, but not between swimming caps at either water temperature. The TSB was significantly greater at WW than at MW, but not between types of caps. TSH also significantly differed between water temperatures. In WW, the TSB induced by WP was significantly greater than that of NWP. Since there was a significant correlation between thermal sensation and core or skin temperature (Toner et al., 1986) the difference in thermal sensation between water temperatures supports the results indicated by the temperature parameters ($T_{sk}$, $T_{h}$, $T_{ty}$). The present study found similar results to those of previous study (Toner et al., 1986) at low water temperature, indicating that temperature parameters affect temperature sensation. At high water temperature, the thermal sensation induced by the waterproof cap after sub-maximal swimming was greater than that induced by the non-waterproof cap. This result indicates that a WP cap will increase the skin and tympanic temperatures as swimming intensity increases and the duration of swimming is extended.

An increase in body temperature is the main factor limiting endurance movement (Nielsen, 1988; Cheung and MacLellan, 1998). Because of the relationship between thermal sensation and temperature parameters, the sensational response (hot) accompanying an increase in body temperature might also be considered as a factor that works against continued movement. Since endurance performance decreases more in a hot, than in an optimal environment (Nielsen et al., 1993; Febbraio et al., 1994; Galloway and Moughan 1997), wearing a waterproof swimming cap is considered to affect the endurance performance of maximal swimming movements in a pool at a comparatively high water temperature.

In conclusion, waterproof swimming caps increase the temperature of the head and enhance thermal sensation. This influence is particularly large at a higher water temperature and during a prolonged swim. Therefore, during swimming training in multi-use pool and/or long distance competition in pool condition near the upper limit described in FR 2.11, waterproof caps should be avoided to train it severely or increase endurance performance. It is necessary to examine the effects of swimming caps on swimmer’s performance in the future.
Table 5-1. Swimming distance, heart rate and RPE for 20 minutes swims

<table>
<thead>
<tr>
<th>trials</th>
<th>distance (m)</th>
<th>HR (beat/min)</th>
<th>RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP (26.1°C)</td>
<td>1697.7±17.8</td>
<td>181.7±3.7</td>
<td>16.1±0.3</td>
</tr>
<tr>
<td>WP (29.1°C)</td>
<td>1690.1±19.7</td>
<td>185.6±3.5</td>
<td>16.4±0.6</td>
</tr>
<tr>
<td>NWP (26.1°C)</td>
<td>1676.2±21.9</td>
<td>177.6±5.4</td>
<td>15.6±0.5</td>
</tr>
<tr>
<td>NWP (29.1°C)</td>
<td>1667.1±21.1</td>
<td>179.3±6.4</td>
<td>17.4±0.9</td>
</tr>
</tbody>
</table>

Note: no significant differences among all trials. Values are mean ± SE.
Figure 5-1. Change in Tsk throughout the NWP and WP trials in the MW (△/▲) and WW (○/●). Values are mean ± SE. * Trunk skin temperature was significantly higher ($P<0.05$) throughout trials in the WW.
Figure 5-2. Change in $T_h$ throughout the WP and NWP trials in the MW ($\triangle/\blacktriangle$) and WW ($\bigcirc/\bullet$). Values are mean ± SE. * Head temperature was significantly higher ($P<0.05$) with waterproof swim cap throughout trials in the MW and WW. # denote $P<0.05$ significant higher the NWP and the WP trials in the WW.
Figure 5-3. Changes in tympanic (T$_{ty}$) and oral (T$_{oral}$) before and after NWP (□) and WP (■) trials in the MW and the WW. Values are mean ± SE.

