Autonomic and behavioural thermoregulation in tennis

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ABSTRACT

Objectives: This report describes physiological and behavioural mechanisms behind the control of body temperature and thermal comfort during competitive singles tennis.

Methods: Thermoregulatory responses and workload were observed during "best of three sets" tennis matches among 25 players. In total, 94 matches were played in ambient temperatures ranging from 14.5 to 38.4°C. The thermal environment was assessed by dry bulb, wet bulb and natural wet bulb temperatures, globe temperature and wind speed. Core body and skin temperatures were recorded each minute throughout the match, and body mass and fluid intake were measured before the match, after 30 minutes of play and at the completion of the match to determine sweat rate. Subjective ratings of thermal strain included thermal comfort, sweatiness and perceived exertion. Workload observations included match, game and point durations, and the proportion of match time spent in play (effective playing time).

Results: Change in rectal temperature was positively correlated with point duration ($p<0.001$) and effective playing time ($p<0.05$). Sweat rate showed positive associations with air ($p<0.0001$), rectal ($p<0.03$) and skin ($p<0.0001$) temperature. Thermal comfort was reduced with increasing rectal ($p<0.03$) and skin ($p<0.0001$) temperature. Point duration and effective playing time were reduced when conditions were rated increasingly difficult ($p<0.002$ and $p<0.0002$, respectively).

Conclusion: Autonomic (increase in sweat rate) and behavioural (reduction in workload) thermoregulation are responsible for the control of body temperature and thermal comfort during tennis.

Tennis is played throughout the world in wide-ranging conditions. Often, players in the Australian Open, held in the middle of summer, are faced with air temperatures >40°C. Despite the potential for extreme heat, findings from previous studies have shown that thermoregulatory strains during tennis are moderate and pose minimal threat to a player's ability to maintain thermal equilibrium. The relative exercise intensity (% VO_{2max}) during tennis has been predicted in a number of studies,[1–4] with the average of these being a moderate 56.4% VO_{2max}. Relative exercise intensity has been linked to steady-state core temperature.[5,6] Therefore, body core temperatures observed during tennis are also moderate, at an average of 38.3°C,[7–10] which is within safe and healthy levels for exercise. The descriptive account of overall thermoregulatory strains during tennis provided by these studies suggests that thermoregulation is successful during tennis in moderate thermal environments; however, the means by which this thermoregulation is achieved remains unknown.

There are two types of thermoregulation: autonomic and behavioural, with the two functioning together to maintain health and safety and thermal comfort. The association between the two forms of thermoregulation is illustrated in fig 1.

Autonomic thermoregulation involves the control of blood flow through cutaneous vasodilation, which serves to increase convective heat dissipation to the environment.[12] However, convective transfer between the skin and the environment provides cooling for the body only when air temperature is less than skin temperature. When air temperature exceeds the physiological maximum skin temperature of approximately 35°C, the thermal gradient for convection is reversed and heat is gained from the environment.[13,14] Therefore, autonomic thermoregulation through vasomotor activity is limited, particularly in warm weather. Furthermore, it is unlikely that dissipation of the required heat load during physical activity could be achieved through convection alone, as metabolic heat production is between 5 and 15 times the resting levels.[15] Therefore, evaporation of sweat becomes the primary means of cooling during exercise and during high air temperatures.[16,17] This is illustrated by the positive association between sweat rate and exercise intensity/metabolic heat production, and between sweat rate and skin temperature during exercise.[16,18–20] However, this association has not been observed during tennis. It seems reasonable to assume that sweat rate should also show a positive association with exercise intensity and skin temperature during tennis, which would provide the autonomic thermoregulation required to maintain thermal equilibrium.

Behavioural thermoregulation is an innate thermoregulatory response that exists in all animals, and is shown by the selection of suitable microclimates.[11,15] Behavioural thermoregulation is a consequence of an individual's drive to achieve thermal satisfaction (the absence of thermal discomfort), which is a psychological rather than physiological response.[12,21] Factors involved in thermal discomfort include physiological strains of skin temperature, body core temperature and skin wetness,[22] in addition to environmental air temperature.[23] Environmental psychology has been investigated in the past, and a number of models developed. The determinist model developed by Canter[24] relates to behaviourism, which suggests that behaviour results from the meaning that an individual links to environmental stresses. Several studies have investigated behavioural thermoregulation during

