
Link to official URL (if available):
http://dx.doi.org/10.1249/MSS.0b013e318257d2db

This is a non-final version of an article published in final form in O. C. Witard, J. E. Turner, S. R. Jackman, K. D. Tipton, A. E. Jeukendrup, A. K. Kies, J. A. Bosch, 'High-Intensity Training Reduces CD8+ T-cell Redistribution in Response to Exercise' in Medicine and Science in Sports and Exercise (September 2012) Volume 44, Issue 9, pp. 1689 - 1697. DOI: 10.1249/MSS.0b013e318257d2db

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High-intensity training reduces CD8$^+$ T cell redistribution in response to exercise

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Running title: Exercise training and immune surveillance

Funding received from DSM Foods, The Netherlands.

Conflict of Interest Statement: All authors declare that there are no conflicts of interest.
Abstract

Purpose: We examined whether exercise-induced lymphocytosis and lymphocytopenia are impaired with high-intensity training. Methods: Eight trained cyclists ($\dot{V}O_2$ max: 64.2 ± 6.5 mL·kg$^{-1}$·min$^{-1}$) undertook one week of normal-, and a second week of high-intensity training. On day seven of each week, participants performed a cycling task, consisting of 120 min sub-maximal exercise followed by a 45 min time trial. Blood was collected before, during and after exercise. CD8$^+$ T lymphocytes (CD8$^+$TLs) were identified, as well as CD8$^+$TL sub-populations on the basis of CD45RA and CD27 expression. Results: High-intensity training (18,577 ± 10,984 cells·µL$^{-1}$×~165 min) was associated with a smaller exercise-induced mobilization of CD8$^+$TLs compared with normal-intensity training (28,473 ± 16,163 cells·µL$^{-1}$×~165 min, $p = 0.09$). The response of highly cytotoxic CD8$^+$TLs (CD45RA$^+$CD27$^-$) to exercise was smaller following one week of high- (3,144 ± 924 cells·µL$^{-1}$×~165 min) compared with normal-intensity training (6,417 ± 2,143 cells·µL$^{-1}$×~165 min; $p < 0.05$). High-intensity training reduced post-exercise CD8$^+$TL lymphocytopenia (~436 ± 234 cells·µL$^{-1}$) compared to normal-intensity training (~630 ± 320 cells·µL$^{-1}$; $p < 0.05$). This was driven by a reduced egress of naïve CD8$^+$TLs (CD27$^+$CD45RA$^+$). High-intensity training was associated with reduced plasma epinephrine (~37%) and cortisol (~15%) responses ($p < 0.05$). Conclusions: High-intensity training impaired CD8$^+$TL mobilization and egress in response to exercise. Highly cytotoxic CD8$^+$TLs were primarily responsible for the reduced mobilization of CD8$^+$TLs, which occurred in parallel with smaller neuro-endocrine responses. The reduced capacity for CD8$^+$TLs to leave blood post-exercise with high-intensity training was accounted for primarily by naïve, and also, highly cytotoxic CD8$^+$TLs. This impaired CD8$^+$TL redistribution in athletes undertaking intensified training may imply reduced immune-surveillance.

Key words: Exercise training, CD8$^+$ T Lymphocytes, immune surveillance, epinephrine, cortisol, humans.
Introduction

**Paragraph 1.** Epidemiological evidence shows that athletes undertaking prolonged periods of high-intensity exercise training are more susceptible to infectious disease (e.g., upper respiratory tract infection (URTI)) (12). Longitudinal studies demonstrate a 40% increase in the incidence of URTI in athletes undertaking a very high training load (11). To better understand the mechanisms that may underlie these observations, a variety of immune parameters have been investigated in response to, and following bouts of exercise (23). For example, intense exercise can alter several aspects of cell mediated immunity including; impaired neutrophil function, natural killer (NK) cell cytotoxicity, and lymphocyte cytokine production (12,21,34). These immune parameters, however, appear not to be predictive of viral infection incidence in athletes (23).

**Paragraph 2.** One process that has not been examined in the context of high-intensity exercise training is lymphocyte redeployment. Lymphocytes continuously traffic into and out of the blood and this process is essential to immune surveillance and elimination of virally infected self cells (20). The trafficking pattern of lymphocytes is very sensitive to exercise and is largely driven by CD8$^+$ T cells (CD8$^+$TL) and Natural Killer (NK) cells (39). Indeed, the exercise-induced mobilization and egress of lymphocytes into and out of the blood, respectively, referred to as lymphocytosis and lymphocytopenia, is one of the most established effects of exercise on the immune system (6). It has been argued that this exercise-induced mobilization of cells evolved to reflect a ‘primed’ immune system under conditions where tissue damage and infection is more likely (6).

