ORIGINAL ARTICLE

Preload maintenance protects against a depression in left ventricular systolic, but not diastolic, function immediately after ultraendurance exercise

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Objective: To investigate indices of left ventricular (LV) function before and after a 224 km Ironman triathlon, specifically in the presence of unaltered haemodynamic loading.
Method: LV loading and function were assessed before and after the race using M mode and Doppler echocardiography in 39 (mean (SD) age 33 (8) years, body mass 77.6 (8.6) kg; 36 male) triathletes in the Trendelenburg position. Specifically left ventricular end diastolic volume (LVEDV) was assessed to estimate preload, and systolic blood pressure to estimate afterload as well as heart rate (HR). Systolic functional indices included ejection fraction (EF) and the end systolic pressure/volume ratio (ESPV), and diastolic functional indices included peak mitral flow velocity in early (E) and atrial (A) filling as well as the ratio E/A. Data obtained before and after the race were compared by *t* tests, and delta LV functional indices were correlated with delta heart rate.
Results: Preload (LVEDV: 143 (34) ml before *v* 147 (34) ml after) and afterload (systolic blood pressure 121 (13) *v* 115 (20) mm Hg) were not significantly altered after the race ($p>0.05$), nor were EF (61 (8)% *v* 58 (10)%) and ESPV (2.4 (0.9) *v* 2.1 (0.8) mm Hg/cm^3). The diastolic filling ratio E/A was significantly reduced after the race (1.73 (0.25) *v* 1.54 (0.23); $p<0.05$) due primarily to a reduction in E. HR was significantly higher after the race (57 (9) *v* 75 (8) beats/min; $p<0.05$), but delta HR was not related to delta E/A ($p>0.05$).
Conclusion: When preload and afterload are unaltered after the race, because of the adoption of a unique assessment posture, LV systolic function is not depressed. A depression in LV diastolic function persists which is not explained by an increase in heart rate after the race.

In 1978 two runners developed acute pulmonary oedema during the 90 km Comrades Marathon foot race in South Africa.[1] The absence of cardiac disease, identifiable by either echocardiography or coronary and left ventricular angiography, in both athletes as well as the rapidity with which these abnormalities regressed despite negligible treatment suggested transient pulmonary oedema of cardiac origin. At the time no mechanism for this condition could be determined. Subsequently, a number of studies have shown altered left ventricular function after prolonged exercise,[2–12] which may explain the symptoms noted in the two Comrades runners. Such alterations in cardiac function after prolonged exercise have been termed ''cardiac fatigue''.[2]

At present, the aetiology of cardiac fatigue is not known, and, although previous authors have suggested many possible factors, to date no one has provided conclusive support for any proposed mechanism. In any study of prolonged exercise, it is impossible to divorce the influence of changes in loading conditions from intrinsic contractile and relaxation properties of the ventricles. It is possible that prolonged exercise results in hypovolaemia and/or redistribution of central blood volume which would facilitate a reduction in venous return and thus decrease preload. Indeed, in most previous studies on the effects of prolonged exercise on left ventricular function, a reduction in end diastolic volume after the race has been reported.[2 5–9 11 12] Further, prolonged exercise produces significant changes in peripheral vascular function, including a persistent reduction in total peripheral vascular resistance sufficient to produce postural hypotension[13] and post-exercise collapse[14] which reduces afterload on the heart. In only one previous study[2] of left ventricular function after exercise has the blood pressure been the same before and after exercise. Rather, most studies have shown a reduction in systolic blood pressure after exercise.[4–9 11 12 15] It is therefore possible that the change in left ventricular function observed previously represents an artefact of altered haemodynamics rather than a true depression in inotropy or intrinsic relaxation properties.