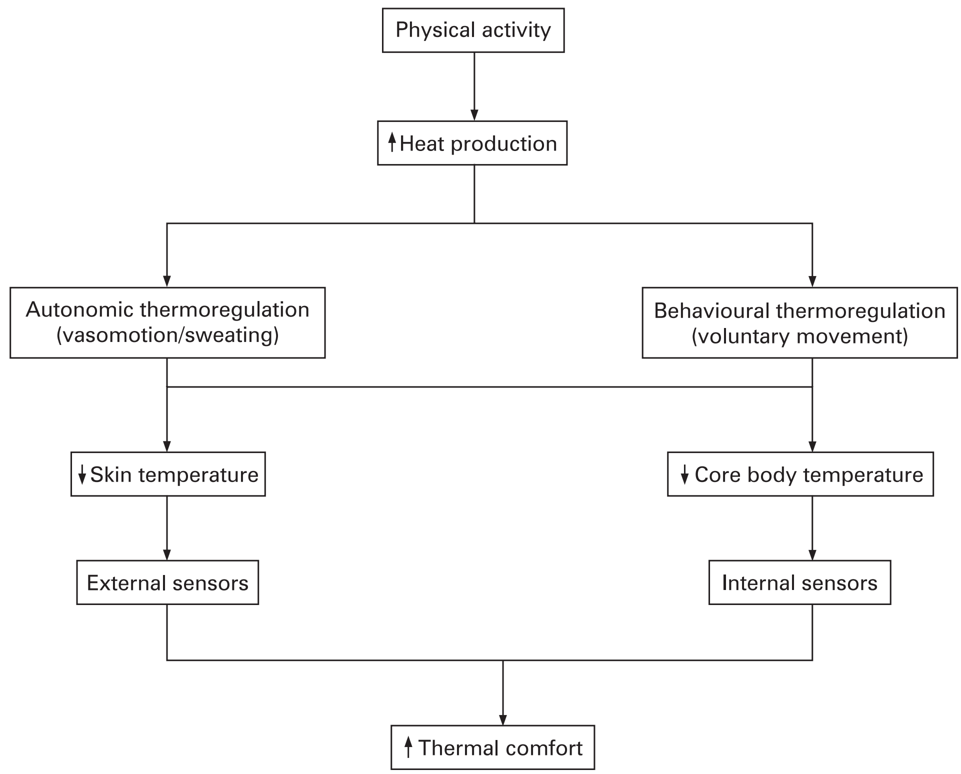

Figure 1 Autonomic and behavioural thermoregulation during physical activity (adapted from Hensel[11]).

work[25] and exercise.[26–30] Tatterson *et al*[26] investigated physiological responses and performance during cycling in hot (32°C) and moderate (23°C) air temperatures in a climate chamber. In hot conditions, they found that perceived exertion was higher whereas power output during self-paced cycling was lower. This increased subjective strain and subsequent behavioural modification are likely contributors to the similar core body temperatures found between the hot and moderate conditions. A similar study was conducted by Tucker *et al*,[27] which discovered that thermoregulatory strains (rectal temperature, heart rate and rate of perceived exertion were similar under hot (35°C) and cool (15°C) environmental temperatures, yet performance (power output and integrated electromyography results) was reduced. The behavioural modification noted by these studies indicates that this is an anticipatory response that serves to protect the body from thermal stress during exercise in the heat.[28–30] However, there is no known description of behavioural thermoregulation during any sport other than running and cycling. Tennis is somewhat similar to these studies in that it is relatively "self-paced". In continuous sports such as distance running or cycling, a reduction in power output would result in impaired performance (longer time to cover a given distance or less distance covered for a given time). In contrast, tennis allows players to manipulate the work and rest intervals by selecting to use little or all of the time between points (20 s), games (90 s) and sets (120 s).[31] Therefore, in warmer conditions players would be expected to modify their behaviour to reduce the work rate and thus metabolic heat load. An example of this conscious behaviour modification occurred on a warm day (air temperature ~ 40.8°C) at the 2007 Australian Open, where one player was quoted: "…you were just mentally trying to find a way to kind of make points shorter…".[32] Behavioural thermoregulation is a critical component of thermoregulation and therefore must be considered when examining thermal stresses and strains. Hence, the current investigation of thermoregulation during tennis provides an original investigation of this form of thermoregulation.

METHODS

This study was a quantitative analysis of competitive singles tennis, where measurements of workload occurred simultaneously with observations of the thermal environment and physiological responses as reported in our previous work.[3] All participants gave their written informed consent and the project was approved by the University of Sydney Human Research Ethics Committee.

