

LJMU Research Online

Veltmeijer, MT, Eijsvogels, TM, Barteling, W, Verbeek-Knobbe, K, van Heerde, WL and Hopman, MT

The impact of exercise-induced core body temperature elevations on coagulation responses.

<https://researchonline.ljmu.ac.uk/id/eprint/3388/>

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Veltmeijer, MT, Eijsvogels, TM, Barteling, W, Verbeek-Knobbe, K, van Heerde, WL and Hopman, MT (2016) The impact of exercise-induced core body temperature elevations on coagulation responses. Journal of Science and Medicine in Sport. ISSN 1878-1861

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

The impact of exercise-induced core body temperature elevations on coagulation responses

Matthijs T.W. Veltmeijer, MD¹

Thijs M.H. Eijsvogels, PhD^{1,3}

Wideke Barteling, BSc²

Kitty Verbeek-Knobbe, BSc²

Waander L. van Heerde, PhD²

Maria T.E. Hopman, MD, PhD¹

Radboud university medical center, Radboud Institute for Health Sciences, Department of
Physiology¹ and Department of Laboratory Medicine, Laboratory for Haematology²,
Nijmegen, the Netherlands.

Hartford Hospital, Division of Cardiology³, Hartford, Connecticut, USA.

Abstract Word Count: 248

Word Count: 2831

Figure Count: 1

Table Count: 2

Author for Correspondence:

Prof. Dr. Maria Hopman, Department of Physiology, Maria.Hopman@Radboudumc.nl
Radboud University Medical Center, PO Box 9101, 6500 HB Nijmegen, the Netherlands. E-
mail: Telephone: +31 24 361 3650, Fax: +31 24 361 6413

ABSTRACT

Objectives: Exercise induces changes in haemostatic parameters and core body temperature (CBT). We aimed to assess whether exercise-induced elevations in CBT induce pro-thrombotic changes in a dose-dependent manner.

Design: Observational study.

Methods: CBT and haemostatic responses were measured in 62 participants of a 15-km road race at baseline and immediately after finishing. As haemostasis assays are routinely performed at 37°C, we corrected the assay temperature for the individual's actual CBT at baseline and finish in a subgroup of n=25.

Results: All subjects (44 ± 11 years, 69% male) completed the race at a speed of 12.1 ± 1.8 km/h. CBT increased significantly from $37.6\pm 0.4^{\circ}\text{C}$ to $39.4\pm 0.8^{\circ}\text{C}$ ($p<0.001$). Post-exercise, haemostatic activity was increased, as expressed by accelerated thrombin generation and an attenuated plasmin response. Synchronizing assay temperature to the subjects' actual CBT resulted in additional differences and stronger acceleration of thrombin generation parameters.

Conclusions: This study demonstrates that exercise induces a prothrombotic state, which might be partially dependent on the magnitude of the exercise-induced CBT rise. Synchronizing the assay temperature to approximate the subject's CBT is essential to obtain more accurate insight in the haemostatic balance during thermoregulatory challenging situations. Finally, this study shows that short-lasting exposure to a CBT of 41.2°C does not result in clinical symptoms of severe coagulation. We therefore hypothesize that prolonged exposure to a high CBT or an individual-specific CBT threshold needs to be exceeded before derailment of the haemostatic balance occurs.

Key-Words: Athletes, Haemostasis, Heatstroke, Hyperthermia, Thermoregulation.

1 Introduction

2 Strenuous exercise induces a hypercoagulable state, hallmarked by an increased factor VIII
3 concentration and a subsequently increased (in vitro) thrombin generation¹⁻³. The increased
4 thrombin enables fibrin formation, which stabilizes the platelet plug⁴. Simultaneous to these
5 prothrombotic changes, increased levels of tissue plasminogen activator and reduced levels
6 of plasminogen activator inhibitor hallmark increased fibrinolysis^{1 3 4}. In this manner, the
7 prothrombotic effects of exercise are offset by increased fibrinolysis, which prevents the
8 formation of excess blood clots. Whilst the magnitude of these haemostatic changes are
9 generally well balanced during general aerobic exercise, they are associated with an
10 increased risk of cardiovascular complications such as acute coronary syndrome in individuals
11 with previous cardiovascular disease⁵.

12
13 In addition to prothrombotic changes, exercise also leads to an increase in core body
14 temperature (CBT)^{6 7}. Whilst this exercise-induced CBT increase is a normal result of
15 metabolic heat production⁸, excessive increases in CBT to values above 40°C can potentially
16 result in heatstroke^{6 9 10}. Heatstroke is characterized by neurological symptoms (delirium,
17 coma) and a derailed haemostatic response that results in a disease state similar to diffuse
18 intravascular coagulation⁹⁻¹¹. Potential consequences of heatstroke are multi-organ failure, in
19 part due to thrombotic complications, and may result in death⁹. Hence, strong CBT rises during
20 exercise bear the risk of developing potential serious thrombotic complications. Conversely,
21 hypothermia (a CBT <35°C) has been shown to negatively impact on haemostatic activity,
22 resulting in an increased bleeding diathesis^{12 13}. These observations suggest that CBT directly
23 impacts on the activity of the haemostatic system, and the procoagulant responses during
24 exercise could thus theoretically be partly caused by an increased CBT. However, whether an
25 increased CBT during exercise actually induces prothrombotic changes in a dose-dependent
26 manner is currently unknown.

