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Extreme endurance training and coronary artery disease: A systematic review and a meta-analysis

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ABSTRACT

Background: Physical activity is advocated for cardiovascular health; however, excessive endurance exercise may pose risks. This systematic review and meta-analysis explore the relationship between endurance training and coronary artery disease (CAD) diagnosed at coronary CT angiography (CCTA).

Methods: Following PRISMA guidelines, we searched MEDLINE, Embase, and Scopus up to January 4th, 2024. Inclusion criteria encompassed studies on adults with sample size >10, various study designs, and assessment of endurance training and CAD via CCTA.

Results: Endurance athletes exhibited a higher prevalence of coronary atherosclerosis compared to controls. However, they did not demonstrate a greater prevalence of high-risk or obstructive plaques. Continuous coronary artery calcium (CAC) scores did not significantly differ between athletes and controls. Athletes showed a slight increase in the odds of having CAC > 400.

Conclusion: Endurance athletes are more likely to have coronary atherosclerosis but not more likely to have high-risk plaques compared to sedentary individuals. Further research is needed to establish threshold values for physical exercise beyond which sports can become harmful and identify which types of sports carry the greatest risk.

1. Introduction

The benefits of engaging in physical activity are widely recognized [1], so much that international guidelines recommend regular exercise to prevent cardiovascular diseases. The 2020 European Society of Cardiology (ESC) guidelines recommend 150 min per week of moderate-intensity, or 75 min per week of a more vigorous-intensity aerobic training, or a combination equivalent to this. Moreover, an incremental rise in aerobic exercise to 300 min per week of moderate-intensity, or 150 min per week of vigorous-intensity aerobic exercise are more beneficial, and for additional benefits for all adults this activities can be combined together [2].

However, increasing evidence suggests that excessive endurance exercise, both in terms of volume and intensity, may be associated with the presence of coronary atherosclerotic disease [3].

Extreme exercise can potentially pose risks, including adverse cardiac remodeling, atherosclerosis and myocardial damage. Research suggests a correlation between prolonged endurance training and the presence of coronary plaques, challenging the traditional belief that exercise solely protects against cardiovascular issues [3]. Athletes demonstrate distinct plaque compositions, prompting inquiries into the impact of exercise on arterial health. Additionally, markers of myocardial damage following prolonged exertion highlight potential hazards.

The identification of the optimal balance between exercise intensity and cardiovascular well-being remains a topic of ongoing investigation. Understanding these complexities is crucial for tailoring exercise recommendations to promote long-term cardiovascular health in individuals involved in vigorous endurance activities.

While studies contribute significantly to sports cardiology literature, they also raise as many questions as they answer. Addressing remaining areas of uncertainty requires acknowledging and focusing on three key issues: limitations inherent in cross-sectional data, potential effects of unmeasured confounders, and the absence of clinical outcomes.

To address this uncertainty, we conducted a systematic review and a

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metanalysis of the studies investigating the presence of atherosclerotic disease in endurance athletes detected with coronary CT angiography (CCTA).

2. Methods

This systematic review has been conducted in accordance with the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [4]. The full checklist is available in the supplementary material.

2.1. Search strategy

We conducted electronic searches for eligible studies within each of the following databases, up to January 4th, 2024: MEDLINE (accessed via PubMed), Embase, and Scopus.

Records were identified in each database with tailored search strings, which can be found in the supplementary material. In order to maximize sensitivity, the search strings only included elements related to the exposure (extreme endurance training) and outcome (coronary artery disease).

2.2. Selection criteria

Inclusion criteria were as follows:

- Studies on human adults (over 18 years)
- Sample size >10 subjects
- RCT, nRCT, observational studies (prospective and retrospective)
- Studies on endurance training and coronary artery disease. Here, extreme endurance training refers to participation in long-distance races or multi-day events, including but not limited to running (such as marathons and ultra-marathons), endurance cycling, open water swimming, and Ironman triathlons. Although no specific thresholds for training volume, intensity, or duration were set, participation in these events typically requires training at levels beyond those of conventional sports.
- Articles written in one of the following languages: English, Italian, German, French, Romanian, Russian, Dutch, Spanish, Portuguese.