A limited number of studies on cardiac function and prolonged exercise have attempted to maintain preload through saline infusion.[3 16] Typically, however, these studies have been relatively short in duration and have used laboratory based exercise protocols. Maintenance of left ventricular loading in the field study models commonly used in cardiac fatigue research is difficult. It is possible, however, to manipulate the posture in which assessments are made before and after exercise in an attempt to standardise loading conditions and thus separate loading and possible intrinsic fatigue effects. This has not previously been attempted in the cardiac fatigue literature. Therefore, the aim of this study was to examine left ventricular function before and after a prolonged bout of exercise while attempting to minimise the influence of altered haemodynamic loading conditions by adoption of the Trendelenburg posture. We hypothesised that measurements of left ventricular function obtained in this posture before and after the race would show diminished evidence of cardiac fatigue.

Abbreviations: E/A, ratio of early to late peak diastolic filling; EF, ejection fraction; ESPV, end systolic pressure/volume ratio; SV, stroke volume

MATERIALS AND METHODS

After local ethics approval had been obtained, 39 athletes (36 male; mean (SD) age 33 (8) years, body mass 77.6 (8.6) kg) competing in the 2001 Cape Town Ironman Triathlon competition (3.8 km swim, 180 km cycle, and 42.2 km run) volunteered for the study. All subjects provided informed consent before participation and, through self report, were deemed healthy. During the race, subjects were permitted to consume food and fluid ad libitum. On the day of the race, weather conditions were as follows: air temperature ranged from 15.6 to 20.9℃ (mean 17.2℃), sea temperature was 15℃, and relative humidity was 63% with a maximum of 79% and a minimum of 48%. Data were collected in the two to five days before the race and again immediately after race completion (within 30 minutes). At each assessment, measures consisted of body mass (kg), blood pressure, and echocardiography.

Echocardiographic measurement

All echocardiograms were obtained with the athletes in the left lateral decubitus position in the head down (Trendelenburg) position (~25°). This posture was adopted in the belief that it would optimise central blood volume and thus result in equal preload before and after exercise. In addition, this posture should produce some peripheral vasoconstriction resulting in similar afterload before and after exercise. All scans were performed by a single experienced sonographer using a commercially available ultrasound system (Acuson Cypress; Siemens Medical Division, Plymouth Meeting, PA, USA) with a 2.5 MHz probe.

Blood pressure and heart rate were measured simultaneously with echocardiographic acquisition using an electrocardiograph inherent to the ultrasound system and standard auscultation techniques. Intrinsic left ventricular contractile function was represented by two variables: ejection fraction (EF) and the end systolic pressure/volume ratio (ESPV). Both were used, as EF is a common estimate of contractile function, whereas ESPV has been suggested to be a load independent measure.[17] Data for stroke volume (SV), EF and ESPV were obtained from measurements taken from the apical four chamber view using the modified Simpson's rule.[18] For all measurements, a minimum of three consecutive cardiac cycles were digitised, and the values obtained were averaged.

Doppler echocardiography was used to assess diastolic filling using a 2.5 MHz transducer. A two dimensional apical four chamber view was imaged, taking care to maximise the diameter of the mitral valve annulus. Pulsed wave Doppler interrogation of mitral valve inflow velocities was then performed with alignment of the sample volume cursor parallel to flow at the level of the mitral annulus. Minor transducer adjustments were made to obtain optimal spectral display (highest velocity with least spectral dispersion). The Doppler velocity curves of three to five consecutive cardiac cycles were obtained, and the measurements were averaged. Peak early filling (E), and peak late filling (A) velocities were measured, and the ratio of early to late diastolic filling (E/A) was calculated.

Statistical analysis

Cardiovascular variables were compared before and after the race using paired Student's *t* tests. The change in left ventricular functional measures after the race (delta scores) were correlated with age, finishing time, and the increase in heart rate after the race by Pearson product-moment correlations. Data were analysed for normality using the Kolmogorov-Smirnov test. Significance was taken at $p \leqslant 0.05$. All data are expressed as mean (SD). Data analysis was performed using statistical computer software (Statistica; Statsoft Ltd, Tulsa, Oklahoma, USA).

