

Heat stress and fetal risk. Environmental limits for exercise and passive heat stress during pregnancy: a systematic review with best evidence synthesis

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ABSTRACT

Objective Pregnant women are advised to avoid heat stress (eg, excessive exercise and/or heat exposure) due to the risk of teratogenicity associated with maternal hyperthermia; defined as a core temperature (T_{core}) $\geq 39.0^{\circ}\text{C}$. However, guidelines are ambiguous in terms of critical combinations of climate and activity to avoid and may therefore unnecessarily discourage physical activity during pregnancy. Thus, the primary aim was to assess T_{core} elevations with different characteristics defining exercise and passive heat stress (intensity, mode, ambient conditions, duration) during pregnancy relative to the critical maternal T_{core} of $\geq 39.0^{\circ}\text{C}$.

Design Systematic review with best evidence synthesis.

Data sources EMBASE, MEDLINE, SCOPUS, CINAHL and Web of Science were searched from inception to 12 July 2017.

Study eligibility criteria Studies reporting the T_{core} response of pregnant women, at any period of gestation, to exercise or passive heat stress, were included.

Results 12 studies satisfied our inclusion criteria ($n=347$). No woman exceeded a T_{core} of 39.0°C . The highest T_{core} was 38.9°C , reported during land-based exercise. The highest mean end-trial T_{core} was 38.3°C (95% CI 37.7°C to 38.9°C) for land-based exercise, 37.5°C (95% CI 37.3°C to 37.7°C) for water immersion exercise, 36.9°C (95% CI 36.8°C to 37.0°C) for hot water bathing and 37.6°C (95% CI 37.5°C to 37.7°C) for sauna exposure.

Conclusion The highest individual core temperature reported was 38.9°C . Immediately after exercise (either land based or water immersion), the highest mean core temperature was 38.3°C ; 0.7°C below the proposed teratogenic threshold. Pregnant women can safely engage in: (1) exercise for up to 35 min at 80%–90% of their maximum heart rate in 25°C and 45% relative humidity (RH); (2) water immersion ($\leq 33.4^{\circ}\text{C}$) exercise for up to 45 min; and (3) sitting in hot baths (40°C) or hot/dry saunas (70°C ; 15% RH) for up to 20 min, irrespective of pregnancy stage, without reaching a core temperature exceeding the teratogenic threshold.

INTRODUCTION

Seminal work by the late Dr Marshall Edwards provided animal model-based evidence that hyperthermia (41°C – 43°C) during gestation can result in fetal malformations and/or pregnancy complications.^{1–3} Following these studies, retrospective studies in humans demonstrated a greater risk of fetal malformations if severe hyperthermia was attained (primarily through fever) during pregnancy.^{4–9} A

maternal core temperature exceeding 39.0°C (or an elevation of $\sim 1.5^{\circ}\text{C}$ to 2.0°C from baseline) has been suggested as the critical threshold for an increased risk for teratogenic consequences to a fetus.^{10–12}

Guidelines from the American Congress of Obstetrics and Gynaecologists (ACOG),¹³ the Royal Australian and New Zealand College of Obstetricians and Gynaecologists¹⁴ and the Royal College of Obstetricians and Gynaecologists¹⁵ discourage the use of hot water baths and saunas during pregnancy and suggest ‘...avoiding high heat and humidity to protect against heat stress.’¹³ Without objective definitions, the terms ‘hot’ and ‘humid’ environments are ambiguous and subject to a wide scope of individual interpretation that may be further confounded by an altered perception of thermal stimuli with pregnancy.^{16 17}

Despite the clear downstream health benefits of exercise during pregnancy to child and mother,^{18–20} only a small proportion of pregnant women meet the recommended physical activity requirements,^{21 22} with hot weather a reported perceived barrier.^{23 24} Given that thermoregulatory capacity may be enhanced during pregnancy,^{11 25–27} in most circumstances women may be unnecessarily avoiding physical activity in warm environments due to unfounded concerns about the risk of attaining harmful core temperatures. Thus, identifying the combinations of climatic conditions, and exercise intensity, duration and mode that can be performed without exceeding a critical maternal core temperature of 39.0°C is an urgent priority. Assessing the evidence for whether different stages of pregnancy alter thermoregulatory capacity is important for obstetricians and gynaecologists, and other clinicians who might be advising pregnant women about exercise and heat exposure.

The aims of this systematic review were to (1) determine the critical environmental and exposure limits for exercise and/or heat exposure during pregnancy, and (2) assess whether thermoregulatory capacity (indicated by changes in core temperature) during exercise and/or heat exposure is altered throughout pregnancy.

