The acute impact of endurance exercise on right ventricular structure and function: A systematic review and meta-analysis

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Synopsis:

There have been many studies since the late 80's investigating the effect of endurance exercise on the left ventricle. More recently, attention has shifted to the right heart, with suggestions that endurance exercise may have a detrimental effect on the right ventricle. This systematic review and meta-analysis summarises and critiques twenty-six studies, including 649 athletes, examining the acute impact of endurance exercise on the right ventricle. We also present a sub-analysis contrasting ultra-endurance with endurance exercise. Finally, we identify areas for future research.

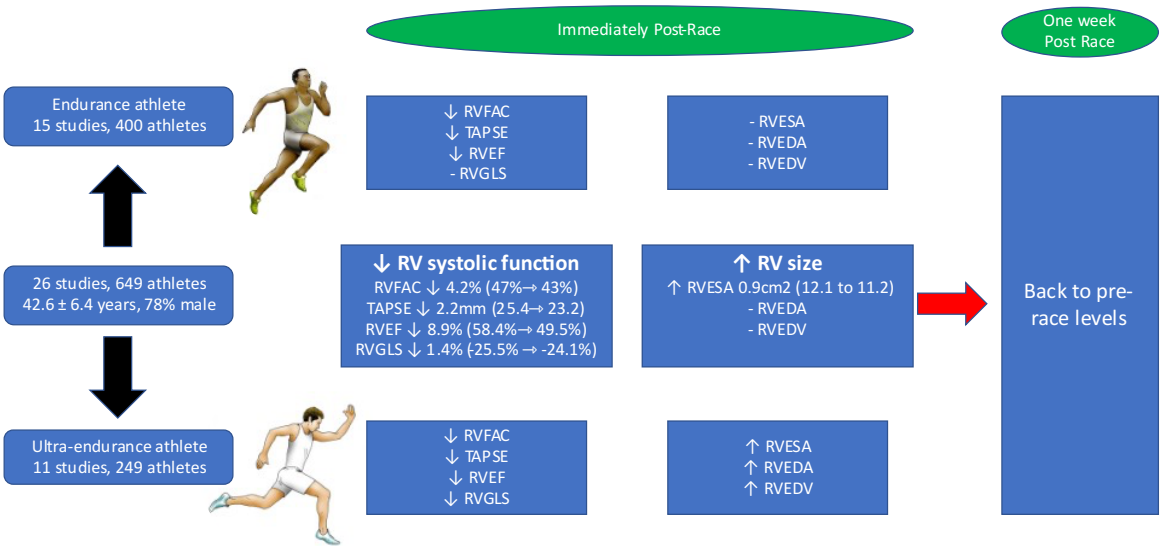
Keywords:

Adaptation, Endurance, Ultra-endurance, Exercise, Right Ventricle

Key points:

- Endurance exercise is associated with acute RV dilatation and reduction in systolic function.
- There is a dose-response relationship as acute RV effects appear to be amplified following ultra-endurance events.
- Those training more hours per week demonstrate a larger acute reduction of RVFAC following endurance events.
- RV systolic impairment resolves within a week following acute exercise, suggesting a reversible, short-term impact.

Graphical Abstract



Introduction

The benefits of regular exercise for cardiovascular health are well publicised, and at population level, evidence suggests that more exercise is better.[1,2] Regular exercise is associated with several cardiac adaptations, which is collectively referred to as "The athlete's heart". Such adaptations are evident in those who participate in regular training and competitions in sports of moderate to high intensity and are more prevalent in individuals participating in endurance sports. Since 1979, there have been in excess of 50 studies that have investigated the effect of endurance exercise on the left ventricle (LV). Studies suggest acute impairment of LV systolic and diastolic function post endurance exercise with increased LV volume and mass in the longterm.[1,3,4]

In recent years, attention has focused on the right heart, with suggestions that the RV is exposed to disproportionately increased workload during exercise compared to the LV.[5] At rest, the right ventricle (RV) functions against a very low resistance and highly compliant pulmonary circulation. However, during exercise, right ventricular wall stress increases 30-fold, reflecting a minimal reduction in pulmonary vascular resistance and a significant rise in pulmonary artery systolic pressures.[6] As such, there are significant haemodynamic changes that occur during endurance exercise, which may magnify during ultra-endurance events, leading to acute RV insult and reduced function.[7] Some researchers have gone a step further and postulated an exercise-induced right ventricular arrhythmogenic cardiomyopathy model in endurance athletes due to cumulating RV insults and inadequate recovery time.[8,9]

To understand the acute impact of endurance exercise on RV structure, function and mechanics, we performed a systematic review and meta-analysis. To explore a dose-response relationship between endurance exercise and acute RV changes, we further performed a sub-group analysis between endurance and ultra-endurance events.

Methods

This systematic review and meta-analysis was performed according to the PRISMA guidelines[10], and is registered with PROSPERO (Reference: CRD42022302907). A systematic literature search was carried out using the Healthcare Databases Advanced Search (Embase, Medline, and PubMed) for articles published in English language only, using **"(((("right ventric*") AND (Endurance)) AND (Exercise)) AND (Athlete)".** No restrictions or