**Paragraph 3.** Likewise, the post-exercise lymphocytopenia, whereby cell counts fall below baseline levels, is also thought to be important for immune surveillance and antigen detection (6,20,39).
Recently, it has become clear that lymphocytopenia is driven by a preferential egress of highly cytotoxic CD8⁺TLs from peripheral blood (39). Moreover, animal studies have shown that lymphocytes migrate to ‘front-line’ locations such as the skin and lungs in response to exercise (20). Thus, changes in the cellular composition of peripheral blood during and following exercise appear to be adaptive immunological processes. If high-intensity exercise training is associated with decreased lymphocyte trafficking, and potentially impaired immune surveillance, then this might provide one explanation why athletes are at greater risk of infection following high-intensity exercise training (4,6).

**Paragraph 4.** The mobilization and egress of CD8⁺TLs and NK cells in response to exercise is primarily driven by specific highly cytotoxic sub-populations (2,39). Thus, the trafficking of CD8⁺TLs is determined by the kinetics of four CD8⁺ sub-populations: a subset of antigen inexperienced cells; the naïve population (NA; CD45RA⁺CD27⁺) and three types of antigen-experienced memory cells; central memory (CM; CD45RA⁻CD27⁺); effector memory (EM; CD45RA⁻CD27⁻); and terminally differentiated CD8⁺TL which have re-expressed the ‘naïve’ cell marker CD45RA (EMRA; CD45RA⁺CD27⁻) (15,35,39). NA and CM CD8⁺TL re-circulate between the blood and secondary lymphoid organs, whereas EM and EMRA CD8⁺TL preferentially migrate to the peripheral tissues, such as the skin and lungs (15,35). EM and EMRA subsets are able to employ immediate effector functions, such as the killing of virally infected cells (15,35).

**Paragraph 5.** NK cells also can be divided into sub-populations with distinct functional properties, identified as cells that express high levels of CD56 (CD56<sup>hi</sup>) and cells which express low levels of CD56 (CD56<sup>lo</sup>) (5). The CD56<sup>lo</sup> subset is comparable to CD8⁺ EM and EMRA cells; preferentially migrating into peripheral tissues and capable of rapidly killing target cells (22).
Paragraph 6. Considering the association between exercise training load and infection risk (12), it is unknown whether the redeployment of CD8$^+$TL and NK cells is maintained or impaired during a period of high-intensity exercise training. Therefore, this study compared the exercise-induced mobilization and subsequent egress of CD8$^+$TL and NK cells, and their sub-populations, following one week of either normal- or high-intensity exercise training. To improve the relevance and applicability of results, lymphocyte responses were assessed following controlled sub-maximal exercise (simulating aspects of training), in addition to a maximal effort time trial (which simulates competition). On the basis of prior research, it was hypothesised that lymphocytosis (i.e., cell mobilization) and lymphocytopenia (i.e., cell egress) of CD8$^+$TL and NK cells would be reduced following a period of high-intensity training. Further, we speculated that any effects of high-intensity training would be most prominent in the most cytotoxic CD8$^+$TL and NK cell sub-populations.

Methods

Participants

Paragraph 7. Eight well-trained male cyclists (Mean ± SD; age 27 ± 8 yr; body mass index 22.8 ± 2.2 kg·m$^{-2}$ maximal oxygen uptake ($\dot{V}O_2$ max) 64.2 ± 6.5 mL·kg$^{-1}$·min$^{-1}$) took part in this study. Participants were non-smokers, not taking any medication and had remained free from respiratory infection for four weeks. All participants provided informed written consent and the study was approved by the Research Ethics Committee of the School of Sport and Exercise Sciences, University of Birmingham, UK.

Experimental design
**Paragraph 8.** Participants were engaged in a seven day period of prescribed normal-intensity exercise training, followed by another seven day period of high-intensity exercise training (see *Exercise training conditions*). The order of these conditions was not randomised. On the final day of each condition, and at least 18 h after the last exercise session, participants undertook a standardized exercise trial (see *Exercise trials*), in which immune cell responses to exercise were quantified.

