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Abstract

Objective: To explore the relationship of wet bulb globe temperature (WBGT) on heat-related incidents and alterations in matchplay and behavioural characteristics in women's tennis at the Australian Open.

Methods: From 360 main draw Australian Open women's matches (2014-2016), data describing on-court calls for trainers, doctors, cooling devices and water, post-match medical consults and matchplay characteristics were collated. Data were referenced against estimated WBGT and categorised into standard zones (zone 5: >32.3°C, zone 4: 30.1-32.2°C, zone 3: 27.9-30°C, zone 2: 22.3-27.9°C, zone 1: <22.2°C). Generalized linear models assessed the association of WBGT zone on heat-related medical incidences, court call-outs and match characteristics.

Results: With an increased estimated WBGT zone, there was an increase in total trainer calls (+19.5%/zone; p=0.019), total doctor calls (+54.1%; p<0.001), total calls for heat related incidents (+55.9%; p<0.001), and cooling devices (+31.4%; p<0.001) calculated from the regression slope. When match characteristics were adjusted for match quality, significant decreases (p<0.001) in the number of winners and net approaches and increase in double faults were associated with increased estimated WBGT zone.

Conclusion: An association between higher estimated WBGT and medical callouts (heat and non-heat related) was evident, with an increased call rate >32°C WBGT, despite no heat-related retirements. As estimated WBGT increased, the number of winners and net approaches were reduced, while double faults increased, particularly >30°C WBGT. Accordingly, the manner in which female players manage and play in the heat during women's Grand Slam tennis appears to change at ≈30°C WBGT.

Keywords: heat illness, court sports, matchplay.

Introduction

As the Australian Open (AO) is played each year during the Southern Hemisphere summer, tennis matchplay during extreme heat (>35ºC dry bulb) and its potential implications for athlete wellbeing and performance is a constant source of discussion. This scrutiny exists against the backdrop of the American College of Sports Medicine (ACSM) stating that exercise in temperatures >28ºC Wet Bulb Globe Temperature (WBGT) places individuals at high risk for heat illness [1]. In turn, the Women's Tennis Association (WTA) introduced an extreme heat policy that allows players to receive a 10-min rest period between the second and third set (if a third set is to be played) in conditions >28ºC WBGT [2]. Notwithstanding the lack of publically available evidence surrounding the effect of extreme heat on player wellbeing and performance in women's tennis, the logic was that this rest allows for core temperature reductions[3]. The AO has followed the WTA's lead, providing players with this choice prior to commencing the deciding set.

Heat illness is a multi-factorial occurrence, yet prolonged or high-intensity exercise in hot/humid environments is a significant contributor [1]. In professional women's tennis, the prevalence of heat illness remains poorly reported. Of the limited literature available, the 1994-2009 US Open reported a heat illness rate of 1.42 per 1000 match exposures in women, although no association with ambient temperature was found (26-33ºC) [4]. Interestingly, reduced heat illness rates in women were evident compared to men (1.45 vs 2.45/1000h) [4]; potentially due to the variation in their heat policy compared to the men's, as well as the shorter match durations, reduced number of sets and/or the more baseline oriented playing style of the female game[5]. Current heat policies also dictate that women's matches receive a 10-min break between the 2nd and 3rd set if the WBGT >28ºC. Such a rest period may mitigate the rise in core temperature and reduce the risk of heat illness[3]. This gender-based policy difference may have some physiological basis as it has been suggested that women gain heat faster once the environmental temperature rises above that of the skin due to their larger skin surface area to body mass ratio [6]. However, it must be noted that these claims remains contentious owing to a lack of definitive supporting evidence[6]. Regardless, reported heat illness rates do not necessarily capture all player discomfort, which might otherwise be informed by the behavioural responses of players (i.e. cooling and water call outs). These changes in behavioural responses may also infer that increased core temperature > 39.0°C can affect cognitive function[7]. Hence, thermal comfort, decision making and tennis performance may become compromised.