Exclusion criteria were as follows:

- Studies without CCTA or CAC score;
- Case reports, conference abstracts, reviews, letters, and editorials.

Citations identified from the literature searches were imported to Rayyan (https://rayyan.ai/) and duplicates were automatically removed by the software. Two reviewers (FEP and GG) then independently screened the titles and abstracts of all records. In case of disagreement about eligibility, a consensus was reached through discussion. Full texts of all potentially eligible studies, systematic reviews and meta-analyses were retrieved, and reference lists were checked to identify additional eligible studies and to elucidate theoretical aspects in the discussion.

2.3. Data extraction

Data extraction from eligible studies was performed by FEP and GG independently. We extracted data about study design: sample size, age, type of sport or training, inclusion and exclusion criteria, setting, performed exams, variables included, as well as findings and limitations of the study.

2.4. Data analysis

A meta-analysis was performed for the variables collected in more than one paper, including CACS, presence of plaques, presence of high-risk plaques, presence of coronary stenosis >50 %, CACS >100 and CAC > 400. CACS was analyzed by comparing pooled means and medians between athletes and controls. For the other variables, pooled OR were computed. A random effect model was used. In cases in which only median-based measures were provided, two approaches were used and compared, namely mean-based and median-based approaches based on quantile estimation, following the considerations made in McGrath, 2023 [5]. For the mean-based approach we left the number of bootstrap replicates at 1000 as per the default option. Only the median-based results are reported in the manuscript; mean-based results can be found in the supplementary material. In case the papers included more than one active group, different analyses were performed with one group at the time. The packages *metamedian* and *metafor* in R 4.3.0 were used to run the analyses and generate forest plots. If there was significant heterogeneity, as shown by high I^2, a leave-one-out approach was used to address the sources of heterogeneity. Since the studies by Feuchtner had overlapping samples (as confirmed by the authors, *personal communication*), we ran separate analyses with their mutual exclusion in case they both reported the same variables.

3. Results

We identified 1343 records after the initial search. After duplicate removal, 838 titles were screened. After abstract and title screening, 21 reports were assessed for eligibility, and 14 were included in the review (the flow diagram is shown in Fig. 1). The majority of the available studies predominantly include male subjects. However, studies that incorporate a significant proportion of female participants include Feuchtner, Jafar (where females comprise 66 % of the study population), Kleiven (with 29 % female subjects), and Merghani (where women represent 44 % of the total cohort). Reference checking did not add any additional study and was omitted in the fig.

A list of the relevant data of each study is presented in the Table 1.

1. **CAC score**

There were no significant differences in medians of continuous CAC scores between athletes and controls (Fig. 2). This was confirmed in sensitivity analyses with estimated means and including the results from Feuchtner 2020 instead of Feuchtner 2019.

Athletes showed an increased OR of 1.61 [95 % CI: 1.22–2.12, $p < 0.001$] of having a CAC over 100 (Fig. 3). The OR was slightly lower (1.48), but still significant when including the late-onset athletes in the study by De Bosscher, instead of the life-long athletes. When running the analysis with the age-matched controls instead of the age- and risk-matched controls from the study of Mohlenkamp 2008, the OR was no longer significant.

Analogously, athletes had a significant increase (OR = 1.49, 95 % CI 1.10–2.01, $p = 0.009$) in the odds of having a CAC over 400 (Fig. 3). This was marginally significant (OR = 1.35, 95 % CI 1.00–1.81, $p = 0.051$) when considering the late-onset athletes in the study by De Bosscher. Again, the OR was no longer significant when we included the age-matched controls from Mohlenkamp 2008.

The results of all the sensitivity analyses, together with the results of the leave-one-out approach to address high heterogeneity, can be found in the supplementary material (**Figs. S1-S8**).