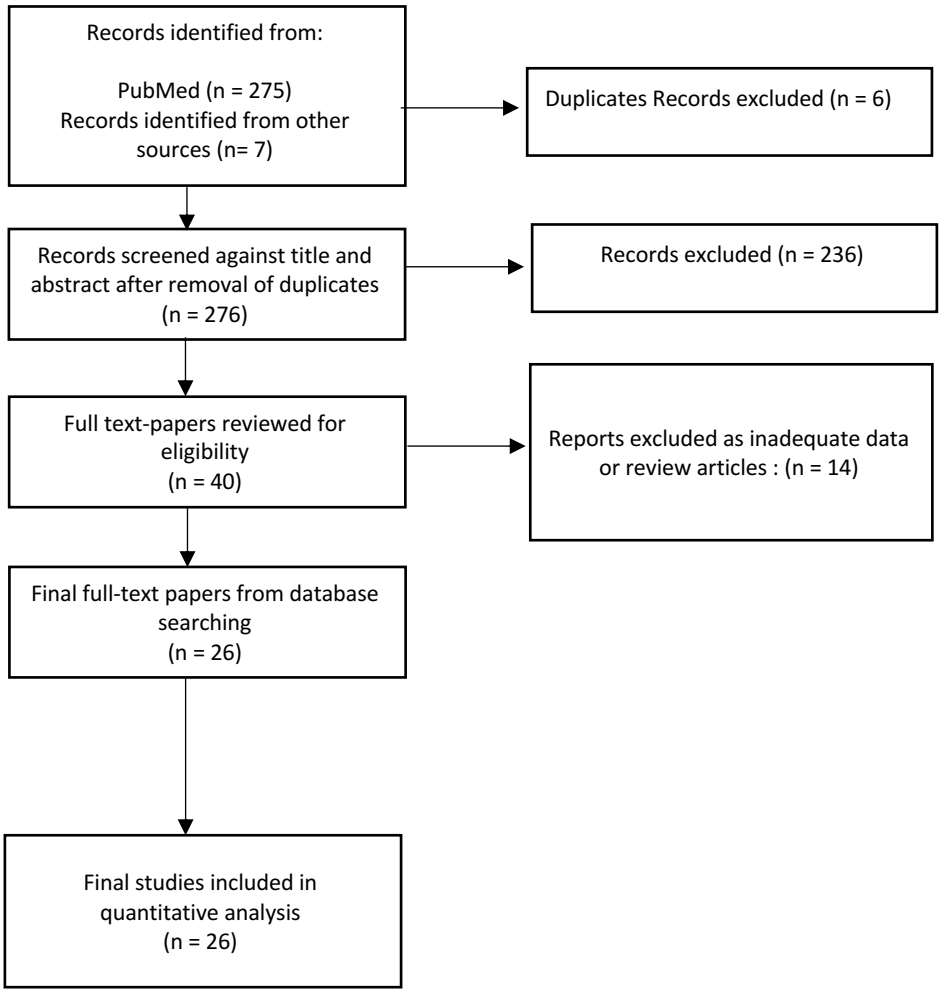
filters were applied to the search. Full-text articles were accessed from the St George's University Library catalogue, NHS Open Athens, University of Birmingham catalogue, and Clinical Key. Conference abstracts were also reviewed to gauge upcoming/unpublished research.

Following the exclusion of duplicates, articles were screened by title and then by abstract for relevance. Appropriate studies were then evaluated by full text according to the inclusion criteria of, "studies reporting acute impact of exercise on the RV", "at least one pre and post exercise functional, structural, or mechanic RV parameter measurement", "endurance or ultra-endurance sporting events", and "adult only studies". For this review, endurance exercise is defined as continuous exercise >1.5 hours and ultra-endurance as >4 hours.[3,11] Following study recruitment, the respective pre and post means, and standard deviations of all included studies were extracted. When data was reported in a different format (i.e. standard error), it was appropriately converted.

Quantitative Analysis

The extracted raw data was manually inputted into the statistical analysis software Comprehensive Meta-Analysis (Comprehensive Meta-Analysis Version 3, Biostat, Englewood, NJ, USA). All data for each individual parameter were pooled and analysed for weighted mean differences (WMD) with corresponding 95% confidence intervals. Sub-group analysis of event type was performed to discern any differences in acute RV changes between endurance and ultra-endurance events. Separately, where sufficient data was present, meta-regression analyses were run to determine the effects of any potential moderators on acute RV changes. The moderators analysed were age, sex, and training status. Statistical heterogeneity was assessed for each outcome via the I^2 statistic with a significance threshold of >40%.[12] Once beyond this threshold, random effects analysis was selected.[12] Additionally, post-hoc Egger's tests were run to assess for potential publication bias by assessing the presence of funnel plot asymmetry.[13] The analysis of any given outcome was considered significant with a P value of <0.05 and a Z-value of >2.

Figure 1: PRISMA search methodology



Results

Characteristic of included studies:

Full details of screened and included studies can be seen in Figure 1. Twenty-six studies[8-33] over a 32-year period were included (Table 1). In total, there were 649 athletes, with a mean age of 42.6 ± 6.4 years. 78% of all athletes were male. Of the 26 studies, 15 involved endurance events and 11 involved ultra-endurance events. Imaging modalities utilised included a combination of transthoracic echocardiography (TTE) and cardiac magnetic resonance imaging (CMR). All analyses were performed via a random-effects model due to significant heterogeneity.