From a performance perspective the impact of environmental conditions on the characteristics of professional women's tennis matchplay have not been examined. In men's tennis in the heat (33.6±0.9°C WBGT), an increase in rest periods (+9.6±3.6s) between points has been reported, while point length, number of points and games, aces and double faults were stable between hot and cool conditions [8]. This increase in rest may explain the maintenance of core temperatures (<40.0°C) during matchplay even in extreme environmental conditions [9, 10]. Further, such a manipulation could also explain the absence of reduced physical performance outcomes, i.e. speed and power, following matchplay in the heat [11]. However, as yet there is no comparable insight describing the effect of higher thermal stress on tennis matchplay characteristics in professional women's tennis.

This study aimed to retrospectively determine the effect of environmental conditions on heat-related trainer and doctor call outs, behavioural responses and match characteristics in women's Grand Slam tennis at the AO. It was hypothesised that with increasing WBGT there would be an increase in heat related medical consults, along with increases in water and cooling device call outs but with minimal changes to match characteristics.

Methods

Data were obtained from all 360 matches in the first four rounds of the 2014, 2015 and 2016 AO Women's Main Draw. The participants held a mean Women's Tennis Association rank of 67±72, age 25±4 and were from 45 different countries. Participant consent for the use of data for research purposes was gained upon tournament entry via tournament conditions of entry. Ethical approval was granted by the institutional Human Research Ethics Committee (UTS HREC REF NO. 2015000126).

Descriptive point level data and player rank information were collected from the AO tournament organisers (outlined in Supplementary Table 1). Data from match umpires and match coding professionals were combined to provide real-time point level data. The coding professionals were extensively trained and used a platform that is widely used in professional tennis and has high inter- and intra-tester reliability [12]. Weather data were retrospectively collated from half-hourly recordings from an Australian Bureau of Meteorology weather station located within 100m of the venue. As this station did not record globe temperature, an estimated WBGT is provided by Australian Bureau of Meteorology, based on the formula;

$$WBGT = 0.567 \times Ta + 0.393 \times e + 3.94,$$

Where: Ta= dry bulb temperature (^{o}C) and e = Water vapour pressure (hPa) [humidity] [13, 14].

Whilst recognised as a limitation, this formula has previously been used to estimate WBGT without black globe temperature [15-17]. It is also acknowledged that WBGT is only one measure of thermal stress, and has limitations related to air movement, calibration and lack of adjustment for clothing type [18]. Regardless, it is currently the primary measure of heat stress at the AO and throughout international tennis, and as such is the most relevant measure for this study over multiple years and courts [2, 19].

Records of on-court calls for medical consults made by AO medical doctors and physiotherapists as well as calls for cooling devices/water were gathered from time stamped tournament communication call logs. Post-match heat related consults were collated from the tournament's medical database, where consults were considered to be heat related if identified by the treating medical practitioner as the result of hot environmental loads or heat illness. Matches with large amounts of missing data were excluded from analyses (i.e., WBGT, on-court calls, or large amounts of match data; n=12), as were matches suspended for rain or played under a closed roof (i.e., environmental conditions altered or unknown; n=2). All data were collated into Microsoft Excel and classified into a WBGT zone according to the ASCM classification [1], zone 5: >32.3ºC, zone 4: 30.1-32.2ºC, zone 3: 27.9-30ºC, zone 2: 22.3-27.9ºC, zone 1: <22.2ºC (with ACSM's zones <10 and 10.1-22.2ºC being combined to form zone 1, and zones 22.3-25.6ºC and 25.7-27.8ºC being combined to form zone 2). Thus, a numerical increase in zone indicates a change from more temperate to extreme heat temperatures.

Analyses for the present study were completed in RStudio version 0.99.902 (RStudio: Integrated Development for R. RStudio, Inc., Boston, MA). The association of estimated WBGT zone and study outcomes were assessed through generalised linear models (GLM). Poission distributions were modelled with count outcomes, and continuous outcomes with a Gaussian distribution. Medical and behavioural outcomes were considered per match as well as per 1000 match hours; the later rates being determined by dividing the number of medical and behavioural call outs per zone by the total duration of matches for each estimated WBGT zone and reported as rates per 1000 h. The risk of inconsistency in trends owing to rare events was measured with the average relative standard error , with continuity corrections for cases where no eventswere observed. Odds ratios were also calculated for the likelihood of medical or behavioural call occurring in each estimated WBGT zone compared to zone 5.

