The Right Ventricle following Ultra-Endurance Exercise: Insights from Novel Echocardiography and 12-lead Electrocardiography

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Abstract

Purpose: There is contradictory evidence related to the impact of ultra-marathon running on right ventricular (RV) structure and function. Consequently, the aims of this study were to; 1) comprehensively assess RV structure and function before and immediately following a 100 mile ultra-marathon in highly trained runners, 2) determine the nature of RV recovery 6 hours post-race, and 3) document 12-lead electrocardiogram (ECG) changes post-exercise.

Methods: Echocardiography and 12-lead ECG were assessed in 15 competitors in a repeated measures design before and immediately after completion of the 2013 Western States Endurance Race. A subset of 9 were reassessed 6 hours into recovery. Standard echocardiography was used to determine RV size, function and wall stress. Myocardial speckle tracking (MST) provided peak, time to peak and temporal indices for RV longitudinal strain and strain rates (ε and SR).

Results: RV size was increased post-race (inflow tract 14 %, outflow tract 11 %, P = 0.004 and 0.002). RV wall stress was elevated by 11 % post-race. Peak RV ε was reduced by 10 % (P = 0.007) and significantly delayed post-race (P = 0.008). Most changes in RV function persisted at the 6 hour assessment. Post-race there was an increase in the prevalence of right-sided ECG changes.

Conclusions: Completion of a 100 mile ultra-marathon resulted in acute changes in RV structure and function that persisted 6 hours into recovery and are consistent with sustained exposure to an elevated RV wall stress. These findings were supported by right sided changes to the 12-Lead ECG.

INTRODUCTION

Evidence of left ventricular (LV) dysfunction during recovery from prolonged endurance exercise, commonly described as exercise-induced cardiac fatigue (EICF), has been frequently documented (Douglas et al. 1987; George et al. 2005; George et al. 2009; Hart et al. 2007; Middleton et al. 2006; Oxborough et al. 2006; Oxborough et al. 2011b; Oxborough et al. 2010; Shave et al. 2004a; Shave et al. 2002; Shave et al. 2004b). Interest in the RV response to prolonged exercise was initially stimulated by 2 case studies of pulmonary oedema (McKechnie et al. 1979). The assessment of global RV function after endurance exercise (Davila-Roman et al. 1997; Douglas et al. 1990; McKechnie et al. 1979; Oxborough et al. 2006) provided contradictory evidence of RV cardiac fatigue which may be a consequence of inherent limitations of conventional echocardiographic imaging (Ho and Nihoyannopoulos 2006).

The advent of new echocardiographic techniques such as tissue velocity (TVI) and strain (ε) imaging have allowed a more comprehensive assessment of RV structure and function in the post-prolonged exercise setting (La Gerche et al. 2011a; La Gerche et al. 2008; Neilan et al. 2006a; Neilan et al. 2006b; Oxborough et al. 2011b; Oxborough et al. 2010). Recent studies reported an increase in RV outflow and inflow tract size and concomitant decrease in RV lateral wall ε following ultra-endurance exercise (La Gerche et al. 2012; Oxborough et al. 2011a). Although there appears to be an acute effect of prolonged exercise on RV function, it is not known how RV function responds during early recovery.

The study of cardiac electrical changes consequent to endurance exercise has received limited attention (Sahlen et al. 2009; Stewart et al. 2014). There is some evidence of post-exercise repolarisation abnormalities (Sahlen et al. 2009), including lengthening of the QTc interval (Stewart et al. 2014). The standard ECG affords some assessment of right sided electrical properties, as demonstrated in pulmonary embolism (Kucher et al. 2003), and would augment non-invasive imaging data.

Consequently, the aims of the current study are to; 1) comprehensively assess RV structure and function before, immediately following a 100 mile ultra-marathon in highly trained runners, 2)

determine the nature of RV recovery 6 hours post-race, and 3) document 12-lead ECG changes post-exercise. We hypothesize that the completion of a 100 mile ultra-marathon will result in an acute alteration in RV structure and function as well as ECG changes indicative of right sided electrical adaptation. Further, we hypothesize that there will be a rapid recovery in RV function at 6 hours post-race.