METHODS

Search strategy

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines for reporting systematic reviews. All searches were conducted between 3 October 2016 and



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12 July 2017. We searched the EMBASE, MEDLINE, SCOPUS, CINAHL and Web of Science electronic databases for articles pertaining to thermoregulation during pregnancy. Specifically, two search strategies were used following the PICO format (PICO: P (Population), I (Intervention), C (Comparison), O (Outcome)):

1. A combination of pregnancy terms (P), exercise terms (I) and heat/temperature terms (O).
2. A combination of pregnancy terms (P), hot bath/sauna terms (I) and heat/temperature terms (O).

Search terms were customised for the coding of each database to search title, abstract and keywords and then combined with 'AND' to produce the final search yield (see online supplementary file 1 for the search strategy as applied to MEDLINE with yields at each step). All retrieved articles were exported to reference management software (Endnote V.X7).

Selection of studies

Titles and abstracts of retrieved articles were independently reviewed by three reviewers (NMR, WC and TE) to assess whether inclusion criteria were met. In the case of uncertainty of inclusion, the full text was retrieved and discussed. Disagreements were resolved by consensus. Reference lists of retrieved articles were also manually searched for additional relevant studies. Following the title and abstract screening, the three reviewers (NMR, WC and TE) independently retrieved the full articles of prospective studies to confirm whether they satisfied the inclusion criteria.

Study inclusion criteria

We included studies with an experimental (ie, implemented an intervention) design that assessed pregnant women (independent of gestational age). Included studies must have used a thermal stimulus to challenge the thermoregulatory system, and reported at least one index of core temperature as a dependent variable. Studies with or without a non-pregnant control group were included. We included full-text articles published in the English language.

Data extraction

Participant characteristics (ie, mass, age, weeks of gestation), experimental protocol (ie, exercise intensity, duration, mode and environmental conditions) and core temperature data were extracted by one assessor. Data were checked for accuracy by two independent assessors. For different articles using the same cohort, with no additional findings satisfying the inclusion criteria, the most comprehensive study was included. All core temperature data were extracted and expressed as a mean with 95% CIs (M (95% CI)). The change in core temperature was determined as the difference between baseline and at the end of exercise/heat exposure. Data for mean heat production (H_{prod}) expressed in watts (W) during exercise (ie, the net difference between metabolic energy expenditure and external work) were also extracted. If H_{prod} was not provided it was estimated using equations from Nielsen and Davies²⁸ if the rate of oxygen consumption (VO_2) was reported. If VO_2 was not reported, VO_2 was estimated using the American College of Sports Medicine standardised equations,²⁹ provided an objective index of external work was provided.

Risk of bias assessment

Risk of bias was independently assessed by two assessors using the Cochrane Risk of Bias Assessment (ROB) V.2.0 tool for

randomised crossover or other matched designs.³⁰ Disagreements were resolved by consensus. The individual studies' overall risk of bias was determined using the following modified assessment: *low risk of bias*: four or more domains with a low risk of bias; *some concerns*: a minimum of two domains with some concerns, or one domain with some concerns and one high risk of bias; *high risk of bias*: two or more domains with a high risk of bias.

Best evidence synthesis

A modified version of the 2009 Centre for Evidence-Based Medicine (CEBM³¹) levels of evidence for interventions was used to synthesise and rank the evidence. Our modified version (I–IV) ranked the source of evidence in the following manner: level I randomised controlled trial, level II cohort study, level III case-control study, level IV a case series or study. Studies were grouped based on the environment of exercise and/or heat stress: (1) land-based exercise, (2) water-based exercise and (3) hot bath or sauna use.

The strength of the evidence included was then evaluated using a modified version of the CEBM 'Grades of Recommendation' using the A–D grading system: A signifies consistent findings in >2 level I studies; B signifies consistent findings in >2 level II or III studies, or ≤2 level I studies; C signifies consistent findings in >2 level IV studies, or ≤2 level II or III studies; D signifies level IV evidence or inconsistent findings, independent of level. Consistency among studies was defined as the core temperature response of pregnant women during heat stress either above or below the 39.0°C threshold. The level of evidence in any study was downgraded if a *high risk of bias* or *some concerns* were determined using the Cochrane ROB V.2.0 tool.

RESULTS

We identified 1329 non-duplicate articles for title and abstract screening (EMBASE: 230; MEDLINE: 184; SCOPUS: 184; CINAHL: 55; Web of Science: 676). We screened 18 studies in full text (figure 1). One article was excluded as only an abstract was available³²; we found two instances of multiple reports from the same cohorts (totalling five articles^{33–37}) and were included.^{34 37} A total of 12 studies were included in our review.^{25 26 34 37–45}

Characteristics of included studies

The heat stress response of a total of 347 pregnant women was captured. In addition, 26 non-pregnant controls of child-bearing age were included.^{34 44} Three studies had 10 or fewer participants,^{25 37 39} six had 10–20 participants^{26 34 38 40 42 43} and three studies had more than 50 participants.^{41 44 45} Twenty-nine subgroups were tested across the gestational period and control (figure 2).

