Post-exercise management of exertional hyperthermia in dogs participating in dog sport (canicross) events in the UK

Carter, Anne J.; Hall, Emily J.; Bradbury, Jude; Beard, Sian; Gilbert, Sophie; Barfield, Dominic; O'Neill, Dan G.

Published in:
Journal of Thermal Biology

DOI:
10.1016/j.jtherbio.2024.103827

Print publication: 01/04/2024

Document Version
Publisher's PDF, also known as Version of record

Journal of Thermal Biology 121 (2024) 103827

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Post-exercise management of exertional hyperthermia in dogs participating in dog sport (canicross) events in the UK

Anne J. Carter [a,*], Emily J. Hall [b], Jude Bradbury [b], Sian Beard [c], Sophie Gilbert [d], Dominic Barfield [b], Dan G. O'Neill [c]

[a] Veterinary and Animal Sciences, Barony Campus, Scotland's Rural College, Parkgate, Dumfries, DG1 3NE, UK
[b] Department of Clinical Science and Services, The Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Herts, AL9 7TA, UK
[c] Pathobiology and Population Sciences, The Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Herts, AL9 7TA, UK
[d] Vets Now, Penguin House, Castle Riggs, Dunfermline, KY11 8SG, UK

A R T I C L E I N F O

Keywords:
Canine hyperthermia
Canine heat-related illness
Active cooling
Cold-water immersion
Evaporative cooling
Cooling dogs
Hot dogs
VetCompass

A B S T R A C T

Exercise is a common trigger of heat-related illness (HRI) events in dogs, accounting for 74% of canine HRI cases treated under primary veterinary care in the United Kingdom. However, few empirical studies have evaluated the effectiveness of differing cooling methods for dogs with exertional hyperthermia or HRI. This study aimed to prospectively evaluate effects of ambient conditions and post-exercise management practices (cooling methods and vehicular confinement) on the post-exercise temperature change of dogs participating in UK canicross events. Canine temperature was recorded at three intervals post-exercise: as close as possible to 0- (immediately post-exercise), 5-, and 15-min post-exercise. Ambient conditions and post-exercise management were recorded for 115 cooling profiles from 52 dogs. In 28/115 (24.4%) profiles, the dog's temperature increased during the first 5-min post-exercise. Overall, 68/115 (59.1%) profiles included passive cooling (stood or walked outside), 35 (30.4%) active cooling (cold-water immersion or application of a cooling coat), and 12 (10.4%) involved no cooling and were immediately housed in vehicles. No dogs developed hypothermia during the study and no adverse effects were observed from any cooling method. In hyperthermic dogs, overall post-exercise body temperature change was significantly negatively associated (i.e. the dogs cooled more) with 0-min post-exercise body temperature ($\beta = -0.93$, $p < 0.001$), and not being housed in a vehicle ($\beta = -0.43$, $p = 0.013$). This study provides evidence cold-water immersion (in water at 0.1–15.0 °C) can be used to effectively and safely cool dogs with exertional hyperthermia. Progressive temperature increases in many dogs - even after exercise has terminated - supports the message to "cool first, transport second" when managing dogs with HRI. When transporting dogs post-exercise or with HRI even after active cooling, care should be taken to cool the vehicle before entry and promote air movement around the dog during transport to facilitate ongoing cooling and prevent worsening of hyperthermia during travel.

1. Introduction

Regular exercise is important for supporting physical and behavioural health of domestic dogs, with habitual physical activity often used as an indicator of good quality of life in both humans (Aoyagi and Shephard, 2010) and dogs (Aromaa et al., 2023). However, as global temperatures continue to rise and heat wave events become more severe and frequent (Ebi et al., 2020; Fischer et al., 2021), inappropriate exercising also brings new health risks. Exercise is a common trigger of heat-related illness (HRI) events in companion (Bruchim et al., 2006; Drobatz and Macintire, 1996) and working dogs (Lagutchik et al., 2018; Miller et al., 2018; Stojsih et al., 2014), accounting for 74% of canine HRI cases treated under primary veterinary care in the United Kingdom (UK) (Hall et al., 2020a, 2022b). The majority of canine exertional HRI events in the UK occur following dog walking (Hall et al., 2020a) - a relatively low intensity activity – with a median ambient temperature of 16.5 °C (Hall et al., 2022a). Dog owners who provide higher intensity exercise for their dogs are generally more aware of the risks associated with HRI and potential strategies to reduce its occurrence (Hall et al., 2021b). For this reason, canine sports such as canicross (cross-country

* Corresponding author.
E-mail addresses: heatstroke.dog@gmail.com, anne.carter@sruc.ac.uk (A.J. Carter).

https://doi.org/10.1016/j.jtherbio.2024.103827
Received 10 November 2023; Received in revised form 27 February 2024; Accepted 27 February 2024
Available online 11 March 2024
0306-4565/

running with a dog in harness) largely occur in the cooler autumn and winter months in the UK (Carter and Hall, 2018). However, given HRI is a potentially fatal disorder and predicted to affect increasing numbers of people and animals as global temperatures continue to rise (Hajat et al., 2014; Protopopova et al., 2021), development of more effective mitigation strategies is an urgent priority.

Exertional hyperthermia is defined as body temperature elevation beyond the normal temperature reference range resulting from an imbalance between muscular heat production and heat loss during exercise (Miller, 2015). Without successful intervention, exertional hyperthermia can lead to exertional HRI, where the elevated body temperature progressively leads to physiological dysfunction (including hypoxia, circulatory failure, increased metabolic demand and haemostatic abnormalities) and cell death, then organ damage, neurological dysfunction and, ultimately death (Bouchama and Knochel, 2002; Bruchim et al., 2017; Miller, 2015). Exertional HRI has been studied extensively in both humans and horses (Armstrong et al., 2007; Brownlow et al., 2016; Duncan, 1903; Lucke and Hall, 1980; Shapiro and Seidman, 1990), originally due to the impact the condition had on military personnel (Duncan, 1903) and more recently due to the high visibility and potentially fatal consequences of the condition in human and equine athletes competing at televised events such as the Olympics (Casa, 2018; Marlin et al., 1998; Tanaka et al., 2023). The effectiveness of various cooling methods in humans affected by exertional HRI has been explored (Casa et al., 2007; Demartini et al., 2015; Hadad et al., 2004; Kielblock et al., 1986; Klous et al., 2022; Shapiro and Seidman, 1990), with cold-water immersion in temperatures between 1.7 and 15.0 °C recommended as 'best practice' for cooling human athletes with HRI (Binkley et al., 2002; Casa et al., 2007). Direct body application of cold-water (either water sprays or from buckets) is the most effective reported method of cooling equine athletes with exertional hyperthermia (Marlin et al., 1998; Takahashi et al., 2020). Water-based cooling methods are explicitly described and recommended in the Fédération Équestre Internationale's guidance for equestrian events taking place in high ambient temperatures (Marlin et al., 2018).

There are limited empirical studies evaluating the effectiveness of cooling methods for dogs with HRI (Davis et al., 2019; Hall et al., 2023; Hanel et al., 2016; Parnes et al., 2023). First aid cooling methods proposed for dogs with HRI range from cold-water immersion to application of wet towels on the body (S. Flournoy et al., 2003; Hemmelgarn and Gannon, 2013a; Johnson et al., 2006). One early study measured cooling rates of dogs with experimentally induced HRI immersed in water of various temperatures, reporting that water at 15.0–16.0 °C and 1.0–3.0 °C resulted in the fastest cooling rate for conscious dogs and unconscious dogs respectively (Magazanik et al., 1980). However, immersion in water at 30.0 °C (replicating working conditions in desert climates) still cooled dogs with exertional hyperthermia faster than placing the dogs on a cooling mat alongside air movement from a fan (Davis et al., 2019), and 30 s of immersion in 22.2 °C water has been demonstrated to cool working dogs faster than application of isopropyl alcohol to the footpads (Parnes et al., 2023). Despite this information on the value of active cooling to prevent clinical deterioration in hyperthermic dogs, a review of cooling methods used in UK veterinary practice revealed just over half the HRI events presented during 2016–2018 had evidence of receiving cooling in the patient's clinical record (Hall et al., 2023). However that study showed the use of wet towels was the most commonly used method of cooling dogs (Hall et al., 2023), despite evidence (in humans and horses) to suggest this is less effective than evaporative cooling methods (Bouchama et al., 2007; Foreman et al., 2006). Whilst there is limited evidence relating to the cooling methods used on dogs following high intensity exercise (such as during competitive canine sports), greater understanding of the rate of body temperature change post exercise is key to interpreting the effect of different canine management actions and evaluating the effectiveness of cooling methods (Gogolski et al., 2020; Hall et al., 2023; Parnes et al., 2023).

The recommendation of the American College of Veterinary Emergency and Critical Care's Veterinary Committee on Trauma (Vet-COT) is that dog owners "cool first, transport second" to optimise clinical management of dogs with HRI (Hanel et al., 2016). The cooling methods recommended by Vet-COT are cold-water immersion for young healthy dogs, and evaporative cooling (application of water alongside air movement) for elderly or unwell dogs (Fig. 1A–C) (Hanel et al., 2016). However, these recommendations were based on best available evidence, which at the time of publication (2016) was limited to human and equine cooling studies. As dogs are often transported to a location away from home for outdoor exercise, they are likely to be returned into the vehicle in the immediate post-exercise period and may enter the vehicle with an elevated body temperature. The interiors of cars left static with little or no airflow are likely to become much warmer than the external ambient temperature, especially if parked with full sun exposure (Carter et al., 2020; Grundstein et al., 2009; McLaren, 2005). Evaluation of the effects of different cooling methods, vehicular confinement, and environmental conditions on canine post-exercise body temperature profiles is therefore needed to validate the Vet-COT recommendations, and to ensure the current advice to dog owners on managing canine HRI is safe and effective.