Subjects

In total, 25 players volunteered to participate in matches throughout 2005 and 2006. There were 19 men (mean (SD) age 23.9 (5.1) years, height 180 (9) cm, body mass 76.7 (10.1) kg, VO_{2max} 55.3 (8.1) ml/kg/min, maximum heart rate (HR_{max}) 197.3 (8.8) beats/min, sum of nine skin folds 90.4 (34.8) mm

Table 1 Responses to the question "How strenuous does this work feel?"

Scale unit	Descriptive category
20	
19	Very, very hard
18	
17	Very hard
16	
15	Hard
14	
13	Somewhat hard
12	
11	Fairly light
10	
9	Very light
8	
7	Very, very light
6	

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Table 2 Responses to the question "How warm do you feel?"

Scale unit	Descriptive category
7	Much too warm
6	Just too warm
5	Comfortably warm
4	Neither warm nor cool
3	Comfortably cool
2	Just too cool
1	Much too cool

and predicted body fat 10.2 (5.1)%) and 6 women (age 21.8 (2.3) years, height 165 (3) cm, body mass 60.1 (5.6) kg, VO_{2max} 56.0 (3.4) ml/kg/min, HR_{max} 192.8 (4.1)beats/min, sum of nine skin folds 92.6 (29.5) mm and predicted body fat 16.0 (4.9)%).

Procedures

Best of three tie-break set singles matches between players of similar playing standard were analysed. All matches were conducted on a hard-court surface and adhered to the rules set by the International Tennis Federation.[31] Three new tennis balls were used for each match, with players retrieving balls between points.

Thermal environment

A whirling psychrometer shielded from sunlight was used to measure dry and wet bulb temperatures at 20-minute intervals throughout the match. An unshielded wet bulb thermometer was used to measure natural wet bulb temperature every 20 minutes, for calculation of the wet bulb globe temperature index (WBGT). A calibrated thermistor at the centre of a 15 cm blackened copper bulb was used to measure globe temperature for calculation of mean radiant temperature along with air temperature and air movement.[22] A calibrated short arm anemometer set 1.5 m from the ground was used to measure wind speed. Globe temperature and wind speed were recorded every minute throughout the match using a customised Davis Perception II weather station and WeatherLink (Davis Instruments Corp., Hayward, California, USA).

Physiological and subjective responses

Rectal temperature and skin temperature[33] were logged each minute, and heart rate was recorded every 15 seconds throughout the match. Subjective responses of perceived exertion,[34] thermal comfort[35] and sweatiness were recorded during the change of ends after every six games.

Responses to the printed questions "How strenuous does this work feel?" (table 1), "How warm do you feel?" (table 2) and "How sweaty do you feel?" (table 3) were used to give ratings of perceived exertion,[34] thermal comfort [35] and sweatiness, respectively. A subjective rating of conditions was recorded at the same time as the other subjective responses, and used a 10 cm Likert scale with the following question and anchor points: How do you rate the conditions today for playing tennis?

Ideal/perfect |——————————————| Bad/difficult

Table 3 Responses to the question "How sweaty do you feel?"

Scale unit	Descriptive category
4	Dripping wet
3	Wet
2	Moist
1	Sticky
0	Dry

Workload

The analytical procedures which were adapted from Christmass *et al*[36] and Smekal *et al*[4] have been described in our previous work.[37] A stopwatch was used to measure the duration of each game, starting with the serve of the first point and ending when the final point was complete. A second stopwatch was used to measure the duration of each point, starting with the ball toss of the serve and ending when the ball had bounced twice or passed a player. These measurements enabled the calculation of effective playing time: the percentage of match spent within play and excluding the time between points and games. The procedures have a high level of reliability for assessing activity patterns in tennis.[37]

Statistical analysis

Statistical analyses were performed using SPSS V.15.0 (SPSS Inc, Chicago, IL, USA). The effects of the thermal environment, physiological responses and subjective responses on the match characteristics were examined through regression analysis. The α-level was set at $p<0.05$.

RESULTS

Table 4 presents the environmental conditions during competitive singles tennis. The mean data indicates moderate environmental stresses; however, the ranges of observations include some more extreme conditions.

Table 5 presents physiological and subjective responses during competitive singles tennis. Rectal temperatures and skin temperature indicate a moderate thermoregulatory strain. This is supported by a perceived exertion of "somewhat hard", a rating of thermal comfort as "comfortably warm" and a rating of sweatiness as "moist".