Participant characteristics

Age was reported as either range only ($n=2^{26 37}$), mean only ($n=4^{38 40 42 43}$), range and mean ($n=3^{25 34 45}$) or unreported ($n=2^{39 41}$) (online supplementary table S1 and figure 2). Four studies reported participant mass on the day of testing,^{26 38 42 44} two reported the mean mass across gestation and group tested^{34 40} and six studies did not report mass.^{25 37 39 41 43 45} Studies either did not report participant fitness levels ($n=2^{41 43}$) or objectively defined participants as sedentary ($n=2^{42 45}$) or physically active ($n=8^{25 26 37–40 42 44 45}$). The sole study using saunas stated that participants were accustomed to the practice.³⁴

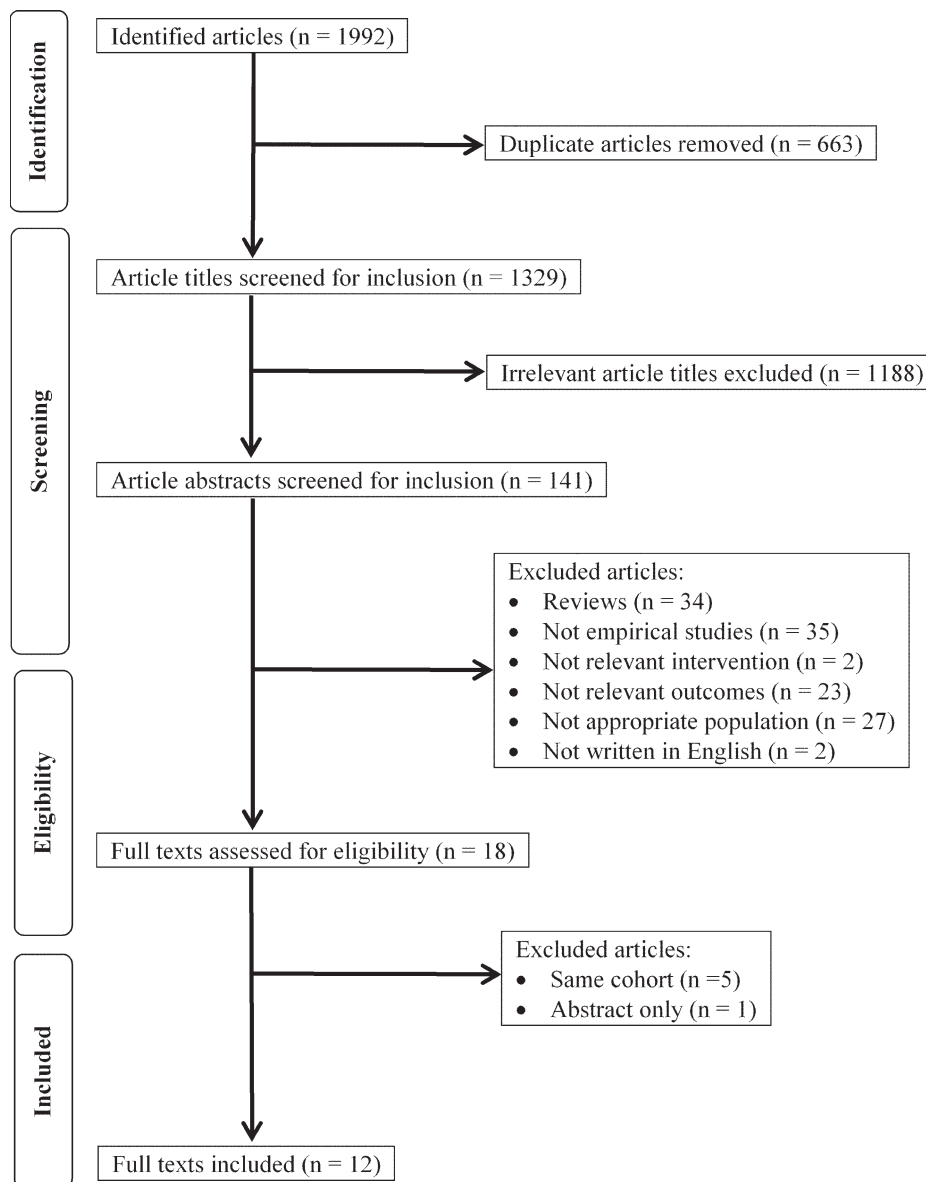


Figure 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram showing the selection and exclusion process of papers, including number of articles included in the review.