With this wider background, the present study aimed to prospectively evaluate the effects of ambient conditions and post-exercise management practices (cooling methods and vehicular confinement) used for dogs at canicross events in the UK dogs on post-exercise temperature change.

2. Materials and methods

Ethical approval: This prospective observational cohort study was approved by the School of Animal, Rural and Environmental Sciences Ethical Review Group of Nottingham Trent University (reference number ARE634).

2.1. Canine participants

Dogs were recruited opportunistically from sports dogs attending training and racing events with Canicross Midlands (https://www.canicrossmidlands.co.uk/) and Crysalis K9. Informed owner consent was gained prior to participation in the study, and only dogs tolerant of the ear thermometer were included. Canicross is a canine sport that involves human and canine athletes competing together on cross-country routes over distances around 3–5 km (Carter and Hall, 2018; Erjavec et al., 2022). Data were collected at 12 canicross events during 2017–2018 at venues in the East and West Midlands, UK. From previous research using the same population of canicross dogs, a 2.0 °C body temperature reduction had been observed within a 20-min post-exercise period for dogs immersed in water after the race (Carter and Hall, 2018). A study of military working dogs reported a 0.7 °C temperature reduction within 15-min post-exercise in dogs rested in a kennel at approximately 30 °C ambient temperature (Benito et al., 2022). Sample size estimation using Epitools (Ausvet, 2023) calculated a sample size of 50 dogs with 25 in each cooling method group was needed to detect a mean temperature reduction of 1.5 °C in one cooling method group, and a mean temperature reduction of 0.7 °C in another cooling method group, with an assumed variance of 1.0 °C, 95% confidence level, and 80% power.

Between 4 and 20 dogs were recruited at each event, providing overall data for 115 cooling events from 52 unique dogs (31 male, 21 female) including 24 breed types of which Springer Spaniels (n = 8, 14.8%), Pointers (n = 8, 14.8%), Labrador Retrievers (n = 5, 9.3%) and crossbreeds (n = 3, 5.6%) were the most numerous. It was not possible to weigh the dogs at the events, so canine bodyweight was estimated based on the breed/sex mean for UK pet dogs calculated using dogs under primary veterinary care in the VetCompass database during 2016 (Hall et al., 2020b). For analysis, bodyweight was grouped into four categories: <10 kg, 10-<20 kg, 20-<30 kg and 30 kg or over. Eight breed types (16 dogs, 30.8%) were identified as having a double coat (The

Fig. 1. A, (left) Cold-water immersion of a dog in an existing body of water. B, (middle) cold-water immersion of a dog in a temporary body of water (paddling pool). C, (right) evaporative cooling of a dog in the shade using a hose to apply tap-water temperature water alongside air movement from a fan. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Kennel Club, 2023).

2.2. Canine body temperature

Following completion of the canicross race or training event, tympanic membrane temperature (TMT) was recorded for each recruited dog at three intervals post-exercise to generate a post-exercise cooling profile. These three temperatures were measured, as close as possible to 0- (immediately post-exercise), 5-, and 15-min post-exercise. Either the left or right ears were opportunistically selected depending on the positioning of the dog following light restraint by the owner. A Vet-Temp VT-150 Instant Ear Thermometer (Advanced Monitors Corporation, California, USA) covered by a single use Vet-Temp DPC-500 probe cover was used to measure TMT. The Vet-Temp thermometer measures temperatures between 32.2 and 43.3 °C, with a stated accuracy of ±0.2 °C. The thermometer was used as per the manufacturer's instructions with no lubrication and with the reading taken following the audible alarm. If a reading reported an error code, the probe cover was changed, and the process repeated. If an error code occurred a second time, the reading was discounted. All TMT measurements were performed by a veterinary surgeon familiar with the thermometer device (Author 2).

2.3. Ambient conditions

Ambient conditions were recorded as wet bulb globe temperature (WBGT °C) at approximately 30-min intervals until all cooling profile measurements at the event had been recorded. Measurements were taken using a Kestrel 5400 WBGT heat stress tracker (Kestrel, Boothwyn, PA). Temperature of water used for immersion (lakes, ponds, and water troughs) was measured using a water-resistant digital thermometer (Brannan, Cumbria, UK). Whilst other studies have used heat index (a measure that combines ambient temperature and relative humidity) to monitor ambient conditions when studying canine body temperature or HRI (Azeez et al., 2022; Bruchim et al., 2006; Moon et al., 2021), Gogolski et al. (2020) explored the relationship between both heat index and WBGT, and canine body temperature during exercise. Gogolski et al. (2020) used heat index as a measure of shade conditions and WBGT as a measure of non-shade conditions, and reported neither were predictors of working dogs' temperatures during exercise. As the present study was conducted in locations with minimal shade or shelter, and a primary aim was to evaluate the effect of ambient conditions on canine cooling, WBGT was selected as the measure of ambient conditions, to incorporate both solar radiation and air movement alongside air temperature and relative humidity.

2.4. Evaluation of cooling methods used

Owners managed their dogs as per their own standard practice with no intervention from the study team, thus no attempt at randomisation was made. No attempt was made to blind observers or dog owners to canine temperature as canine safety was considered more important therefore owners were informed of the dog's temperature at each measurement event. Post-exercise management of the dogs was observed and recorded, including cooling actions taken immediately post-exercise (e.g., immersion in water, walked outside to ensure air movement, stood outside to rest), and whether and when the dog was housed in a vehicle following initial management (dogs housed in vehicles remained under owner supervision). Observation of post-exercise management was performed by one of the authors (Author 1 or 2), who remained at the sites for several hours after each event to monitor dogs for signs of HRI as part of the study risk assessment. Dogs were monitored for any signs indicative of heat-related illness, from mild (heat stress resulting in excessive panting – the dog's tongue appearing scooped or elongated alongside squinting eyes – and/or lethargy/disengagement) to moderate/severe (vomiting or diarrhoea, collapse, seizures, or central nervous dysfunction) (Bruchim et al., 2017; Hall et al., 2021a; Parnes et al., 2023). Water for immersion was available at all events. However, due to the remote locations of the events, there was no immediate access to running water that could be used for water spraying. It was not possible to monitor the dogs' fluid intake although drinking water was available to the dogs at the finish line and was also provided by owners throughout the event. All events took place outdoors, where the exercise finish point was always open to the elements and gave limited shelter from any wind. Where cooling coats were used by owners, these were soaked prior to application using the available water as per manufacturer guidelines.

2.5. Analysis of post-exercise cooling

Data were analysed using Microsoft Excel (v16, Redmond, WA, USA) and SPSS v29 (IMB Inc., Armonk, NY, USA). Body temperature and temperature change had a parametric distribution when assessed with the Kolmogorov–Smirnov test. Temperatures at each measurement point (0, 5, and 15 min post-exercise) and the temperature change from 0 to 5 min and 0–15 min post-exercise were summarized as the mean, standard deviation (SD) and range. ANOVA and post-hoc Bonferroni tests were used to identify differences in 0-min TMT between the post-exercise management groups. The number of dogs with a positive temperature change (indicating an increase in body temperature during the post-exercise period) was recorded at 5 min and 15 min post exercise. The number of dogs with hyperthermia at each of the three TMT measurement points was noted; hyperthermia was defined as TMT >38.8 °C, as the normal TMT range for healthy dogs is currently defined at 36.6–38.8 °C (Hall and Carter, 2017). Wet bulb globe temperature had a non-parametric distribution when assessed with the Kolmogorov–Smirnov test and was summarized as median and interquartile range (IQR). A Mann-Whitney U test was used to compare the distribution of WBGT between dogs housed in cars and not housed in cars at any time during the observation period. Statistical significance was set at the 5% level.

General linear mixed models were used to evaluate the effect of ambient temperature (WBGT), canine characteristics (sex, double coat, estimated bodyweight category), post-exercise management, being housed in a vehicle, and immediate post-exercise TMT on temperature change from 0- to 5-min post-exercise, and 0- to 15-min post-exercise in all dogs. Additional models were run that included only dogs with hyperthermia at the 0-min post-exercise measurement point. Hyperthermic dogs were analysed separately because they could be considered physiologically different to normothermic dogs, as hyperthermic dogs would be employing thermoregulation mechanisms such as panting and postural changes (Hemmelgarn and Gannon, 2013b). Dog and canicross event were included as random effects to account for repeated measures from 28 dogs. All variables and relevant biological interactions were initially included in the model. Backward stepwise regression was performed (initially sequentially removing variables with a *p*-value >0.2) until variable removal resulted in a reduction of the Akaike's Information Criterion (AIC) by < 3, at which point variables were retained. Variables were considered significantly associated with canine post-exercise cooling if the 95% confidence intervals (CI) of the β coefficient did not span zero.