Keywords: endurance, exercise, ultrasound, running, cardiology physiology

Abbreviations:

Abbreviation	***Definition***
A'	late diastolic myocardial tissue velocity
AP4CH	apical 4 chamber view
ASE	Amercican Society of Echocardiography
E'	early diastolic myocardial tissue velocity
ECG	electrocardiogram
EI	eccentricity index
EICF	exercise induced cardiac fatigue
FAC	fractional area change
HR	heart rate
IVCT	isovolumic contraction time
IVRT	isovolumic relaxation time
LV	left ventricle
MST	myocardial speckle tracking
PASP	pulmonary artery systolic pressure
PLAX	parasternal long axis view
PSAX	parasternal short axis view
PW	pulsed wave
RA	right atrium
RAD	right axis deviation
RV	right ventricle
RVAs	right ventricular systolic area
RVH	right ventricular hypertrophy
RVOT	right ventricular outflow tract
RVSp	right ventricular systolic pressure
S'	systolic myocardial tissue velocity
ε	myocardial strain
SRA	late diastolic strain rate
SRE	early diastolic strain rate
SRS	systolic strain rate
SV	stroke volume
TDI	tissue Doppler imaging

TsPeak	time to peak strain
T_{SRA}Peak	time to peak late diastolic strain rate
T_{SRE}Peak	time to peak early diastolic strain rate
T_{SRS}Peak	time to peak systolic strain rate
TVI	tissue velocity imaging

MATERIALS AND METHODS

Fifteen (14 male, 1 female) elite participants at the 2013 Western States Endurance Run (29th June, Squaw Valley to Auburn, CA) (Body mass 70.1 ± 8.8 kg, height 179 ± 6 cm, age 40 ± 8 years) were recruited to take part in the study. Participants self-reported: no known cardiovascular disease, no prescribed medications and no comorbidities for cardiovascular disease. The current training status was 6 ± 1 training days per week, 65 ± 12 miles per week, 12 ± 3 training hours per week and 38 ± 32 completed ultra-marathons. Written informed consent was obtained and Ethics approval was granted by the Liverpool John Moores University Ethics Committee.

Protocols

The 15 participants were assessed pre-race (24 - 48 hours prior to the race) and immediately post-race (within 30 minutes of race completion). A sub-sample (n = 9) returned for a final data collection 6 hours post-race completion. Height, body mass, resting blood pressure and a supine echocardiogram were recorded at each data collection point. Standard resting 12-lead ECG was recorded at baseline and immediately post-race prior to the echocardiographic examination. Participants were requested to avoid vigorous training, alcohol and caffeine for the 24 hours prior to the pre-race assessments. Participants were permitted to consume food and fluid *ad libitum* during the race and ambient temperature ranged from 5 to 39 °C.

Echocardiographic Assessments

All echocardiographic images were acquired using a commercially available ultrasound system (Vivid Q, GE Medical, Horten, Norway) with a 1.5-4 MHz phased array transducer. Images were obtained by a single experienced sonographer (DO) with the participant in the left lateral decubitus position. Images were recorded to DVD in raw DICOM format and data were analysed offline by a single

experienced sonographer (RL) using commercially available software (EchoPac version 7, GE Medical, Horten, Norway). A minimum of three cardiac cycles were averaged for all peak indices.

Conventional Echocardiography

Standard 2D, pulsed wave Doppler and pulsed tissue Doppler (TDI) echocardiographic indices were obtained from parasternal long (PLAX) and short axis (PSAX) acoustic windows. A modified apical 4-chamber (AP4CH) orientation was acquired to allow accurate assessment of the right heart (Rudski et al. 2010). A comprehensive structural and functional assessment of the RV was undertaken in accordance with American Society of Echocardiography (ASE) guidelines (Rudski et al. 2010). LV eccentricity index (EI) was calculated as a measure of interventricular septal displacement as previously described (Ryan et al. 1985). Right atrial (RA) volume was measured using an AP4CH view and calculated using Simpson's method at end-systole.