Impact on RV systolic function:

There was a significant reduction in RV systolic function post exercise across studies. (Figure 2). Using traditional echocardiography markers, right ventricular fractional area change (RVFAC) was measured in 16 studies with a WMD reduction of 4.2% (95% CI 1.8% to 6.6%, I2= 97.3%, p=0.001), from 47% before exercise to 43% post exercise. Tricuspid annular plane systolic excursion (TAPSE) was measured in 12 studies and reduced by a WMD of 2.2mm (95% CI 0.5mm to 3.9mm, I2= 96.3%, p=0.011), from 25.4mm to 23.2mm post exercise. Using 3D TTE or CMR, right ventricular ejection fraction (RVEF) was measured in 9 studies and was shown to be reduced by a WMD of 8.9% (95% CI 2.8% to 15%, I2= 99.2%, p=0.004) from 58.4% to 49.5% following exercise. Using advanced longitudinal functional indices, RV global longitudinal strain (RVGLS) was measured in 9 studies and was shown to reduce by a WMD of 1.4% (95% CI 0.6% to 2.2%, I2= 93.0%, p=0.001) from -25.5% to -24.1% following exercise. Right ventricular S' and strain rate (RVSR) did not significantly differ pre and post exercise.

Seven studies[9.10.13,14,19,20,22] re-assessed RV function following recovery from acute exercise, of which 5 showed normalisation of all markers within one-week.[9,10,13,19,22] The remaining two studies showed normalisation of the RVFAC and TAPSE but persistent reduction of RV S', although the WMD was not reduced.[14,20]

Comparing the studies reporting on ultra-endurance events with endurance events, there was no significant difference in reduction of RVEF or RVFAC before and after exercise. However, there was a greater attenuation in RVGLS (less negative) following ultra-endurance compared to endurance events (WMD: 2.2% vs 0.01%, p=0.006, Figure 3). In fact, when analysed separately, RVGLS did not significantly change following an endurance event (WMD: 0.01%, 95% CI -1.22% to +1.25%, p=0.987, 3 studies), but was significantly depressed (less negative) following ultra-endurance (WMD: 2.2%, 95% CI +1.26% to +3.14%, p<0.001, 6 studies). There was insufficient data to compare TAPSE, RV S' and RVSR.

Impact on RV diastolic function:

RV diastolic function was assessed in 5 studies using Doppler imaging (E/A), myocardial tissue velocity (E'/A'), and/or strain imaging (SR E/A), but there were insufficient data to perform quantitative analyses.

Impact on RV size:

Change in RV size was assessed by using either RV area or volume, utilising TTE or CMR. Only RV end-systolic area, which was measured in 12 studies, showed an increase by a WMD of 0.9cm^2 (95% CI 0.1cm^2 to 1.7cm^2, I2= 96.9%, p=0.028) from 11.2cm^2 to 12.1cm^2 following exercise. There were insufficient study data to perform quantitative analysis for RV end-systolic volume (RVESV). Both RV end-diastolic area (RVEDA: WMD of 0.7cm^2, 95% CI -0.1cm^2 to 1.4cm^2, I2=93.3%, p=0.071) and RV end-diastolic volume (RVEDV: WMD 19.97ml, 95% CI -11.4ml to 51.3ml, I2 – 99.1%, p=0.21) showed an increase which, however, did not achieve significance.

Davila-Romen et al reported normalisation in RV size after 24 hours of recovery following the endurance exercise.[14]

Comparing ultra-endurance to endurance events demonstrated that increase in RVEDA was significantly greater following ultra-endurance compared to endurance events (WMD: 1.5cm^2 vs -0.1cm^2, p=0.017, Figure 3). When analysed separately, RVEDA did not change following endurance events (WMD: -0.1cm^2, 95% CI -1.2cm^2 to -0.9cm^2, p=0.791, 7 studies), whereas it was significantly increased following ultra-endurance events (WMD: 1.5 cm^2, 95% CI 0.5cm^2 to 2.5cm^2, p<0.001, 8 studies). Similarly, change in RVESA was greater following ultra-endurance compared to endurance events (WMD: 1.9cm^2 vs 0.2cm^2, p=0.006, Figure 3), and when analysed separately, RVESA did not change following endurance events (WMD: 0.2cm^2, 95% CI -0.8cm^2 to 1.2cm^2, p=0.699, 7 studies), but significantly increased following ultra-endurance events (WMD: 2cm^2, 95% CI 0.7cm^2 to 3.2cm^2, p=0.003, 5 studies). There was insufficient data to compare RVEDV.

Impact on RV Pressure:

Tricuspid regurgitant (TR) velocity can be used to estimate right ventricular systolic pressure (RVSP), which in the absence of right ventricular outflow tract (RVOT) obstruction, approximates pulmonary artery systolic pressure (PASP). Five studies assessed change in RVSP/PASP following acute endurance exercise. No significant increase in pressure was noted (WMD 2.0mmHg, 95% CI -13.1mmHg to 9.1mmHg, I2 – 99.5%, p=0.72) .

Moderator analyses and publication bias

Moderator analyses were run to assess the effects of age, sex, and training status on any of the functional or structural RV changes. There was no significant moderator effect of age or sex. Conversely, moderator analysis of training status demonstrated a significant association with RVFAC, with those training more hours per week demonstrating a larger acute reduction following endurance events ($b=0.0072$, $p<0.001$). RVEDA showed no significant effect from training status whilst there was insufficient data for analysis for RVEF, RVGLS, RVEDV, RVESV and RVESA.

RVEF ($p=0.037$) was the only parameter to produce statistically significant funnel plot asymmetry on the Egger's regression test, indicating publication bias.

Discussion

Our meta-analysis suggests a transient increase in RV size with associated reduction of the systolic function after acute endurance exercise. These effects seem to be more pronounced with ultra-endurance events and reverse within a week.