3. Results

A total of 115 TMT cooling profiles were recorded from the 52 dogs in the study. The mean 0-min post-exercise canine TMT for the 115 cooling profiles was 39.5 °C (SD = 1.0 °C, range = 37.0–42.2 °C). Twenty-nine (25.2%) of the dogs' TMT measurements were normothermic at the 0-min post-exercise measurement, of which five dogs went on to develop hyperthermia during the post-exercise period. Overall, 28/115 (24.4%) TMTs increased and 19/28 (67.9%) developed hyperthermia from the 0- to 5-min measurement, with 10/115 (8.7%) remaining elevated above the 0-min measurement and 3/10 (33.3%) hyperthermic by 15-min post-exercise.

As part of the study risk assessment, the dogs were also monitored beyond the data collection period for signs of HRI. Throughout the data collection period, no dogs displayed any signs indicative of moderate to severe HRI (e.g., vomiting or diarrhoea, collapse, seizures, or central nervous dysfunction) (Hall et al., 2021a). Most dogs were panting post-exercise, some excessively during the initial cooling period, and some dogs were also reluctant to stand during immersion in water (see Fig. 1B). Therefore, some dogs were likely experiencing mild heat stress in the immediate post-exercise period (Hall et al., 2021a), however all dogs were fully recovered before travelling home. As an additional observation, none of the dogs immersed in water experienced any adverse effects during the study, and none of the monitored dogs developed hypothermia.

3.1. Canicross event conditions and observation of cooling methods

The mean ambient conditions (measured as WBGT) at the canine sports events was 8.5 °C (SD = 5.4 °C, range = 0.4–24.6 °C). The mean water temperature for immersion was 6.2 °C (SD = 5.1 °C, range = 0.1–15.0 °C). Observed immediate post-exercise management actions ranged from immediate active cooling (cold-water immersion in any available water, application of an evaporative cooling coat – see Fig. 2) coupled with exposing the dog to outside air movement, to passive cooling (allowing the dog to stand or lie down outside, walking the dog outside) whilst exposing the dog to outside air movement, and no cooling (immediately housing the dog in a vehicle). Immersion in water was frequently initiated by the dogs themselves, with no prompting by their owner (Fig. 1B).

3.2. Analysis of canine cooling post-exercise

From the 115 cooling profile observations, 30 (26.1%) were cooled using water immersion, five (4.4%) were cooled with an evaporative cooling coat, 42 (36.5%) were walked outside, 26 (22.6%) were stood outside, and 12 (10.4%) received no cooling and were immediately housed in a vehicle. Thirty-six of the cooled dogs were housed in a vehicle following cooling. Fig. 3 illustrates the 0-min post-exercise body temperatures of the dogs in each post-exercise management category. The 0-min post-exercise body temperature differed statistically significantly between the different post-exercise management categories ($F = 3.72$, $p = 0.007$); Bonferroni corrected post-hoc tests revealed dogs managed using water immersion were significant hotter at 0-min than dogs stood outside (mean difference = 0.8 °C, $p = 0.012$) and walked outside (mean difference = 0.7 °C, $p = 0.025$). Table 1 presents the variation in ambient temperature (WBGT) when each post-exercise management action was observed. The distribution of WBGT was significantly higher when dogs were not housed in vehicles, compared to when dogs were housed in vehicles at any time during their post-exercise management ($Z = -5.64$, $p < 0.001$).

Fig. 2. An evaporative cooling coat applied to a dog post-exercise.

By 5-min post-exercise, the mean canine temperature was 39.0 °C (SD = 0.7 °C, range 37.0–40.5 °C), at this point 67 (58.3%) dogs were hyperthermic, no dogs were hypothermic. The mean temperature change from 0- to 5-min was −0.5 °C (SD = 0.8 °C, range −2.4 to 1.8 °C). By 15-min post-exercise, the mean canine temperature was 38.3 °C (SD = 0.7 °C, range 36.6–39.8 °C), and 21 (18.3%) dogs were still hyperthermic, no dogs were hypothermic. The mean temperature change from 0- to 15-min post-exercise was −1.2 °C (SD = 1.1 °C, range = −5.1 to 1.0 °C). Fig. 4 illustrates the 0- to 5-min and 0- to 15-min post-exercise body temperature change of the dogs in each post-exercise management category (descriptive statistics are presented in Appendix A2). Fig. 5 illustrates the mean overall temperature change of the dogs by post-exercise management category from 0- to 15-min.

3.3. Evaluating factors influencing canine cooling in all dogs

The final linear mixed model selected for temperature change from 0- to 5-min included three variables (Table 2): being housed in a vehicle, 0-min TMT, and WBGT. The 0-min TMT and WBGT were both significantly associated with canine temperature change; the 0-min TMT was negatively associated (the dogs cooled more), the WBGT was positively associated (the dogs cooled less) with temperature change. The intra-class correlation for 'dog' was 0.05, and the conditional pseudo R^2 was 0.54.

The final linear mixed model selected for 0- to 15- minutes temperature change included three variables (Table 3): being housed in a vehicle, 0-min TMT, and WBGT. The 0-min TMT was significantly negatively associated with temperature change (the dogs cooled more). The intra-class correlation for 'dog' was 0.11, and the conditional pseudo R^2 was 0.67.

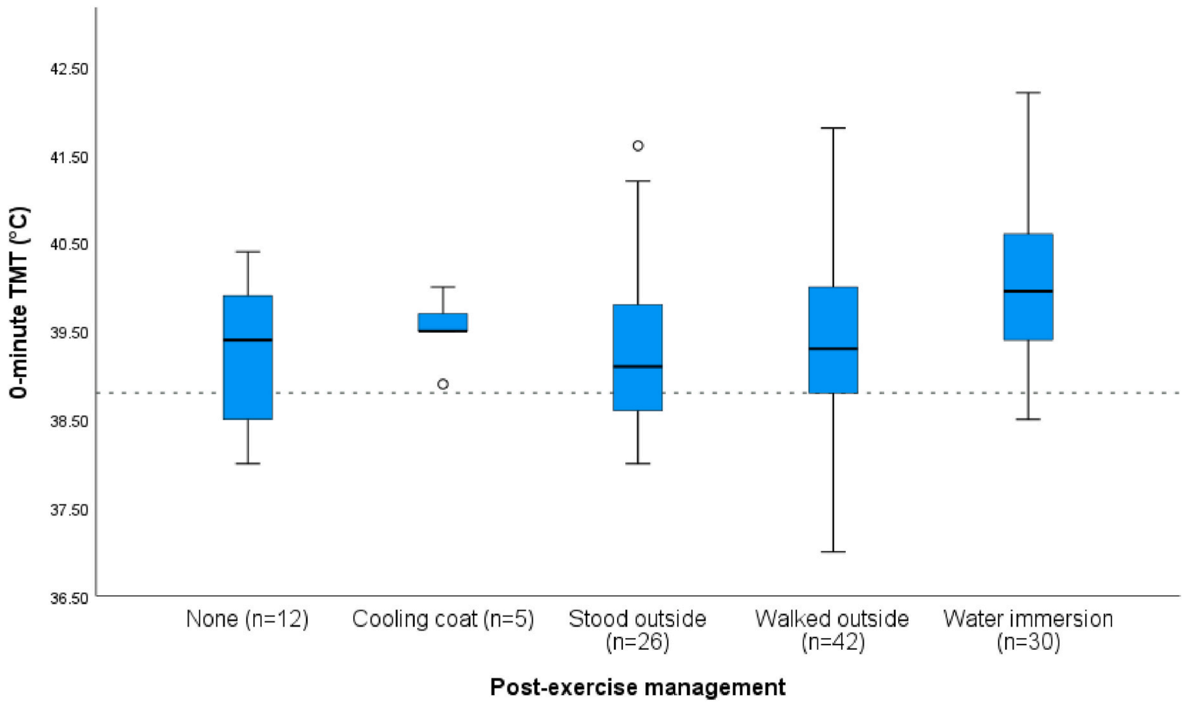

Fig. 3. Boxplot of 0-min post-exercise canine body temperature grouped by immediate post-exercise management action for UK dogs participating in canicross events (dashed line indicates upper limit of normal canine tympanic membrane temperature, 38.8 °C) (n = 115).

Table 1
Descriptive statistics (median and interquartile range [IQR]) of environmental conditions measured by wet bulb globe temperature (WGBT, °C) for each post-exercise management observed for dogs at canine sports events (n = 115).

Post-exercise management	Not housed in a vehicle		Housed in a vehicle	
	n	Median WGBT (IQR) (°C)	n	Median WGBT (IQR) (°C)
Stood outside	23	12.2 (10.4–12.3)	3	10.0
Cooling coat	5	10.4 (9.2–12.2)	0	
Walked outside	16	10.0 (9.3–10.4)	26	0.6 (−0.4-6.2)
Water immersion	23	9.0 (6.2–12.2)	7	9.04 (0.6–10.0)
No cooling	0		12	9.95 (2.0–10.0)

3.4. Exploring factors influencing post-exercise cooling in hyperthermic dogs

The final linear mixed model selected for temperature change from 0- to 5-min in hyperthermic dogs included three variables (Table 4): being housed in a vehicle, 0-min TMT, and WBGT. Not being housed in a vehicle and the 0-min TMT were both significantly negatively associated with temperature change (the dogs cooled more). The intra-class correlation for ‘dog’ was 0.00, and the conditional pseudo R^2 was 0.44.

The final linear mixed model selected for 0- to 15- minutes temperature change in hyperthermic dogs included three variables (Table 5): being housed in a vehicle, 0-min TMT, and WBGT. Not being housed in a vehicle and the 0-min TMT were significantly negatively associated with temperature change (the dogs cooled more). The intra-class correlation for ‘dog’ was 0.08, and the conditional pseudo R^2 was 0.60.