Right ventricular systolic pressure (RVSp) was derived from the tricuspid regurgitant jet using continuous wave Doppler. Pulmonary artery (PA) systolic pressure (PASP) was calculated as (PASP (mmHg) = RVS_p + 5mmHg). For RV end-systolic wall stress, Laplace's law was used to calculate according to the formula Pr/2h where P (pressure) was quantified as PASP, r (radius) was calculated using the formula $r = 0.620(\mathrm{RVSa})^{\frac{1}{3}}$, assuming spherical geometry as previously described (Marcus et al. 2008) and h was quantified as RV wall thickness. RVOT (RV outflow tract) peak velocity and velocity time integral (VTI) were obtained using pulsed wave (PW) Doppler and RV stroke volume (ml) (SV) calculated as $\left(\pi\left(\frac{\mathrm{RVOT}_{2(\mathrm{systole})}}{2}\right)^2 * \mathrm{VTI}\right)$. Pulmonary artery acceleration time (PA Acc Time) was calculated as the time from onset of flow to peak flow velocity. Peak tricuspid myocardial annular velocities were obtained using a 4mm PW TDI sample volume placed in the RV lateral wall using an AP4CH view to allow the assessment of peak systolic (S'), early (E') and late (A') diastolic velocities, isovolumic contraction (IVCT) and isovolumic relaxation (IVRT) times.

2D Myocardial Speckle Tracking

Standard 2D echocardiography was used to obtain a modified, lateral apical 4 chamber view for MST derived ε imaging of the RV lateral wall and images optimized as previously described (Korinek et al. 2005; Mor-Avi et al. 2011). Offline analysis involved placing the region of interest around the RV

lateral wall from base to apex only and excluding the septum. Regional peak longitudinal ε and systolic (SRS), early diastolic (SRE) and late diastolic (SRA) strain rates were obtained for RV basal, mid and apical wall segments. Global peak ε and SR were calculated as an average of the three RV myocardial segments. In order to standardise for variable heart rates (HR), temporal data for RV ε and SR was obtained throughout the cardiac cycle using cubic spline interpolation in Microsoft Excel (2010) to provide 300 data points for both systole and diastole as previously described (Burns et al. 2010). Time to peak (TsPeak) RV ε, time to peak SRS (T_{SRS} Peak), SRE (T_{SRE} Peak) and SRA (T_{SRA} Peak) were calculated from the raw data and were corrected for heart rate using the Bazetts formula.

12-Lead Electrocardiogram

The 12-lead ECG was undertaken in accordance with recommended guidelines on standard limb and precordial electrode positions (Kossmann et al. 1967). Extracted data included P duration, PR interval, QRS, P and T axis, QRS duration, QTc interval (Bazetts formula) and the summation of the R wave in lead V1 and S wave in lead V5. The incidence of the following findings were recorded; J point elevation in lead V1 (>1mm), partial or complete RBBB, T wave inversion in lead V1, right axis deviation (RAD), right ventricular hypertrophy (RVH) and early repolarisation. The percentage of athletes with right sided ECG changes and corresponding changes in RV size and function > 10 % or < 10 % post-race was calculated in an attempt to link the severity of RV echocardiographic and ECG changes.

Statistics

Echocardiographic data and continuous data from the 12-lead ECG were analysed for normality of distribution using a Shapiro-Wilk test. Peak and temporal data pre-race versus post-race and post-race versus recovery were compared using Student's Paired T-tests. 12-lead ECG data was collated and presented as specific incidence (%) at each data collection point. All statistical tests were performed using commercially available software (IBM SPSS version 21) and statistical significance was set as $P < 0.05$. Bivariate correlation analysis was undertaken between delta changes in all echocardiographic variables from pre to post-race.

RESULTS

Baseline Demographics

All participants completed the race (range 18:55 to 23:55 hours). Body mass did not change whereas systolic (P < 0.001) and diastolic (P = 0.03) systolic and diastolic blood pressure were significantly reduced post-race when compared to baseline measures (133 ± 11 to 114 ± 12 and 84 ± 10 to 74 ± 22 mmHg respectively).