Therefore, the first aim of this study was to investigate whether the exercise-induced elevation in CBT induces prothrombotic changes in a dose-dependent manner. To that end, we measured thermal and haemostatic responses in 62 participants of a 15-km road race at baseline and immediately after finishing.

Interestingly, haemostatic assays are routinely performed at a temperature of 37°C, whilst the *in vivo* CBT in the present study population was expected to be substantially higher ($\geq 39.0^{\circ}\text{C}$) at the finish line⁷. Routinely obtained haemostasis data might thus provide inaccurate information due to potentially changing properties of the clotting factors at elevated temperatures¹⁴⁻¹⁶. Therefore, as a second aim, we corrected the temperature at which the assay is performed to approximate the subjects' actual CBT at baseline and after finishing in a subgroup of 25 individuals and investigated whether this leads to different results compared to the routine assessment at 37°C. We hypothesized that an increased CBT at the finish line would enhance prothrombotic responses, and that adjusting the temperature at which the haemostasis assay is performed to approximate the subjects' actual CBT would show a more pronounced haemostatic activation.

Methods

Sixty-two individuals (43 males, 19 females; age 44 ± 11 years; height 178 ± 8 cm; body weight 72.8 ± 10.5 kg; body mass index 22.9 ± 2.3 kg/m²) who participated in a 15-km road race (Seven Hills Run, Nijmegen, the Netherlands) were recruited for the present study. Recruitment took place identically as previously described by the present authors⁷. Before being included in the present study, all subjects provided a written informed consent and all subjects were screened for the presence of any exclusion criteria for using the temperature pill: 1. A history of obstructive or inflammatory bowel disease or prior abdominal surgery, 2. The presence of any implanted electric (medical) device, 3. A scheduled MRI scan within 1 week after the event, or 4. Pregnancy. None of the subjects had a history of cardiovascular or thrombotic disease,

1 none of the subjects used any anticoagulant medication. The average training status of our
2 subjects was 3.6 ± 2.1 hours of running exercise per week for the past year. Study procedures
3 were approved by the Radboud university medical center Ethics Committee and accorded to
4 the principles of the declaration of Helsinki.

5
6 Baseline measurements were performed 2 hours before the start of the race in a laboratory
7 set up 50 meters from the start/finish line. CBT was measured at baseline, 1 minute before
8 the start, and within 15-seconds after finishing. Venous blood samples were obtained via
9 venipuncture from an antecubital vein at baseline and within 5 minutes after finishing. No
10 measurements were performed during exercise, and subjects completed the race at a self-
11 selected pace. Body weight was measured at baseline and immediately after finishing (Seca
12 888, Hamburg, Germany), and relative changes in body weight were calculated to determine
13 the hydration status of participants. Dehydration was defined as a body weight loss $\geq 2\%$ ¹⁷.

14 Subjects ingested an individually calibrated telemetric temperature pill at least five hours (8
15 a.m.) before the race (start 1 p.m.) to prevent interaction of the CBT measurements with fluid
16 ingestion during testing¹⁸. CBT was measured using a portable telemetry system (CorTemp™
17 system, HQ Inc., Palmetto, USA), which has been demonstrated to safely and reliably
18 measure CBT^{19 20}. The average of three consecutive measurements for each time point was
19 used for further analyses.

20 Based on finish CBT, subjects were classified as low- (CBT <39) moderate- ($39 \geq$ finish CBT
21 <40) or high-responders (CBT ≥ 40). The exercise-induced increase in CBT (Δ CBT) was
22 calculated by subtracting baseline CBT from finish CBT. Again, three subgroups were created
23 to classify low- (Δ CBT < 1.5) moderate- ($1.5 \geq \Delta$ CBT <2.5) and high-responders (Δ CBT ≥ 2.5).