Recognising that player quality may influence matchplay outcomes, analysis of match performance was undertaken with (adjusted model) and without (unadjusted model) adjustments for player quality. In the adjusted analyses, players were considered of similar quality when pre-match Elo ratings were within 50 points[20]. Elo ratings are based on the strength of each player's career wins and have been proposed to provide a more accurate sense of player ability than traditional ranking systems[20]. Unadjusted analyses simply compared the performance outcomes of all matches in each zone. To limit the impact of different distributions of player quality, which can confound the assessment of the associations, adjusted analysis matched each player and opponent in an extreme group (5-3) to a moderate zone (1-2). Confidence intervals are reported at the 95% level and statistical significance was defined as an effect of 5% significance or less.

Results

With each increase in estimated WBGT zone, there was an increase in total trainer calls (+19.5%/zone; p=0.019), total doctor calls (+54.1%; p<0.001), total calls for heat related incidents (+55.9%; p<0.001), post-match heat related consults (+68.3%; p=0.010), and calls for cooling devices (+31.4%; p<0.001). When medical and behavioural events were examined as a rate per 1000 h (Table 1), both heat related call outs and non-heat related call outs increased with each increase in estimated WBGT zone. Calls for cooling devices were highest in zone 4 (107.84/1000h) and calls for water increased in zone 4 (53.92/1000h) and 5 (55.47/1000h).

Table 2 shows the odds ratio of a medical and behavioural events when compared to zone 5. All zones showed lower odds than zone 5 for trainer call outs ($p<0.05$), while on-court calls for water and cooling devices did not show any significant differences ($p>0.05$). Zone 2 showed significantly lower odds of an on-court doctor call ($p<0.001$) than zone 5. Players calling for a doctor or trainer regarding heat related event ($p<0.001$) and post-match heat related events ($p=0.007$) in zone 2 had a lower odds of occurrence than that of zone 5.

Supplementary Table 2 shows the match characteristics per estimated WBGT zone along with change per estimated WBGT zone, without the player quality adjustment. With increased estimated WBGT zone, increases were observed in match duration by 2.5±0.1 min ($p=0.022$), double faults by 9.3±0.01% ($p<0.001$), unforced errors by 1.5±0.01% ($p=0.024$), and return points won by 1.9±0.55%. First serve percentage (-0.64±0.3%; $p=0.034$), winners (-3.2±0.008%, $p<0.001$), net approaches (-6.2±0.01%, $p<0.001$), fastest serve (-1.31±0.6 km/h, $p=0.039$), first serve speed (-1.86±0.51 km/h, $p<0.001$), and 2nd serve speed (-1.65±0.46 km/h, $p<0.001$) all decreased with each increase in the estimated WBGT zone.

Table 3 shows the match characteristics per WBGT zone and change per zone when adjusted for differences in player quality. Following adjustment, double faults showed a 13.8±0.03% ($p<0.001$) increase per increase in WBGT zone, whilst winners (-7.3 ± 0.013%,) and net approaches (-8.4±0.019%) decreased per WBGT zone ($p<0.001$).

Discussion

The current study showed higher estimated WBGT's were associated with increased heat (and non-heat) related on-court trainer and doctor callouts, peaking >32°C WBGT (zone 5), despite no heat-related retirements. However, the increased prevalence of heat call outs from zone 4 implies that players started to become noticeably thermally challenged in zone 4 (>30°C WBGT). The positive linear association between estimated WBGT and non-heat related trainer and doctor call outs may infer that players are either more susceptible to injury or use trainer call outs strategically as thermal strain climbs. Possible reasons for the absence of heat related retirements may relate to the format of Grand Slam women's tennis (where a maximum of 3 sets are played) and/or the playing styles of elite female players. For example, professional women's tennis features higher proportions of baseline rallies with a slower shot rate, a less dominant serve and fewer net approaches, relative to their male counterparts[5]. The comparatively shorter format and different tactical structure of the female game may assist in the preservation of core temperature and explain the reduced rates of heat illness in women's tennis compared to their male counterparts [4].