Heat stress protocols

The methods to induce heat stress in the included studies were separated into three primary categories: eight studies conducted land-based exercise,^{25 26 37 39–43} three conducted water immersion exercise ($n=3$ ^{37 38 45}) and two conducted passive heating at rest ($n=2$ ^{34 41}) (online supplementary table S1 and figure 2).

Heat production: 6 of 11 exercise-based studies^{25 26 37–39 42} provided sufficient data to extract H_{prod} , with values provided for a total of 18 groups of pregnant women at various periods of gestation (figure 2). The range of H_{prod} was 305–1195 W.

Core temperature: figure 2 illustrates the mean and 95% CI of the absolute core temperature responses of pregnant women following exercise/heat stress in the included studies. Irrespective of exercise mode, intensity or duration, or type of heat exposure, no study reported any participant exceeding a core temperature above the recommended maternal threshold of 39.0°C, with 38.9°C the highest individual core temperature reported.²⁵ The study inducing the highest H_{prod} (1195 W; 30 min running by aerobically fit pregnant participants at 80%–90% of HR_{max})

observed mean end-exercise core temperatures of 38.3°C (95% CI 37.7°C to 38.9°C³⁹; figure 2). Further, the highest mean core temperature observed during exclusively non-weight-bearing exercise (eg, cycling) on land during pregnancy was 37.6°C (95% CI 37.4°C to 37.8°C³⁷). The highest mean core temperature for pregnant women with warm water (30°C) immersion cycling was 37.5°C (95% CI 37.3°C to 37.7°C³⁸). Aqua-aerobic exercise in water temperatures ranging from 28.8°C to 33.4°C resulted in a mean core temperature of 36.7°C (95% CI 36.6°C to 36.8°C⁴⁵). Studies assessing pregnant women during passive heating via sauna or a 40°C water immersion reported mean maternal core temperatures peaking at 37.6°C (95% CI 37.5°C to 37.7°C³⁴) and 36.9°C (95% CI 36.8°C to 37.0°C⁴¹), respectively. In general, the rise in core temperature with exercise/heat exposure declined with progressive pregnancy (figure 3). The change in core temperature was significantly smaller^{46 47} later in pregnancy compared with a non-pregnant state in three of five land-based exercise studies. However, similar changes in core temperature were observed throughout pregnancy during