24
25 Venous blood samples were collected from an anticubital vein in CTAD (sodium citrate
26 theophylline, adenosine dipyridamol) buffered collection tubes in our on-site laboratory.
27 Samples were centrifuged at 4200 rpm for 15 minutes, after which the plasma was
28 immediately transferred into new uncoated Eppendorf tubes which were subsequently snap

frozen in liquid nitrogen and stored at -80°C until further analysis. Thrombin and plasmin generation were simultaneously measured using the 'Nijmegen Haemostasis Assay'²¹. This assay allows simultaneous measurement of *in vitro* thrombin and plasmin generation in the same blood specimen in a single well (Supplemental Figure 1). Lag time thrombin generation describes the lag time between activation of the coagulation cascade and the time at which the initiation of thrombin generation is measured. Time to thrombin peak refers to the time between activation of the coagulation cascade and reaching the peak thrombin generation value. Thrombin peak height refers to the maximal thrombin generation rate. The area under the curve reflects the total thrombin potential (AUC_{thrombin}). Plasmin peak time refers to the time between activation of the coagulation cascade and the time at which the plasmin peak is reached. Plasmin peak height refers to the maximal plasmin generation rate. Fibrin lysis time refers to the time between the start of plasmin generation and the moment at which plasmin peak height is attained. In all instances, each plasma sample was analysed in duplicate and the average of each duplicate was used for further analysis. The inter-assay variation of thrombin generation parameters varies from 5.9% (AUC_{thrombin}) to 25% (lag time thrombin generation). The inter-assay variation of plasmin generation parameters varies from 10% (plasmin peak height) to 14% (plasmin potential).

For aim 2, we re-analysed the plasma samples at an assay temperature nearest to the subject's CBT at baseline and finish in a subgroup of n=25. For example, if a subject had a baseline CBT of 37.4°C, the assay was performed at 37°C, whereas in case of a baseline CBT of $\geq 37.5^\circ\text{C}$ and $\leq 38.4^\circ\text{C}$ the assay was performed at 38°C. Likewise, a finish CBT of 39.4°C was analysed at an assay temperature of 39°C and finish CBT $\geq 39.5^\circ\text{C}$ at 40°C. Within this subgroup we also measured additional haemostatic parameters, in order to quantify the *in vivo* haemostatic activity. Plasma prothrombin fragment 1+2 was measured to assess the *in vivo* thrombin generation using an enzyme-linked immunosorbent assay (ELISA; Enzygnost F1+2, Behring Diagnostics GmbH, Frankfurt, Germany), while plasma D-dimer levels were measured to quantify the *in vivo* fibrinolysis activity using an ELISA (Zymutest D-dimer, Hyphen BioMed, Neuville-sur-Oise, France). Furthermore, we determined the isolated effect

of the assay temperature on haemostasis parameters by performing the analyses at 37°C, 38°C, 39°C and 40°C in the subgroup of n=25.

Statistical analyses were performed using the Statistical Package for the Social Sciences (IBM SPSS Statistics for Windows, Version 20.0, IBM Corp., Armonk, NY, USA). Data were reported as mean \pm standard deviation unless otherwise indicated. All haemostasis data were visually inspected for normality distribution. In case of a non-Gaussian distribution, log-transformation was performed and data were re-inspected. If a normal distribution could not be attained, non-parametric analyses were performed. The impact of exercise on changes in haemostatic parameters was assessed using a paired Student's T-Test. To test the hypothesis that a higher finish CBT would aggravate the exercise-induced haemostatic responses two-way repeated measurements analysis of variance (Gaussian distributed data) and Kruskal-Wallis or Friedman test (non-Gaussian distributed data) were used. The relationship between finish CBT and post-exercise haemostasis parameters was calculated using a Pearson (Gaussian distributed data) or Spearman's rank correlations (non-Gaussian distributed data).

Results

All subjects completed the race in cool environmental conditions (Wet bulb globe temperature 12.5°C, Dry-Bulb temperature 10.5°C, relative humidity 87%, wind speed 3.4 – 5.4 m/s) at an average running speed of 12.1 \pm 1.8 km/h. The average body weight loss during the race was -1.4 \pm 0.6% of total body weight, and 18% of all subjects classified as dehydrated. Post-exercise, lag time in thrombin generation (baseline 4.5 \pm 1.1 *versus* finish 3.8 \pm 0.7 min; p<0.001) and time to thrombin peak (9.0 \pm 1.4 vs. 8.0 \pm 0.9 min; p<0.001) were significantly shortened, whilst thrombin peak height (207 \pm 29 vs. 208 \pm 25 nmol/L; p=0.70) and AUC_{thrombin} (1293 \pm 172 vs. 1292 \pm 172 nmol/L/min; p=0.94) did not differ between baseline and post-exercise. Plasmin peak time (36.6 \pm 9.1 vs. 35.3 \pm 8.2 min; p=0.20) and fibrin lysis time (30.6 \pm 8.6 vs. 30.4 \pm 8.3 min; p=0.81) did not change after exercise, whereas a significant reduction in plasmin peak height

(19.2±12.2 vs. 10.0±9.0 nmol/L; Wilcoxon Signed Ranks Test $p<0.001$) was observed after finishing.

Baseline CBT was 37.6±0.4°C and increased significantly (1.8±0.9°C, $p<0.001$) to 39.4±0.8°C at the finish line (range: 38.0–41.2°C). We identified 24 low-responders, 20 moderate-responders and 18 high-responders for finish CBT. Coagulation and fibrinolysis responses did not differ across low-, moderate- and high-responders for all but one parameter (Table 1). A group effect ($p<0.02$) was found for AUC_{thrombin} , with significantly higher values in moderate- and high-CBT responders compared to low-CBT responders. Similarly, the magnitude of ΔCBT did not interact with changes in haemostatic parameters (Supplemental Table 1). Lastly, neither finish-CBT nor ΔCBT correlated significantly with post-exercise haemostasis parameters, body weight loss or running speed (Supplemental Table 2).