**Preliminary exercise testing and familiarization**

**Paragraph 9.** Participants visited the laboratory for two preliminary visits prior to the experimental period. During the first visit, participants undertook a maximal oxygen uptake test ($\dot{V}O_2\text{max}$ test; workloads of 35 watts, 3 minute intervals) to exhaustion on a cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands) as described previously (14). In the final min of each stage, heart rate was recorded (Polar Vantage NV, Kempele, Finland) and expired gas samples were collected using Douglas bags. The intensity of each acute exercise trial was determined using $\dot{V}O_2\text{max}$ values assessed during preliminary testing, whereas the intensity of the two experimental training conditions (normal- and high-intensity exercise training) was derived using percentages of maximal heart rate (HRmax) as previously described (40) (see *Exercise training conditions*). The second preliminary visit consisted of a familiarisation exercise trial conducted under fasted conditions.

**Exercise training conditions**

**Paragraph 10.** Five training zones, defined in accordance with British Cycling guidelines (14) were defined: zone 1: <70% HRmax, zone 2: 70-80% HRmax, zone 3: 80-90% HRmax, zone 4: 90-95% HRmax, and zone 5: >95% HRmax. During the normal-intensity training condition, participants engaged in their usual level of regular exercise (one session/day, 4-5 training days/wk). The high-intensity training condition required athletes to markedly increase training load: exercise volume,
(i.e., duration of each training session) and exercise intensity (i.e., difficulty of each training session) were increased by ~70% relative to normal-intensity training (1-2 sessions/day, 7 training days/wk). In the high-intensity training condition, cyclists typically undertook one sprint interval session per day and one continuous ride. To rule out immunological differences during exercise trials as a result of possible changes in $\dot{V}O_2$ max following the normal- and high-intensity exercise training conditions, a $\dot{V}O_2$ max test was conducted on day 6 of each training condition.

**Exercise trials**

**Paragraph 11.** Exercise trials took place on the seventh day of each exercise training condition. Trials started at ~06:30 after an overnight fast. Following a 15 min rest, a baseline blood sample was drawn from a forearm vein using an indwelling catheter. The catheter was flushed regularly with saline to maintain patency. Each exercise trial was identical, and consisted of two stages completed in short succession. First, participants cycled for 120 min at a fixed exercise intensity equivalent to ~60% $V_2$ max (sub-maximal effort cycling). Second, participants undertook a maximal-effort time trial lasting ~45 min (~85-100% $V_2$ max). The time trial required a target amount of work (mean ± SD, energy target; 670 ± 52 kJ) to be completed in as short a time as possible (18). The total amount of work to be performed was individualized, based on their Watt-max achieved during the $\dot{V}O_2$ max test, and was calculated using the following formula:

$$\text{Total work (J)} = 0.7 \times \text{Watt-max} \times 2700 \text{ s}.$$ 

A two-stage exercise trial was employed to assess endurance performance in a glycogen depleted state for a separate investigation (40).

**Paragraph 12.** Physiological and psychological data (e.g., HR, RPE, $\dot{V}O_2$ and RER) were collected at 20 min intervals during sub-maximal effort cycling. To minimize distraction to the cyclist during...
the maximal-effort time trial, only HR and RPE were assessed at 25, 50, 75 and 100% completion of this phase. Cyclists could monitor task progress (i.e., kJ of energy expended) however performance time, power output or cadence (RPM) data were not made available.

**Paragraph 13.** In addition to the resting sample before exercise, blood was collected in the final min of each exercise stage and also 1 h post-exercise. Pilot data showed that 1 h post-exercise was the nadir of lymphocytopenia.

**Dietary control**

**Paragraph 14.** To rule out possible immunological changes during exercise which might be caused by a differential energy expenditure between the normal- and high-intensity exercise training conditions, diet was controlled to maintain energy balance (i.e., energy intake was equal to energy expenditure in both training conditions) (40). Daily energy requirements were calculated by the summation of basal metabolic rate (kcal•day⁻¹) (predicted using the Harris Benedict equation) and estimated energy expenditure during cycling activity (26). All food and drink consumed by participants was provided, and was matched to the energy expenditure of each training condition using internet-based nutrition software (weightlossresources.co.uk). In both training conditions, the macronutrient composition of the diet was equivalent to 1.5 g of protein•kg⁻¹ body mass•day⁻¹ and 6 g of CHO•kg⁻¹ body mass•day⁻¹, with the remainder of energy derived from fat. Calorie intake was higher during high-intensity training (4410 ± 437 kcal•day⁻¹) compared with normal-intensity training (3711 ± 456 kcal•day⁻¹, p < 0.05). Participants consumed only food and drink provided, and did not consume alcohol and caffeine. All athletes maintained a stable body weight throughout the experimental period.
**Flow Cytometry**