Acute impact of endurance exercise on the RV

The most consistent finding across individual studies and a previously published meta-analysis is the acute reduction of RV systolic function post endurance events, as evident by several echocardiographic and CMR indices. Although it is difficult to determine cause and effect, individual studies suggest that it is the acute increase in PASP and therefore RV afterload during endurance exercise, that most likely accounts for the acute RV dysfunction. The thick walls of the LV and the ability of the systemic circulation to reduce vascular resistance, results in proportionately lower increase in the systolic blood pressure and LV "wall stress". The RV is a thin-walled structure which normally contracts against a very low-pressure circulation. During exercise it must considerably increase its cardiac output to match the LV cardiac output.[15] Given the limited ability of the pulmonary vascular resistance to reduce further, the increased cardiac output results is an increase in PASP which corelates with exercise intensity, with values of up to 90mmHg recorded in elite endurance athletes.[16,17]

The higher the RV afterload, the greater the RV "wall stress". Consequently, the RV is disproportionally impacted by endurance exercise, leading to acute impairment in ventricular contractility, which recovers once RVSP/PASP normalises. Indeed, our meta-analysis did not identify persistently elevated RVSP/PASP post event suggesting that it is the repeated transient elevations in RV pressures and RV afterload that are likely to be responsible for the acute, as well as the reported chronic RV changes.

Alternately, as the RV dilates, less "contraction" is needed to produce similar stroke volume, and this could partly explain the reduction in systolic function. Lord et al used area-deformation loops to suggest that this RV dilation with reduced systolic function may be a form of adaptation and not dysfunction.[18] However, this contrasts with some chronic endurance athletes having resting RV dilation but without systolic impairment.

The importance of exercise duration

This meta-analysis demonstrates that the significant reduction in RV systolic function following acute endurance exercise, is amplified following ultra-endurance events, giving weight to a dose-response relationship between exercise duration and acute systolic RV functional impairment.[23,19] The acute RV functional impairment reported transcends both global and longitudinal function. The RVGLS is attenuated in a dose response manner with increasing endurance exercise, suggesting that the RV functional impairment is not simply a haemodynamic effect from fluid shifts, but that endurance exercise has a real effect on the RV myocardium.

The meta-analysis also shows the increase in RV size following acute endurance exercise, is amplified following ultra-endurance events. Sanz de la Garza et al showed that RV dilation is proportional to the duration and intensity of exercise with a similar dose-response relationship to systolic function.[20] Studies that examined RV size following recovery from acute endurance events showed normalisation to pre-event size.[14] Similarly, studies of chronic adaptation to exercise, show significant RV enlargement in endurance athletes compared to sedentary controls, suggesting that endurance exercise has both acute temporary and chronic effects on RV adaptation.

Clinical implications

Clinicians should be aware of the transient increase in RV size and reduction in RV systolic function post endurance exercise and the incremental impact of ultra-endurance events. This is relevant to physicians supervising endurance events but also to those who may encounter athletes following endurance events as part of cardiac screening or during acute presentation with cardiac or non-cardiac symptoms. The presence of reduced RV systolic function with a dilated RV size should be interpreted in the right clinical context to avoid a cascade of potentially unnecessary further tests and erroneous diagnosis. This is even more important when one considers that the acute RV changes have also been associated with transient increase of serum Troponin levels.[21]

The attenuated systolic function appears to resolve within a week following acute exercise, suggesting that the acute effect of endurance exercise has only a short-term impact on RV systolic function. The chronic repeated impact of endurance exercise on RV function and mechanics remains to be elucidated. The association of more training hours per week with greater acute reduction of RVFAC following endurance events offers some support to the suggestion that veteran endurance athletes can develop an acquired, exercise-induced ARVC phenotype,[7,22] due to repeated insults from endurance events, when coupled with inadequate recovery between events.

Critique of literature

Strengths

This systematic review and meta-analysis has several strengths. These include an extensive review of the literature on the acute effects of endurance exercise on RV function and mechanics, with twenty-six articles and almost 650 athletes included. This allowed multiple parameters to be compared, with no studies having vastly different results increasing confidence in conclusions. Additionally, all studies were prospective and designed to allow post-exercise investigations to be performed as close to activity completion as possible to improve accuracy in the findings.

A previous meta-analysis on the effect of endurance exercise on the RV by Elliott et al in 2014, utilising fourteen studies, including some that have been reviewed in our study, also demonstrated an increase in RV size and decrease in RV function from endurance exercise.[11] Our meta-analysis builds on this work, confirming the effect on RV size/function but also underlines the dose-response relationship of endurance exercise by comparing endurance to ultra-endurance events.

Limitations

There are several limitations both from individual study designs as well as from comparing studies to each other. Firstly, studies included used predominantly male populations, introducing both sex bias as well as making sub-analysis of sex differences less powered. As such the lack of any sex differences in our study should be interpreted with caution. Additionally, most studies did not mention ethnicity, making it difficult to comment on the effect of ethnicity on RV responses to exercise. Studies are heavily biased towards white, male endurance athletes and further work must improve the demographic and sex distribution of included athletes to better represent the realities of modern endurance sport so that we are able to apply research evidence more accurately into clinical practice. Potential publication bias should also be considered when interpreting RVEF. Finally, consideration of age in future studies would be a useful sub-analysis, particularly to compare adolescent with veteran endurance athletes, and to explore whether the demonstrated changes in RV size and function are more pronounced in veteran athletes due to a potentially less compliant circulation.

Conclusions

Acute endurance exercise results in RV dilation and attenuated systolic function, which is dose dependant, with greater attenuation as the volume of endurance exercise increases. These effects reverse within a week.

Future research is required to investigate the implications of these acute responses to chronic adaptions in athletes and further explore the influence of sex, ethnicity and age.