Synchronisation of the haemostatic assay temperature to actual baseline and finish CBT resulted in a significant decrease of lag time thrombin generation, time to thrombin peak, thrombin peak height and AUC_{thrombin} between baseline and finish (Figure 1A-D respectively). Plasmin peak time synchronized to actual CBT and plasmin peak height decreased significantly between baseline and finish (Figure 1E + F), whilst fibrin lysis time did not change significantly (Figure 1G). Interestingly, a high finish CBT resulted in a prolonged fibrin lysis time, which was in contrast with subjects that reported a moderate and low finish CBT and demonstrated a shorter fibrin lysis time (Table 2). In addition, fragment 1+2 increased from 223±121 pmol/L to 482±623 pmol/L ($p<0.001$), while d-dimer increased from 247±128 ng/L to 1223±2821 ng/L ($p<0.001$). No correlation was found between the change in Fragment 1+2 and finish CBT ($r=-0.01$; $p=0.96$) or the change in d-dimer and finish CBT ($r=0.04$; $p=0.87$). A similar effect of assay temperature on haemostasis parameters was observed in the subgroup analyses of $n=25$ (Supplemental Table 3).

Discussion

The purpose of this study was to investigate whether the exercise-induced CBT-rise causes prothrombotic changes in a dose-dependent manner, and whether correcting the temperature at which the haemostasis assay is performed to approximate the subjects' actual CBT alters the haemostasis outcomes. Our study demonstrates that thrombin generation peaked significantly earlier after the race compared to baseline and that plasmin peak height was significantly lower after finishing. However, changes in haemostatic parameters were not related to finish CBT or Δ CBT. The novelty of our findings lies in the adjustment of the assay temperatures to approximate the subjects' CBT. Correcting the assay temperature resulted in more pronounced changes of time to thrombin peak and AUC_{thrombin} , and resulted in the additional identification of a significantly shortened lag time thrombin generation, decreased thrombin peak height and a significant impact of finish CBT on fibrin lysis time. These results suggest that increases in CBT may partially contribute to the exercise-induced haemostatic activation, but that (short lasting) exposure to CBTs up to 41.2°C does not result in clinical symptoms of increased coagulation. Hence, prolonged exposure or a higher CBT is needed to induce excessive coagulation that is typically observed in athletes diagnosed with heatstroke. Most importantly, our results demonstrate that synchronization of the temperature at which haemostasis assays are performed significantly influences the results. In situations where CBT is outside of normal (36.0 – 37.5°C) range, it is essential to adjust the assay temperature to obtain the most accurate results.

Participants of our study demonstrated a large ($1.8 \pm 0.9^\circ\text{C}$) and significant increase in CBT after running a 15 km road race, with an average finish CBT of $39.4 \pm 0.8^\circ\text{C}$. These thermoregulatory responses are in agreement with a previous study⁷. Our subjects were well trained (3.6 ± 2.1 hrs/week) and were thus well accustomed to the elevated CBT caused by the exercise itself. We also observed a significant activation of the haemostatic balance, as expressed by a faster thrombin generation and an attenuated plasmin response. These

findings confirm the prothrombotic effects of exercise that were reported previously^{4 5 22}. Since prolonged endurance training has previously been shown to attenuate the prothrombotic effects of exercise²³, our findings might have been more pronounced in an untrained control group. Independent of training status, the combination of a large inter-individual variation in CBT with a significant haemostatic activation allows us to explore the potential relationship between these exercise-induced phenomena.

Haemostatic responses were largely comparable between low, moderate and high responders of finish CBT. Although the AUC_{thrombin} was significantly higher in moderate- and high-responders compared to low-responders, the other exercise-induced haemostatic changes did not differ across finish-CBT groups. In contrast to our hypothesis, these data suggest that the exercise-induced pro-thrombotic changes do not depend on finish CBT. The observation of a massive haemostatic activation in patients with heatstroke suggests that excessive thrombotic responses may only occur above a certain CBT threshold or after prolonged exposure to a high CBT^{24 25}. Hence, the peak finish CBT that was reported in our study (41.2°C) was apparently either too low to induce substantial activation of the coagulation cascade, or too short lasting to induce substantial changes. Data from several animal studies reinforced this hypothesis and showed that prolonged (2.5 - 3 hours) passive heating with a CBT >42°C was needed to induce excessive activation of the haemostatic response^{11 26 27}. Indeed, the finish CBTs that were observed in our subjects did not result in a derailed haemostatic response nor in clinical symptoms. This was supported by the statistically significant, though clinically irrelevant, increase in plasma prothrombin fragment 1+2 and d-dimer levels in absence of a correlation of these parameters with finish CBT. Therefore, physical exercise typically performed by the general population does not necessarily result in a derailment of blood haemostasis.