4. Discussion

This study reports the cooling methods used to manage a sample of 52 dogs competing in the canine sport canicross in the UK during 2017–2018, resulting in 115 cooling profile records. Overall, 24.4% of cooling profiles demonstrated a temperature increase during the initial 5-min post-exercise, with 8.7% remaining elevated by 15-min post-exercise. From the 115 observed cooling profiles, 68 (59.1%) were passively cooled (stood or walked outside), 35 (30.4%) were actively cooled (water immersion or application of a cooling coat), and 12 (10.4%) received no cooling but were immediately housed in vehicles. The passive cooling methods (standing or walking the dog outside) likely facilitated air movement to allow convective cooling from the dog’s surface alongside the dog’s thermoregulatory activity such as panting. The active cooling methods observed included immersion in cold-water (0.1–15.0 °C) and application of an evaporative cooling coat. None of the dogs developed hypothermia during the study period, despite 25.2% being normothermic at the 0-min post-exercise measurement point, and none of the dogs suffered any adverse effects from the post-exercise management actions.

Although ambient conditions (WGBT) were not significantly associated with canine temperature change at either 5- or 15- minutes post-exercise in hyperthermic dogs in the present study, WGBT was retained in the final linear mixed models as removal increased the model AIC. In the model including all dogs, WBGT significantly positively affected canine temperature change (dogs cooled less) between 0- and 5-min post-exercise. Temperature gradient between the dog and the surroundings is an important factor in facilitating heat exchange (Hemmelgarn and Gannon, 2013b; Lewis and Foster, 1976). Most of the canicross events attended during the study took place during the autumn to winter season. Therefore, dogs standing or walking outside were exposed to ambient weather conditions of WBGT typically below 10 °C with constant air movement due to wind. Dogs housed immediately in vehicles post-exercise would have been exposed to internal vehicle air temperatures that facilitated further cooling, as the events were held early in the morning when internal vehicle temperatures rarely exceed 25 °C in the UK and solar radiation is limited (Carter et al., 2020). Zero-minutes post-exercise TMT was significantly associated with canine cooling in all models; therefore, it is highly probable the rate of canine cooling would be reduced in warmer ambient temperatures.

The results of the linear mixed models in the current study also suggest housing hyperthermic dogs in a vehicle post exercise reduces the rate of canine cooling. Dogs not housed in a vehicle cooled significantly more with a greater effect on overall cooling ($\beta = -0.35$) compared to

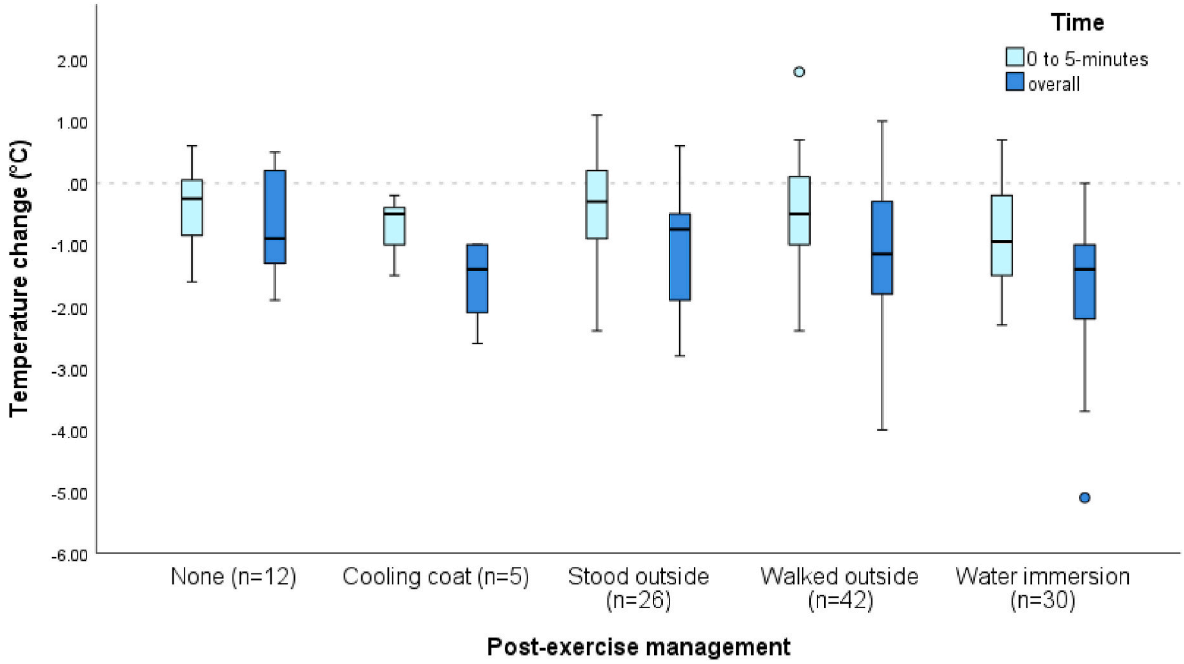

Fig. 4. Boxplot of canine body temperature change from 0- to 5-min and 0- to 15-min post-exercise, grouped by immediate post-exercise management action (dashed line indicates no temperature change) (n = 115).

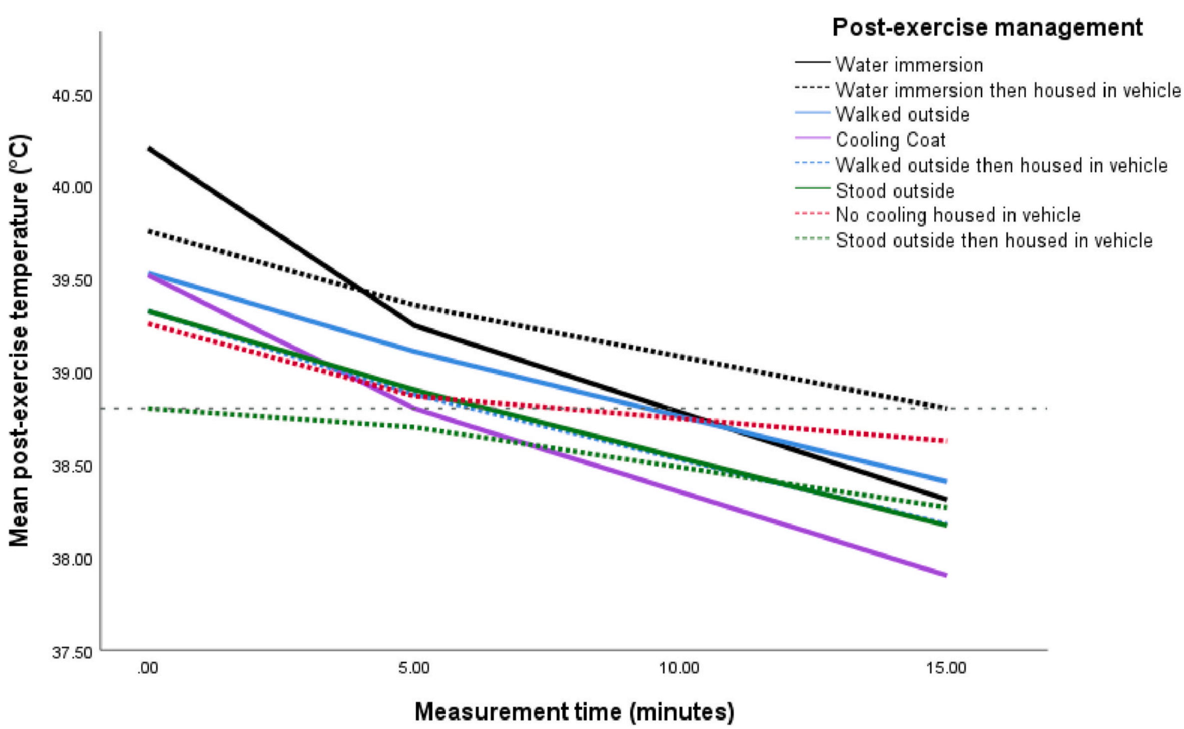

Fig. 5. Mean canine body temperature (°C) for each post-exercise management type by post-exercise measurement point (minutes) for UK dogs participating in canicross (n = 115). Dotted lines indicate the dogs were housed in a vehicle after initial cooling action (if any). The horizontal dashed line indicates the upper limit of normal canine tympanic membrane temperature, 38.8 °C.

cooling during the first 5-min ($\beta = -0.27$). Ambient temperatures inside vehicles may be higher than the external temperature, and along with likely reduced air movement inside the vehicle compared to outside, may reduce the effectiveness of evaporative heat loss from panting or any residual moisture on the coat. Additionally, internal vehicle temperatures would be higher in summer months (Carter et al., 2020), therefore the slower rate of cooling experienced by dogs housed in a vehicle would likely be more pronounced. Reduced effectiveness of cooling methods when followed by vehicular confinement should be considered when providing advice to canine guardians managing dogs with exertional HRI. Dog owners should be warned that when using vehicles to house or transport dogs post-exercise, any pre-transport cooling interventions will be less effective if the dog is then housed in a vehicle with limited air movement.

Table 2
Linear mixed model results for the outcome temperature change from 0- to 5-min in UK dogs post-exercise at canicross events, with dog and event as random effects (n = 115).