Table 6 shows workload during competitive singles tennis. Peak activity periods are short (5.8 seconds) and comprise only 23.7% of the total duration, which equates to approximately 20 minutes of peak physical activity within a tennis match.

Figure 2 illustrates the influence of the two thermal stresses: (1) physical activity and (2) air temperature on rectal temperature and perceived exertion during singles tennis. These findings indicate that higher workloads during tennis (ie higher point duration and effective playing time) result in

Table 4 Environmental conditions during competitive singles tennis

Variable	Mean (SD)	Range
Air temperature (°C)	25.0 (5.4)	14.5 to 38.4
Relative humidity (%)	50.7 (14.3)	21.8 to 73.7
Vapour pressure (mb)	15.9 (4.8)	7.5 to 28.4
Mean radiant temperature (°C)	35.2 (7.5)	21.3 to 53.5
Air movement (m/s)	1.5 (0.6)	0.5 to 3.3
Wet bulb globe temperature (°C)	22.5 (4.3)	13.5 to 29.2

Data from 47 matches.

Table 5 Physiological and subjective responses during competitive singles tennis

Variable	Mean (SD)	Range
Rectal temperature (°C)	38.45 (0.36)	37.43 to 39.98
Change in rectal temperature (°C)	1.32 (0.40)	0.47 to 2.40
Maximum rectal temperature (°C)	38.72 (0.38)	37.52 to 39.59
Skin temperature (°C)	31.82 (2.27)	25.74 to 36.50
Sweat rate (ml/kg/min)	13.32 (5.56)	2.74 to 26.00
Heart rate (beats/min)	136.79 (13.62)	99.01 to 167.66
Perceived exertion	12.9 (1.9)	8.5 to 17.0
Thermal comfort	5.1 (0.8)	3.0 to 7.0
Sweatiness	1.9 (1.0)	0.0 to 10.0
Conditions	6.0 (2.2)	0.5 to 10.0

Data from 94 observations.
Perceived exertion: 6, "very, very light" to 20, "very, very hard".
Thermal comfort: 1, "much too cool" to 7, "much too warm".
Sweatiness: 0, "dry" to 4, "dripping wet".

Table 6 Workload during competitive singles tennis

Variable	Mean (SD)	Range
Match duration (min)	82.5 (25.3)	60.0 to 190.0
Game duration (s)	164.7 (21.9)	108.4 to 212.7
Point duration (s)	5.8 (1.3)	3.9 to 10.4
Effective playing time (%)	23.7 (5.2)	12.2 to 39.6

Data from 47 matches.

greater thermoregulatory strain (higher body core temperature and rating of perceived exertion). This is supported by positive associations between heart rate and point duration ($p<0.0001$; $R^2 = 0.16$) and effective playing time ($p<0.05$; $R^2 = 0.06$).

Figure 3 presents mechanisms of autonomic thermoregulation and their influence on body core temperature during singles tennis. The broken line in fig 3A indicates the capacity for convective heat dissipation, with all data points above this line representing convective heat loss and the data points below this line indicating convective heat gain.

Figure 4 illustrates the effects of body temperatures on the ratings of thermal comfort and conditions, and the subsequent influence of these subjective strains on behaviour as indicated by workload during singles tennis. Physiological responses were found to be correlated with the rating of thermal comfort but not rating of conditions, whereas behavioural responses were associated with rating of conditions but not thermal comfort.

DISCUSSION

The control of body core temperature at an average of 38.3°C during tennis, as shown in table 1, indicates that thermoregulation is successful. It is hypothesised that this is achieved