**Paragraph 15.** Blood was collected into K$_3$EDTA Vacutainers and processed within 5 h. Whole blood was incubated with two separate antibody panels for 25 min at room temperature. Panel 1; CD45RA FITC, CD27 PE, CD3 PERCP and CD8 APC. Panel 2; CD16 FITC, CD56 PE, CD3 PERCP and CD14 APC (Antibodies from Pharmingen San Diego, USA, except CD3 PERCP; Becton Dickinson San Jose, USA). Erythrocytes were lysed using FACS lysing solution (Becton Dickinson, San Jose, USA). Cells were washed by centrifugation at 500 × g for 6 min at 4°C, and re-suspended in 300 µL of 2% paraformaldehyde phosphate buffered saline. Cells were stored in the dark at 4°C and read on a FACS calibur flow cytometer (Becton Dickinson, San Jose, USA), collecting 20,000 lymphocytes.

**Paragraph 16.** CD8$^+$TL subsets were identified by the expression of the cell-surface molecules CD45RA in and CD27, as previously described (15,39). NK cells were identified as being CD3$^-$ and CD56$^+$. The NK sub-populations; CD56$^{hi}$ and CD56$^{lo}$ were determined by CD16 expression as described by Cooper et al. (5). Data were analyzed using FlowJo v5.2 (Tree Star Inc., Aston, Oregon). Whole blood cell counts (i.e., total leukocytes, lymphocytes, granulocytes and monocytes) were determined based on the Coulter principle using an automated haematology analyzer (Coulter GEN-S, Beckman-Coulter, Miami, USA).

**Neuro-endocrine measurements**

**Paragraph 17.** Plasma cortisol and epinephrine concentrations were measured using commercially available kits (Cortisol, IDS, Tyne and Wear, UK; CAT-COMBO, IDS, Tyne and Wear, UK, respectively). Plasma was obtained by centrifugation at 1500 × g for 10 min at 4°C. Samples were stored at −80°C until analysis. Epinephrine was not measured 1 h post-exercise due to the short half-life in the blood following the exercise stimulus.
Paragraph 18. Leukocyte, neuro-endocrine, physiological and psychological responses to exercise were analyzed within-subjects using two-way repeated measures analyses of variance (ANOVA). Post-hoc least-significant difference (LSD) tests identified time-point differences. To examine differences in immune cell counts between training conditions over the defined exercise period (measurements collected at baseline, sub-maximal exercise and maximal exercise, only), data were expressed as incremental area under the curve (iAUC) (33). iAUC is routinely used to detect differences across multiple time-points (33). An advantage of using this technique is that both the magnitude of response (increases in immune cell counts above baseline) and changes over time (i.e., time intervals between consecutive measurements of immune cell counts) are accurately captured, irrespective of non-uniform time intervals between measurements (10,33). Post-exercise lymphocytopenia was expressed as absolute change in cell number (i.e., cell count upon immediate cessation of time trial minus cell count 1 h post-exercise). Differences in mobilization or egress of cells between training conditions were examined with paired samples t-tests, or ANOVA, including key variables entered as individual covariates (ANCOVA). This strategy allows investigation of variables mediating observed relationships. Key variables included change in epinephrine, cortisol (expressed as iAUC), HR, RPE, performance time and power output between normal and high-intensity exercise training. This approach is routinely used in analyses of this sort (39) and provides a robust statistical test for mediation (17).