* denotes $P<0.05$ from before swim. # denotes $P<0.05$ for MW trial vs WW trial.
Figure 5-4. Perceived thermal sensation of the body (TSB) and head (TSH) (Scale = 0-8) following NWP (□) and WP (■) trials in the MW and WW. Values are mean ± SE. * TSB and TSH were significantly higher ($P<0.05$) in the WW than in the MW. # denotes $P<0.05$ for NWP trial vs WP trial in the WW.
Chapter 6

Influences of waterproof swimming cap on prolonged swimming performance

Introduction

The regulation temperature of water in which swimming competitions are held is between 25 °C and 28 °C according to the Facilities Rules (FR 2.11) of the Federation Internationale de Natation (FINA). However, when competitions are held in outdoor pools, such as at the XXVIII Olympic Games in Athens and the 2005 FINA World Championships, the influence of the air temperature makes adjusting the water temperature more difficult than for indoor pools.

Swimming is performed submersed in water, a condition in which body heat conductivity is 25 times higher, resulting in rapid cooling of the body (Costill et al., 1967, Nielsen and Davies, 1976). However, the influence of the thermal response to exertion varies according to the water temperature. When the water temperature is high, body temperature during exercise rises (Nielsen, 1973) and, when the exercise intensity was high, the core and ear temperature increased at warm water temperature (Craig, 1968), furthermore, the decrease of the body temperature delayed (McArdel et al., 1984b). Furthermore, the body temperature of a swimmer is increased if the swimmer is wearing the clothing, which reduces the body’s contact with the water (Nielsen, 1973). Another factor is whether a swimmer is wearing a waterproof swimming cap. As swimmers believe that reducing direct contact of the head with the water will reduce their water resistance, such waterproof swimming caps are worn exclusively.

The head, over which a swim cap is worn, shows a more remarkable heat loss capacity than any other region of the human body, except working muscles (Froese and Burton, 1957), and plays an important role in releasing exercise-induced hyperthermia (Nagasaka et al., 1998; Rasch et al., 1991; Rasch and Cabanac, 1993). It has been demonstrated that when a waterproof cap is worn, the thermal sensation of the head during swimming is higher than that of the body (Matsunami and Taimura, 2001); moreover, it has also been shown that waterproof caps increase the skin temperature of the head more than non-waterproof swimming caps (Matsunami and Taimura, 2003). Therefore, in pools where the water temperature is at the upper limit (28 °C) of the FINA rules, waterproof swimming caps may
influence competition results, particularly the results of long-distance events (800m or 1500 m), which require prolonged maximum-intensity effort.

The present study aims to elucidate the influence of wearing waterproof swimming caps on prolonged swimming performance in pools with comparatively high water temperatures.
Methods

**Subjects.** Nine male swimmers (age, 19.6 ± 0.8 y; height, 175.3 ± 6.0 cm; body weight, 69.5 ± 6.6 kg) volunteered to participate in this study. The swimmers had been involved in competitive swimming for at least 6 years and habitually trained 10 times per week. All subjects were given written information concerning the nature, aims, possible risks, and benefits of this study both verbally and gave their written informed consent document in accordance with the guidelines set forth by the Declaration of Helsinki. This study was approved by the Ethnical Committee of Department of Natural Environment Conservation, Faculty of Environmental Studies, University of Nagasaki. Table 6-1 shows the characteristics of the subjects.

**Experimental protocol.** Subjects completed two 1500 m freestyle swimming trials at maximal effort in a 50 m indoor swimming pool. The water temperature (29.4 ± 0.2 °C) was maintained at a level similar to that of an outdoor pool in hot summer weather. Subjects performed the trials wearing either a waterproof swimming cap (WP) or a non-waterproof swimming cap (NWP). For the duration of the study, the subjects were asked to maintain their normal dietary intake and sleep patterns and to refrain from vigorous exercise and alcohol consumption in the 24 hours prior to each trial. Each test was conducted at approximately the same time of day in order to minimize the influence of circadian rhythms on variations in internal body temperature.