In the MARC-2 study, a follow-up to the MARC-1 study, middle-aged and older men were assessed for the presence and severity of CAC and plaques using CCTA. The volume and intensity of exercise training, measured in metabolic equivalent of task (MET) hours per week, were quantified during the follow-up period. Results from the study, involving 289 participants with a median age of 54 years, revealed that participants exercised for an average of 41 MET hours per week during the 6.3-year follow-up. The prevalence of CAC increased from 52 % to 71 %, and the median CAC score rose from 1 to 31. The intensity of

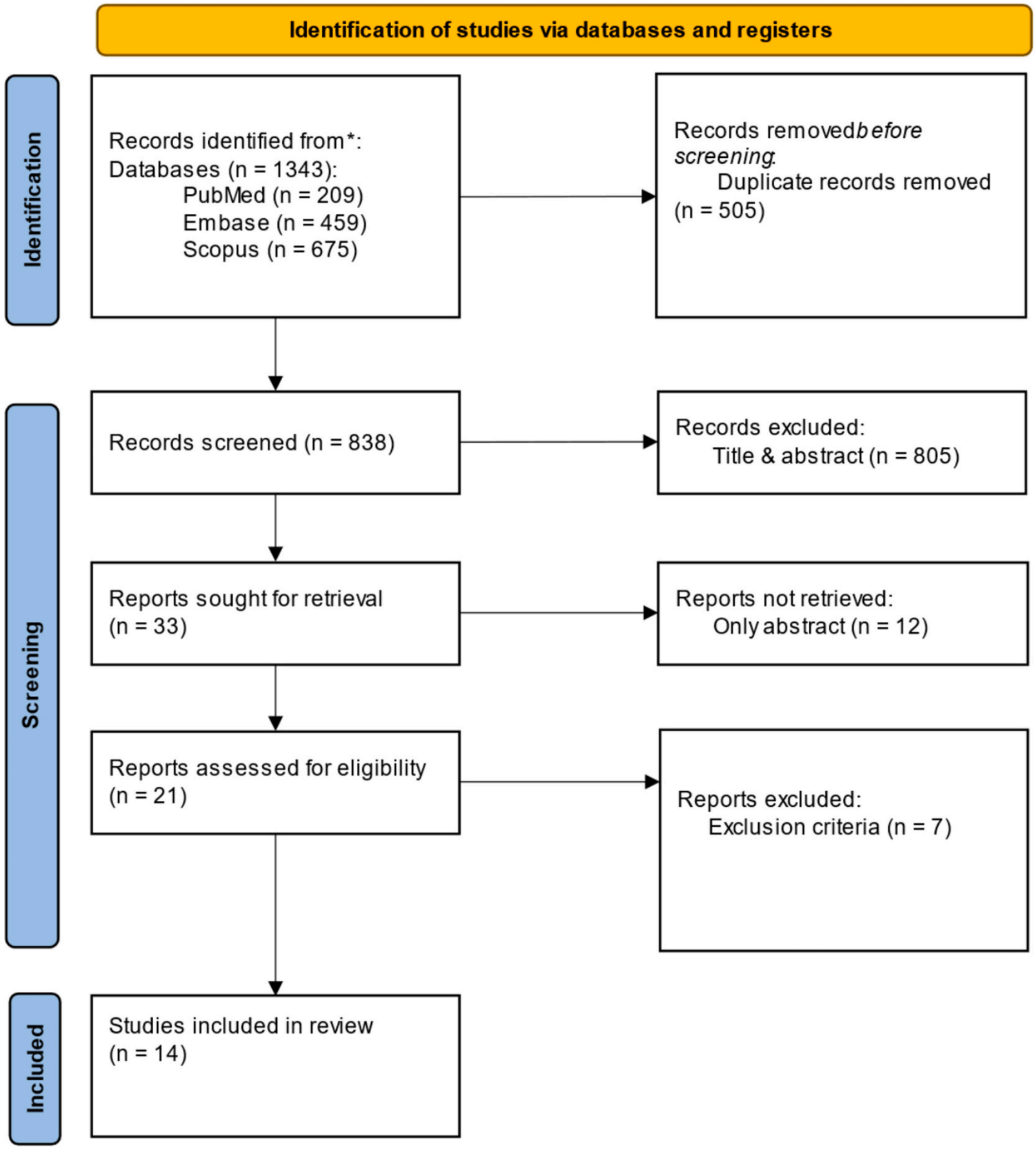

Fig. 1. PRISMA flow-chart.

exercise showed interesting associations. Vigorous intensity exercise was linked to a lesser increase in CAC, while an increase in very vigorous intensity exercise was associated with a greater increase in CAC.