Variable	β coefficient	95% confidence interval	p-value
Intercept	22.17	17.93 to 26.41	<0.001
Housed in a vehicle	Comparator		
Not housed in a vehicle	−0.16	−0.41 to 0.09	0.216
0-min dog temperature	−0.58	−0.69 to −0.47	<0.001
Ambient temperature	0.03	0.00 to 0.06	0.043

Table 3
Linear mixed model results for the outcome temperature change from 0- to 15-min in UK dogs post-exercise at canicross events, with dog and event as random effects (n = 115).

Variable	β coefficient	95% confidence interval	p-value
Intercept	32.94	27.84 to 38.03	<0.001
Housed in a vehicle	Comparator		
Not housed in a vehicle	−0.27	−0.57 to 0.03	0.080
0-min dog temperature	−0.86	−0.99 to −0.73	<0.001
Ambient temperature	0.02	−0.01 to 0.05	0.246

Table 4
Linear mixed model results for the outcome temperature change from 0- to 5-min in hyperthermic UK dogs post-exercise at canicross events, with dog and event as random effects (n = 86).

Variable	β coefficient	95% confidence interval	p-value
Intercept	23.37	17.27 to 29.48	<0.001
Housed in a vehicle	Comparator		
Not housed in a vehicle	−0.35	−0.63 to −0.07	0.016
0-min dog temperature	−0.60	−0.76 to −0.45	<0.001
Ambient temperature	0.03	−0.01 to 0.06	0.109

Table 5
Linear mixed model results for the outcome 0- to 15- minutes temperature change from 0- to 15-min in hyperthermic UK dogs post-exercise at canicross events, with dog and event as random effects (n = 86).

Variable	β coefficient	95% confidence interval	p-value
Intercept	35.53	28.13 to 42.93	<0.001
Housed in a vehicle	Comparator		
Not housed in a vehicle	−0.43	−0.77 to −0.09	0.013
0-min dog temperature	−0.93	−1.11 to −0.74	<0.001
Ambient temperature	0.03	−0.01 to 0.07	0.144

Mirroring results reported in studies of working dogs and racing Greyhounds (Baker et al., 2020; Davis et al., 2019; O'Brien et al., 2017; Pellegrino et al., 2018; Rovira et al., 2008), 24.4% of the canine cooling profiles in the current study included peak temperatures recorded after cessation of exercise. The dog's temperature continues to rise as heat within the muscles is gradually redistributed via blood flow, thus the tympanic or rectal membrane temperature elevation lags behind (Kruk et al., 1985). This further supports the imperative for broad acceptance of, and clear messaging to "cool first, transport second" when managing dogs with exertional HRI. Some dogs in both studies (Davis et al. (2019) and the present study) demonstrated continued temperature elevation despite the application of cooling methods, suggesting the duration or extent of temperature elevation would have been greater without application of active cooling. A reduction in a dog's cardiovascular function, for example severe hypovolemia or distributive shock due to severe HRI (Bruchim et al., 2017), could further delay redistribution of heat from the muscles, prolonging the duration of core (blood) temperature elevation without adequate cooling. This highlights the importance of educating canine guardians to recognise the signs of mild HRI (Hall et al., 2021a) so exercise can be stopped as quickly as possible to limit further elevations in body temperature and potential progression to moderate or severe HRI (Parnes et al., 2023).

Despite some dogs being immediately housed in vehicles upon completion of the exercise, only three dogs (from all 115 cooling profiles) had temperatures >39.5 °C by the 15-min post-exercise temperature measurement, and no dogs were showing signs of moderate or severe HRI up to the end of the end of observation period. Most veterinary texts recommend cooling is stopped once the dog's temperature drops below 39.5 °C (Boag and Marshall, 2020; Mazzaferro, 2017; Miller, 2015), although as noted in the human literature, the reasoning behind this recommendation is unclear (Bouchama et al., 2007; Gaudio and Grissom, 2016), and few dog owners typically have the means of measuring their animal's temperature in an emergency situation. Further research is needed to evaluate the accuracy of this recommended cut off for cooling, as no dogs developed hypothermia in the present study despite many dogs being normothermic at the point of cooling application. Drobatz and Macintire (1996) reported hypothermia at presentation was associated with non-survival in dogs presented for veterinary treatment of HRI, which may have supported the recommendation to cease cooling once the dog's body temperature drops below 39.5 °C. However, more recent studies have found no association between hypothermia and non-survival in dogs (Bruchim et al., 2006; Hall et al., 2021a), although evidence from human medicine suggest extreme hypothermia may be associated with adverse outcomes (Chen et al., 2023). Whilst no adverse effects of water immersion were observed and none of the physically active healthy dogs in the present study developed hypothermia, additional research is needed to fully evaluate the safety of cold-water immersion in dogs with underlying health conditions or advanced age. Therefore, the current VetCOT recommendations to use evaporative cooling to treat HRI in elderly or unwell dogs, and only use cold-water immersion for young healthy dogs should continue to be followed (Hanel et al., 2016).

Whilst cooling method used was not retained in the model for canine temperature change at either 5- or 15-min post-exercise in the present study, it is worth noting that although the dogs experienced hyperthermia, none were suffering from HRI. In addition, due to the colder and generally wet racing conditions of typical UK canicross events, dogs often finished with a wet coat; many race events included standing water on the course and some dogs rolled on wet/frosty ground upon completing their activity effectively wetting their coats. Except for dogs placed immediately into a vehicle, evaporative cooling was therefore likely occurring even when only passive cooling methods (such as walking or standing outside) were recorded due to exposure to air movement outside. In warmer conditions, dogs may have had less access to standing water on the course, which would have reduced opportunities for dogs to achieve evaporative cooling through self-application of water.

In a survey of dog owners, around a quarter reported using cooling aids such as cooling coats in the belief this would allow continuation of exercise in hot weather (particularly in brachycephalic breeds) and to aid cooling post-exercise (Hall et al., 2021b). There is limited evidence to support the effectiveness of cooling coats either to effectively keep a dog cool during activity in hot weather or as a useful method of active cooling post-exercise. Cooling coat application was the least common post-exercise management action observed in the present study, with only 4.4% of owners using this method. The only published study to evaluate the effect of cooling coats on canine body temperature investigated the impact of two types of cooling coat (a phase change cooling vest requiring freezing prior to use and evaporative cooling coats) that were applied during exercise (Benito et al., 2022). Benito et al. (2022) suggested the cooling coats were effective in aiding cooling, reporting a mean canine temperature difference of −0.6 °C (between dogs without a coat versus wearing cooling coats) immediately after 20 min of running. Therefore, the mean post-cooling temperature difference of −0.8 °C reported (between dogs left to rest with no active cooling versus dogs wearing an evaporative cooling coat) was likely influenced by the cooling effect during exercise rather than purely post-exercise cooling (Benito et al., 2022). In the present study, application of a cooling coat resulted in a similar overall mean temperature change to just walking the dog outside to facilitate evaporative cooling via air movement. Further evaluation of the effectiveness of cooling coats is therefore needed before they can be widely recommended.

The current study limited itself to quantitative analysis of the data collected on cooling methods used by dog owners engaged in canicross. It is important to note the members of Canicross Midlands have been actively involved in canine temperature research projects with the authors of this study since 2015, including attending annual seminars reporting current evidence relating to management and prevention of canine HRI. This prior interest/exposure to the research group may have influenced dog owners' decisions regarding cooling methods. Extension of this data collection and analysis to enable qualitative investigation could have extended the inference from the study to greater exploration of decision-making behind which cooling methods were selected. Participation in the study was voluntary which may have led to some selection bias, with particularly safety conscious owners perhaps more likely to take part.

In addition, as noted above, some of the cooling decisions were made by the dogs themselves independent of their owner. Although, Fig. 3 (0-min post-exercise body temperature distribution by cooling method) could indicate the dog's temperature played a role in the method selected by the owner and/or dog, especially for water immersion because most dogs cooled with this method were profoundly hyperthermic. It must be noted however, owners would not typically know their dog's temperature (although they may recognise signs of hyperthermia in their dog) during a training session or after a race, therefore the results of the present study may not truly reflect normal practice at canine sports events. It is also probable the current results are impacted by the Hawthorne effect (Gale, 2004), with some participating dog owners changing their behaviour simply as a result of being observed even without any additional information on TMT being considered, possibly as a form of social desirability bias. Additionally, Table 1 suggests the ambient conditions (WBGT) may have influenced participants' decisions to move dogs into vehicles following cooling, as the mean WBGT was lower when the dogs were housed in a vehicle when compared to dogs kept outside following cooling. As the present study was limited to relatively cool ambient conditions with a relatively small sample size, further study is warranted to evaluate the impact of higher ambient temperatures on canine cooling.

As this was a field-based observational study rather than a randomised controlled trial, it was not possible to directly compare the cooling effects of the various cooling methods used by dog owners, as the dogs' post-exercise temperatures and exercise intensity varied, as did the dogs' general husbandry and ambient weather conditions during the study. Therefore, it is not possible to make firm recommendations on which are the most effective cooling methods based on the results of this study alone. Recording of wet/dry coat during the post-exercise period would aid in understanding the effects of evaporative cooling where water had not specifically been poured over the dog, or the dog immersed in water post exercise. However, alongside evidence from human and equine sports medicine (Casa et al., 2007; Marlin et al., 1998; Takahashi et al., 2020), and a recent study in working dogs (Parnes et al., 2023) this present study provides some evidence supporting cold-water immersion (in water at 0.1–15.0 °C) as an effective method of cooling dogs with exertional HRI, albeit in healthy athletic dogs.