The waterproof temperature sensors (3650, HIOKI, JAPAN) for the measurement of body and head skin temperature were fitted to the forehead and body (chest, upper arm, thigh and calf) with a transparent dressing (TegatermTM, 3M Health Care, St. Paul, MN) for calculate of weighted mean skin temperature according to the methods of Ramanthan (1968) and in the occipital region, were placed between the scalp and swimming cap, and a heart rate monitor (S610, POLAR, Finland) fitted with a transparent dressing. Subjects’ oral (Toral) and tympanic (Tty) temperatures were determined before and after exercising using a waterproof thermorecorder (RT-30S, Espec, JAPAN) and an infrared tympanic membrane thermometer thermometer (FirstTemp Ginius 3000A, Sherwood Medical Co., St. Louis, MO). The Toral was measured for 3 minutes before and after swimming. Each subject was instructed to place the sublingual thermometer far back under his tongue in order to minimize the influence of the temperature outside the mouth. Each swimmer’s tympanic temperature was taken 3 times.

At the completion of the each swim, the time required to swim 1500 m was recorded, and
the subjects were immediately asked to numerically evaluate their perceptions of their overall effort (RPE). Subjects were also asked to evaluate their localized heat sensations for their head (TSH) and body (TSB) using the Thermal Sensation Scale (evaluations ranged from 8: Unbearably hot, through 4: Neutral (comfortable), to 0: Unbearably cold) described by Shefeeld-Moore et al. (1997)

Blood samples were collected from the fingertip of each swimmer 3 minutes after completing the 1,500 m swim. Blood lactate concentration (Bla) was analyzed using a portable lactate analyzer (Lactate Pro™ Test Meter, ARKRAY, Inc, KYOTO, JAPAN).

**Statistical analysis.** A Student’s $t$ test for paired samples was used to determine the changes in temperature and the effect on their physiological (HR, Bla) and perceptual (RPE, TSB, TSH) responses upon the completion of the 1,500 m swim. Statistical significance was established at the $P<0.05$ level.
Results

Oral and tympanic temperature

Figure 6-1 shows the tympanic ($T_{ty}$) and oral ($T_{oral}$) temperatures before and after the trial wearing WP and NWP. The $T_{ty}$ in WP (-0.24 ± 0.13 °C) and NWP (-0.16 ± 0.12 °C) trials decreased after swimming, whereas the $T_{oral}$ increased in the both trials (WP: 0.50±0.18 °C, NWP: 0.51±0.23 °C). The increase of $T_{oral}$ in WP was significant alteration ($P<0.05$), whereas there was no significant alteration in NWP ($P=0.06$). Moreover, alteration in $T_{ty}$ and $T_{oral}$ did not differ significantly between the WP and NWP conditions.

Skin temperature

Figure 6-2 shows weighted mean body skin temperature ($T_{sk}$) calculated according to the equation of Ramanthan (1968). $T_{sk}$ following trials was no significant difference between WP (32.67 ± 0.31 °C) and NWP (32.21 ± 0.15 °C) condition.

Head temperature

Figure 6-3 shows that significant differences in $T_h$ were observed between the WP and NWP conditions. Upon the completion of the 1500 m swim in the WP condition, $T_h$ (32.86 ± 0.29 °C) were significantly higher than those observed after the NWP condition (31.28 ± 0.19 °C) ($P<0.05$).

Thermal sensation

Figure 6-4 shows the thermal sensation levels of the head (TSH) and body (TSB) after the trials. The TSB did not significantly differ between the caps in each cap (WP: 6.39±0.27, NWP: 6.50±0.20). No significant differences in TSH also were observed between the WP (6.89±0.23) and NWP (6.11±0.32) conditions. However, in the WP condition, TSH was significantly higher than TSB ($P<0.05$), whereas, TSH in the NWP trial was lower than TSB.