Another aspect of the women's game that may aid in the preservation of core temperature and the reduction in match retirements may be the implementation of a subsection of the extreme heat policy, which provides a 10-minute break in play between the 2nd and 3rd set if WBGT > 28°C and if a 3rd set is to be played [3]. This subsection may have had a substantial impact on the prevention of heat related match retirements in the current data set. With previous evidence supporting the use of the heat rule in professional women's tennis by demonstrating the successful reduction in core temperatures (0.25 ± 0.20°C) during matchplay in the heat in live professional women's tennis, which potentially reduces the risk of heat illness [21].

Calls for cooling devices and water also increased with estimated WBGT, particularly in estimated WBGT >30°C (i.e. zone 4 and 5). We reason that this presents a behavioural sign of players feeling thermally challenged, although due to zonal analysis used here a specific inflection point was not determined. This inference is supported by the commensurate rise in calls for medical assistance noted earlier. Previous investigations of simulated matchplay settings show male players to record core temperatures as high as ~39.4°C [8]. Whilst direct measurement of core temperature is precluded in this Grand Slam context, it would appear that conditions >30°C WBGT might sufficiently increase the core or skin temperatures of female players resulting in additional calls for cooling devices and water. The increased call outs for heat-related issues and cooling devices >30°C WBGT, without heat-related retirements, might suggest appropriate implementation of the extreme heat policy for women's tennis at the AO.

Changes in estimated WBGT were associated with significant changes in particular match characteristics. In the unadjusted analyses an increased estimated WBGT was associated with increased match duration. It has previously been demonstrated that match durations were increased during professional men's simulated match play in the heat (33.6 °C WBGT) [8]. In these simulated contexts, longer rest periods between points (+9.6 ±3.6 s) were observed to contribute to this increase [8]. However, due to the enforcement of a maximum of 20s rest between points on the Women's Tennis Association tour and at Grand Slams [22], other explanations should be considered. That said, the increased match duration was not present when adjusted for player quality. Given that an individual player can influence rest time independent of the opponent, this may represent an artefact of mismatched player quality in these zones.

The unadjusted analyses highlighted a negative association between estimated WBGT zone and serve speed. This reduced serve speed, in conjunction with no significant change to first serve percentage, points to players potentially reducing their serve speed to preserve the accuracy of their serve. Such a response to higher WBGT would suggest altered serve tactics, albeit one that is in keeping with the situational evidence that women tend to rely less on their serve to win points than men [5]. The increase in double faults evident in both adjusted and unadjusted analysis highlights that the second serve appears to become particularly more vulnerable in the heat in women's tennis [23]. The balance between speed and accuracy that is seemingly adjusted in hotter conditions is not uncommon in other skill and team-based sports where there is a decreased level of fine motor control with fatigue that is exacerbated in the heat [24]. Hence, in Grand Slam women's tennis, the heat may challenge the technique and/or tactics of players on their first and second serves.

The increase in unforced errors (unadjusted analysis) and reduction in winners (in both adjusted and unadjusted analysis) can be variously explained. First, fatigue may force players to attempt shots that are riskier, heightening the chances of committing unforced errors [25]. Second, players might be less prepared to create appropriate opportunities to attack once fatigue increases [26], meaning that unforced errors rise and winners fall. Third, it may be speculated that players attempt to preserve energy, and position themselves further behind the baseline, which creates a less favourable court position (on the opponent's side of the net) to exploit. Simultaneously, and logically, it lengthens the distance to the net, which might explain the reduced number of net approaches observed in both the adjusted and unadjusted group.