RESULTS

The 39 athletes successfully completed the Ironman competition with a mean completion time of 712 (96) minutes (swim = 67 (12) minutes, bike = 376 (49) minutes, run = 268 (46) minutes). Body mass was significantly reduced after the race (77.6 (8.6) *v* 73.6 (8.4) kg; $p<0.05$). Results from the Kolmogorov-Smirnov test showed that all data were normally distributed ($p>0.05$).

Left ventricular loading

Table 1 presents data for aspects of left ventricular preload, afterload, and heart rate. It is apparent that left ventricular end diastolic volume, an indirect index of preload, was not

Table 1 Data pertinent to left ventricular loading before and after a 224 km Ironman triathlon

	Before	After	p Value
Heart rate (beats/min)	57 (9)	75 (8)	<0.0001
LVEDV (ml)	143 (34)	147 (34)	0.49
Systolic BP (mm Hg)	121 (13)	115 (19)	0.09

Values are expressed as mean (SD).
LVEDV, Left ventricular end diastolic volume.

Table 3 Relation of age and finishing time to delta scores for ejection fraction (EF), end systolic pressure/volume ratio (ESPV), and ratio of early to late diastolic filling (E/A)

	Delta EF (%)	Delta ESPV (mm Hg/cm^3)	Delta E/A
Age (years)	−0.27	−0.07	0.15
Finishing time (min)	−0.33*	−0.14	−0.08

*p<0.05.

Table 2 Data for indices of left ventricular systolic and diastolic function before and after a 224 km Ironman triathlon

Variable	Before	After	p Value
SV (ml)	88 (25)	86 (27)	0.80
EF (%)	61 (8)	58 (10)	0.14
ESPV (mm Hg/cm^3)	2.4 (0.9)	2.1 (0.8)	0.10
E (m/s)	1.10 (0.15)	0.98 (0.17)	<0.0001
A (m/s)	0.65 (0.12)	0.64 (0.11)	0.73
E/A ratio	1.73 (0.25)	1.54 (0.23)	0.0008

Values are expressed as mean (SD).
SV, Stroke volume; EF, ejection fraction; ESPV, end systolic pressure/volume ratio; E, early transmitral flow velocity; A, late transmitral flow velocity.

significantly altered after the race ($p>0.05$) in spite of the significant decline in body mass. Similarly mean blood pressure after the race was not significantly depressed, suggesting that afterload on the left ventricle was also unchanged by the ultraendurance exercise ($p>0.05$). Heart rate was, as expected, significantly higher after the race ($p<0.05$).

Left ventricular function

No significant change in SV, EF, or ESPV was noted after the race ($p>0.05$). The peak early (E) transmitral filling velocity decreased significantly ($p<0.05$), whereas peak late (A) transmitral filling velocity remained unchanged ($p>0.05$) after the race, which resulted in a significantly lower E/A ratio after the race ($p<0.05$) (table 2). Because of the wide range of subject ages and finishing times, we compared delta EF, ESPV, and E/A with these variables to determine if any of these factors contributed to individual responses (table 3). The only significant correlation was between completion time and the change in EF ($r = 0.33$, $p<0.05$). Because of the increased heart rate after the race, we investigated the correlation between delta scores for heart rate and EF, ESPV, and E/A ratio (fig 1). It is clear from the data plots and the correlation coefficients that the altered heart rate after the event did not explain any significant proportion of the alterations in function.