Swimming time

Figure 6-5 shows that there was a significant effects of caps on the time required to swim 1500 m. Faster swim times were observed in the NWP (17:05.8 ± 9.2) condition than in the WP (17:17.2 ± 8.8) condition ($P<0.05$).
Physiological responses

Figure 6-6 shows the HR, Bla and RPE upon the completion of the 1500 m swim in the WP and NWP condition. HR (188.4 ± 1.7 bpm), Bla (7.9 ± 0.4 mmol/l) and RPE (18.4 ± 0.7) in the NWP trial were significantly higher than in the WP trial (184.8 ± 1.7 bpm, 6.5 ± 0.5 mmol/l and 17.6 ± 0.8) (P<0.05).
Discussion

The purpose of this study was to examine whether mild heat stress induced by wearing a waterproof swimming cap while swimming in relatively warm water affects performance.

The primary finding obtained in this study was that certain types of swimming cap materials had an influence on swimming performance. *Toral* measured before and after maximal swimming, raised in the both swimming caps, while the *Tty* decreased conversely. No significant changes were observed in *Toral* and *Tty*, respectively, when comparing WP with NWP. Though the extent of the elevation in *Toral* observed the similar with WP and NWP, the significant alteration was observed in WP (*P*<0.05), whereas, the alteration of NWP was no significant (*P* = 0.06). With the low work, there was a continuous decline in rectal temperature when the water was less than 32 °C (Craig and Dvorak, 1968). However, with the high work load, rectal temperature was attenuated decrease of core temperature (McArdel et al., 1984,1992) and/or increases core temperature (Craig, 1968). For moderate intensity swimming, the thermal stress apparently is dependent on the exercise intensity (Houston et al., 1978). Therefore, the results indicate that swimming trial in this study was an exercise with sufficient intensity to increase the body.

On the other hand *Tty* decreased after swimming either with WP or with NWP. When the water temperature is 37 °C or lower, *Tty* lower than temperature recorded orally or rectally after swimming should be caused by the heat dissipation due to convection associated with air and water temperature (Arnett, 2002). Therefore, the decrease of *Tty* could be due to the influence of the water temperature. The pervious study showed that *Tty* was higher than rectal or esophageal temperature before swimming, but as it increased only slightly during exercise, *Tty* become lower than the core temperature during exercise (Rasch and Cabanac, 1993). It was also shown that this result was caused by a function that suppresses the increase of brain temperature (Rasch and Cabanac, 1993). Therefore, it may be also speculate that this function associate with decrease of *Tty* during swimming.

The change in *Toral* and *Tty* in maximal swimming were the between WP trial and NWP trial and no significant difference between the caps was observed depending on the caps. A previous study on clothing showed that a wet suit increased core temperature during swimming, higher than swimwear (Lowdon et al., 1992). Unlike the wet suit, the swimming cap did not increase core temperature. This is because the area of the head occupies only about 9% of the body surface area (Watanuki, 1992) and hence covering area is too small compared to the body.

There was no significant difference in *Tsk* measured after trial between WP and NWP.
Moreover, the trial increased the skin temperature by 3.27 °C with WP and 2.81 °C with NWP. Several previous studies showed that the skin temperature while swimming is almost equal to the water temperature (Nielsen, 1973) or higher by 0.25-0.75 °C (Nadel et al., 1974). These studies conducted the measurement under the conditions of a swimming speed of 0.5m/s and 50% VO2max, i.e. measurement for swimming at low intensity. Heat production enhances during exercise due to muscular contraction and is directly proportion to the exercise intensity (Power and Howley, 1997). With higher exercise intensity, the skin temperature increases to 0.8-1.6 °C higher than water temperature (Craig, 1968). It was also indicated that age, gender, training history, and swimming ability possibly affect an individual’s thermal responses (Trappe et al., 1995; Kerr et al., 1998). Selected subjects in this study were homogeneity in ages and swimming abilities and asked them to swim at maximal efforts, which is a key to this study. Therefore, this measurement result should demonstrate the thermal response was caused by the enhanced heat production in swimming as high intensity, and indicate that the swimming trial was conducted at sufficiently high intensity to enhance the heat production. Pool condition set in this study was the water temperature relatively warm to have the core temperature increased by the exercise (Craig and Dvorak, 1968). The temperature graduation between the water and skin surface was slight, might have affected the large increase of the skin temperature caused by the heavily swimming.