Table 1: Details of studies looking at acute endurance exercise effects

Study	Year	Country	Number of participants	M:F ratio	Mean Age, years (SD)	Event
*Douglas et al[23]	1990	USA	41	22:19	38 (10)	Ironman triathlon
*Carrio et al[24]	1990	Spain	10	Unk	Unk	Ultramarathon
*Davila-Roman et al[14]	1997	USA	14	Unk	Unk	High-altitude ultramarathon
Neilan et al A[25]	2006	USA	20	10:10	34 (10)	Marathon
Neilan et al B[26]	2006	USA	60	41:19	41 (11)	Marathon
Neilan et al. C[27]	2006	USA	17	12:5	37	Rowers
Oxborough et al A[28]	2006	UK	35	29:6	30 (8)	Marathon
*La Gerche et al A[29]	2008	Australia	26	Unk	32	Ironman triathlon
Mousavi et al[21]	2009	Canada	14	8:6	33 (6)	Marathon
Trivax et al[30]	2010	USA	25	13:12	39 (9)	Marathon
O'Hanlon et al[31]	2010	UK	17	17:0	34 (7)	Marathon
*Oxborough et al C[32]	2011	UK	16	12:4	42 (8)	Ultramarathon
Oomah et al[33]	2011	Canada	15	7:8	32 (6)	Half-marathon
Karlstedt et al[34]	2012	Canada	25	21:4	55 (4)	Marathon
Schattke et al[35]	2012	Germany	21	21:0	46 (15)	Marathon
*La Gerche et al B[8]	2012	Australia	40	36:4	37 (8)	Ultra-triathlon
Claessen et al[36]	2014	Belgium	14	14:0	36 (6)	Cycling
*Lord et al[37]	2015	USA	15	14:1	40 (8)	Ultramarathon
*Sanz de la Garza et al[19]	2016	Spain	55	55:0	37 (7)	High-Altitude Ultramarathon
*Maufrais et al.[38]	2016	France	15	15:0	46 (13)	Ultramarathon
Stewart et al[39]	2017	Australia	23	23:0	28 (8)	Cycling
Gajda et al[40]	2019	Poland	12	7:5	Unk	Swimmers

Martinez et al[41]	2019	Spain	33	26:7	41 (7)	Swimmers
*Christou et al[42]	2020	Greece	25	19:8	45 (7)	Ultramarathon
*Coates et al[43]	2020	Canada	8	6:2	45 (10)	Ultramarathon
Chen et al[44]	2021	Germany	50	40:10	45 (10)	Triathlon

*M: Male, F: Female, Unk: Unknown, *Ultra-endurance events*

FIGURES

Figure 2: Random-effects meta-analysis of the effect of endurance exercise on A) RVEDA, B) RVESA, C) RVFAC, D) RVGLS