Another study that showed a linked between CAC and endurance activities and that we could not be included in the meta-analysis due to the heterogeneity in the expression of its data compared to the other studies compared Ironman and marathon runners, dividing 85 participants based on their endurance race history over 10 years. Group A consisted of those in $\geq$10 ultra-marathons or full-distance triathlons, Group B had $\geq$9 marathons, and Group C participated in >9 shorter races. Excluding 29 partecipants with cardiovascular risk factors, the study evaluated CAC scores. Groups A and B showed no significant difference in CAC >0 or > 100, but combined had significantly higher rates than Group C (CAC >0: 73 % vs. 21 %, $P = 0.0002$; CAC >100: 33 % vs. 12 %, $P = 0.05$). Adjusting for age, sex, and running years, Groups A and B had higher likelihoods of CAC >50th percentile (10-fold, $P = 0.02$) and abnormal CAC (8.8-fold, $P = 0.03$), despite no significant prediction for CAC >100 ($P = 0.12$) [6].

The works of Mohlenkamp confirm previous studies and show that endurance athletes more frequently have CAC scores >100. Furthermore, the study published in 2013 [7] is the only one that shows a correlation between CAC values and coronary events; indeed, higher CAC scores are associated with an increased risk of coronary events.

Kim investigated marathon runners aged 40–60 with exercise-induced hypertension (EIH). Participants were divided into two groups: normal blood pressure group (NBPG) and EIH group (EIHG), based on their blood pressure readings during exercise. The EIHG had significantly higher CAC scores and higher proportions of CAC scores $\geq$10 or $\geq$ 100 [8].

Three studies, on the other hand, do not show a correlation between high CAC scores and extreme endurance activity [9–11].

The main conclusions of the included studies are shown in Table 1.

2. Plaque burden

Athletes had increased odds of having at least one coronary plaque (OR = 1.63, 95 % CI 1.21–2.21, $p = 0.001$), as shown in Fig. 4. Again, the OR was slightly lower (1.42) for the analysis with late-onset athletes in De Bosscher (**Fig. S9** in the supplementary material).

Athletes consistently showed a lower OR of having high-risk plaques,

Table 1
Characteristics of the included studies.