Despite the novel findings reported here regarding medical, behavioural and matchplay responses for women's Grand Slam tennis in the heat, several limitations need to be acknowledged. Firstly, many heat indices are available, and although the WBGT has been subject to criticism due to its limitations, it is the most common measure in professional tennis (including the AO) and thus most practical measure for this study [2]. Nevertheless, it is still important to highlight that WBGT limitations include concerns surrounding the standardisation of equipment and calibration, the use of a natural wet bulb as a thermodynamic parameter, lack of accounting for air movement and clothing within WBGT calculation [18], as well as the noted variation in thermal stress between conditions with equivalent WBGT's [30]. It is also important to note that WBGT provides an indicator of thermal stress, but does not directly inform thermal strain. This study also relied on the use of estimated WBGT from a central position (not courtside) which could underestimate the true WBGT in the full sun and high humidity [13]. However, the use of zone analysis and the large data set is proposed to reduce the impact of this measurement method. Further, given the elite nature of a Grand Slam event, measurement of physiological or perceptual responses were not possible, though such data would feasibly add to greater understanding of the thermal strain of such conditions. Similarly, infomation of prior heat exposure, predisposition to heat tolerance and if athletes underwent acclimatisation prior to the AO was not avalible, and hence not accounted for in the analyses. ~~Of note however is that during Grand Slam tournaments players are unlikely to play singles matches on consecutive days thus reducing the likilehood of consecvutive days of heat stress.~~ It is also important to note that some of the medical and behavioural data reported trend inconsistancies within the average relative standard error trend analysis.

Conclusion

This is the first study to examine the effect of environmental temperature on heat related incidents, behavioural responses and matchplay characteristics in women's professional Grand Slam Tennis. In line with previous findings, as estimated WBGT increases so did match duration, the number of calls for cooling devices and medical heat-related call outs, particularly in conditions >30^{o}C WBGT. Significant associations between estimated WBGT and changes in matchplay characteristics such as the number of winners, unforced errors, double faults and number of net approaches were also found, suggesting that estimated WBGT impacted on the manner in which female tennis players competed in the heat. Possible changes to serve tactics and the court positioning of players may explain some of these changes. Accordingly, heat related incidents and behavioural responses in women's Grand Slam tennis appear to significantly increase at 30^{o}C WBGT.

Practical Applications

- For professional tennis tournaments in conditions > 30^{o}C; tournament organisers should have extra cooling device and water available court side for athletes and be vigilant for signs of heat illness
- Tournament organisers should also encourage the use of the heat rule in Women's matches; once WBGT reach 28^{o}C with the suspension of match play above 32^{o}C
- In high environmental temperatures coaching staff should also be aware of the potential changes to athlete's performance, particularly the decreased number of winners and net approaches, reduced serve speed and an increase in the number of double faults.

References

1. Armstrong LE, Casa DJ, Millard-Stafford M, Moran DS, Pyne SW, Roberts WO. American College of Sports Medicine position stand. Exertional heat illness during training and competition. *Medicine and Science in Sports and Exercise.* 2007; 39(3):556-572.
2. womens Ws. 2016 WTA Official Rule Book. United States of America WTA Tour, Inc.; 2016.
3. Tippet ML, Stofan JR, Lacambra M, Horswill CA. Core temperature and sweat responses in professional women's tennis players during tournament play in the heat. *Journal of Athletic Training.* 2011; 46(1):55.
4. Sell K, Hainline B, Yorio M, Kovacs M. Illness data from the US Open tennis championships from 1994 to 2009. *Clinical Journal of Sport Medicine.* 2013; 23(1):25-32.
5. O'Donoghue P, Ingram B. A notational analysis of elite tennis strategy. *Journal of sports sciences.* 2001; 19(2):107-115.
6. Cheuvront SN, Haymes EM. Thermoregulation and marathon running. *Sports Medicine.* 2001; 31(10):743-762.
7. Schmit C, Hausswirth C, Le Meur Y, Duffield R. Cognitive Functioning and Heat Strain: Performance Responses and Protective Strategies. *Sports Medicine.* 2016:1-14.
8. Périard JD, Racinais S, Knez WL, Herrera CP, Christian RJ, Girard O. Thermal, physiological and perceptual strain mediate alterations in match-play tennis under heat stress. *British Journal of Sports Medicine.* 2014; 48(Suppl 1):i32-i38.
9. Morante SM, Brotherhood JR. Autonomic and behavioural thermoregulation in tennis. *British Journal of Sports Medicine.* 2008; 42(8):679-685.