Although there was no significant difference in Toral, Tty, and Tsk between WP and NWP in the trial, Th after swimming was significantly higher with WP than with NWP. This implies that the characteristic of waterproof increased thermal stress on the head. The environment medium, water, has a large conductivity and heat dissipation is extremely higher in water than on the ground (Nadel et al., 1974; Nielsen, 1969), but wearing the clothes has the effects of suppressing heat dissipation in water. Wolff et al. (1985) investigated the wet suit’s effect on heat exchange at rest, and showed that the wet suit could maintain body temperature because the water held between the suit and the skin halved the heat dissipation. Gloves and boots that divers wear can also increase skin temperature (Choi et al., 1988; Park et al., 1992) and waterproof cap increase the head temperature when swimming at maximal efforts (Matsunami and Taimura, 2005). Therefore, the significant difference in Th between WP and NWP observed in the trial indicates that, a waterproof swimming cap can attenuate heat dissipation, in a similar fashion to wet suits or gloves, and maintain the temperature.

In the thermal sensation measured on the body (TSB), there was no significant difference between WP and NWP in the trial (0.11, P=0.45). Although the difference was lager with WP (0.78, P=0.09), there was no significant difference in the thermal sensation between the caps.
In the TSB and TSH between WP and NWP, TSH in swimming with WP was significantly higher than TSB (0.50, \( P<0.05 \)). This result implies that the subjects had a larger thermal stress on their head than on body when swimming with WP. Lowdon et al. (1992) showed that the perceived comfort rating was higher when subjects swam maximal 1500m wearing a wet suit that suppressed the decrease of skin temperature than when wearing a swimsuit. Thermal sensation between WP and NWP on head did not observed any statistical differences but it was expected that WP tends to enhance the thermal stress more than NWP since \( Th \) was higher with WP.

When wearing WP, the subjects had a larger thermal stress on head than on body that has a lot of exercise muscle. Although the head area is only 9% of the body surface area, the head contains 15% of the entire blood flow volume (Watanuki, 1992), and has the second highest dissipation, following working muscle (Froese and Burton, 1957). Therefore, the head play an important role in heat dissipation (Froese and Burton, 1957). This is why the waterproof swimming cap enhanced the thermal stress more drastically than exercise muscle, even though the head occupies a smaller area than the body. The result observed in this study, uphold previous studies in which the head is an essential part of the body in terms of heat dissipation.

The type of swimming cap also affected swimming performance. This effect might be related to the influence that the swimming caps had on the thermal response and the thermal sensation. In maximal swimming, the subjects showed a significantly better swimming record when wearing NWP than when wearing WP (\( P<0.05 \)). This result indicates the influence of the type of cap on the swimming performance irrespective the head area, which is smaller than the body surface area. Exercise performance lowers as the body temperature increase, irrespective of the exercise intensity or method of exercise (Suzuki, 1980; Hirata et al., 1987; Morris et al., 1998). Work in the heat drives the human body to the muscular fatigue earlier than exercise in a cool environment (Parkin et al., 1999; Ftaiti et al., 2001).

When the body temperature increases more and reaches hyperthermia, the central nervous system reduces the mental drive for motor performance (Sawka, 1992). Nybo et al. (2001) demonstrated that the hyperthermia-induced voluntary force weakening in maximal isometric contraction was caused by central fatigue, and that the reduction of exercise performance in a hot environment was associated with alterations in cerebral activity. Furthermore, Drust et al. (2004) showed that the impaired performance does not relate to accumulation of metabolic fatigue agent, but may relate to influence of elevated core temperature on the function of central nervous system. Although exercise-induced elevation of the markedly temperature do not observed under the water in comparison with the land, the increase of the thermal stress
which by the wear of waterproof swimming cap had an influence on the central fatigue and resulted in low swimming performance. Craig and Dvorak (1968) showed that body temperature during exercise increased at a relatively warm water temperature. Therefore, when water temperature is warm, the fatigue threshold might be attributed to change with caps.