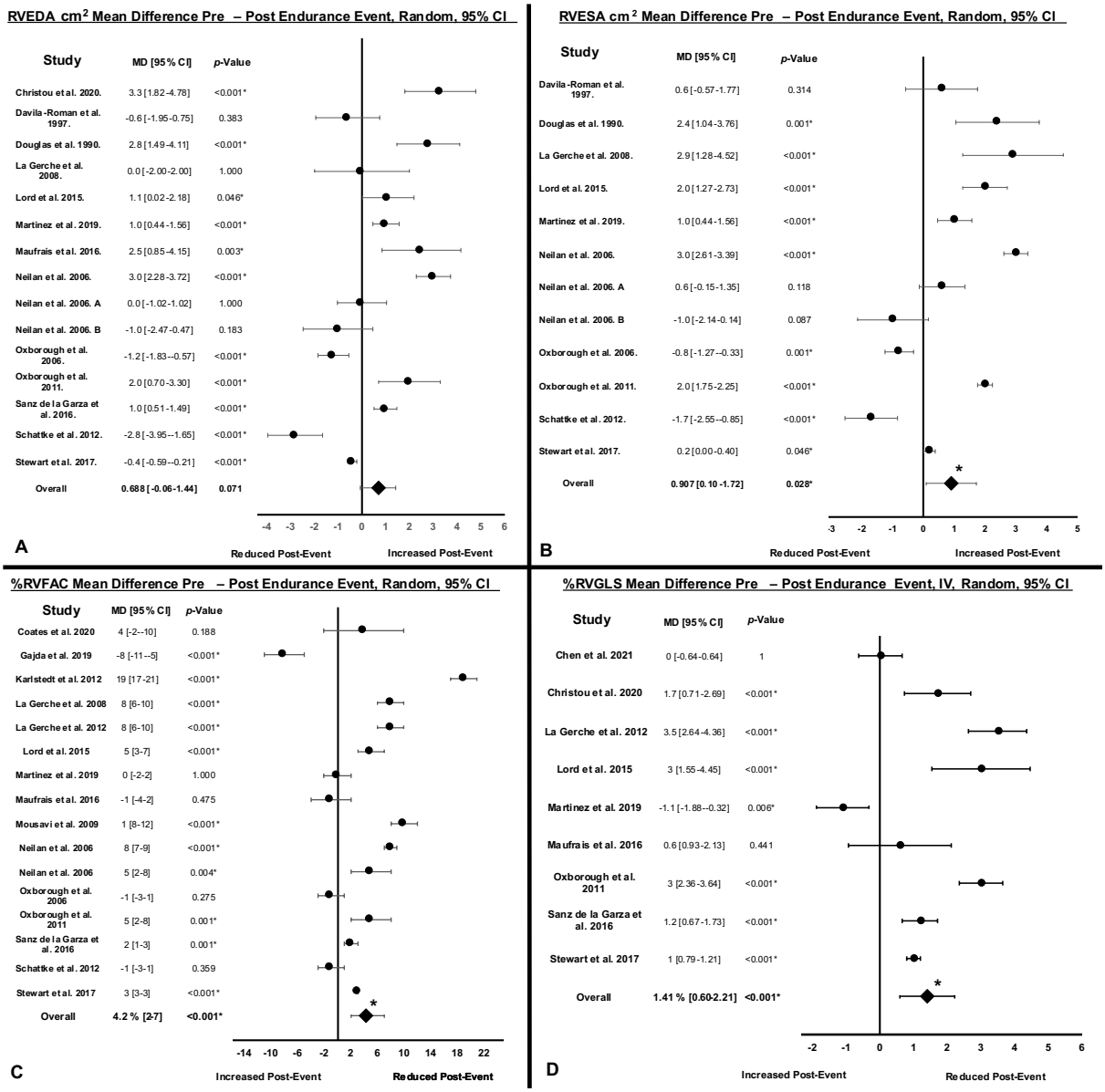
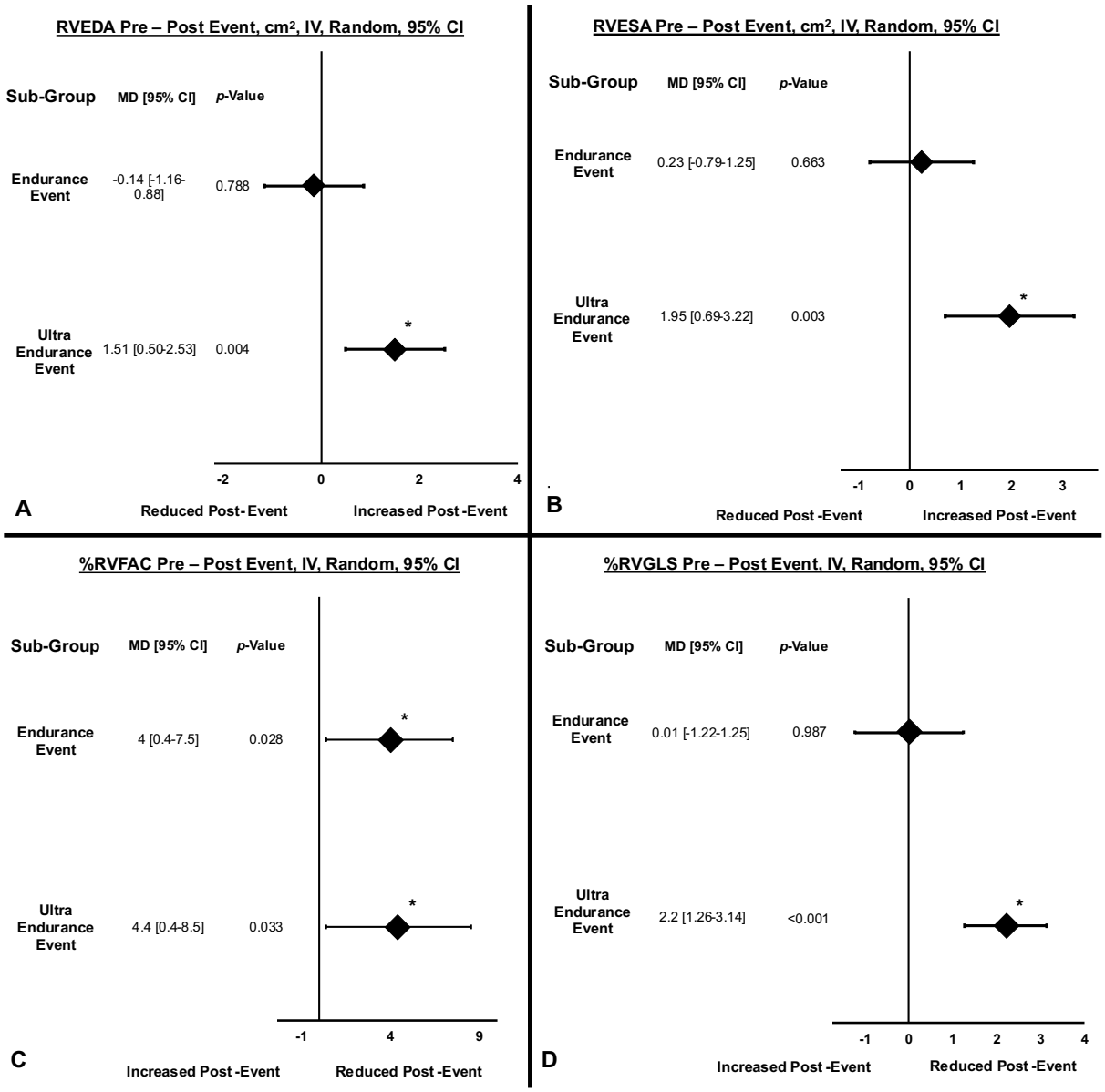


Figure 3: Random-effects meta-analysis comparing endurance exercise with ultra-endurance exercise on A) RVEDA, B) RVESA, C) RVFAC, D) RVGLS



REFERENCE LIST:

1. Middleton N, Shave R, George K, Whyte G, Hart E, Atkinson G. Left ventricular function immediately following prolonged exercise: A meta-analysis. *Medicine and Science in Sports and Exercise*. 2006;38(4):681-687. doi:10.1249/01.mss.0000210203.10200.12

2. Loef M, Walach H. The combined effects of healthy lifestyle behaviors on all cause mortality: A systematic review and meta-analysis. *Preventive Medicine*. 2012;55(3):163-170. doi:10.1016/j.ypmed.2012.06.017