Standard 2D, Doppler and Tissue Doppler

Pre and post-race data for RV structure and function are presented in Table 1.There was a post-race increase in RV inflow and outflow tract dimensions of 14 and 11 % (P = 0.004 and 0.002, respectively). RV systolic area (RVAs) was significantly increased by 10 % (P = 0.003) resulting in a 10 % decrease in RV fractional area change (FAC) post-race (P = 0.02). The EI in systole was increased by 6 % post-race (P = 0.04).

RVOT VTI was reduced by 22 % post-race (P = 0.001). RV lateral wall S' and E' tissue velocities were reduced by 18 % post-race (P = 0.005 and 0.04, respectively) whereas A' was unchanged. RV IVRT and IVCT were increased by 62 and 33 % post-race (P = 0.001 and >0.001 respectively). PASP and RV wall stress were not significantly changed post-race. The cohort data did mask some degree of heterogeneity but a post-race increase in RV size > 10 % was observed in 67 % of the participants. RV data remained different to pre-race levels 6 hours into recovery, except for IVCT and RVOT VTI (see Table 1).

INSERT TABLE 1

Right Ventricular Deformation

RV ε data are presented in Table 2 and Figures 1 and 2. Peak RV lateral wall ε was reduced by 10 % post-race ($P = 0.007$). In systole, RV ε was reduced at each time point post-race and was significantly lower from 60-100 % systole ($P < 0.05$). In diastole, there was a delay in relaxation resulting in an increased ε at each time point in early diastole and delayed and reduced peak SRE post-race (Figure 2). Pre to post race comparison of temporal SRE data showed a significant reduction during early diastole 5-50% of diastole ($P < 0.05$). Peak SRA was significantly different from 65-80 % diastole ($P < 0.05$) pre to post-race (Figure 2). Heart rate corrected TsPeak was significantly delayed ($P = 0.008$) and T_{SRA} Peak occurred significantly earlier ($P = 0.008$) post-race. A decrease in RV ε > 10 % was apparent in 47 % of the athletes. Peak RV lateral wall ε and peak SRE remained depressed and delayed after 6 hours of recovery compared to baseline values.

INSERT TABLE 2 AND FIGURES 1 AND 2

Correlation Analysis

The number of previous ultra-marathons completed and the race completion time correlated negatively with increases in RV inflow tract diameter (see Table 3). Significant negative relationships were also observed between the number of previous ultra-marathons completed and increases in EI in systole, RA size, area, pre A and end diastolic volumes (see Table 3).

INSERT TABLE 3

12 Lead ECG

The summated R wave in V1 and S wave in V5 increased by 19% post-race but the incidence of RVH was unchanged. The prevalence of J point elevation in V1, partial RBBB, T wave inversion in lead V1 and early repolarisation increased at post-race (27 % to 60 %, 27 % to 40 %, 47 % to 80% and 33 % to 53 %, respectively; Figures 3 and 4). There was a significant increase in QTc interval pre to post-race (Table 4). An increased summated R wave in V1 and S wave in V5 was evident in 57 vs 88 %, increased prevalence of T wave inversion in 29 vs 63 %, increased prevalence of J point elevation in 14 vs 25 %, increased partial RBBB in 14 vs 13 % and increase in early repolarisation in 29 vs 25% of athletes with >10 % and <10 % reduction in RV ε respectively. An increased summated R wave in V1 and S wave in V5 was observed in 80 % of athletes with RV dilatation >10 % post-race compared with 60 % of athletes with RV dilatation <10 %. An increased prevalence of T wave inversion was evident in 40 vs 60 %, an increased prevalence of J point elevation in 20 vs 20 %, an increased partial RBBB in 10 vs 20 % and an increase in early repolarisation in 20 vs 40% of athletes with RV dilatation >10 % and <10 % respectively.

INSERT TABLE 4 and FIGURES 3 and 4

DISCUSSION

The key findings of this study are; 1) an acute alteration in RV structure and function immediately following a 100 mile ultra-marathon which 2) persisted 6 hours into recovery, and 3) an increased incidence of right sided electrical parameters post-race as well as a lengthening of the QTc interval.