In the present study, Bla, HR, and RPE were all significantly increased when the subjects wore NWP. The increase of muscle temperature by exercise or thermal load augments glycogen utilization during submaximal cycling (Starkie et al., 1999), the increased muscle temperature by intense exercise affects carbohydrate metabolism and the thermal load elevates the lactate accumulation in the muscle (Ferbbraio et al., 1996). There was no significant difference in the $T_{sk}$ between WP trial and NWP trial, and therefore consider that thermal stress on the exercise muscle were similar across the cap conditions. So the significantly high Bla, HR, and RPE observed with NWP indicate that the subjects performed sufficiently high intensity trial when wearing NWP, compared to when wearing WP and that they show higher performance if they did not have thermal stress on their head.

In conclusion, it is unlikely that body temperature is higher in the water than on the land, because of the influence of water temperature. However, in the water where the physiologic neutral temperature range is extremely narrow (Craig and Dvorak, 1968; Nielsen, 1974), swimming performance may be affected by what the swimmer wear. Therefore, these results suggested that swimming cap could not be ignored as tool, which assign the prolonged swimming an influence.
Table 6-1. Physical characteristics of the subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>400m best record (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>19.6</td>
<td>175.3</td>
<td>69.5</td>
<td>244.7</td>
</tr>
<tr>
<td>SD</td>
<td>0.8</td>
<td>6.0</td>
<td>6.6</td>
<td>4.9</td>
</tr>
</tbody>
</table>
Figure 6-1. Changes in tympanic (T\textsubscript{ty}) and oral (T\textsubscript{oral}) before and after 1500m maximal swimming wearing waterproof swimming cap (WP: ■) and non-waterproof swimming caps (NWP: □). Values are mean ± SE. * Significant alteration compared with before swim (P<0.05).
Figure 6-2. Skin temperature (Tsk) following 1500m maximal swimming wearing waterproof swimming cap (WP) and non-waterproof swimming caps (NWP). Values are mean ± SE. No significant differences between NWP and WP trials.
Figure 6-3. Head temperature (Th) following 1500m maximal swimming wearing waterproof swimming cap (WP) and non-waterproof swimming caps (NWP). Values are mean ± SE. * Head temperature was significantly higher (P<0.05) in the WP trial.
Figure 6-4. Mean time for 1500m maximal swims wearing waterproof swimming cap (WP) and non-waterproof swimming caps (NWP). Values are mean ± SE. * Swim time was significantly faster ($P<0.05$) in the NWP trial.
Figure 6-5. Perceived thermal sensation of the body (TSB) and head (TSH) (Scale = 0-8) following 1500m maximal swimming wearing waterproof swimming cap (WP : ■) and non-waterproof swimming caps (NWP : □). Values are mean ± SE. * TSH in the WP condition was significantly higher than TSB ($P<0.05$).
Figure 6-6. Physiological responses (Blood lactate : Bla, Heart rate : HR, Rating of perceived exertion : RPE) following wearing waterproof swimming cap (WP : ■) and non-waterproof swimming caps (NWP : □). Values are mean ± SE. * Significantly higher than the WP trial ($P<0.05$).
Chapter 7

Conclusion

The present study investigates the influence of swimming caps on thermal responses and the performance of swimmers.

In chapter 3, the $T_{fh}$ and $T_{oc}$ began to increase five minutes after starting a swim. $T_{fh}$ did not significantly elevate before or after swimming, whereas, $T_{oc}$ significantly elevated. Though $T_{ty}$ was significantly increased after swimming, there was no significant change in $T_{oral}$. $T_{ty}$ before and after swimming was significantly higher than $T_{oral}$. The perceived thermal response significantly differed between TSB and TSH. These results indicated that waterproof caps obstruct heat dissipation from the head, and increase the head temperature. Therefore, waterproof swimming caps obstruct heat dissipation, and act as a thermal barrier like a wet suit. It was suggested that thermal stress was increased in the head while swimming by wearing a waterproof swimming cap.