Importantly, the absence of an interaction between CBT and haemostasis may relate to the fact that analyses were performed at 37°C instead of the actual CBT at the time of blood

collection. When synchronizing the assay temperature to the individual's baseline and finish CBT, we observed additional and stronger baseline-to-finish changes in several haemostatic parameters compared to the findings from the assay at 37°C (Figure 1). Differences were not limited to finish results, but also showed altered baseline values when synchronizing for baseline CBT. Athletes with a finish CBT $\geq 40.0^{\circ}\text{C}$ demonstrated a significantly larger fibrin lysis time compared to peers with a lower finish CBT who demonstrated a reduced fibrin lysis time. These findings were confirmed by the analysis in which we varied the assay temperature (Supplemental Table 3) and suggest a direct impact of CBT on exercise-induced haemostatic responses. Interestingly, we have observed this effect after analysis of frozen plasma samples which had already been exposed once *in vivo* to an elevated temperature during the exercise bout. The fact that we were able to identify additional significant changes or stronger baseline-to-finish changes compared to when the assays were performed routinely at 37°C suggests that at least part of the observed procoagulant effects are temperature-dependent. Evidence from previous studies in hypothermic patients support our observations. These studies showed that lowering the haemostatic assay temperature to mimic the real-life CBT resulted in a prolonged initiation of blood clotting, whilst the absolute concentration of clotting factors remained unchanged^{15 28 29}. Altogether, these data suggest that altering the CBT causes the enzymatic coagulation reaction to become slower at lower temperatures *versus* faster at higher temperatures²⁹. Our findings therefore demonstrate that it is essential to adjust the assay temperature to approximate the subject's CBT in order to obtain the most accurate results. This may not only apply to exercise-induced CBT rises, but also to other conditions where CBT is outside of the normal physiological range.

We found that running a 15 km road race resulted in a pro-coagulant state, which is partially dependent on the magnitude of the exercise-induced rise in CBT. None of our subjects experienced clinical coagulation-related problems, which indicates that changes in haemostatic parameters that are accompanied by a CBT up to 41.2°C are of minor clinical relevance. Hence, our data suggest that heatstroke-induced disseminated intravascular

1 coagulation, which is a serious threat for endurance athletes³⁰, occurs when CBT passes a
2 certain threshold value. Once an athlete exceeds this threshold and is diagnosed with
3 heatstroke, our data underline the importance of rapid and aggressive cooling, which may
4 reduce the CBT related stimulation of the coagulation cascade and could result in a better
5 outcome. Notably, given the diverse range of peak core body temperatures that individuals
6 develop during exercise⁷, this CBT threshold might be individually determined.

7
8 A potential limitation of the present study is that blood samples were collected within 5 minutes
9 after finishing, while CBT was assessed directly at the finish line. Due to the time difference,
10 subjects may have had a slightly lower CBT at the time of blood collection due to passive
11 cooling. Nevertheless, it is unlikely that these minor CBT differences would impacted our
12 haemostasis results, apart from the fact that it would even underestimate our findings. Another
13 potential limitation of the present study is that we did not correct for exercise-induced changes
14 in plasma volume. However, 82% of our study population was well hydrated, making it unlikely
15 that shifts in plasma volume had a large impact on study outcomes. Importantly, all
16 measurements for the temperature adjusted assays were performed on the same plasma
17 samples and the only manipulated factor was assay temperature. Therefore, the adjusted
18 assay temperature data were not affected by plasma volume changes. Lastly, whilst the
19 applied haemostasis assay has a low inter-assay variability for analyses performed on a single
20 say, the variability is slightly larger when comparing analyses performed on separate days (for
21 example Table 1 *versus* Supplemental Table 3). All results reported within each table were
22 therefore acquired on a single day and all reported results can thus be safely interpreted within
23 each table. However, even though the assay variability when performed on separate days was
24 limited, caution should be applied when comparing several tables with one another.

Conclusion

In conclusion, this study demonstrates that exercise induces a procoagulant state, and our results suggest that this might partially be dependent on the magnitude of the exercise-induced CBT rise. Moreover, athletes with a finish CBT as high as 41.2°C do not necessarily demonstrate haemostatic activation leading to clinical symptoms. We therefore hypothesize that prolonged exposure to, or a specific CBT threshold needs to be exceeded before derailment of the haemostatic balance occurs. Most importantly, our results show that adjusting the assay temperature to approximate the subject's CBT is highly recommended to obtain more accurate insight in the haemostatic balance when CBT lies outside the physiological range.