A reduction in RV function after prolonged exercise supports previous ultra-endurance studies that have used a range of echocardiographic techniques and indices (Davila-Roman et al. 1997; La Gerche et al. 2011a; La Gerche et al. 2008; McKechnie et al. 1979; Oxborough et al. 2011b). Taken together, these studies demonstrated increased RV size, decreased RVFAC, decreased trans tricuspid early to late filling velocity ratio, decreased RV lateral wall myocardial annular velocities (S', E' and A') and a reduction in RV ε and SR. Our findings confirm these data but also document a delayed TsPeak. This may be indicative of an electromechnical delay (Chan-Dewar et al. 2010) within the RV and provides further evidence of a negative impact on global and regional RV longitudinal function, that is likely intrinsic to the cardiomyocyte. The current data contradict findings in

some studies (Douglas et al. 1990; Neilan et al. 2006b; Oxborough et al. 2006; Oxborough et al. 2010) but this could reflect a combination of shorter exercise duration / intensity, limited RV interrogation and/or differences in participant groups. This may suggest an impact of exercise duration on acute RV structural and functional changes which has also been implied in data collected on the LV (Middleton et al. 2006). Despite confirming previous work it is important to note that whilst mean cohort data was often significantly altered by the prolonged exercise the individual response displayed a degree of heterogeneity which supports case study data presented previously (George et al. 2009).

The mechanisms responsible for the changes in RV structure and function are not fully understood. Despite this, a theory has been proposed recently which implicates increased relative pulmonary vascular resistance during exercise (La Gerche et al. 2011b; Oxborough et al. 2011b). The pulmonary vasculature is unable to vasodilate to the same degree as the systemic vasculature in the presence of an increasing stroke volume and consequently PA pressures rise. A recent meta-analysis highlighted that mean PA pressure during exercise often exceeds 30 mmHg and is dependent, in part, on age and exercise intensity (Kovacs et al. 2009). The lack of change in PASP in our data likely reflects the fact that these indices were only recorded during supine rest/recovery. That aside the increased RV size and wall stress, allied to a decrease in RV function as well as flattening of the septum in systole post-race, are all indicative of sustained exposure to an elevation in RV afterload (Puwanant et al. 2010). Our data also demonstrated a negative correlation between finishing time and magnitude of RV enlargement at the inflow. This is in fitting with other work (Oxborough et al 2011) and raises the likelihood of exercise intensity being a primary driver in acute RV adaptation. The relationship between previous experience and RV remodeling is equally intriguing and suggests that repeated exposure to an ultramarathon results in chronic adaptation that may well be protective. These findings leads us to consider that the magnitude of acute RV adaptation is very likely to be related to exercise volume (i.e. intensity x duration) particularly in those athletes that are less experienced.

An increase in blood and/or plasma volume has also been implicated in the mechanisms of EICF, however no significant relationship was evident between increased blood and plasma volume and

changes in RV and LV functional indices (Vitiello et al. 2013). That said, data on plasma volume is sparse and requires further investigation before this can be discounted as a potential contributor to changes in LV and RV structure and function. Alongside this, the release of cardiac troponins and naturetic peptides correlate strongly with changes in RV structure and function in particular RV wall stress and future studies should focus on establishing a causal link between RV afterload, changes in the RV post exercise and cardiac biomarker release.

The changes in 12-lead ECG data pre to post-race are intriguing. An increased incidence of partial RBBB, T-wave inversion and J point elevation in lead V1 suggest changes in RV electrical activity, although we cannot directly link these to the degree of altered RV structure and function observed in echocardiographic indices in the current study and this is supported by findings in pulmonary embolism (Stein et al. 2013). Kucher and colleagues (2003) presented similar 12-lead ECG findings in patients following pulmonary embolism and suggest that this was consistent with RV strain (Kucher et al. 2003). Although the incidence of these findings was greater in pulmonary embolism than after prolonged exercise, it is important to acknowledge that these findings were in the presence of a marked elevation in RV afterload. The sustained exposure of intense exercise undertaken by the participants in the current study likely induces an elevation in RV afterload but to a lesser magnitude than those seen in the diseased population and may explain the “mild” ECG changes we observed.