Study	Cardiovascular profile risk	Sample	Sport and volume of training	Volume of training	Age	Males	Main findings
Aengevaren 2023 [15]	Low to intermediate, 7 % hypertensive, 6 % statin use, 50 % previous or current smoker	289	Any,	41 MET hours/week	60.2 ± 7.2	100 %	CAC score and plaque prevalence increased over time
De Bosscher 2023 [3]	Low	558	Cycling, running, triathlon	Cycling >8 h for week, running >6 h weekly, triathlon >8 h weekly	55.6 ± 7.8	100 %	Lifelong athletes had a higher CAC percentile and mixed plaque than controls; more prevelance of atherosclerosis in athletes than in controls;
Feuchtner 2019 [16]	Low to intermediate	252	Cycling, running	Moderate volume (3–5 times per week) or high volume (5–7 times per week)	55 ± 22.3	64 %	CAC low in recreational endurance athletes (moderate-to-high level) and lower atherosclerosis burden by CTA compared to sedentary controls
Feuchtner 2020 [17]	Low to intermediate	100	Cycling, running	Moderate volume (3–5 times per week) or high volume (5–7 times per week)	56 ± 11.6	71 %	Lower coronary atherosclerosis burden by CTA in recreational athletes (moderate-to-high intensity)
Jafar 2019 [6]	Low	56	Marathon	At least 40.0 ± 10.9 miles/week of run	59.1 ± 7.8	34 %	Runners participating in extreme distance running had more CACS >0 ($p < 0.0002$).
Kim 2020 [8]	Low	50	Marathon	At least 2 run of training per week	53.2 ± 5.1	100 %	More subjects with EIH had CACS >10 and CACS >100
Kleiven 2020 [11]	Low to intermediate, 45 % former smoker	61	Marathon	56 MET/h	45.9 ± 9.6	74 %	Exercise training dose is not related to coronary artery calcification
Kroger 2011 [10]	Low to intermediate, 57 % ever smoked	100	Marathon	Not specified	57 ± 6	100 %	Prevalence of atherosclerosis is related to risk factors
Kwasniewska 2016 [18]	Low to intermediate, 17 % current smokers	62	Any	Three groups representing stable low-to-moderate (<2050 kcal/week), high (2050–3840 kcal/week) and very high physical activity (>3840 kcal/week).	59.8 ± 8.6	100 %	Very high intensity of physical activity leads to more coronary inflammation than high intensity
Merghani 2017 [19]	Low	244	Cycling, running	Run ≥10 miles or cycle ≥30 miles per week	54.4 ± 8.5	66 %	Sedentary males have predominantly mixed plaque, whereas athletes have more calcific plaques
Mohlenkamp 2008 [20]	Low to intermediate, 56 % current or former smokers, 7 % hypertension	324	Marathon	4686 ± 2285 MET/week	57.1 ± 5.6	100 %	Higher rates of CAC > 100 in marathoners compared to FRS-matched controls
Mohlenkamp 2013 [7]	Low to intermediate	324	Marathon	Not specified	57.1 ± 5.6	100 %	Higher CAC correlates with coronary event
Nassenstein 2008 [21]	Low to intermediate, smoker or previous smoker included	105	Marathon	From 45 to 65 km per week	57.2 ± 5.7	100 %	Runners with LVMM >150 g had significantly higher CAC scores than runners with LVMM<150 g
Roberts 2017 [22]	Low to intermediate, 48 % previous or current smoker, 24 % with history of hypertension, 46 % with hyperlipidemia	50	Marathon	Not specified	59.4 ± 0.9	100 %	CAC correlates to risk factors, not to number of marathons or years of activity

Continuous data are presented as mean ± standard deviation. Abbreviations: CAC = coronary artery calcium; IQR = interquartile range; SBP = systolic blood pressure; DBP = diastolic blood pressure; EIH = exercise-induced hypertension; LVMM = left ventricular muscle mass.

although this did not reach statistical significance in any of the analyses. Similarly, athletes did not show a significantly increased OR of having a coronary stenosis >50 %. The forest plots for these analyses are shown in the supplementary material (**Figs. S10-S11** in the supplementary material). All studies included in the meta-analysis go in the same direction, but the result is mainly due to the Merghani study, which showed a higher prevalence of atherosclerotic plaques in athletes compared to controls (44.3 % versus 22.2 %; $P = 0.009$); moreover, endurance athletes have a higher risk of developing calcified coronary plaques compared to sedentary individuals, who develop more mixed composition plaques. Additionally, the years of intense exercise are correlated with the likelihood of having obstructive coronary stenosis [12].

Instead, the Master Heart study analyzed coronary atherosclerosis and plaque composition in three different groups: in lifelong endurance athletes, in those who started later and in sedentary individuals. The results indicated that endurance athletes could develop even more dangerous lipid plaques. This risk is present not only in those who start later in life but also in those who have been athletes their entire lives. Furthermore, these athletes were carefully selected by excluding all individuals with cardiovascular risk factors [3].

The Marc-2 study confirms the impact of very intense physical activity on the progression of coronary plaques over a follow-up period of about six years; however, such activity is not associated with an increase in high-risk plaques.

In the study made by Kim, EIHG had a higher prevalence of coronary plaques compared to the normal blood pressure group (NBPG). Luminal