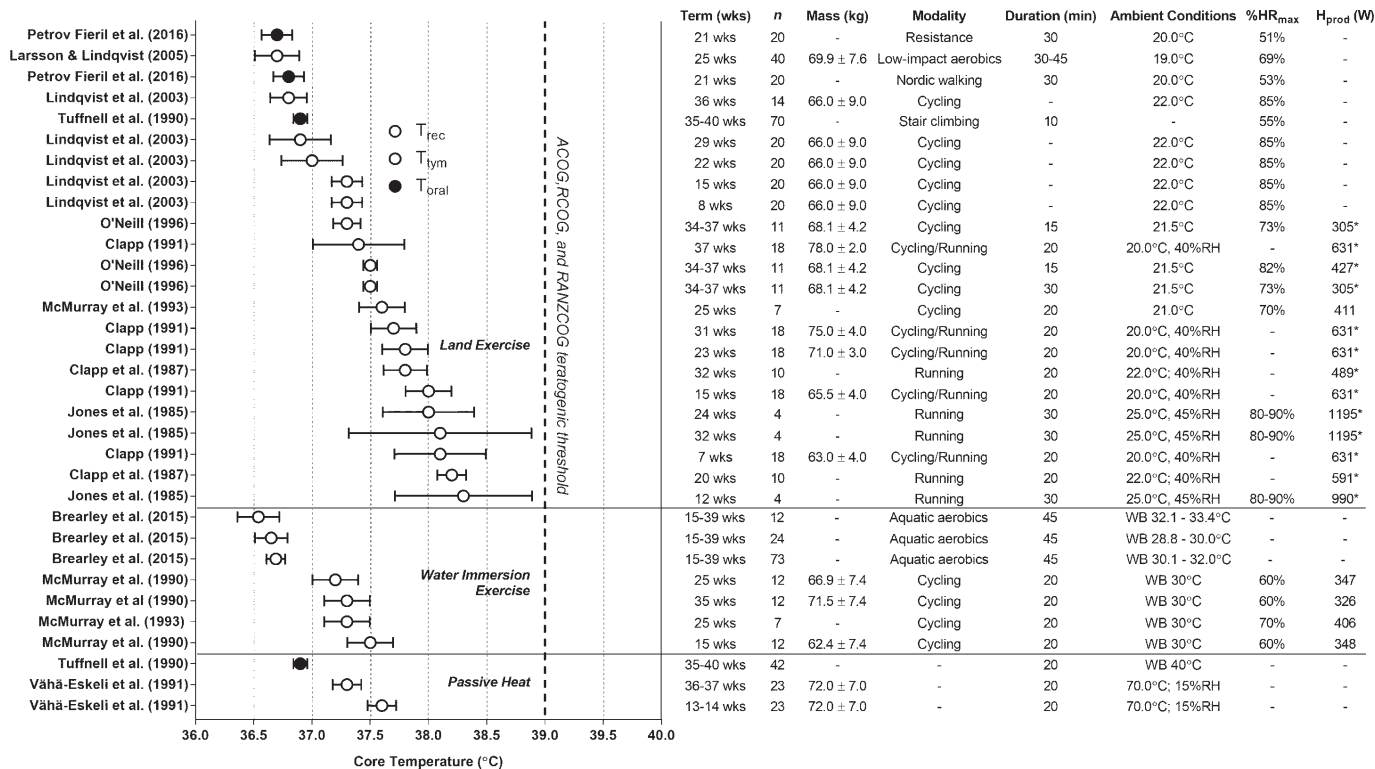


Figure 2 Mean (95% CI) absolute rectal (T_{rec}), tympanic (T_{tym}) or sublingual (T_{oral}) temperature reported following exercise on land or water immersion, and passive heat stress during pregnancy. The modality of exercise, ambient conditions and exercise intensity relative to estimated maximum heart rate (%HR_{max}) and heat production (H_{prod}) are provided. The black dotted line reflects the teratogenic temperature threshold defined by ACOG,¹³ RCOG¹⁵ and RANZCOG.¹⁴ * H_{prod} estimation from provided information. ACOG, American Congress of Obstetrics and Gynaecologists; HR, heart rate; RANZCOG, Royal Australian and New Zealand College of Obstetricians and Gynaecologists; RCOG, Royal College of Obstetricians and Gynaecologists; RH, relative humidity; WB, Water Bath.

the one study reporting warm water immersion exercise³⁸ and during sauna use.³⁴

Risk of bias assessment

Using our modified Cochrane ROB V2.0 tool, six studies (out of 12) had some concerns about (n=5) or were at high risk (n=1) of selection bias,³⁹ detection bias⁴⁵ and intervention bias.^{25 26 40 42}

Best evidence synthesis

There is level B evidence to support the low risk of maternal core temperature exceeding 39.0°C during land-based exercise, independent of gestational age and modality (eg, running, cycling, aerobics, resistance), and at intensities up to 90% of HR_{max} by fit pregnant women for up to 35 min, in ambient conditions not exceeding 25°C and 45% relative humidity (RH). This recommendation is supported by six studies with level II–III evidence and two studies with level IV evidence (online supplementary table S2).

There is level C evidence to support the low risk of maternal core temperature exceeding 38.0°C, during aquatic-based cycling or aerobics lasting 20 and 45 min, respectively, in water temperatures up to 33.4°C by pregnant women, independent of gestational age. This recommendation is supported by three studies ranging from level I to level III evidence (online supplementary table S2).

There is level D evidence to support the low risk of maternal core temperature exceeding 38.0°C, during passive heat exposure to warm baths (40.0°C) or sauna use (70.0°C, 15% RH) for up to 20 min. This recommendation is supported by two studies

ranging from level II to level IV evidence (online supplementary table S2).

DISCUSSION

Our systematic review suggests that pregnant women can participate in up to 35 min of very high-intensity aerobic exercise (~90% HR_{max}) at air temperatures of up to 25°C and 45% RH without attaining or exceeding a core temperature of 39.0°C; the hypothesised teratogenic threshold during pregnancy.¹⁰⁻¹² Similarly, no study has ever reported the core temperature of a pregnant woman to exceed 38.0°C, 1.0°C lower than the critical maternal core temperature, when exercising in a warm bath (30°C^{37 38}) or during resting exposure to a hot and dry sauna (70°C; 15% RH³⁴) or immersion in a 40°C water bath⁴¹ for up to 20 min. Change in core temperature during exercise/heat exposure appears to decline with progressive pregnancy (figure 3).