Paragraph 19. All data were expressed as means ± SEM, unless otherwise stated. iAUC was calculated using PRISM software (v4 Graph pad INC., San Diego, CA) with baseline set as the basal immune cell sub-population/subset count measured in the corresponding training condition. Data were analysed using SPSS 18.0 for Windows (SPSS Inc., USA). Significance was set at the \( p < 0.05 \) level.
Results

Exercise training conditions

**Paragraph 20.** Training volume (duration of exercise per week) during high-intensity training was increased compared to normal-intensity training (Mean ± SD; 1084 ± 203 min vs. 650 ± 173 min, respectively; Paired samples t-test; $t(7) = -14.9, p < 0.001$). As a measure of exercise intensity (i.e., difficulty of exercise training each week), average heart rate during training was increased during high- compared to normal-intensity training (Mean ± SD; 140 ± 7 bpm vs. 131 ± 5 bpm, respectively; Paired samples t-test; $t(7) = -6.2, p < 0.05$). The high-intensity training regimen did not improve cardio-respiratory fitness, but instead caused a slight reduction (Normal-intensity training: 63.3 ± 4.9 mL·kg⁻¹·min⁻¹; High-intensity training: 56.9 ± 7.2 mL·kg⁻¹·min⁻¹, Paired samples t-test; $t(7) = 1.9, p < 0.05$).

Physiological and psychological responses to exercise

**Paragraph 21.** Physiological responses to sub-maximal cycling were not different between trials, ($\dot{V}O_2$ and RER data not shown) although RPE was greater following high-intensity training (see supplementary table which shows exercise duration, power output, RPE and HR responses to exercise following normal- and high-intensity training). Time to completion (min) and power output (watts) during maximal-effort cycling were slightly reduced following high-intensity training (Paired samples t-test; $t(7) < 1.9, p < 0.05$), however, HR and RPE were not significantly different (Paired samples t-test; $t(7) > 4.4, p > 0.05$; see supplementary table). Physiological, and psychological variables were not significant covariates mediating any of the training-induced immunological responses to acute exercise (all interaction effects; $F_{(1,6)} < 3.2, p > 0.05, \eta_2 < 0.3$). In other words, changes in these variables between training conditions did not confound any of the results reported below.
Leukocyte responses to exercise

**Paragraph 22.** Table 1 presents total leukocyte and leukocyte sub-population responses to exercise following the normal- and high-intensity training conditions, respectively. In both training conditions, total leukocytes, lymphocytes, granulocytes and monocytes showed the largest increase upon immediate completion of the maximal-effort time trial. Sixty minutes post-exercise, total leukocytes and granulocytes remained elevated, monocytes returned to baseline, and lymphocytes fell below pre-exercise levels (see Table 1, main effects of time all; \(F_{(1,7)} > 8.5, p < 0.05\)). High-intensity training was associated with a smaller exercise-induced mobilization of leukocytes (Mean ± SD iAUC; 366 ± 50 vs. 467 ± 69 cells/µL; high- and normal-intensity training, respectively) and granulocytes (Mean ± SD iAUC; 255 ± 51 vs. 377 ± 76 cells/µL; high- and normal-intensity training, respectively) (Paired samples \(t\)-tests both; \(t_{(7)} > 3.2, p < 0.05\)). There were no significant differences in total lymphocyte and monocyte responses to exercise between training conditions (see Table 1).

Total CD8\(^+\) T Lymphocyte responses to exercise

**Paragraph 23.** Figure 1 shows CD8\(^+\)TL responses to exercise following the normal- and high-intensity training conditions. CD8\(^+\)TL increased during exercise (~300 %) and fell below baseline levels 1 h post-exercise (~45 %) (see Figure 1 A, Main effects of time \(F_{(1,7)} = 29.8; p < .05\)). There was a trend for a smaller exercise-induced mobilization of CD8\(^+\)TL in the high-intensity training condition (see Figure 1 B, Paired samples \(t\)-tests iAUC between training conditions; \(t_{(7)} = 2.1; p = 0.09\)). The egress of CD8\(^+\)TL 1 h post-exercise (Paired samples \(t\)-tests between training conditions; \(t_{(7)} = 3.047; p < 0.05\)) was attenuated in the high-intensity training condition (see Figure 1 C).
CD8+ T Lymphocyte subset responses to exercise

Paragraph 24. Figure 2 shows EMRA CD8+TL responses to exercise following the normal- and high-intensity training conditions. The mobilization of EMRA CD8+TL was smaller in the high-intensity condition (see Figure 2 B, Paired samples t-test iAUC between conditions; $t_{(1,7)} = 2.5; p < 0.05$). 1 h post exercise, the number of circulating EMRA CD8+TL was reduced by ~65% compared to pre-exercise with normal-intensity training. In the high-intensity condition, there was a trend for a smaller post-exercise egress; EMRA CD8+TL fell by ~55% relative to baseline (see Figure 2 C, Paired samples t-tests between conditions; $t_{(1,7)} = 2.2; p = 0.06$).