Practical implications

- 15-km running exercise resulted in a significant increase of core body temperature to $39.4 \pm 0.8^\circ\text{C}$, and significant procoagulant haemostasis activity by increasing thrombin generation and attenuating plasmin responses.
- Whilst haemostatic responses were comparable between individuals with a low or high finish core body temperature, adjusting the assay temperature to approximate the individual's actual core body temperature revealed a significant interaction between core body temperature and fibrinolytic activity.
- These findings suggest that the prothrombotic state induced by exercise might be partially dependent on the exercise-induced core body temperature rise. Adjusting the assay temperature to approximate the individual's actual core body temperature is essential to obtain the most accurate results when body temperature is outside the normal ($36.0\text{-}37.5^\circ\text{C}$) range.

- 1 **Acknowledgements:** We thank Joan Merx and Ronald Veerbeek of the ‘Seven Hills Run’ for providing facilities to
- 2 set up our on-site laboratory and their endorsement of this study.

References

1. Arai M, Yorifuji H, Ikematsu S, et al. Influences of strenuous exercise (triathlon) on blood coagulation and fibrinolytic system. *Thromb Res* 1990;57(3):465-471.
2. El-Sayed MS, Lin X, Rattu AJ. Blood coagulation and fibrinolysis at rest and in response to maximal exercise before and after a physical conditioning programme. *Blood Coagul Fibrinolysis* 1995;6(8):747-752.
3. Lee KW, Lip GY. Effects of lifestyle on hemostasis, fibrinolysis, and platelet reactivity: a systematic review. *Arch Intern Med* 2003;163(19):2368-2392.
4. El-Sayed MS, El-Sayed Ali Z, Ahmadizad S. Exercise and training effects on blood haemostasis in health and disease: an update. *Sports Med* 2004;34(3):181-200.
5. Menzel K, Hilberg T. Blood coagulation and fibrinolysis in healthy, untrained subjects: effects of different exercise intensities controlled by individual anaerobic threshold. *Eur J Appl Physiol* 2011;111(2):253-260.
6. Armstrong LE, Casa DJ, Millard-Stafford M, et al. American College of Sports Medicine position stand. Exertional heat illness during training and competition. *Med Sci Sports Exerc* 2007;39(3):556-572.
7. Veltmeijer MT, Eijvogels TM, Thijssen DH, et al. Incidence and predictors of exertional hyperthermia after a 15-km road race in cool environmental conditions. *J Sci Med Sport* 2015;18(3):333-337.
8. Gonzalez-Alonso J, Quistorff B, Krstrup P, et al. Heat production in human skeletal muscle at the onset of intense dynamic exercise. *J Physiol* 2000;524 Pt 2:603-615.
9. Bouchama A, Knochel JP. Heat stroke. *N Engl J Med* 2002;346(25):1978-1988.
10. Casa DJ, Armstrong LE, Ganio MS, et al. Exertional heat stroke in competitive athletes. *Curr Sports Med Rep* 2005;4(6):309-317.
11. Bouchama A, Roberts G, Al Mohanna F, et al. Inflammatory, hemostatic, and clinical changes in a baboon experimental model for heatstroke. *J Appl Physiol* 2005;98(2):697-705.

12. Rajagopalan S, Mascha E, Na J, et al. The effects of mild perioperative hypothermia on blood loss and transfusion requirement. *Anesthesiology* 2008;108(1):71-77.
13. Brown DJ, Brugger H, Boyd J, et al. Accidental hypothermia. *N Engl J Med* 2012;367(20):1930-1938.
14. Hart SR, Bordes B, Hart J, et al. Unintended perioperative hypothermia. *Ochsner J* 2011;11(3):259-270.
15. Rohrer MJ, Natale AM. Effect of hypothermia on the coagulation cascade. *Crit Care Med* 1992;20(10):1402-1405.
16. Shimokawa M, Kitaguchi K, Kawaguchi M, et al. The influence of induced hypothermia for hemostatic function on temperature-adjusted measurements in rabbits. *Anesth Analg* 2003;96(4):1209-1213, table of contents.
17. Casa DJ, Clarkson PM, Roberts WO. American College of Sports Medicine roundtable on hydration and physical activity: consensus statements. *Curr Sports Med Rep* 2005;4(3):115-127.
18. Wilkinson DM, Carter JM, Richmond VL, et al. The effect of cool water ingestion on gastrointestinal pill temperature. *Med Sci Sports Exerc* 2008;40(3):523-528.
19. Byrne C, Lim CL. The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. *Br J Sports Med* 2007;41(3):126-133.
20. Gant N, Atkinson G, Williams C. The validity and reliability of intestinal temperature during intermittent running. *Med Sci Sports Exerc* 2006;38(11):1926-1931.
21. van Geffen M, Loof A, Lap P, et al. A novel hemostasis assay for the simultaneous measurement of coagulation and fibrinolysis. *Hematology* 2011;16(6):327-336.
22. Weiss C, Seitel G, Bartsch P. Coagulation and fibrinolysis after moderate and very heavy exercise in healthy male subjects. *Med Sci Sports Exerc* 1998;30(2):246-251.
23. Hilberg T, Menzel K, Wehmeier UF. Endurance training modifies exercise-induced activation of blood coagulation: RCT. *Eur J Appl Physiol* 2013;113(6):1423-1430.
24. Dematte JE, O'Mara K, Buescher J, et al. Near-fatal heat stroke during the 1995 heat wave in Chicago. *Ann Intern Med* 1998;129(3):173-181.