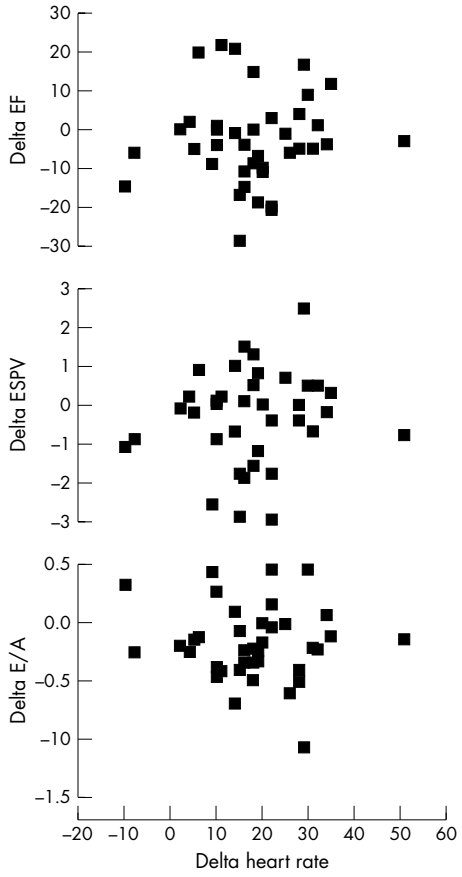

Figure 1 Relation of elevated heart rate after the race to delta scores for ejection fraction (EF) ($r = 0.08$, $p = 0.60$), end systolic pressure/volume ratio (ESPV) ($r = 0.13$, $p = 0.40$), and ratio of early to late diastolic filling (E/A) ($r = -0.09$, $p = 0.60$).

DISCUSSION

The aim of this study was to see if the maintenance of loading conditions on the left ventricle at assessments before and after an Ironman triathlon would shed some light on the underlying mechanisms responsible for exercise induced cardiac fatigue. The first important and unique finding is that indices of both preload and afterload were similar before and after the triathlon. Thus the use of the Trendelenburg position resulted in much closer loading at both assessments than has been reported in many previous studies.[2 5–9 11 12] Previous work has shown increased early diastolic filling and end diastolic volume on moving from the standard supine position to the Trendelenburg position in a normal population.[19] In our study, the change in haemodynamics in response to the Trendelenburg posture may therefore have ameliorated the decrement in preload observed in previous studies.[2 5–9 11 12] Venous pooling that may have previously been apparent may have been negated by the posture adopted in our study, resulting in comparable loading conditions before and after exercise.

The effect of ultraendurance exercise on indices of left ventricular systolic function in this study, with maintenance of loading, was seemingly negligible. The lack of alteration in EF and ESPV after the exercise is in contrast with most previous research investigating exercise durations similar to the Ironman triathlon.[2 12 20] Our data suggest that previous findings of a decrease in left ventricular systolic function after ultraendurance activity may have actually been due to altered loading rather than an intrinsic depression in inotropy.

As a counterpoint, it is noteworthy that, although no significant decrease was observed in EF and ESPV group data, individual differences were apparent. In addition, there were also individual changes in loading (left ventricular end diastolic volume up and blood pressure down), which would have normally resulted in a small rise in contractility. Taken in tandem, these points suggest that it may be presumptuous to completely dispel the occurrence of some intrinsic contractile cardiac muscle fatigue after ultraendurance exercise. Suffice it to say that this effect may be much smaller, and thus have less clinical and performance related significance, than has been suggested in previous work. Indeed there has been some interesting work on the role of reduced β-adrenoreceptor function after prolonged exercise that may explain the reduction in left ventricular contractility.[21–23] It seems likely that this effect is independent of left ventricular loading and thus may still explain the small individual changes in EF and ESPV found in our study.

The decrease in E/A after the race, in the absence of changes in left ventricular systolic function, has been reported previously in studies examining exercise of shorter duration.[24 25] Although still statistically significant, the fall in E/A of about 0.2 unit is somewhat less than reported previously (about 0.5 unit[6]). The magnitude of change after the race may reflect a small ameliorative role for preload and its maintenance in this study, although changes in preload have not been found to correlate significantly with changes in E/A in previous studies.[24]

Interpretation of the changes in diastolic data after the race is also complicated by the natural increase in heart rate after exercise.[26] Importantly, the changes in transmitral flow pattern after exercise in the present study were not related to delta heart rate values. Thus we must conclude that some factor(s) intrinsic to the left ventricular myocytes is responsible for the significant depression in E/A after the race. Direct identification of the mechanism(s) responsible for the significant fall in E/A after the race is beyond the scope of this study. However, some further discussion and speculation is warranted. Unlike findings in previous

What is already known on this topic

- Prolonged exercise has been shown to induce reductions in left ventricular systolic and diastolic function