Paragraph 25. There were no differences in the mobilization of NA, CM and EM CD8+TL to exercise between the normal and high-intensity training conditions (data only shown for NA, see Figure 3 A-B). The post-exercise egress of NA CD8+TL was smaller in the high-intensity training condition (see Figure 3 C, Paired samples t-tests between training conditions; $t_{(7)} = 3.6; p < 0.05$), however the egress of CM and EM was unaffected (data not shown).

NK cell responses to exercise

Paragraph 26. NK cells increased during exercise (~420%) and fell below baseline 1 h post-exercise (~36%). NK CD56lo cells showed a larger mobilization into peripheral blood (~430%) compared to CD56hi cells (~240%) without any differences between the normal- and high-intensity training conditions (data not shown).

Neuro-endocrine responses to exercise

Paragraph 27. Figure 4 shows the plasma epinephrine and cortisol responses to exercise following the normal- and high-intensity training conditions. Epinephrine concentrations showed the expected
increase in response to exercise (see Figure 4 A, main effects of time; $F_{(1,7)} = 4.9; p < 0.05$). High-intensity training was associated with a smaller epinephrine response to exercise (Mean ± SD iAUC between conditions; 24,133 ± 31,792 pg/mL× ~165min vs. 33,120 ± 36,078 pg/mL× ~165min; high- and normal-intensity training, respectively; Paired samples $t$-test; $t_{(7)} = 3.3, p < 0.05$).

**Paragraph 28.** Cortisol concentrations increased in response to the maximal-effort time trial and remained elevated at 1 h post-exercise (see Figure 4 B, main effects of time; $F_{(1,7)} = 20.0; p < 0.05$). Cortisol responses to exercise were reduced after high-intensity training (Mean ± SD iAUC; 10,344 ± 3382 ng/mL× ~165min; 8754 ± 1268 ng/mL× ~165min during normal- and high-intensity training, respectively; Paired samples $t$-test; $t_{(7)} = 2.4, p < 0.05$).

**Paragraph 29.** Epinephrine and cortisol concentration were not significant covariates mediating any of the training-induced immunological responses to acute exercise (all interaction effects; $F_{(1,6)}<3.5, p > 0.05, \eta^2 <0.4$). In other words, the reduced neuro-endocrine response to exercise with high-intensity training, was not responsible for the training-induced reduced immune responses to exercise.

**Discussion**

**Paragraph 30.** This study investigated whether CD8$^+$TL mobilization and subsequent egress from blood in response to a standardized bout of exercise, is affected by a period of high-intensity exercise training. Using a validated model of high-intensity training (14), our data suggest that both the mobilization and egress of CD8$^+$TL to an acute bout of intense exercise is reduced after a week of high-intensity training in well trained cyclists. Further analyses showed that these effects observed in total CD8$^+$TL were driven by a differential response of CD8$^+$TL sub-populations.
EMRA CD8+ TL cells exhibited a smaller mobilization during exercise with high-intensity exercise training. Following exercise, the reduced egress of CD8+ TL was largely driven by a smaller egress of NA and to a lesser extent, a smaller egress of EMRA cells.

Paragraph 31. The smaller mobilization of CD8+ TL with high-intensity exercise training occurred in parallel with a reduced epinephrine response to exercise. CD8+ TL, and in particular the EMRA sub-population, express the β2 adrenergic receptor very densely at the cell surface (19). Exercise is associated with increased adrenergic activity, and these cells become selectively mobilized via an adrenergic-dependent mechanism (8,19). Moreover, epinephrine infusion alone causes a similar mobilization of lymphocytes (8,19) which confirms previous assumptions that exercise-induced lymphocytosis is largely dependent on epinephrine release (28). The observed blunting of epinephrine and CD8+ TL responses to acute exercise following high-intensity training is consistent with previous reports. For example, physically fit individuals, who engage regularly in exercise training, exhibit a smaller exercise-induced lymphocytosis compared to unfit individuals, which is independent of absolute exercise intensity (16,29). It has previously been reasoned that β2 adrenergic receptors are desensitized due to repeated exercise-induced adrenergic activity (16,29). Also consistent with our findings is the observation that relative to unfit individuals, physically fit individuals tended to show more modest epinephrine responses to stress and exercise tasks (16). Thus, our findings and those of others, suggest that periods of high-intensity exercise training are associated with a reduced CD8+ TL mobilization, which might be in part mediated by β2 adrenergic receptor down-regulation, a decline in adrenergic output, or a combination of the two.