3. Lord R, Oxborough D, Somauroo J, George K. Echocardiographic Evidence of the Cardiac Stress of Competing in Ultra-Endurance Exercise. *Dtsch Z Sportmed*. 2014;65(March):93-101. doi:10.5960/dzsm.2014.122

4. Baggish AL, Yared K, Wang F, et al. The impact of endurance exercise training on left ventricular systolic mechanics. *American Journal of Physiology - Heart and Circulatory Physiology*. 2008;295(3):1109-1116. doi:10.1152/ajpheart.00395.2008

5. la Gerche A, Heidbüchel H, Burns AT, et al. Disproportionate exercise load and remodeling of the athlete's right ventricle. *Medicine and Science in Sports and Exercise*. 2011;43(6):974-981. doi:10.1249/MSS.0b013e31820607a3

6. D'Ascenzi F, Pisicchio C, Caselli S, Di Paolo FM, Spataro A, Pelliccia A. RV Remodeling in Olympic Athletes. *JACC: Cardiovascular Imaging*. Published online 2017. doi:10.1016/j.jcmg.2016.03.017

7. Zaidi A, Sharma S. Arrhythmogenic right ventricular remodelling in endurance athletes: Pandora's box or Achilles' heel? *European Heart Journal*. 2015;36(30):1955-1957. doi:10.1093/eurheartj/ehv199

8. la Gerche A, Burns AT, Mooney DJ, et al. Exercise-induced right ventricular dysfunction and structural remodelling in endurance athletes. *European Heart Journal*. 2012;33(8):998-1006. doi:10.1093/eurheartj/ehr397

9. la Gerche A, Robberecht C, Kuiperi C, et al. Lower than expected desmosomal gene mutation prevalence in endurance athletes with complex ventricular arrhythmias of right ventricular origin. *Heart*. 2010;96(16):1268-1274. doi:10.1136/hrt.2009.189621

10. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *The BMJ*. 2021;372. doi:10.1136/bmj.n71

11. Elliott AD, Gerche A la. The right ventricle following prolonged endurance exercise: are we overlooking the more important side of the heart? A meta-analysis. doi:10.1136/bjsports-2014-093895

12. Huedo-Medina TB, Sánchez-Meca J, Marín-Martínez F, Botella J. Assessing heterogeneity in meta-analysis: Q statistic or I 2 Index? *Psychological Methods*. 2006;11(2):193-206. doi:10.1037/1082-989X.11.2.193

13. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *British Medical Journal*. 1997;315(7109):629-634. doi:10.1136/bmj.315.7109.629

14. Dávila-Román VG, Guest TM, Tuteur PG, Rowe WJ, Ladenson JH, Jaffe AS. Transient right but not left ventricular dysfunction after strenuous exercise at high altitude. *J Am Coll Cardiol*. 1997;30(2):468-473. doi:10.1016/S0735-1097(97)00179-4

15. la Gerche A, Rakhit DJ, Claessen G. Exercise and the right ventricle: A potential Achilles' heel. *Cardiovascular Research*. 2017;113(12):1499-1508. doi:10.1093/cvr/cvx156

16. D'Andrea A, Riegler L, Golia E, et al. Range of right heart measurements in top-level athletes: The training impact. *International Journal of Cardiology*. 2013;164(1):48-57. doi:10.1016/j.ijcard.2011.06.058

17. Buchan TA, Wright SP, Esfandiari S, et al. Pulmonary hemodynamic and right ventricular responses to brief and prolonged exercise in middle-aged endurance athletes. *American Journal of Physiology - Heart and Circulatory Physiology*. 2019;316(2):H326-H334. doi:10.1152/ajpheart.00413.2018

18. Lord R, George K, Somauroo J, et al. Alterations in Cardiac Mechanics Following Ultra-Endurance Exercise: Insights from Left and Right Ventricular Area-Deformation Loops. *Journal of the American Society of Echocardiography*. 2016;29(9):879-887.e1. doi:10.1016/j.echo.2016.05.004

19. Sanz De La Garza M, Grazioli G, Bijnens BH, et al. Inter-individual variability in right ventricle adaptation after an endurance race. *European Journal of Preventive Cardiology*. 2016;23(10):1114-1124. doi:10.1177/2047487315622298

20. Sanz De La Garza M, Grazioli G, Bijnens BH, et al. Inter-individual variability in right ventricle adaptation after an endurance race. *European Journal of Preventive Cardiology*. 2016;23(10):1114-1124. doi:10.1177/2047487315622298

21. Mousavi N, Czarnecki A, Kumar K, et al. Relation of Biomarkers and Cardiac Magnetic Resonance Imaging After Marathon Running. *American Journal of Cardiology*. 2009;103(10):1467-1472. doi:10.1016/j.amjcard.2009.01.294

22. Zaidi A, Sheikh N, Jongman JK, et al. Clinical differentiation between physiological remodeling and arrhythmogenic right ventricular cardiomyopathy in athletes with marked electrocardiographic repolarization anomalies. *J Am Coll Cardiol*. 2015;65(25):2702-2711. doi:10.1016/j.jacc.2015.04.035

23. Douglas PS, O'Toole ML, Miller WDB, Reichek N. Different effects of prolonged exercise on the right and left ventricles. *J Am Coll Cardiol*. 1990;15(1):64-69. doi:10.1016/0735-1097(90)90176-P

24. Carrio Ignas, Serra-grima R, Martinez-duncker C, Ordoflez J. Transient alterations in cardiac performance following a six hour race. Published online 1990:1471-1474.