- 1 25. al-Mashhadani SA, Gader AG, al Harthi SS, et al. The coagulopathy of heat stroke:
2 alterations in coagulation and fibrinolysis in heat stroke patients during the pilgrimage
3 (Haj) to Makkah. *Blood Coagul Fibrinolysis* 1994;5(5):731-736.
- 4 26. Bouchama A, Al-Mohanna F, Assad L, et al. Tissue factor/factor VIIa pathway mediates
5 coagulation activation in induced-heat stroke in the baboon. *Crit Care Med*
6 2012;40(4):1229-1236.
- 7 27. Roberts GT, Ghebeh H, Chishti MA, et al. Microvascular injury, thrombosis,
8 inflammation, and apoptosis in the pathogenesis of heatstroke: a study in baboon
9 model. *Arterioscler Thromb Vasc Biol* 2008;28(6):1130-1136.
- 10 28. Bunker JP, Goldstein R. Coagulation during hypothermia in man. *Proc Soc Exp Biol Med*
11 1958;97(1):199-202.
- 12 29. Doufas AG. Consequences of inadvertent perioperative hypothermia. *Best Pract Res*
13 *Clin Anaesthesiol* 2003;17(4):535-549.
- 14 30. Yankelson L, Sadeh B, Gershovitz L, et al. Life-threatening events during endurance
15 sports: is heat stroke more prevalent than arrhythmic death? *J Am Coll Cardiol*
16 2014;64(5):463-469.