There was a significant increase in QTc interval and incidence of early repolarisation post-race. Although these findings may not relate to the right ventricle they do warrant some consideration. Previous work has highlighted repolarisation changes (Sahlen et al. 2009) and increased QTc interval (Stewart et al. 2014) in response to prolonged strenuous exercise which was postulated to be related to increased parasympathetic activity in the recovery stage. Our data appears to add some ‘food for thought’ in this area and clearly highlights the requirement for further work focused on providing a comprehensive understanding of post-exercise electrical repolarisation with right sided and posterior leads to determine the possible implications to the athlete.

Clinical Implications

There is still some debate over the transient nature of these changes with the majority of studies only assessing participants immediately following exercise. Whilst Oxborough and colleagues (Oxborough et al. 2010) documented a return to baseline RV structure and function 6 hours after a marathon, other studies (La Gerche et al. 2008; Neilan et al. 2006b) reported evidence of a persistent depression in RV function at 1 week and 3-4 weeks post marathon and Ironman triathlon, respectively. The current study assessed a sub sample of athletes 6 hours into recovery and supports the notion that a return to baseline RV structure and function does not occur within 6 hours of race completion. The mechanism behind these persistent changes is not fully understood but may be as a result of intrinsic changes in the myocardium and it is pertinent to further investigate the duration and aetiology. Assessment of athletes in the days/weeks following exercise completion should be undertaken with caution although the possibility that changes in RV structure and function are sustained for a prolonged period is still unlikely given the normal RV observed at baseline.

It is difficult to predict the long-term outcomes on cardiac structure and function in ultra-endurance runners however it is likely that this acute phenomenon acts as a stimulus for RV remodelling. There is strong evidence supporting the disproportionate increase in right heart size in endurance athletes (D'Andrea et al. 2012; Oxborough et al. 2012) but this appears to be physiological in nature. There is however a school of thought that repeated exposure and insufficient recovery time may lead to an acute phenomenon of RV adaptation acting as a stimulus for pathological adaptation (La Gerche et al. 2011b). These theories have yet to be substantiated and there is no clear evidence at this stage of a chronic deleterious effect of ultra-marathon running on cardiac health.

Limitations

This study utilised a small sample for pre and post-race measures, as well as a smaller sub sample for recovery measures. It is important to consider the limited statistical power and possible statistical error within this study. RV deformation was only assessed in the longitudinal plane. The complex nature of RV geometry and fibre orientation makes the assessment of circumferential function challenging and therefore was not included in this study. It is clear that further work utilising more

novel techniques is required to provide evidence to support our theory. The recent advent of 3 dimensional (3D) echocardiography could help to overcome limitations in assessing RV deformation from multiple planes as well as allowing the measurement of RV volumes at end-diastole and end-systole, however this technique still suffers from relatively low frame-rates and 3D speckle tracking has not been applied or validated to the assessment of RV function.

Cardiac biomarkers were not measured during this study, however the inclusion of BNP and/or cardiac troponins may shed some light on RV adaptation / wall stress during prolonged strenuous exercise.

Conclusions

Completion of a 100 mile ultra-marathon in under 24 hours resulted in an acute change in RV structure and function that is consistent with a sustained exposure to an elevation in relative RV wall stress. This “dysfunctional” model of RV function persisted 6 hours into recovery. These findings were also supported by right sided changes to the 12-Lead ECG.

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Ethical standards: Ethics approval was granted by the Liverpool John Moores Ethics committee and the study complied with the current laws of the USA where the research was undertaken.

Conflict of interest: None

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Table 1 – Standard 2D, Doppler and Tissue Doppler derived indices of RV structure and function at baseline, immediately post-race and 6 hours into recovery from the race.