The current study included 52 dogs representing 24 breed types. All these dogs were in active training to compete in canicross races meaning they were likely highly active, physically fit, relatively young adult dogs with no known underlying health conditions that would impact their ability to compete. This sample of dogs is likely to be poorly representative of the wider UK dog population, as it did not include older dogs or brachycephalic dogs for example, and around half of all UK dogs are estimated to be overweight or obese (PFMA, 2019). Older dogs, obese dogs and brachycephalic dogs are all at greater risk of developing HRI (Bruchim et al., 2006, 2017; Drobatz and Macintire, 1996; Hall et al., 2020a, 2020b; Teichmann et al., 2014; Tripovich et al., 2023), and older dogs and brachycephalic dogs that develop HRI are at greater risk of a fatal outcome (Hall et al., 2022a). Whilst the sample size estimation suggested 54 dogs would be sufficient to detect a 0.8 °C difference in the mean temperature change between different cooling methods, this failed to account for repeated measures, owners being free to select the cooling method used (resulting in only 12 dogs in the control group – no cooling), variation in ambient conditions, and variation in canine post-exercise temperature. No attempt to blind observers or dog owners was made during this study, as ethically it was considered inappropriate to withhold canine temperature information from owners given the risk of HRI (Carter and Hall, 2018; Erjavec et al., 2022). Ideally, future work that applied a randomised controlled trial design would be used to compare the cooling rates of hyperthermic dogs exposed to different cooling methods, although ethical approval would still likely require real-time monitoring of core temperature to safeguard dogs developing dangerously elevated temperatures during the study period.

Several factors are reported to influence canine post-exercise temperature and cooling, including respiratory function (Davis et al., 2017; Lilja-Maula et al., 2017), hydration status (Baker et al., 1983; Otto et al., 2017; Zanghi et al., 2018), fitness (Baker and Davis, 2018; Ferasin and Marcora, 2009; Nazar et al., 1992) and heat acclimatisation (Bruchim et al., 2014). As it was not possible to measure these variables within the scope of the present study, the linear mixed models presented here should be considered as explanatory rather than predictive of post-exercise cooling (Waljee et al., 2014). In addition, the use of WBGT as a measure of the ambient conditions provides limited detail about the true environmental conditions (in comparison to individual measures of windspeed, temperature, humidity and solar radiation) (Budd, 2008). There are no environmental heat load measures specifically calibrated for use in relation to dogs (WBGT was designed for evaluating human heat stress) (Gogolski et al., 2020), therefore the decision to use WBGT was based on providing an environmental heat load measure that incorporated both radiant heat from sunlight, and air movement, which contributes to heat dissipation during evaporative cooling following water immersion (Flournoy et al., 2003).

5. Conclusions

This study provides evidence cold water immersion (in water at 0.1–15.0 °C) can be used to effectively cool healthy dogs with exertional hyperthermia. The results of this observational study of cooling methods used to manage hyperthermic dogs at canicross events further highlights the importance of the Vet-COT's message to "cool first, transport second" when managing dogs with HRI, because around a quarter of the dogs in this study continued to get hotter in the 5-min post-exercise and being housed in a vehicle significantly delayed and reduced canine cooling. When transporting dogs post-exercise, care should be taken to cool the vehicle before entry, and owners should ensure air movement around the dog to facilitate ongoing cooling and prevent worsening of hyperthermia.

Informed consent statement

Informed consent was obtained from the owners of all dogs that participated in this study.

Data availability statement

Supporting data is available via this link (https://doi.org/10.6084/m9.figshare.24347290).

Funding

No external funding supported this study.

CRediT authorship contribution statement

Anne J. Carter: Writing – original draft, Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emily J. Hall:** Writing – original draft, Writing – review & editing, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jude Bradbury:** Writing – original draft, Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Sian Beard:** Writing – review & editing, Visualization, Methodology, Investigation. **Sophie Gilbert:** Writing – review & editing, Investigation. **Dominic Barfield:** Writing – review & editing, Investigation. **Dan G. O'Neill:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: **Dan O'Neill** is a member of the "Dogs Die in Hot Cars" consortium. SB, SG and DB work for veterinary companies providing emergency veterinary care to dogs.

Acknowledgments

Thanks go to the canicross participants (both dogs and owners) who took part in the study and to Canicross Midlands and Chrysalis K9 for facilitating the temperature data collection.

Appendix A1

Table A1
Mean and standard deviation (SD) of the temperature difference from 0- to 5-min post-exercise for dogs under different post-exercise management actions (n = 115).

Post-exercise management	*n*	Mean temperature difference from 0- to 5-min post-exercise (SD) (°C)
Water immersion	30	−0.8 (0.8)
Cooling coat	5	−0.7 (0.5)
Walked outside	42	−0.4 (0.8)
Stood outside	26	−0.4 (0.8)
No cooling	12	−0.4 (0.7)

Table A2
Mean and standard deviation (SD) of the temperature difference from 0- to 15-min post-exercise for dogs under different post-exercise management actions (n = 115).

Post-exercise management	*n*	Mean temperature difference from 0- to 15-min post-exercise (SD) (°C)
Water immersion	23	−1.9 (1.2)
Cooling coat	5	−1.6 (0.7)
Stood outside	23	−1.2 (1.0)
Walked outside	16	−1.2 (1.3)
Walked outside then housed in vehicle	26	−1.1 (1.0)
Water immersion then housed in vehicle	7	−1.0 (0.9)
No cooling, housed in vehicle	12	−0.6 (0.8)
Stood outside then housed in vehicle	3	−0.5 (0.6)

References

Aoyagi, Y., Shephard, R.J., 2010. Habitual physical activity and health in the elderly: the Nakanojo Study. Geriatr. Gerontol. Int. 10 https://doi.org/10.1111/j.1447-0594.2010.00589.x.

Armstrong, L.E., Casa, D.J., Millard-Stafford, M., Moran, D.S., Pyne, S.W., Roberts, W.O., 2007. Exertional heat illness during training and competition. Med. Sci. Sports Exerc. 39, 556–572. https://doi.org/10.1249/MSS.0b013e31802fa199.

Aromaa, M., Putro, H., Lilja-Maula, L., Rajamäki, M.M., 2023. Comparison of habitual physical activity in French Bulldogs, Pugs and normocephalic dogs by accelerometry. Anim. Welf. 32, e60. https://doi.org/10.1017/awf.2023.80.

Ausvet, 2023. Sample Size to Detect a Significant Difference between Two Means [WWW Document]. Accessed Novemb. 6th, 2023. URL. https://epitools.ausvet.com.au/twomeansone.

Azeez, O.M., Olaifa, F.H., Adah, A.S., Basiru, A., Akorede, G.J., Ambali, H.M., Suleiman, K.Y., Sanusi, F., Bolaji, M., 2022. Effect of heat stress on vital and hematobiochemical parameters of healthy dogs. Vet. World 15, 722–727. https://doi.org/10.14202/vetworld.2022.722-727.

Baker, J., Dechant, M., Jenkins, E., Moore, G., Kelsey, K., Perry, E., 2020. Body temperature responses during phases of work in human remains detection dogs undergoing a simulated deployment. Animals 10, 673. https://doi.org/10.3390/ani10040673.

Baker, J.A., Davis, M.S., 2018. Effect of conditioning on exercise-induced hyperthermia and post-exercise cooling in dogs. Comp. Exerc. Physiol. 14, 91–97. https://doi.org/10.3920/CEP170039.

Baker, M.A., Doris, P.A., Hawkins, M.J., 1983. Effect of dehydration and hyperosmolality on thermoregulatory water losses in exercising dogs. Am. J. Physiol. Integr. Comp. Physiol. 244, R516–R521. https://doi.org/10.1152/ajpregu.1983.244.4.R516.

Benito, M., Lozano, D., Miró, F., 2022. Clinical evaluation of exercise-induced physiological changes in military working dogs (MWDs) resulting from the use or non-use of cooling vests during training in moderately hot environments. Animals 12, 2347. https://doi.org/10.3390/ani12182347.

Binkley, H.M., Beckett, J., Casa, D.J., Kleiner, D.M., Plummer, P.E., 2002. National athletic trainers' association position statement: exertional heat illnesses. J. Athl. Train. 37, 329–343.

Boag, A., Marshall, R., 2020. Small animal first aid and emergencies. In: Booper, B., Mullineaux, E., Turner, L. (Eds.), BSAVA Textbook of Veterinary Nursing. BSAVA, Gloucester, UK, p. 633.

Bouchama, A., Dehbi, M., Chaves-Carballo, E., 2007. Cooling and hemodynamic management in heatstroke: practical recommendations. Crit. Care 11, R54. https://doi.org/10.1186/cc5910.

Bouchama, A., Knochel, J.P., 2002. Heat stroke. N. Engl. J. Med. 346, 1978–1988. https://doi.org/10.1056/NEJMra011089.

Brownlow, M.A., Dart, A.J., Jeffcott, L.B., 2016. Exertional heat illness: a review of the syndrome affecting racing Thoroughbreds in hot and humid climates. Aust. Vet. J. https://doi.org/10.1111/avj.12454.

Bruchim, Y., Aroch, I., Eliav, A., Abbas, A., Frank, I., Kelmer, E., Codner, C., Segev, G., Epstein, Y., Horowitz, M., 2014. Two years of combined high-intensity physical training and heat acclimatization affect lymphocyte and serum HSP70 in purebred military working dogs. J. Appl. Physiol. 117, 112–118. https://doi.org/10.1152/japplphysiol.00090.2014.