While the downstream benefits to the children of pregnant women who engage in regular physical activity prior to and throughout pregnancy have been well documented,¹⁸⁻²⁰ exercise inevitably results in the production of heat, which must be liberated to the environment to mitigate the rise in internal temperature. The excess heat produced from muscular contractions is first transferred to the surrounding tissue by a combination of conduction and convection through the circulatory system where it will ultimately be dissipated from the skin surface to the surrounding environment through dry or evaporative (ie, sweating) avenues. The temperature gradient for heat transfer flows from fetus to mother at rest, but this gradient is reversed during exercise.⁴⁸

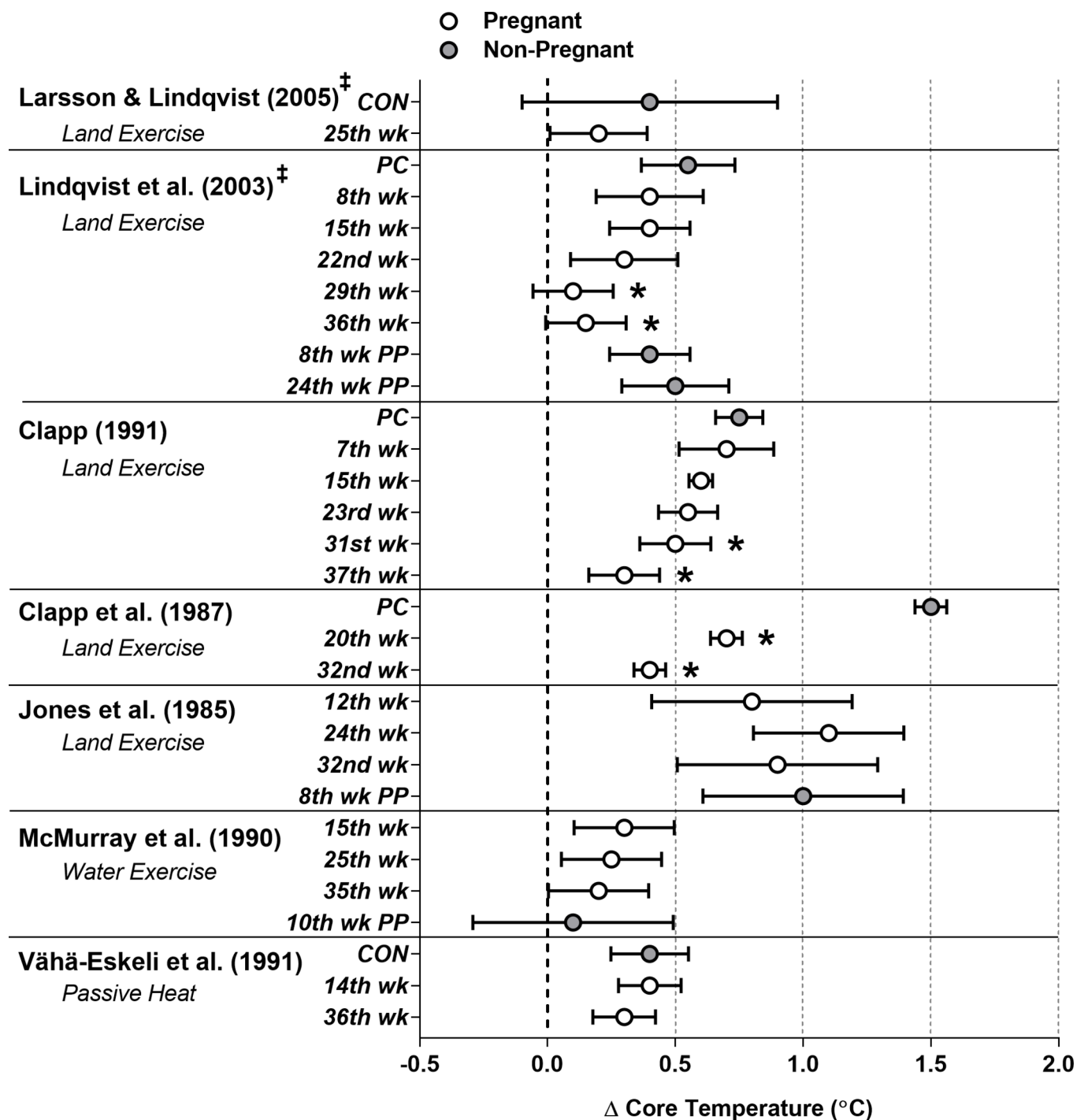


Figure 3 The change in core temperature following land or water immersion exercise, and passive heating in women preconception (PC), across the gestation period and post partum (PP). One study used tympanic temperature as the index of core temperature (‡), while the others used rectal temperature. *Significantly lower than PC. CON denotes an independent non-pregnant control group.