25. Neilan TG, Yoerger DM, Douglas PS, et al. Persistent and reversible cardiac dysfunction among amateur marathon runners. *European Heart Journal*. 2006;27(9):1079-1084. doi:10.1093/eurheartj/ehi813

26. Neilan TG, Januzzi JL, Lee-Lewandrowski E, et al. Myocardial injury and ventricular dysfunction related to training levels among nonelite participants in the Boston Marathon. *Circulation*. 2006;114(22):2325-2333. doi:10.1161/CIRCULATIONAHA.106.647461

27. Neilan TG, Ton-Nu TT, Jassal DS, et al. Myocardial Adaptation to Short-term High-intensity Exercise in Highly Trained Athletes. *Journal of the American Society of Echocardiography*. 2006;19(10):1280-1285. doi:10.1016/j.echo.2006.05.001

28. Oxborough D, Shave R, Middleton N, Whyte G, Forster J, George K. The impact of marathon running upon ventricular function as assessed by 2D, Doppler, and tissue-Doppler echocardiography. *Echocardiography*. 2006;23(8):635-641. doi:10.1111/j.1540-8175.2006.00282.x

29. la Gerche A, Connelly KA, Mooney DJ, MacIsaac AI, Prior DL. Biochemical and functional abnormalities of left and right ventricular function after ultra-endurance exercise. *Heart*. 2008;94(7):860-866. doi:10.1136/hrt.2006.101063

30. Trivax JE, Franklin BA, Goldstein JA, et al. Acute cardiac effects of marathon running. *Journal of Applied Physiology*. 2010;108(5):1148-1153. doi:10.1152/japplphysiol.01151.2009

31. O'Hanlon R, Wilson M, Wage R, et al. Troponin release following endurance exercise: Is inflammation the cause? A cardiovascular magnetic resonance study. *Journal of Cardiovascular Magnetic Resonance*. 2010;12(1):1-7. doi:10.1186/1532-429X-12-38

32. Oxborough D, Shave R, Warburton D, et al. Dilatation and dysfunction of the right ventricle immediately after ultraendurance exercise : Exploratory insights from conventional two-dimensional and speckle tracking echocardiography. *Circulation: Cardiovascular Imaging*. 2011;4(3):253-263. doi:10.1161/CIRCIMAGING.110.961938

33. Oomah SR, Mousavi N, Bhullar N, et al. The role of three-dimensional echocardiography in the assessment of right ventricular dysfunction after a half marathon: Comparison with cardiac magnetic resonance imaging. *Journal of the American Society of Echocardiography*. 2011;24(2):207-213. doi:10.1016/j.echo.2010.10.012

34. Karlstedt E, Chelvanathan A, da Silva M, et al. The impact of repeated marathon running on cardiovascular function in the aging population. *Journal of Cardiovascular Magnetic Resonance*. 2012;14(1):1-7. doi:10.1186/1532-429X-14-58

35. Schattke S, Wagner M, Hättasch R, et al. Single beat 3D echocardiography for the assessment of right ventricular dimension and function after endurance exercise: Intraindividual comparison with magnetic resonance imaging. *Cardiovascular Ultrasound*. 2012;10(1):1-9. doi:10.1186/1476-7120-10-6

36. Claessen G, Claus P, Ghysels S, et al. Right ventricular fatigue developing during endurance exercise: An exercise cardiac magnetic resonance study. *Medicine and Science in Sports and Exercise*. 2014;46(9):1717-1726. doi:10.1249/MSS.0000000000000282

37. Lord R, Somauroo J, Stembridge M, et al. The right ventricle following ultra-endurance exercise: insights from novel echocardiography and 12-lead electrocardiography. *European Journal of Applied Physiology*. 2015;115(1):71-80. doi:10.1007/s00421-014-2995-6

38. Maufrais C, Millet GP, Schuster I, Rupp T, Nottin S. Progressive and biphasic cardiac responses during extreme mountain ultramarathon. *American Journal of Physiology - Heart and Circulatory Physiology*. 2016;310(10):H1340-H1348. doi:10.1152/ajpheart.00037.2016

39. Stewart GM, Chan J, Yamada A, et al. Impact of high-intensity endurance exercise on regional left and right ventricular myocardial mechanics. *European Heart Journal Cardiovascular Imaging*. 2017;18(6):688-696. doi:10.1093/ehjci/jew128

40. Gajda R, Kowalik E, Rybka S, et al. Evaluation of the heart function of swimmers subjected to exhaustive repetitive endurance efforts during a 500-km relay. *Frontiers in Physiology*. 2019;10(MAR):1-9. doi:10.3389/fphys.2019.00296

41. Martinez V, la Garza MS de, Grazioli G, et al. Cardiac performance after an endurance open water swimming race. *European Journal of Applied Physiology*. 2019;119(4):961-970. doi:10.1007/s00421-019-04085-x

42. Christou GA, Pagourelias ED, Anifanti MA, et al. Exploring the determinants of the cardiac changes after ultra-long duration exercise: The echocardiographic Spartathlon study. *European Journal of Preventive Cardiology*. 2020;27(14):1467-1477. doi:10.1177/2047487319898782

43. Coates AM, King TJ, Currie KD, et al. Alterations in Cardiac Function Following Endurance Exercise Are Not Duration Dependent. *Frontiers in Physiology*. 2020;11(September). doi:10.3389/fphys.2020.581797

44. Chen H, Warncke ML, Muellerleile K, et al. Acute impact of an endurance race on biventricular and biatrial myocardial strain in competitive male and female triathletes evaluated by feature-tracking CMR. *European Radiology*. 2021;(0123456789). doi:10.1007/s00330-021-08401-y