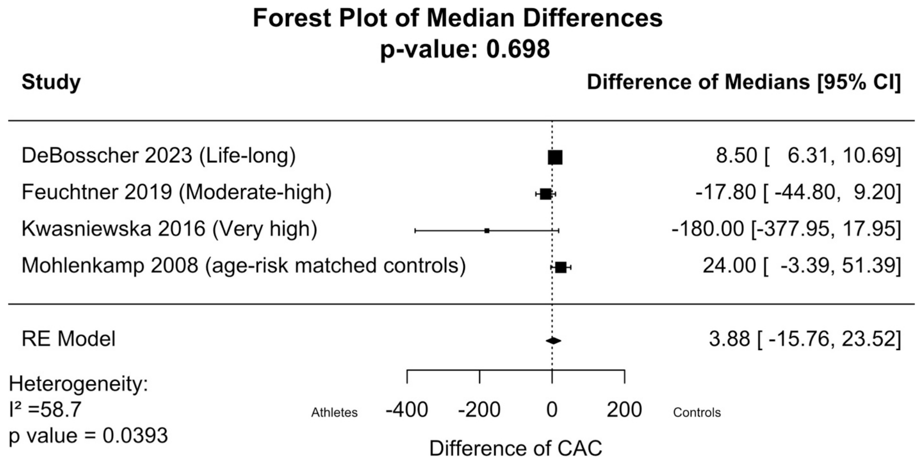

Fig. 2. Forest plot of differences of continuous CAC scores. The long-life athletes in De Bosscher's study are those who began endurance activities before the age of 30. In Feuchtner's study, athletes engage in physical activity at least 3–5 times per week, up to 5–7 times per week. The "very high" athletes in Kwasniewska's study are those who engage in physical activity equivalent to at least 6 MET-hours per week.

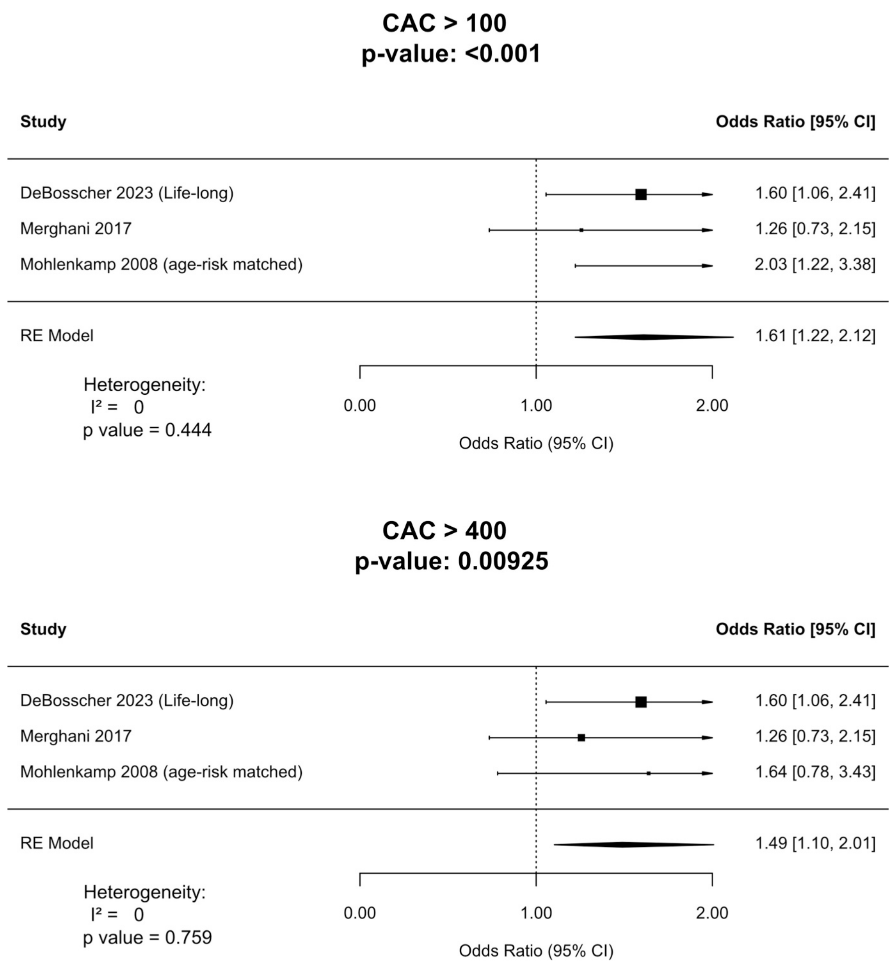

Fig. 3. Forest plot of OR of having a CAC over 100 and a CAC over 400.

stenosis was observed in 36 % of the EIHG subjects, compared to 9.1 % in the NBPG. Specifically, in the EIHG, stenosis was present in one blood vessel in 17.9 % of subjects, in two vessels in 14.3 %, and in three or more vessels in 3.6 %. The most common locations for stenosis in the EIHG were the left anterior descending artery, right coronary artery, left circumflex artery, and obtuse marginal artery, with a total of 12 cases compared to only one case in the NBPG. The EIHG also had a higher prevalence of various stages of maximal luminal artery stenosis.