Bruchim, Y., Horowitz, M., Aroch, I., 2017. Pathophysiology of heatstroke in dogs – revisited. Temperature 4, 356–370. https://doi.org/10.1080/23328940.2017.1367457.

Bruchim, Y., Klement, E., Saragusty, J., Finkeilstein, E., Kass, P., Aroch, I., 2006. Heat stroke in dogs: a retrospective study of 54 cases (1999-2004) and analysis of risk factors for death. J. Vet. Intern. Med. 20, 38–46. https://doi.org/10.1111/j.1939-1676.2006.tb02821.x.

Budd, G.M., 2008. Wet-bulb globe temperature (WBGT)-its history and its limitations. J. Sci. Med. Sport 11, 20–32. https://doi.org/10.1016/j.jsams.2007.07.003.

Carter, A.J., Hall, E.J., 2018. Investigating factors affecting the body temperature of dogs competing in cross country (canicross) races in the UK. J. Therm. Biol. 72, 33–38. https://doi.org/10.1016/j.jtherbio.2017.12.006.

Carter, A.J., Hall, E.J., Connolly, S.L., Russell, Z.F., Mitchell, K., 2020. Drugs, dogs, and driving: the potential for year-round thermal stress in UK vehicles. Open Vet. J. 10, 216–225. https://doi.org/10.4314/ovj.v10i2.11.

Casa, D.J., 2018. Sport and Physical Activity in the Heat. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-70217-9.

Casa, D.J., McDermott, B.P., Lee, E.C., Yeargin, S.W., Armstrong, L.E., Maresh, C.M., 2007. Cold water immersion: the gold standard for exertional heatstroke treatment. Exerc. Sport Sci. Rev. 35, 141–149. https://doi.org/10.1097/jes.0b013e3180a02bec.

Chen, L., Xu, S., Yang, X., Zhao, J., Zhang, Y., Feng, X., 2023. Association between cooling temperature and outcomes of patients with heat stroke. Intern. Emerg. Med. https://doi.org/10.1007/s11739-023-03291-y.

Davis, M.S., Cummings, S.L., Payton, M.E., 2017. Effect of brachycephaly and body condition score on respiratory thermoregulation of healthy dogs. J. Am. Vet. Med. Assoc. 251, 1160–1165. https://doi.org/10.2460/javma.251.10.1160.

Davis, M.S., Marcellin-Little, D.J., O'Connor, E., 2019. Comparison of postexercise cooling methods in working dogs. J. Spec. Oper. Med. 19, 56–60.

Demartini, J.K., Casa, D.J., Stearns, R., Belval, L., Crago, A., Davis, R., Jardine, J., 2015. Effectiveness of cold water immersion in the treatment of exertional heat stroke at the Falmouth Road Race. Med. Sci. Sports Exerc. 47, 240–245. https://doi.org/10.1249/MSS.0000000000000409.

Drobatz, K.J., Macintire, D.K., 1996. Heat-induced illness in dogs: 42 cases (1976-1993). J. Am. Vet. Med. Assoc. 209, 1894–1899.

Duncan, A., 1903. On heat stroke. Edinb. Med. J. XIII, 217–224.

Ebi, K.L., Vanos, J., Baldwin, J.W., Bell, J.E., Hondula, D.M., Errett, N.A., Hayes, K., Reid, C.E., Saha, S., Spector, J., Berry, P., 2020. Extreme weather and climate change: population health and health system implications. Annu. Rev. Publ. Health 42, 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026.

Erjavec, V., Vovk, T., Nemec Svete, A., 2022. The effect of two acute bouts of exercise on oxidative stress, hematological, and biochemical parameters, and rectal temperature in trained canicross dogs. Front. Vet. Sci. 9, 1–13. https://doi.org/10.3389/fvets.2022.767482.

Ferasin, L., Marcora, S., 2009. Reliability of an incremental exercise test to evaluate acute blood lactate, heart rate and body temperature responses in Labrador retrievers. J. Comp. Physiol. B 179, 839–845. https://doi.org/10.1007/s00360-009-0367-z.

Fischer, E.M., Sippel, S., Knutti, R., 2021. Increasing probability of record-shattering climate extremes. Nat. Clim. Change 11, 689–695. https://doi.org/10.1038/s41558-021-01092-9.

Flournoy, S., Macintire, D., Wohl, J., 2003. Heatstroke in dogs: clinical signs, treatment, prognosis, and prevention. Compend. Contin. Educ. Vet. 25, 422–431.

Flournoy, S.W., Wohl, J.S., Macintire, D.K., 2003. Heatstroke in dogs: pathophysiology and predisposing factors. Compend. Continuing Educ. Pract. Vet. 25, 410–418.

Foreman, J.H., Benson, G.J., Foreman, M.H., 2006. Effects of a pre-moistened multilayered breathable fabric in promoting heat loss during recovery after exercise under hot conditions. Equine Vet. J. 38, 303–307. https://doi.org/10.1111/j.2042-3306.2006.tb05558.x.

Gale, E.A.M., 2004. The Hawthorne studies–a fable for our times? QJM 97, 439–449. https://doi.org/10.1093/qjmed/hch070.

Gaudio, F.G., Grissom, C.K., 2016. Cooling methods in heat stroke. J. Emerg. Med. 50, 607–616. https://doi.org/10.1016/j.jemermed.2015.09.014.

Gogolski, S.M., O'Brien, C., Lagutchik, M.S., 2020. Retrospective analysis of patient and environmental factors in heat-induced injury events in 103 military working dogs. J. Am. Vet. Med. Assoc. 256, 792–799. https://doi.org/10.2460/javma.256.7.792.

Grundstein, A., Meentemeyer, V., Dowd, J., 2009. Maximum vehicle cabin temperatures under different meteorological conditions. Int. J. Biometeorol. 53, 255–261. https://doi.org/10.1007/s00484-009-0211-x.

Hadad, E., Rav-Acha, M., Heled, Y., Epstein, Y., Moran, D.S., 2004. Heat stroke A review of cooling methods. Sports Med. 34, 501–511. https://doi.org/10.2165/00007256-200434080-00002.

Hajat, S., Vardoulakis, S., Heaviside, C., Eggen, B., 2014. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J. Epidemiol. Community Health 68, 641–648. https://doi.org/10.1136/jech-2013-202449.

Hall, E.J., Carter, A.J., 2017. Establishing a reference range for normal canine tympanic membrane temperature measured with a veterinary aural thermometer. Vet. Nurse J. 32, 369–373. https://doi.org/10.1080/17415349.2017.1377133.

Hall, E.J., Carter, A.J., Bradbury, J., Barfield, D., O'Neill, D.G., 2021a. Proposing the VetCompass clinical grading tool for heat-related illness in dogs. Sci. Rep. 11, 6828. https://doi.org/10.1038/s41598-021-86235-w.

Hall, E.J., Carter, A.J., Bradbury, J., Beard, S., Gilbert, S., Barfield, D., O'Neill, D.G., 2023. Cooling methods used to manage heat-related illness in dogs presented to primary care veterinary practices during 2016–2018 in the UK. Vet. Sci. 10, 465. https://doi.org/10.3390/vetsci10070465.

Hall, E.J., Carter, A.J., Chico, G., Bradbury, J., Gentle, L.K., Barfield, D., O'Neill, D.G., 2022a. Risk factors for severe and fatal heat-related illness in UK dogs—a VetCompass study. Vet. Sci. 9, 231. https://doi.org/10.3390/vetsci9050231.

Hall, E.J., Carter, A.J., Farnworth, M.J., 2021b. Exploring owner perceptions of the impacts of seasonal weather variations on canine activity and potential consequences for human–canine relationships. Animals 11, 3302. https://doi.org/10.3390/ani11113302.

Hall, E.J., Carter, A.J., O'Neill, D.G., 2020a. Dogs don't Die just in hot cars—exertional heat-related illness (heatstroke) is a greater threat to UK dogs. Animals 10, 1324. https://doi.org/10.3390/ani10081324.

Hall, E.J., Carter, A.J., O'Neill, D.G., 2020b. Incidence and risk factors for heat-related illness (heatstroke) in UK dogs under primary veterinary care in 2016. Sci. Rep. 10, 9128. https://doi.org/10.1038/s41598-020-66015-8.

Hall, E.J., Radford, A.D., Carter, A.J., 2022b. Surveillance of heat-related illness in small animals presenting to veterinary practices in the UK between 2013-2018. Open Vet. J. 12, 5–16. https://doi.org/10.5455/OVJ.2022.v12.i1.2.

Hanel, R.M., Palmer, L., Baker, J., Brenner, J.-A.A., Crowe, D.T.T., Dorman, D., Gicking, J.C., Gilger, B., Otto, C.M., Robertson, S.A., Rozanski, E., Trumpatori, B., 2016. Best practice recommendations for prehospital veterinary care of dogs and cats. J. Vet. Emerg. Crit. Care 26, 166–233. https://doi.org/10.1111/vec.12455.

Hemmelgarn, C., Gannon, K., 2013a. Heatstroke: clinical signs, diagnosis, treatment, and prognosis. Compend. Contin. Educ. Vet. 35, E3.

Hemmelgarn, C., Gannon, K., 2013b. Heatstroke: thermoregulation, pathophysiology, and predisposing factors. Compend. Contin. Educ. Vet. 35, E4.