PARAMETER	***PRE RACE (Mean ± SD)***	***POST RACE (Mean ± SD)***	***Pre vs Post SIGNIFICANCE***	***RECOVERY (Mean ± SD)***	***Post vs Recovery SIGNIFICANCE***
Heart Rate (bpm)	63 ± 10	70 ± 10	*P* = 0.05*	71 ± 12	*P* = 0.75
RVOTplax (mm)	30 ± 4	33 ± 3	*P* = 0.004*	33 ± 4	*P* = 0.22
RVOT1 (mm)	32 ± 4	36 ± 4	*P* = 0.002*	35 ± 5	*P* = 0.75
RVOT2 (mm)	25 ± 2	28 ± 2	*P* = 0.62	27 ± 3	*P* = 0.47
RVD1 (mm)	43 ± 4	48 ± 5	*P* = 0.003*	47 ± 6	*P* = 0.61
RVD2 (mm)	32 ± 3	37 ± 3	*P* ≤ 0.001*	36 ± 3	*P* = 0.29
RVD3 (mm)	84 ± 6	83 ± 7	*P* = 0.43	82 ± 6	*P* = 0.81
RVDarea (cm^2)	26.0 ± 2.7	27.1 ± 2.8	*P* = 0.09	27.7 ± 3.4	*P* = 0.22

RVSarea (cm^2)	11.9 ± 1.8	13.9 ± 1.9	*P* = 0.003*	13.7 ± 2.4	*P* = 0.68
RVFAC (%)	54.1 ± 5.8	48.8 ± 4.7	*P* = 0.02*	50.3 ± 8.2	*P* = 0.31
RV/LV	0.99 ± 0.13	1.01 ± 0.10	*P* = 0.63	0.97 ± 0.11	*P* = 0.54
RA Major (mm)	47 ± 8	47 ± 6	*P* = 0.81	44 ± 7	*P* = 0.42
RA Minor (mm)	47 ± 7	51 ± 5	*P* = 0.05*	50 ± 6	*P* = 0.93
RA Area (mm)	18.4 ± 4.4	19.7 ± 4.3	*P* = 0.25	18.2 ± 4.0	*P* = 0.52
EI Diastole	1.16 ± 0.11	1.22 ± 0.10	*P* = 0.08	1.14 ± 0.08	*P* = 0.39
EI Systole	1.09 ± 0.07	1.15 ± 0.12	*P* = 0.04*	1.14 ± 0.08	*P* = 0.25
RA End Systolic Vol (ml)	64 ± 29	67 ± 21	*P* = 0.66	58 ± 21	*P* = 0.35
TAPSE (mm)	24 ± 4	23 ± 4	*P* = 0.24	26 ± 3	*P* = 0.04*
RV S' ($mm.s^{-1}$)	17 ± 3	14 ± 3	*P* = 0.005*	16 ± 1	*P* = 0.13

RV E' ($mm.s^{-1}$)	17 ± 2	14 ± 4	*P* = 0.05*	14 ± 3	*P* = 0.43
RV A' ($mm.s^{-1}$)	13 ± 5	12 ± 3	*P* = 0.39	13 ± 3	*P* = 0.74
RV E'/A'	1.37 ± 0.49	1.20 ± 0.39	*P* = 0.29	1.16 ± 0.37	*P* = 0.60
RV IVRT (ms)	29 ± 13	47 ± 19	*P* = 0.001*	42 ± 15	*P* = 0.23
RV IVCT (ms)	60 ± 12	80 ± 18	*P* < 0.001*	66 ± 14	*P* = 0.01*
RVOT VTI (cm)	18.8 ± 2.9	14.7 ± 2.8	*P* = 0.001*	17.5 ± 3.3	*P* = 0.003*
RV SV (ml)	92 ± 25	89 ± 25	*P* = 0.55	102 ± 35	*P* = 0.04*
PASP (mmHg)	25 ± 4	22 ± 8	*P* = 0.17	23 ± 2	*P* = 0.04*
PA Acc Time (ms)	153 ± 23	143 ± 21	*P* = 0.40	153 ± 28	*P* = 0.29
RV Wall Stress ($kdynes/cm^2$)	3.97 ± 1.93	4.39 ± 1.30	*P* = 0.49	2.94 ± 2.24	*P* = 0.32