In all cases, a sensitivity analysis with a fixed effect model did not change the results (data not shown).

4. Discussion

Our systematic review and meta-analysis shows that extreme

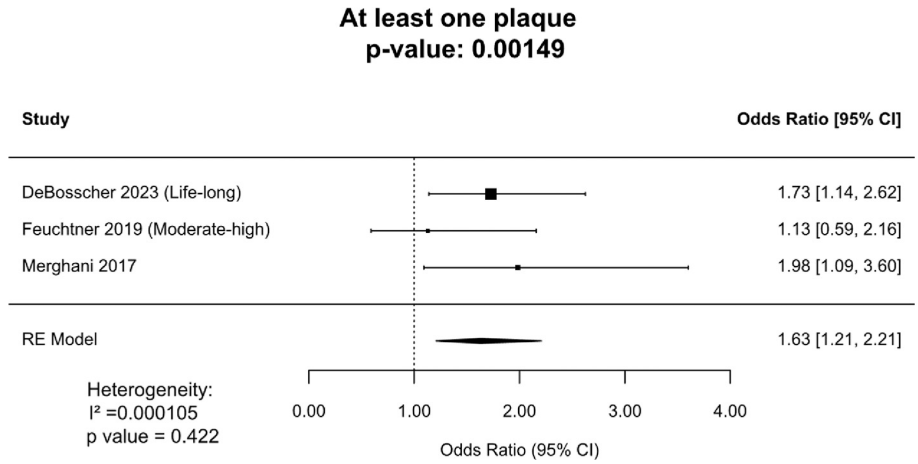

Fig. 4. Forest plot of OR of having at least one coronary plaque.

endurance athletes have a higher prevalence of coronary atherosclerosis compared to those who do not engage in such activities, meaning that the former group has a higher risk of having at least one coronary plaque compared to the latter group. However, this increased prevalence of coronary atherosclerosis does not come with a higher presence of high-risk plaques. Additionally, our research shows that endurance athletes do not have a higher prevalence of obstructive plaques compared to the controls.

Our results are in line with most of the published studies [12]. In fact, it is confirmed that extreme endurance activity can have effects on plaque genesis. However, from our meta-analysis, endurance athletes do not have a higher risk of developing high-risk coronary plaques, namely soft and unstable plaques. Furthermore, our analysis, although not reaching statistical significance with only two studies and a small sample size, indicates that athletic activity tends to lead to less development of high-risk plaques, specifically lipid-rich and soft plaques, compared to sedentary individuals. Therefore, extreme aerobic activity leads to the genesis of atherosclerosis due to the enormous production of free radicals and the consequent oxidative stress generated at the coronary endothelium level during exertion. This phenomenon may lead to the formation of stable coronary plaques. Thus, these plaques ultimately have a lower probability of ulcerating and rupturing, thereby causing an acute infarction event. More likely, these plaques, becoming larger over time, may lead to stable angina.

Another effect potentially related to endurance activity is plaque stabilization. In fact, another possible explanation for the presence of non-high-risk plaques in athletes could be that perhaps before starting physical activity, these individuals had lipid plaques which, over time since starting sports, stabilized and transformed from lipid-rich to calcified plaques. In other words, an effect similar to plaque stabilization seen with statins [13].

However, as shown above, De Bosscher reported a higher incidence of both calcified and lipid plaques [3]. The population in this study is different from the others because it mainly consists of cyclists and includes few triathletes and runners. This is especially relevant considering the significantly more impactful prognostic implications of remodeled lipid lesions compared to calcified ones. Therefore, we would emphasize the necessity, particularly within a subgroup of high cardiovascular risk master participants (familiar history of CAD, SCORE 2), to undergo a CCTA rather or a stress test.