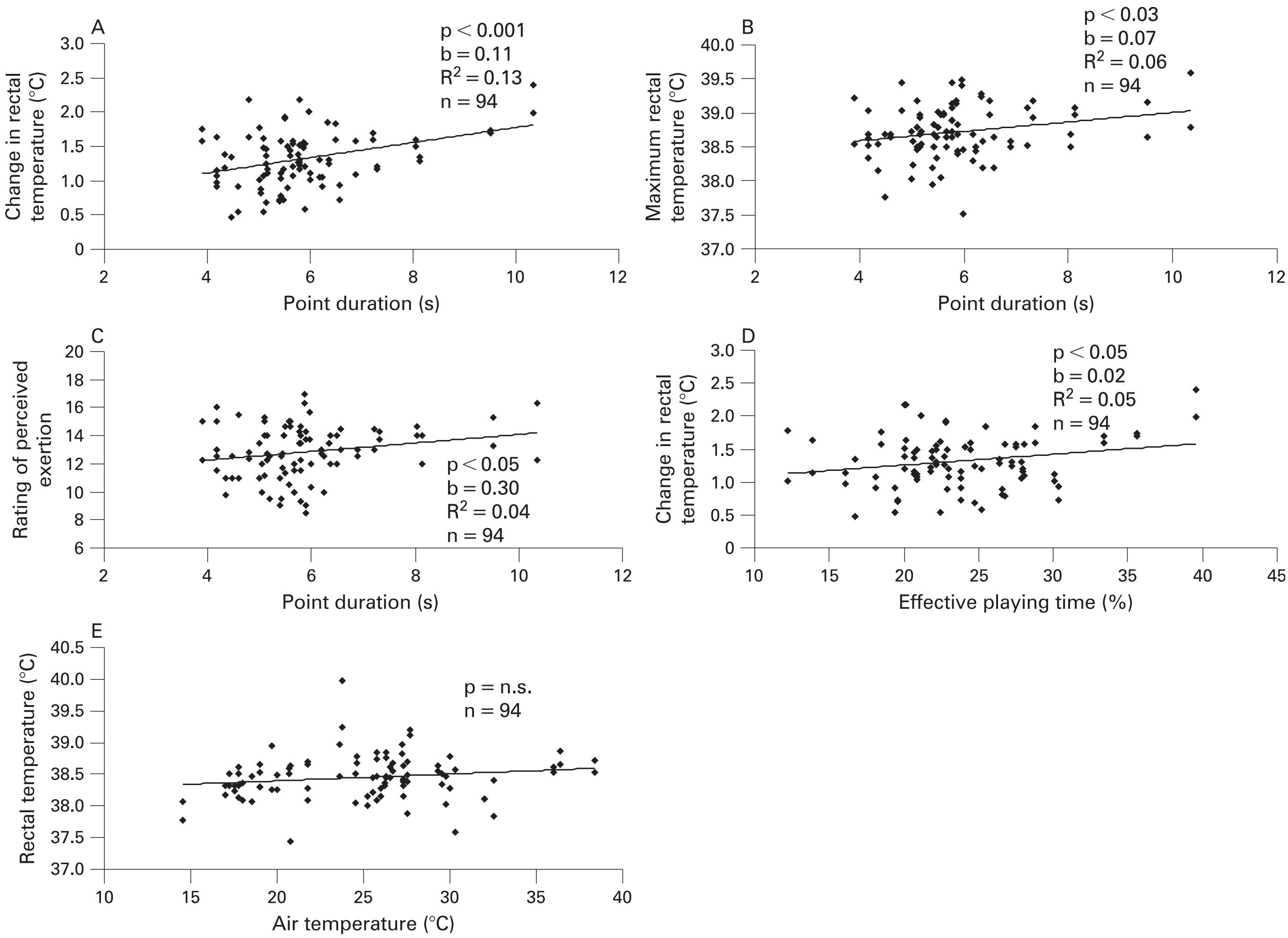

Figure 2 (A) Change in rectal temperature versus. point duration; (B) maximum rectal temperature versus point duration; (C) rating of perceived exertion versus point duration; (D) change in rectal temperature versus effective playing time; and (E) rectal temperature versus air temperature.