During pregnancy, the main avenue for heat transfer between mother and fetus is via the placental wall and uterine blood flow.⁴⁹ With increasing maternal core temperatures, there is evidence of reduced uterine blood flow,^{50 51} although compensatory mechanisms exist to maintain nutrient supply to the fetus.^{48 52 53} Nevertheless, fetal heat balance is entirely dependent on the thermoregulatory capacity of the mother. Thus, progressive hyperthermia will increase the risk of exceeding the teratogenic threshold (maternal core temperature >39.0°C). The teratogenic threshold is based on the

smallest change in core temperature observed to induce fetal defects in animal studies (1.5°C; assuming a resting internal temperature of 37.5°C for humans⁵⁴) and supported by retrospective cohort studies in human populations.^{5 7 8} In absolute terms, the proposed teratogenic threshold is potentially conservative by more than 1°C: animal model evidence in fact suggests a 40°C teratogenic threshold.^{2 3 55-57} Nevertheless, the present systematic review found no study in humans reporting core temperatures exceeding 39.0°C nor a change in core temperature greater than 1.5°C during high-intensity

exercise (ie, $>70\% \text{HR}_{\text{max}}$) or passive heat stress (figures 2 and 3, respectively).

An enhanced thermoregulatory capacity during pregnancy has been previously hypothesised.^{11 25-27} Indeed, we observed a reduction in the rise in core temperature with progressive pregnancy in some studies (figure 3); however, this pattern may not necessarily be indicative of altered thermoregulatory function due to pregnancy per se as results may be confounded by the experimental design used to compare thermoregulatory responses at different time points in different studies. For example, Lindqvist *et al*⁴⁰ employed an exercise intensity ramp protocol without reporting exercise duration. As exercise capacity would presumably be lower during the later stages of pregnancy,^{58 59} a shorter exercise duration, lower cumulative H_{prod} and thus a smaller rise in core temperature would seem likely. Additionally, a larger body size provides a bigger heat sink and a greater potential to dissipate heat by virtue of a larger surface area.⁶⁰ Cramer and Jay⁶¹ recently demonstrated a greater change in core temperature in morphologically smaller men when prescribed the same absolute heat production (ie, in watts). It follows that the rise in core temperature during exercise was dependent on the rate of heat production relative to total body mass (W/kg^{61}), therefore exercise at a fixed heat production at different stages of pregnancy should theoretically lead to smaller rises in core temperature, due to the progressively greater mass. Nevertheless, no study has yet investigated the core temperature response to exercise during pregnancy while accounting for the progressive and often dramatic morphological transformation during pregnancy. As such, the extent that morphological factors independently explain the alterations in the core temperature response during pregnancy remains unclear.

The smallest elevations in core temperature were observed during water-based exercise^{37 38 45} (figures 2 and 3). Indeed, the ~ 25 -fold greater thermal conductivity of water compared with exercise in air (ie, $0.610 \text{ W}/\text{m}/\text{K}$ vs $0.025 \text{ W}/\text{m}/\text{K}$, respectively) hastens non-evaporative heat loss, provided water temperature is lower than skin temperature. Moreover, hydrostatic pressure during water immersion facilitates a greater cardiac filling resulting in a reduced cardiovascular strain compared with land-based exercise for a given exercise intensity in both non-pregnant⁶² and pregnant women.⁶³ When pregnant women engaged in a similar intensity exercise out of water, the elevation in core temperature was slightly greater compared with its water-based equivalent (figure 2)³⁷ although still far below the stated critical core temperature. It is possible that exercising during pregnancy at similar rates of heat production, but in higher ambient air temperatures than previously evaluated,³⁷ will result in core temperatures exceeding the teratogenic threshold; in that setting, it may be recommended to limit physical activity to safer environments such as water immersion.

Health guidelines for pregnant women unanimously state that hot water immersion or sauna use should be restricted due to the elevated risk of maternal hyperthermia and the consequent potential impact on fetal development. However, our results suggest that heat stress risk is low (figure 2). It may be unlikely for pregnant women to achieve teratogenic levels of hyperthermia during passive heating due to high levels of discomfort truncating exposure time.⁶⁴ Indeed, the rate of rise in core temperature during hot water immersion is dependent on the mass of the individual.^{65 66} Therefore, greater body mass towards the latter stages of pregnancy may mean the exposure duration required to achieve a core temperature exceeding 39.0°C could be longer.⁶⁷ With respect to saunas, provided there are no physiological impairments to sweating, the ambient conditions (eg,

hot and dry) facilitate high levels of evaporative heat loss.⁶⁸ As demonstrated by Vähä-Eskeli *et al*,³⁴ the highest mean core temperature in pregnant women following 20 min of sauna exposure (70°C , 15% RH) was more than 1.0°C lower than the critical 39.0°C threshold (37.8°C ; figure 2).