Figure Legends

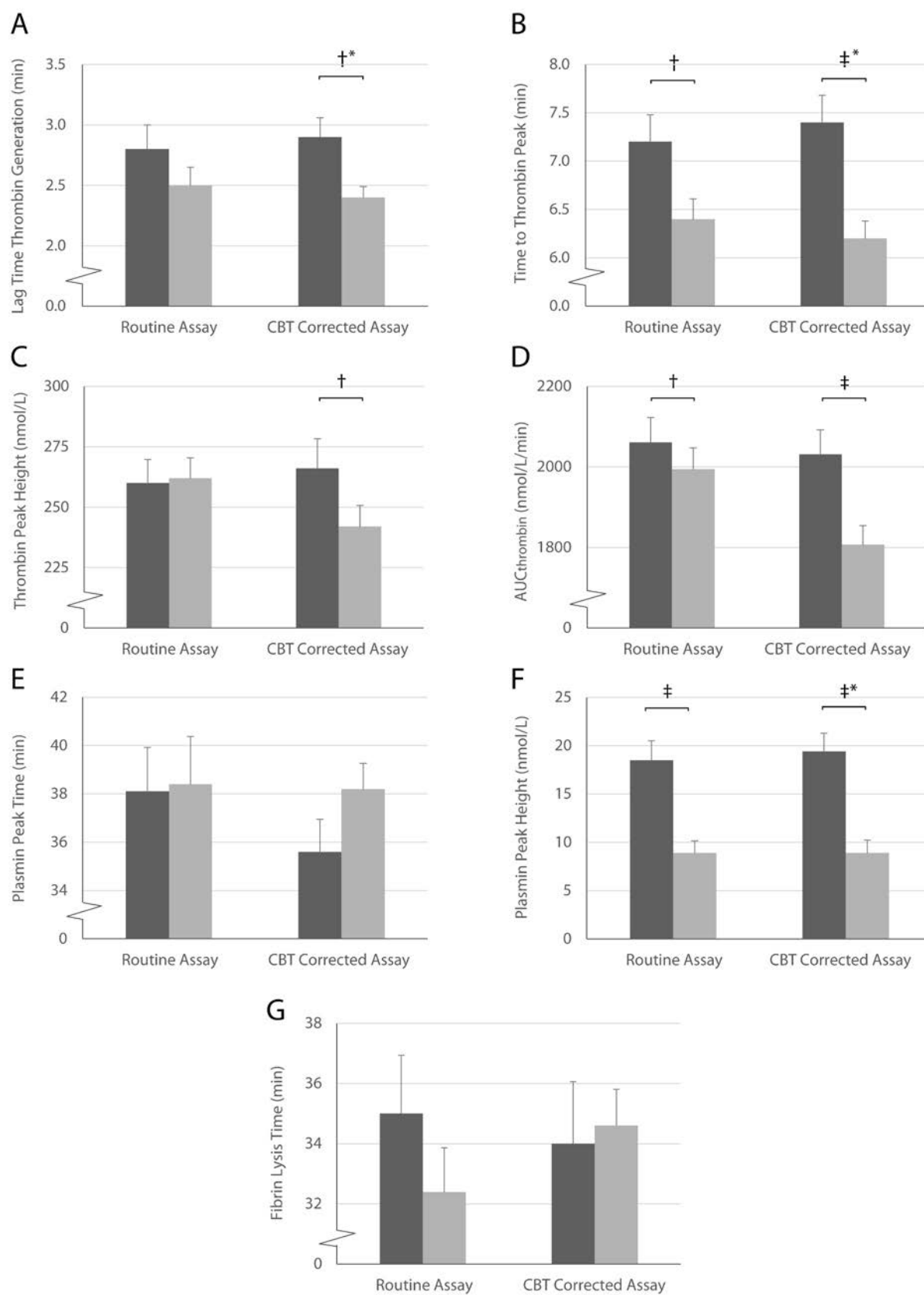
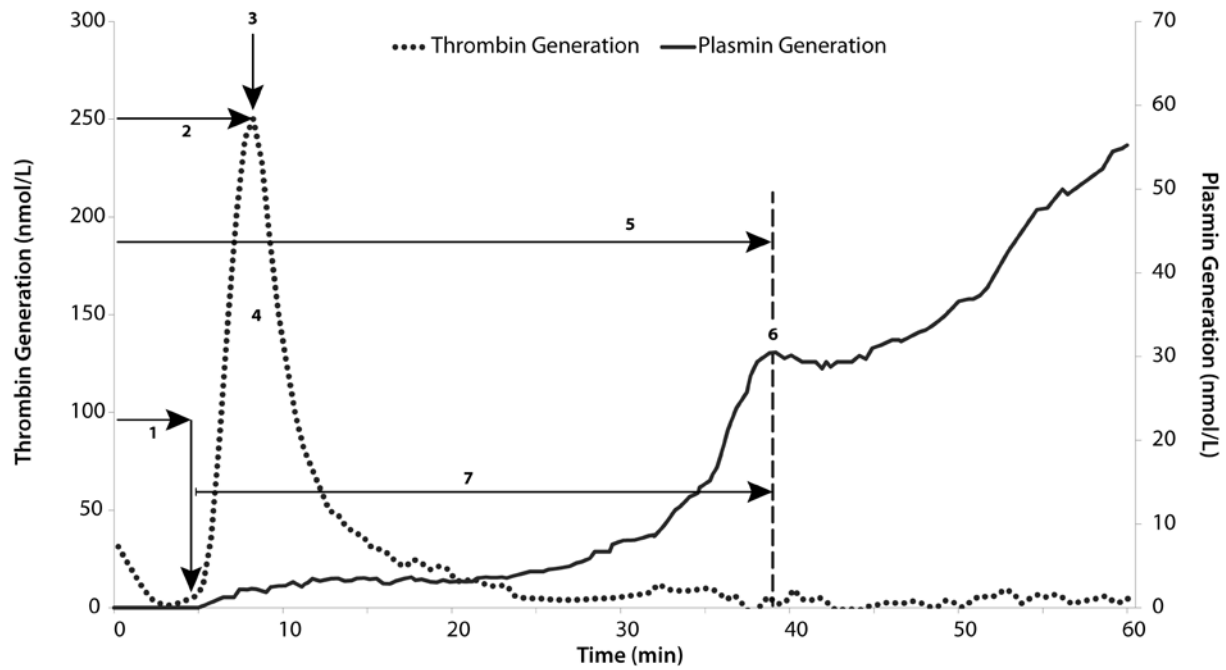


Figure 1: Results of the routinely performed assays (left hand side of graph) *versus* the assay results corrected for the actual core body temperature (right hand side of graph) at baseline and post-finish (black and grey bars respectively). All corrected results for the baseline samples were corrected for CBT at baseline, and all corrected results for the finish samples were corrected for CBT at the finish line. (A) Lag Time Thrombin Generation; (B) Time to Thrombin Peak; (C) Thrombin Peak Height; (D) AUC_{thrombin}; (E) Plasmin Peak Time; (F) Plasmin Peak Height; (G) Fibrin Lysis Time. Legend: # = p<0.05; † = p<0.01; ‡ = p<0.001; * = Statistics are based on non-parametric analysis. Data are presented as mean ± standard error of the mean. CBT = Core Body Temperature



Supplemental Figure 1: Schematic overview of the Nijmegen Haemostasis Assay. The dotted line represents real-time measurement of thrombin generation, whilst the continuous line represents the simultaneous real-time measurement of plasmin generation in the same blood sample. For the purposes of the present study, four parameters were derived from thrombin generation: (1) Lag Time Thrombin Generation (min), (2) Time to Thrombin Peak (min), (3) Thrombin Peak Height (nmol/L) and (4) AUC_{thrombin} (nmol/L/min). From plasmin generation, three parameters were derived: (5) Plasmin Peak Time (min), (6) Plasmin Peak Height (nmol/L) and (7) Fibrin lysis time (min). Adapted from Van Geffen *et al.* (2011).²¹