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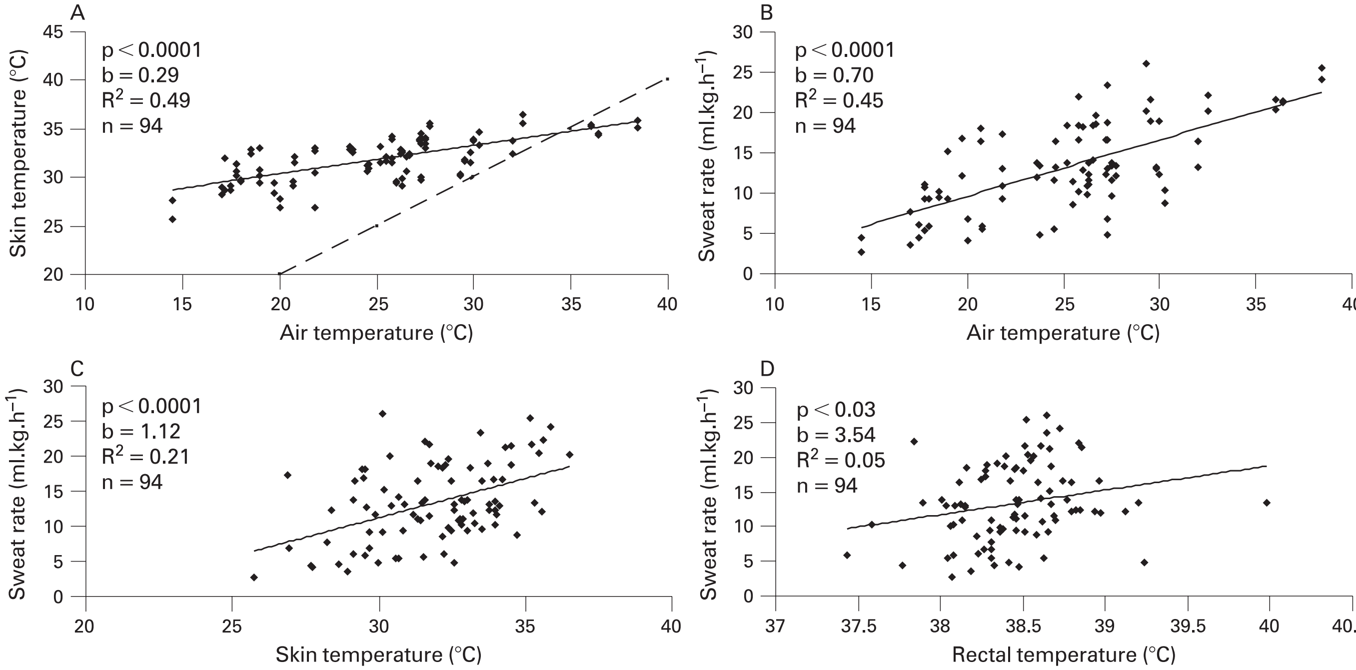

Figure 3 (A) Skin temperature versus air temperature; (B) sweat rate versus air temperature; (C) sweat rate versus skin temperature; and (D) sweat rate versus rectal temperature.

through a combination of autonomic (increase in sweat rate) and behavioural (reduction in workload) thermoregulation.

Body core temperature is a direct function of the relative workload rather than environmental conditions.[5 6] This is seen in fig 2, where the change in rectal temperature, maximum observed rectal temperature and rating of perceived exertion are positively correlated with workload during tennis, whereas mean rectal temperature remains unaffected by air temperature. It has been established that point duration represents the period of peak physical activity during tennis, and is positively linked with oxygen consumption and therefore metabolic heat production.[4] The effective playing time represents the percentage of the match spent in play (excluding the time spent between points and games). Therefore, the greater change in rectal temperature shown when effective playing time is higher (fig 2C) also reflects a higher metabolic heat production, as a larger proportion of the match is spent within points. Despite this evidence of a higher maximum rectal temperature and larger changes in rectal temperature when the workload is high in tennis, overall rectal temperature is maintained at a tolerable average of 38.45°C, which closely agrees with findings reported by other studies.[7–10] Therefore, thermoregulation during tennis is successful; however, the means by which body core temperature is maintained remains to be determined.

Autonomic thermoregulation during tennis is shown in fig 3. Figure 3A presents the positive correlation between skin temperature and air temperature. As discussed above, heat dissipation through convection occurs when skin temperature is greater than environmental temperature. The broken 1:1 line for skin and air temperature in fig 3A was generally negative, resulting in heat loss. Therefore, thermoregulation during tennis is achieved partly through convective heat dissipation. However, it can also be seen in this figure that skin temperature during tennis can exceed air temperature, and thus a fall below the broken line, indicating positive convective heat transfer (ie heat is gained from the environment). Under these circumstances, the evaporation of sweat becomes the sole method of heat dissipation. The role of sweating during thermal stress and strain is illustrated by the positive associations between sweat rate and air (fig 3B), skin (fig 3C) and rectal (fig D) temperature. The higher sweat rates observed at higher air temperatures suggest that the evaporation of sweat must provide additional heat dissipation during tennis, which assists in the control of body core temperature. Therefore, autonomic thermoregulation is present during competitive singles tennis, which is indicated by (1) the increase in skin temperature to preserve maximum convective heat loss and (2) the increase in sweat rate to provide dissipation of heat via evaporation.