There were three different regions used for measuring core temperature responses: rectal, sublingual and tympanic membrane (figure 2). The clinical gold standard index of core temperature is pulmonary artery temperature.⁶⁹ However, this measurement is highly invasive and impractical. Alternatively, rectal temperature closely correlates with pulmonary artery temperature,⁶⁹ and its measurement is endorsed by the American College of Sports Medicine⁷⁰ for assessing exercise-induced hyperthermia. Less invasive core temperature measurements such as tympanic membrane and sublingual temperature may be $\sim 0.5^\circ\text{C}$ lower than rectal measurements during hyperthermia.^{71 72} However, regardless of the method used to define core temperature, the highest reported mean tympanic membrane temperature and sublingual temperature following exercise or passive heat stress during pregnancy in the included studies were 37.3°C and 36.9°C , respectively (figure 2); more than 1.7°C lower than the maternal teratogenic threshold of 39.0°C .

In this review, the assessment of thermoregulatory responses to exercise during pregnancy was limited to warm or temperate conditions ($\sim 25^\circ\text{C}$). There may be an association between high ambient temperatures and an increased risk of poor birth outcomes such as preterm delivery^{73 74} and low birth weight.⁷⁵ However, exercise during pregnancy reduces the risk of infants born at extreme ends of the birth weight range,⁷⁶ protects against preterm birth^{76 77} and improves nutrient delivery to the fetus to support development.⁵² Despite the clear benefits of exercise during pregnancy for mother and unborn child, it remains unclear whether regular physical activity during pregnancy may counterbalance any potential association between high ambient temperatures and birth complications. Thus, more research is needed to identify safe exposure and environmental limits for pregnant women who are physically active in hotter climates, and to elucidate the underlying mechanism responsible for any potential increased risk of poor birth outcomes during prolonged exposure to high ambient temperature.

Limitations

All included studies were at high risk of allocation bias because of the study design, but we considered allocation bias as a lower threat to the internal validity of this review. Overall, the body of evidence is limited by issues related to intervention, selection and measurement bias. Only one study met the criteria for CEBM level I evidence, and there was especially limited evidence for water immersion exercise (grade C) and sauna or hot bath use (grade D). This means that recommendations may change with future research. We only included published full-text articles, which means there is a risk of publication bias.³² There is also a risk for language bias since we only included articles written in English. The small body of literature and inconsistency in study design precluded data pooling. Instead we used best evidence synthesis.⁷⁸

CONCLUSION

Pregnant women may safely engage in: (1) exercise for up to 35 min at 80%–90% of their maximum heart rate in 25°C and 45% RH; (2) water immersion ($\leq 33.4^\circ\text{C}$) exercise for up to 45 min; and (3) sitting in hot baths (40°C) or hot/dry saunas (70°C ; 15% RH) for up to 20 min, irrespective of pregnancy

What is already known on this topic?

- ▶ Animal studies have shown that hyperthermia during pregnancy can be teratogenic.
- ▶ Pregnant women are advised to avoid heat stress such as exercise in the heat, hot baths or saunas, because of concern about the risk of reaching a core temperature above the proposed teratogenic threshold of 39.0°C.
- ▶ An enhanced thermoregulatory capacity has been hypothesised during pregnancy which could increase thermoprotection to the developing fetus.
- ▶ Current guidelines do not clearly define critical heat stress limits that should be avoided.

What are the new findings?

- ▶ Pregnant women can safely engage in: (1) exercise for up to 35 min at 80%–90% of their maximum heart rate in 25°C and 45% relative humidity (RH); (2) water immersion ($\leq 33.4^\circ\text{C}$) exercise for up to 45 min; and (3) sitting in hot baths (40°C) or hot/dry saunas (70°C; 15% RH) for up to 20 min, irrespective of pregnancy stage, without reaching a core temperature exceeding the teratogenic threshold.
- ▶ The previously hypothesised enhancement of the thermoregulatory capacity of pregnant women is supported by smaller changes in T_{core} during exercise/heat exposure as pregnancy progresses. The underlying mechanism is unclear but is likely biophysical in nature, associated with changes in body mass and surface area, and not due to alterations in physiological control.
- ▶ The critical exercise (eg, intensity, duration) and environmental (eg, temperature and humidity) characteristics at which the upper limit for maternal T_{core} (39.0°C) is exceeded remains unknown, and requires urgent future research with further refinement incorporating extrinsic (eg, clothing) and intrinsic (eg, acclimation status) factors.

stage, without reaching a core temperature exceeding the teratogenic threshold.

Contributors NMR, WC, TE, KME and OJ were involved in the conception and design of the systematic review. NMR, WC and TE were responsible for conducting the systematic search. The selection of studies based on the inclusion criteria was primarily conducted by NMR, WC and TE. When disagreement occurred, all authors critically appraised the study inclusion. NMR and WC completed the Cochrane Risk of Bias 2.0 Tool. Data extraction from the included studies was conducted by NMR and independently confirmed by WC and OJ. All authors interpreted the results. NMR, WC and TE drafted the manuscript. OJ and KME critically revised the manuscript. All authors have approved the final version of the manuscript.

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Competing interests None declared.

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