Johnson, S.I., McMichael, M., White, G., 2006. Heatstroke in small animal medicine: a clinical practice review. J. Vet. Emerg. Crit. Care 16, 112–119. https://doi.org/10.1111/j.1476-4431.2006.00191.x.

Kielblock, A.J., Van Rensburg, J.P., Franz, R.M., 1986. Body cooling as a method for reducing hyperthermia. An evaluation of techniques. S. Afr. Med. J. 69, 378–380.

Klous, L., van Diemen, F., Ruijs, S., Gerrett, N., Daanen, H., de Weerd, M., Veenstra, B., Levels, K., 2022. Efficiency of three cooling methods for hyperthermic military personnel linked to water availability. Appl. Ergon. 102, 103700 https://doi.org/10.1016/j.apergo.2022.103700.

Kruk, B., Kaciuba-Uscilko, H., Nazar, K., 1985. Hypothalamic, rectal, and muscle temperatures in exercising dogs: effect of cooling. J. Appl. Physiol. 58, 1444–1448. https://doi.org/10.1152/jappl.1985.58.5.1444.

Lagutchik, M., Baker, J., Balser, J., Burghardt, W., Enroth, M., Flournoy, S., Giles, J., Grimm, P., Hiniker, J., Johnson, J., Mann, K., Takara, M., Thomas, T., 2018. Trauma management of military working dogs. Mil. Med. 183, 180–189. https://doi.org/10.1093/milmed/usy119.

Lewis, S., Foster, R.C., 1976. Effect of Heat on Canines and Felines, vol. 38. Iowa State Univ. Veterrinarian, pp. 117–121.

Lilja-Maula, L., Lappalainen, A.K., Hyytiäinen, H.K., Kuusela, E., Kaimio, M., Schildt, K., Mölsä, S., Morelius, M., Rajamäki, M.M., 2017. Comparison of submaximal exercise test results and severity of brachycephalic obstructive airway syndrome in English bulldogs. Vet. J. 219, 22–26. https://doi.org/10.1016/j.tvjl.2016.11.019.

Lucke, J.N., Hall, G.N., 1980. Further studies on the metabolic effects of long distance riding: golden Horseshoe Ride 1979. Equine Vet. J. 12, 189–192. https://doi.org/10.1111/j.2042-3306.1980.tb03424.x.

Magazanik, A., Epstein, Y., Udassin, R., Shapiro, Y., Sohar, E., 1980. Tap water, an efficient method for cooling heatstroke victims–a model in dogs. Aviat Space Environ. Med. 51, 864–866.

Marlin, D.J., Misheff, M., Whitehead, P.. Preparation for and management of horses and athletes during equestrian events held in thermally challenging environments. https://inside.fei.org/system/files/PREPARATION%20FOR%20AND%20MANAGEMENT%20DURING%20EQUESTRIAN%20EVENTS%20HELD%20IN%20THERMALLY%20CHALLENGING%20ENVIRONMENTS%20Final.pdf pp27.

Marlin, D.J., Scott, C.M., Roberts, C.A., Casas, I., Holah, G., Schroter, R.C., 1998. Post exercise changes in compartmental body temperature accompanying intermittent cold water cooling in the hyperthermic horse. Equine Vet. J. 30, 28–34. https://doi.org/10.1111/j.2042-3306.1998.tb04085.x.

Mazzaferro, E.M., 2017. Heatstroke. In: Ettinger, S.J., Feldman, E.C., Côté, E. (Eds.), Textbook of Veterinary Internal Medicine. Elsevier, St. Louis, Missouri USA, pp. 1516–1522.

McLaren, C., 2005. Heat stress from enclosed vehicles: moderate ambient temperatures cause significant temperature rise in enclosed vehicles. Pediatrics 116, e109–e112. https://doi.org/10.1542/peds.2004-2368.

Miller, J.B., 2015. Hyperthermia and fever. In: Silverstein, D.C., Hopper, K. (Eds.), Chapter 10 - Small Animal Critical Care Medicine. Elsevier, St. Louis, Missouri, pp. 55–59. https://doi.org/10.1016/B978-1-4557-0306-7.00010-6.

Miller, L., Pacheco, G.J., Janak, J.C., Grimm, R.C., Dierschke, N.A., Baker, J., Orman, J. A., 2018. Causes of death in military working dogs during operation Iraqi freedom and operation enduring freedom, 2001-2013. Mil. Med. 183, e467–e474. https://doi.org/10.1093/milmed/usx235.

Moon, K.E., Wang, S., Bryant, K., Gohlke, J.M., 2021. Environmental heat exposure among pet dogs in rural and urban settings in the southern United States. Front. Vet. Sci. 8 https://doi.org/10.3389/fvets.2021.742926.

Nazar, K., Greenleaf, J.E., Pohoska, E., Turlejska, E., Kaciuba-Uscilko, H., Kozlowski, S., 1992. Exercise performance, core temperature, and metabolism after prolonged restricted activity and retraining in dogs. Aviat Space Environ. Med. 63, 684–688. https://doi.org/10.1360/zd-2013-43-6-1064.

O'Brien, C., Karis, A.J., Tharion, W.J., Sullivan, H.M., Hoyt, R.W., 2017. Core temperature responses of military working dogs during training activities and exercise walks. US. Army Med. Dep. J. 71–78.

Otto, C.M., Hare, E., Nord, J.L., Palermo, S.M., Kelsey, K.M., Darling, T.A., Schmidt, K., Coleman, D., 2017. Evaluation of three hydration strategies in detection dogs working in a hot environment. Front. Vet. Sci. 4, 1–10. https://doi.org/10.3389/fvets.2017.00174.

Parnes, S.C., Mallikarjun, A., Ramos, M.T., Stone, T.A., Otto, C.M., 2023. A randomized cross-over study comparing cooling methods for exercise-induced hyperthermia in working dogs in training. Animals 13, 3673. https://doi.org/10.3390/ani13233673.

Pellegrino, F.J., Risso, A., Vaquero, P.G., Corrada, Y.A., 2018. Physiological parameter values in greyhounds before and after high-intensity exercise. Open Vet. J. 8, 64–67. https://doi.org/10.4314/ovj.v8i1.11.

PFMA, 2019. Pet Obesity Ten Years on 2009-2019 [WWW Document]. Accessed August 5, 2021, From. URL. https://www.pfma.org.uk/_assets/docs/WhitePapers/PFMA-Obesity-Report-2019.pdf. (Accessed 8 May 2021).

Protopopova, A., Ly, L.H., Eagan, B.H., Brown, K.M., 2021. Climate change and companion animals: identifying links and opportunities for mitigation and adaptation strategies. Integr. Comp. Biol. 61, 166–181. https://doi.org/10.1093/icb/icab025.

Rovira, S., Munoz, A., Benito, M., 2008. Effect of exercise on physiological, blood and endocrine parameters in search and rescue-trained dogs. Vet. Med. 53, 333–346. https://doi.org/10.17221/1860-VETMED.

Shapiro, Y., Seidman, D.S., 1990. Field and clinical observations of exertional heat stroke patients. Med. Sci. Sports Exerc. 22, 6–14. https://doi.org/10.1249/00005768-199002000-00003.

Stojsih, S.E., Baker, J.L., Les, C.M., Bir, C.A., 2014. Review of canine deaths while in service in US civilian law enforcement (2002-2012). J. Spec. Oper. Med. 14, 86–91.

Takahashi, Y., Ohmura, H., Mukai, K., Shiose, T., Takahashi, T., 2020. A comparison of five cooling methods in hot and humid environments in thoroughbred horses. J. Equine Vet. Sci. 91 https://doi.org/10.1016/J.JEVS.2020.103130.

Tanaka, H., Tanaka, S., Yokota, H., Otomo, Y., Masuno, T., Nakano, K., Sugita, M., Tokunaga, T., Sugimoto, K., Inoue, J., Kato, N., Kinoshi, T., Sakanashi, S., Inoue, H., Numata, H., Nakagawa, K., Miyamoto, T., Akama, T., 2023. Acute in-competition medical care at the Tokyo 2020 Olympics: a retrospective analysis. Br. J. Sports Med. bjsports- 2022–105778. https://doi.org/10.1136/bjsports-2022-105778.

Teichmann, S., Turković, V., Dörfelt, R., 2014. [Heatstroke in dogs in southern Germany. A retrospective study over a 5.5-year period]. Tierarztl. Prax. Ausg. K. Kleintiere. Heimtiere. 42, 213–222.

The Kennel Club, 2023. Breed standards [WWW document]. URL. https://www.thekennelclub.org.uk/breed-standards/. (Accessed 11 April 2023).

Tripovich, J., Wilson, B., McGreevy, P., Quain, A., 2023. Incidence and risk factors of heat-related illness in dogs from New South Wales, Australia (1997–2017). Aust. Vet. J. 1–12 https://doi.org/10.1111/avj.13296.

Waljee, A.K., Higgins, P.D.R., Singal, A.G., 2014. A primer on predictive models. Clin. Transl. Gastroenterol. 5, e44. https://doi.org/10.1038/ctg.2013.19.

Zanghi, B.M., Robbins, P.J., Ramos, M.T., Otto, C.M., 2018. Working dogs drinking a nutrient-enriched water maintain cooler body temperature and improved pulse rate recovery after exercise. Front. Vet. Sci. 5, 202. https://doi.org/10.3389/fvets.2018.00202.