10. Morante SM, Brotherhood JR. Thermoregulatory responses during competitive singles tennis. *British Journal of Sports Medicine.* 2008; 42(9):736-741.
11. Girard O, Christian RJ, Racinais S, Périard JD. Heat stress does not exacerbate tennis-induced alterations in physical performance. *British Journal of Sports Medicine.* 2014; 48(Suppl 1):i39-i44.
12. Hizan H, Whipp P, Reid M. Comparison of serve and serve return statistics of high performance male and female tennis players from different age-groups. *International Journal of Performance Analysis in Sport.* 2011; 11(2):365-375.
13. Australaian A. Thermal Comfort observations. http://www.bom.gov.au/info/thermal_stress/07/01/2017.
14. ACSM Position Statment; Prevention of Thermal Injuries During Distance Running. *The Physician and Sportsmedicine.* 1984; 12(7):43-51.
15. Steeneveld G, Koopmans S, Heusinkveld B, Van Hove L, Holtslag A. Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *Journal of Geophysical Research: Atmospheres.* 2011; 116(D20).
16. Hancock PA, Ross JM, Szalma JL. A meta-analysis of performance response under thermal stressors. *Human Factors: The Journal of the Human Factors and Ergonomics Society.* 2007; 49(5):851-877.
17. American A. Prevention of Thermal Injuries During Distance Running. Position Stand. American College of Sports Medicine. *Med J Aust.* 1984; 141(12):876-879.
18. Budd GM. Wet-bulb globe temperature (WBGT)—its history and its limitations. *Journal of Science and Medicine in Sport.* 2008; 11(1):20-32.
19. Australian A. Australian Open Facts. http://www.ausopen.com/13/08/2014.

20. Kovalchik SA. Searching for the GOAT of tennis win prediction. *Journal of Quantitative Analysis in Sports.* 2016; 12(3):127–138.

21. Tippet ML, Stofan JR, Lacambra M, Horswill CA. Core temperature and sweat responses in professional women's tennis players during tournament play in the heat. *Journal of athletic training.* 2011; 46(1):55-60.

22. International I. ITF Rules Of Tennis. http://www.itftennis.com/media/220771/220771.pdf: ITF LTD; 2016.

23. Hizan H, Whipp P, Reid M. Gender differences in the spatial distributions of the tennis serve. *International Journal of Sports Science & Coaching.* 2015; 10(1):87-96.

24. Sunderland C, Nevill ME. High-intensity intermittent running and field hockey skill performance in the heat. *Journal of Sports Sciences.* 2005; 23(5):531-540.

25. Hornery DJ, Farrow D, Mujika I, Young W. Fatigue in tennis. *Sports Medicine.* 2007; 37(3):199-212.

26. Reid M, Duffield R. The development of fatigue during match-play tennis. *British Journal of Sports Medicine.* 2014; 48(Suppl 1):i7-i11.

27. Morris JG, Nevill ME, Williams C. Physiological and metabolic responses of female games and endurance athletes to prolonged, intermittent, high-intensity running at 30 and 16 C ambient temperatures. *European journal of applied physiology.* 2000; 81(1):84-92.

28. Nassis GP, Brito J, Dvorak J, Chalabi H, Racinais S. The association of environmental heat stress with performance: analysis of the 2014 FIFA World Cup Brazil. *British Journal of Sports Medicine.* 2015; 49(9):609-613.

29. Aughey RJ, Goodman CA, McKenna MJ. Greater chance of high core temperatures with modified pacing strategy during team sport in the heat. *Journal of Science and Medicine in Sport.* 2014; 17(1):113-118.

30. Keatisuwan W, Ohnaka T, Tochihara Y. Physiological responses of men and women during exercise in hot environments with equivalent WBGT. *Applied Human Science.* 2001; 15(6):249-258.