Positive associations between ratings of thermal comfort or rating of conditions with rectal temperature and skin temperature are shown in fig 4(A–D). As rectal temperature and skin temperature become higher, players' rate their comfort as being increasingly warm, which is well documented in previous studies.[38–42] This dissatisfaction forms the basis for an adjustment to workloads with the aim to minimise discomfort. Interestingly, the discomfort reported by players in relation to thermoregulatory strains related to how they felt, rather than how they described the environmental conditions. Yet in contrast, the behavioural modification was not related to thermal comfort but instead the rating of the thermal environment. This difference can be explained by distinguishing thermal comfort from thermal sensation – terms that are often used interchangeably. Thermal comfort relates to how the person feels in a given environmental condition, whereas thermal sensation, on the other hand, relates to a description of the thermal environment surrounding an individual.[11 12] In the present study, higher core body temperatures and skin temperatures caused players to feel warmer (thermal discomfort) and dissatisfaction with the environmental conditions (thermal sensation of conditions being "difficult") instigated the behavioural response. Uniquely, skin temperature was associated with both thermal comfort and thermal sensation, as it is linked to both internal and external conditions. The behavioural modification shown during singles tennis is

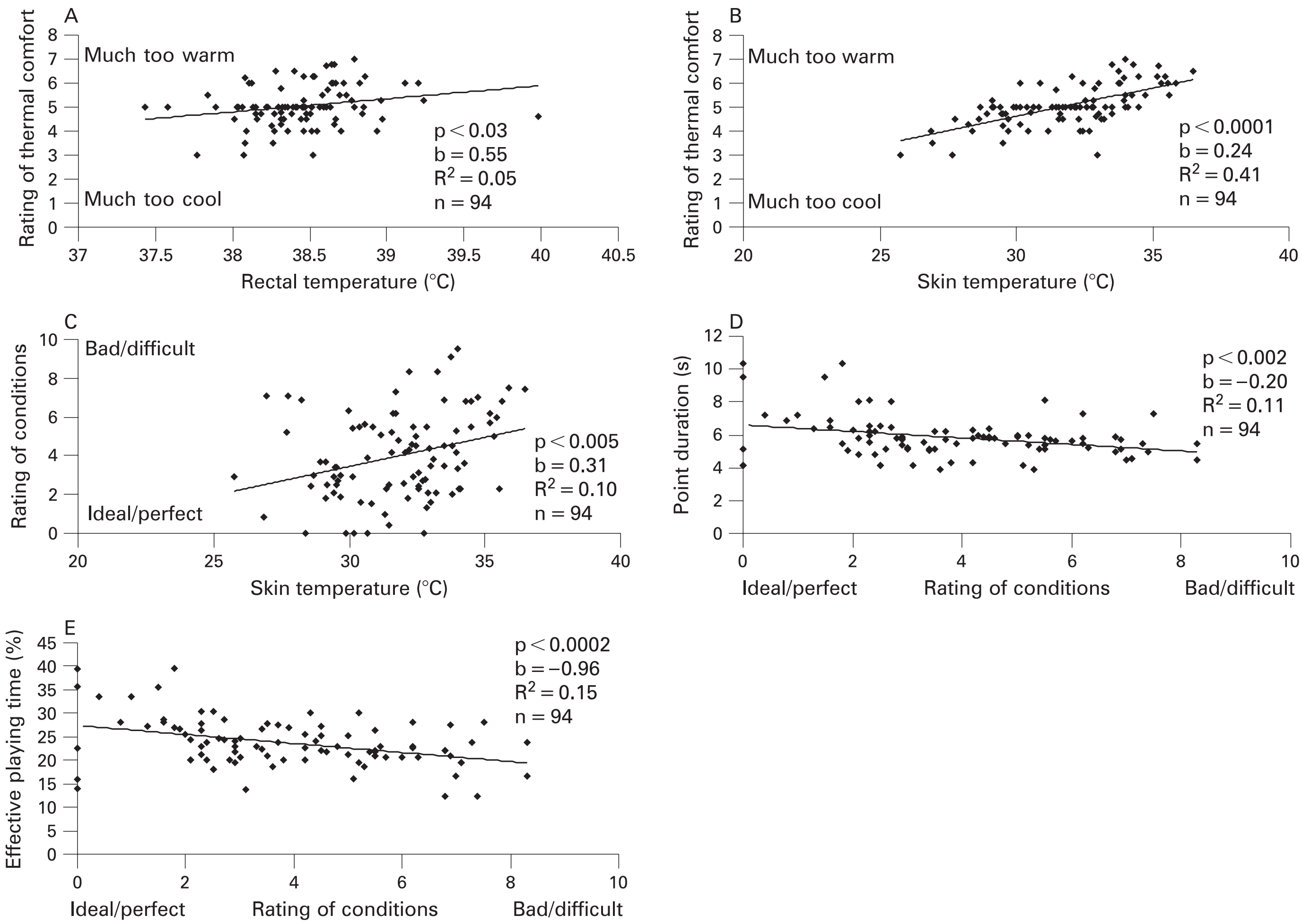

Figure 4 (A) Rating of thermal comfort versus rectal temperature; (B) rating of thermal comfort versus skin temperature; (C) rating of conditions versus skin temperature; (D) point duration versus rating of conditions; and (E) effective playing time versus rating of conditions.