Moreover, our study shows no difference in CAC between athletes and controls. However, athletes have a higher risk of having a both a CAC score > 100 and 400 compared to the controls. Therefore, in general, endurance exercise does not appear to affect the likelihood of having CAC values higher than the controls. However, among individuals with an elevated CAC score, the impact of endurance physical activity seems to be significant. This result may indicate that in people without a predisposition to develop calcific coronary disease, extreme endurance does not play a determining role; however, in people with a predisposition or who would have developed calcific coronary disease due to the presence of other risk factors, extreme physical activity could play a significant role.

Nevertheless, a deep reflection on CAC must be made for several reasons. First, although some studies have shown that athletes have higher CAC levels, there is no evidence that higher CAC levels correlate with worse outcomes. Second, given that endurance athletes have an increased risk of developing plaques, even in the absence of high-risk features, this population should undergo CCTA with plaque analysis rather than just a simple CAC score.

The amount and intensity of physical exercise that remains healthy is currently a subject of debate. The Copenhagen study showed a U-shaped relationship regarding the intensity and amount of physical activity and cardiovascular risk [14]. Those who lead a sedentary lifestyle have an increased cardiovascular risk, as do those who engage in extreme physical activity, while those who engage in light to moderate physical activity, as suggested by the ESC guidelines, reap the most benefits. Our study obviously cannot identify a threshold level beyond which sports activity becomes harmful; moreover, although it can be hypothesized that extreme endurance sports are the most dangerous, the evidence is still unclear on which types of sports should be considered more harmful. Most of the already published studies focused on runners, but the population of the Master Heart study is predominantly composed of cyclists, so there could be a sport-related effect.

Hence, there is a need for new trials to investigate the association between extreme sports activity and cardiovascular risk.

4.1. Limitations

Our meta-analysis includes only few studies because this field generally has limited evidence, and some studies were included in the systematic review but not in the meta-analysis due to their data being expressed very heterogeneously compared to other studies.

Another limitation of our meta-analysis is the high heterogeneity of the populations in the included studies. Although the studies in the meta-analysis consider athletes of endurance sports, such as running and cycling, their composition varies in percentage. For example, Merghani's group was composed predominantly of runners and to a lesser extent cyclists, while the Master Heart population consisted mainly of cyclists, with fewer runners and triathletes; the Feuchtner's population was consisted of different endurance activities such as cycling, running, cross-country skiing, triathlon training and mountaineering.

Furthermore, the patients from the different studies underwent coronary CT scans in different hospitals, in different countries, with different machines, and with varying machine parameters.

Furthermore, the vast majority of studies is made on male population; further investigation will be required to investigate the association between endurance sport and female sex category.

Moreover, our meta-analysis is based on studies that do not investigate primary outcomes such as mortality and major adverse cardiovascular events, but only the correlation between atherosclerotic disease and endurance sports.

Given these limitations, further studies are needed to identify those who will develop coronary plaques and to determine beyond which threshold dose exercise might become harmful instead of beneficial.

5. Conclusions

The data from our study contribute to the sports cardiology literature, but they also raise as many questions as they answer.

The results of this meta-analysis suggest that extreme endurance activity may be associated with a higher incidence of coronary atherosclerotic plaques; however, it does not appear to be linked to an increase in high-risk plaques. Further prospective studies on larger cohorts are needed to confirm these findings. The optimal balance between exercise intensity and cardiovascular health remains an ongoing research topic. Understanding these complexities is vital for tailoring exercise recommendations to promote long-term cardiovascular well-being in individuals engaged in vigorous endurance activities.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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CRediT authorship contribution statement

Gianluca Guarnieri: Writing – original draft, Methodology, Conceptualization. **Federico Emanuele Pozzi:** Data curation. **Edoardo Conte:** Methodology. **Michela Righetto:** Formal analysis. **Antonio Bartorelli:** Investigation. **Daniele Andreini:** Visualization, Supervision.

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Not applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijcard.2025.133172.

Data availability

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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