* denotes statistical significance

Table 2 – RV deformation indices at baseline, immediately post-race and 6 hours into recovery from the race

PARAMETER	**PRE RACE (Mean ± SD)**	**POST RACE (Mean ± SD)**	***Pre vs Post SIGNIFICANCE***	**RECOVERY (Mean ± SD)**	***Post vs Recovery SIGNIFICANCE***
RV Strain (%)	-29 ± 4	-26 ± 3	*P* = 0.007*	-27 ± 4	*P* = 0.39
Ts Peak (ms)	370 ± 36	377 ± 28	*P* = 0.47	371 ± 34	*P* = 0.43
Ts Peak (corrected)	376 ± 37	406 ± 42	*P* = 0.008*	403 ± 63	*P* = 0.56
RV SRS (l/s)	-1.48 ± 0.20	-1.37 ± 0.25	*P* = 0.10	-1.44 ± 0.25	*P* = 0.69
T_{SRS} Peak (ms)	163 ± 64	167 ± 87	*P* = 0.90	193 ± 59	*P* = 0.59
RV SRE (l/s)	1.77 ± 0.48	1.54 ± 0.35	*P* = 0.09	1.80 ± 0.30	*P* = 0.49
T_{SRE} Peak (ms)	95 ± 43	113 ± 57	*P* = 0.32	112 ± 68	*P* = 0.44
RV SRA (l/s)	1.19 ± 0.28	1.15 ± 0.27	*P* = 0.54	1.04 ± 0.23	*P* = 0.51
T_{SRA} Peak (ms)	545 ± 168	371 ± 136	*P* = 0.008*	396 ± 137	*P* = 0.43
RV SRE/SRA	1.53 ± 0.48	1.45 ± 0.61	*P* = 0.52	1.80 ± 0.45	*P* = 0.68

* denotes statistical significance

Table 3 – Significant bivariate correlations

Parameter	Correlation	Significance
Number of ultras: RV inflow tract	-0.54	0.047
Number of ultras: EI systole	-0.62	0.02
Number of ultras: RA pre A volume	-0.67	0.01
Number of ultras: RA end diastolic volume	-0.65	0.01
Number of ultras: RA area	-0.77	0.01
Number of ultras: RA minor	-0.72	0.004
Finishing time: RVD1	-0.79	<0.001

Table 4 – 12-Lead ECG parameters pre and post 100 mile ultra-marathon

PARAMETER	**PRE** **Mean ± SD**	**POST** **Mean ± SD**	**SIGNIFICANCE**
P Wave Duration (ms)	109 ± 22	106 ± 14	P = 0.526
PR Interval (ms)	156 ± 29	148 ± 23	P = 0.137
QRS Duration (ms)	98 ± 10	94 ± 9	P = 0.020
QTc Interval (ms)	415 ± 22	427 ± 21	P = 0.036*
P axis (degrees)	46 ± 25	46 ± 37	P = 0.956
Q axis (degrees)	61 ± 26	60 ± 23	P = 0.592
T axis (degrees)	35 ± 15	38 ± 13	P = 0.349
R in V1 + S in V5	7.1 ± 2.9	8.4 ± 4.4	P = 0.167

* denotes statistical significance

FIGURE AND TABLE LEGENDS

Figure 1 –Temporal RV deformation during systole and diastole pre, post and 6 hours into recovery from the race

Figure 2 - Temporal relationship of SR in systole and diastole pre, post and 6 hours into recovery from the race.

Figure 3 – Incidence of ECG findings pre and post 100 mile ultra-marathon

Figure 4 – Exemplar ECG demonstrating changes in V1 following a 100 mile ultra-marathon

Table 1 – Standard 2D, Doppler and Tissue Doppler derived indices of RV structure and function at baseline, immediately post-race and 6 hours into recovery from the race.

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Table 3 – Significant bivariate correlations

Table 4 – 12-Lead ECG parameters pre and post 100 mile ultra-marathon