What is already known on this topic

- Physiological responses during tennis have been reported in a number of papers, suggesting that the overall strain is moderate.
- Thermoregulation during tennis is generally successful, with core body temperature remaining within healthy levels.

What this study adds

- The two methods of body temperature regulation during tennis, autonomic and behavioural, were examined during tennis.
- A combination of both methods served to protect core body temperature reaching dangerous levels during tennis through: (1) an increase in vasomotor activity for convection, (2) an increase in sweat rate for evaporation and (3) a reduction in workload to decrease metabolic heat production.

characterised by the changes in point duration and effective playing time that occurred when conditions were rated as uncomfortable. As point duration and effective playing time have been shown to be related to metabolic heat production[4] and body core temperature (fig 2A–D), this behavioural reduction in workload acts as a defence mechanism to minimise metabolic heat production, and thereby prevent an increase in body core temperature. This is supported by the findings and conclusions of previous studies.[26-30] Therefore, subjective strain during competitive singles tennis initiates behavioural thermoregulation, which serves to reduce the workload and metabolic heat production, thereby maintaining thermal equilibrium.

CONCLUSION

Body core temperature was controlled within safe levels during tennis through a combination of autonomic and behavioural thermoregulation. Autonomic thermoregulation was achieved through vasomotor activity to improve convective heat dissipation and an increase in sweat rate for evaporative cooling. Behavioural thermoregulation was achieved through a reduction in overall workload to reduce metabolic heat production.

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Competing interests: None.

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Commentary

Over 100 years ago, biologist Charles Morris proposed the revolutionary idea that humans evolved as hot weather hunters. Today it is increasingly accepted that we *Homo sapiens* owe our big brains (and our ability to undertake science) to our sweaty, hairless, long-legged torsos that allowed our (then small-brained) ancestors to outrun antelope in the midday heat on the sultry African savanah starting perhaps 2 million years ago. Studies of modern hunters in the Kalahari desert in Southern Africa suggest that these hunts were most successful when held in dry- bulb temperatures of 40–46°C. Often these hunts can last up to 6 hours. Thus the finding that modern tennis players are able to sustain 25 minutes of actual tennis play at dry-bulb temperatures of up to 39° C without dying is perhaps not so surprising, for these are exactly the conditions for which our excellent thermoregulatory apparatus, more effective apparently than that of any other earthly mammal, was designed.

This exceptional paper makes one telling finding: that human tennis players regulate their body temperatures during exercise by activating their heat loss mechanisms and by changing their behaviour so that as they perceive the environmental conditions becoming increasingly severe they reduce the duration of play for each point and increase the amount of time that they rest between points. As a result, they homoeostatically regulate their body temperatures within a safe range. This anticipatory regulation has been shown to occur in running and cycling, and these data extend that finding to another individual sport, proving that it is a human characteristic regardless of activity.

It is perhaps not surprising that this study and its interpretation should originate in the New World, Australia, for Australians continue to believe in and value human toughness. They perceive humans as a successful species able to survive in most environments, including desert heat. In contrast, the concept is gaining ground in the Old World that humans are essentially fragile; a failing species unable to maintain homeostasis when undertaking anything more vigorous than strenuous television watching. Thus they must be protected from their frailty by the use of a range of supports – from sports drinks to nutritional supplements to detailed academic guidelines detailing exactly how they must conduct themselves under any possible conditions of exercise. This has indeed become a cultural divide of quite alarming proportions that inevitably influences the conduct of sports medicine and the sports sciences in these different "Worlds".

This study shows that humans have all the necessary controls to ensure that they can exercise quite safely even in very hot conditions, provided they can regulate their own behaviour and without the need to be told exactly how they should conduct themselves. We owe this capacity to our ancestors and especially to that individual who woke up one morning and decided that if he chased some antelope in the heat, he might enjoy a more substantial midday meal.

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