In chapter 4, the post trials of $T_{fh}$ and $T_{oc}$ were significantly higher with SC than with MC. $T_{oral}$ did not differ before and after each trial. However, changes in $T_{ty}$ were significantly lower in MC trials than in SC trials. The type of material of swimming caps did not affect, but TSH in SC trials was higher compared with that in MC trials. Therefore, these results were evidently brought about the material of swimming caps, and especially, waterproof swimming caps act as a thermal barrier to the heat production in the head in comparison with non-waterproof swimming caps. Hence, swimmers should choose an appropriate swimming cap considering water temperature and exercise intensity.

In chapter 5, $T_{sk}$ suffered the influence of water temperature, but did not significantly differ between the two types of swimming caps in WW trials and in MW trials. The $T_h$ significantly differed in different water temperatures and between the two types of swimming caps throughout a swim. $T_{ty}$ in WP and NWP trials was significantly higher in tWW than MW, and $T_{oral}$ significantly differed between the MW and WW in the WP. The TSB and TSH in the WP and NWP trial were significantly higher in WW. In WW, the TSH of the WP trial was significantly higher than in NWP trials. These results indicated that a difference in water temperature caused a significant difference in thermal and perceptual responses, and then waterproof swimming caps raise cranialis surface temperature significantly independent of water temperature. Especially, the magnitude of the influence that the waterproof swimming cap in the warm water exerts on the thermal response of head and heat stress was large in
comparison with non-waterproof swimming cap. Therefore, it was suggested that during swimming training in the multi-use pool that established relatively warm water temperature and when prolonged swimming competition were held at pool near the upper limit described in FR 2.11, it was not suitable to wear a waterproof swimming cap.

In chapter 6, $T_{ty}$ and $T_{oral}$ did not significantly differ between WP and NWP trials after a swim. The $T_{sk}$ showed no significant differences between both trials, whereas in WP trial, $T_h$ was significantly higher than in NWP trials. $T_{ty}$ and $T_{oral}$ did not significantly differ between the WP and the NWP trials after a swim. Faster swim times were observed in trials with NWP than with WP. TSB and TSH did not significantly differ between two types of swimming caps. However, TSH in WP trials was significantly higher than TSB. HR, Bla and RPE were significantly higher in NWP trials than in WP trials. These results indicated that the increase of the thermal stress to the cephalicus that induced by wearing waterproof swimming caps during maximal swimming is impacting in the impairment of swimming performance. Therefore, it was suggested that performance during prolonged maximal swimming in the warm water was probably impaired by wearing a waterproof swimming cap.

In conclusion, it is unlikely that body temperature largely increase in water in comparison with on land, because of the characteristics of water. However, in water where a physiological neutral temperature range is extremely narrow, swimming caps may affect swimming performance. Therefore, these results suggest that swimming caps could not be ignored as gear, which affects the prolonged swimming, and then, swimmers might be required to pay more attention in the material of swimming caps. Furthermore, it is desirable to avoid wearing a waterproof swimming cap during swimming training in the multi-use pool and/or it is advisable to choose swimming caps in consideration of water temperature to improve swimming performance.
Chapter 8

Application

The findings of this study suggest;

1. The swimming coaches understand the features of waterproof swimming caps and could instruct to competitive swimmers about the use of swimming caps during swimming training in a multi-use pool.

2. To achieve high swimming performance, competitive swimmers should understand the features of waterproof swimming caps and wear them in consideration of water temperature.

3. Competitive swimmers with injured spinal cord who have a functional disorder for the body temperature regulation could not maintain heat balance should select their swimming caps with water temperature environment in mind in order to avoid heat injury.

4. It is necessary to produce new swimming caps with high thermal conductivity material.
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