What this study adds

- This study shows by postural manipulation that the changes in systolic function after prolonged exercise may be an artefact of altered loading
- Impaired diastolic function is not fully explained by perturbations in loading subsequent to prolonged exercise

studies,[2 5 6 11 12] the reduction in E/A observed in the present study was caused solely by a reduction in E as opposed to the concomitant reduction in E and elevation in A (table 2). This contrasts with the altered filling patterns observed in previous cardiac fatigue studies.[2 5 6 11 12] E/A patterns in previous studies more closely resemble the impaired patterns found in pathological conditions such as left ventricular hypertrophy, myocardial ischaemia, and hypertrophic cardiomyopathy in which the A wave is increased as a result of impaired left ventricular relaxation. Further evaluation of this pattern of E/A ratio is warranted to aid our understanding. Irrespective of the lack of change in A, the significant decrease in E suggests either an alteration in the decline in left ventricular pressure in diastole or some limitation in the increase in left atrial pressure. Without invasive catheterisation or other indirect techniques (tissue Doppler, flow propagation), we cannot differentiate these potential effects. It has been speculated previously that there may be some alteration in intracellular Ca^{2+} handling that may result in impaired relaxation and thus reduced compliance of the left ventricle.[26] Other potential mechanisms, such as damage consequent on increased reactive oxygen species generated by such activity and the effect of altered β-adrenoreceptor function on diastolic filling, have not been fully explored and thus provide interesting avenues for further research.

Determination of the relations of EF, ESPV, and E/A to age and finishing time found that the only significant correlation was between completion time and the change in EF ($r = 0.33$, $p<0.05$). This represents a small degree of shared variance ($r^2 = 0.11$) and is thus potentially biologically meaningless. The lack of significant and meaningful relations supports previous research in marathon running.[24] Taken together, this provides some evidence that the lack of group differences after the race does not mask any significant effect of the race on a subpopulation (older, younger, faster or slower). Thus advancing age with its reduction in resting E/A, or a faster pace with its potential to promote a higher exercise heart rate and circulating catecholamines does not seem to promote the appearance of signs of exercise induced cardiac fatigue.

This paper provides some interesting new insights into the phenomenon of exercise induced cardiac fatigue. However, some limitations must be noted as well as directions for future study. This study is limited by the absence of data collected in the standard left lateral decubitus (almost supine) position. It is worthy of note, however, that previous research on left ventricular function in the supine position after an Ironman triathlon has consistently found a decrease in EF and E/A.[2 12 18] Future investigators should assess function in both the supine and Trendelenburg position to elucidate fully the effect of changes after exercise in left ventricular loading on cardiac function. Further, the measures used in this study are global in nature and may therefore not be sensitive to regional alterations in cardiac function after exercise. The use of novel techniques including tissue Doppler and two dimensional strain would facilitate a more complete assessment of the myocardium after exercise. Further, both this and previous studies have failed to assess function during prolonged exercise; therefore it is not possible to assess whether cardiac function is limited during exercise.

In summary, in this study maintenance of preload and afterload by a postural adjustment in the testing process probably ameliorated any evidence of a depression in left ventricular systolic function. Alterations in diastolic function appear, however, to persist despite the maintenance of loading and are independent of an elevated heart rate. Further work is required to clarify the aetiology and ramifications of exercise induced changes in diastolic function.

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COMMENTARY

This is a well written paper on cardiac fatigue after prolonged exercise. The study sought to clarify the issues associated with reductions in systolic and diastolic function and the influence of loading conditions after an Ironman triathlon. To accomplish this goal, the authors used blood pressure assessment, two dimensional echocardiography, and Doppler echocardiography. The data are similar to those from previous studies on cardiac fatigue after an Ironman triathlon, and the techniques used are fairly basic especially as echocardiography has advanced considerably recently. The novel aspect of this study is the use of the Trendelenburg position when taking the measurements before and after the Ironman triathlon in order to limit the reduction in preload after exercise and so that the afterload is similar before and after the race.

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