Paragraph 32: Adrenergic stimulation is not the only mechanism behind exercise-induced lymphocytosis. For example, lymphocytes are mobilized non-specifically due to increased cardiac output and associated shear forces (36). Indeed, our results suggest that the smaller mobilization of
lymphocytes following high-intensity training is likely to be mediated by several mechanisms. For example, our analyses showed that the smaller epinephrine response to exercise following high-intensity training was not a significant covariate in the smaller training-induced immune responses to exercise. This indicates that the reduced epinephrine response to exercise is not entirely responsible for our observation. Thus, other known processes (e.g., cardiac output and associated shear stresses), as well as unknown factors (e.g., possible changes in lymphocyte adhesion molecule, or tissue ligand expression with high-intensity training) also might have mediated the reduced mobilization of cells in response to exercise.

**Paragraph 33.** Although the mobilization of lymphocytes into blood during exercise is well studied, investigation of post-exercise lymphocytopenia and the mechanism behind this process remains unclear. Cortisol is proposed as a neuro-endocrine mediator of lymphocyte extravasation from blood (9,32). Indeed, Dimitrov et al. (7) showed that cortisol infusion causes a selective egress of NA CD8⁺TL from peripheral blood. Consistent with these findings, we observed a smaller NA CD8⁺TL egress occurring in parallel with a reduced cortisol release with high-intensity exercise training. Together, these findings imply that an impaired ability of NA CD8⁺TL to leave blood post-exercise might, at least in part, be mediated by a blunted cortisol response. However, our mediation analyses suggest that a smaller cortisol response to exercise following high-intensity training was not responsible for the reduced NA CD8⁺TL (or any other CD8⁺TL population) lymphocytopenia. Thus, if cortisol does indeed play a role in lymphocytopenia, it might be related to down-stream mechanistic processes. For example, as with lymphocyte β2 adrenergic receptor down regulation with chronic adrenergic stimulation (16), glucocorticoid receptor density might similarly be affected with chronic cortisol stimulation. Likewise, high-intensity exercise training and/or chronic cortisol release might influence other aspects of lymphocytopenia not investigated in this study. For example, lymphocyte migration to bone marrow, as observed with exercise in rodents (20), is
dependent on lymphocyte expression of the adhesion molecule CXCR4 (25). In turn, the actions of
CXCR4 are dependent on bone-marrow derived ligands (e.g., CXCL12), and the expression of
CXCR4 and CXCL12 is partly governed by cortisol levels (27,31). Thus, it is not surprising that
measuring cortisol levels alone does not explain the reduced lymphocytopenia following high-
intensity exercise training in this study.

Paragraph 34. It has also been proposed that lymphocytopenia is a result of exercise-induced
apoptosis in blood (24). However, apoptosis cannot fully explain the often observed ~50% fall in
lymphocytes following exercise, as <10% of cells in blood become apoptotic (24). In addition,
blood lymphocyte numbers recover within several hours of exercise completion. Replacement of
‘deleted’ lymphocytes so quickly is therefore unlikely. A more accepted view is that CD8+TLs,
important for the detection and elimination of antigen, extravasate from peripheral blood post-
exercise, as part of immune surveillance (6,20). As periods of intense exercise training are
associated with an increased incidence of infection in athletes, we predicted that high-intensity
exercise training would result in a reduced egress of total CD8+TLs post-exercise. Analysis of
CD8+TL numbers following exercise confirmed our hypothesis. Further analysis of CD8+TL sub-
populations showed, although not statistically significant, that there was a strong trend fewer
EMRA CD8+TL to leave the blood post-exercise. Together, these findings imply that high-intensity
exercise training might be associated with a reduced trafficking of lymphocytes to peripheral tissue,
which in turn might be associated with compromised immune surveillance.

Paragraph 35. An alternative possible implication of the current findings is that beneficial effects
of regular exercise on immunity might be reduced if an excessive volume of exercise training is
undertaken. A hypothetical but attractive framework put forward by Simpson (37) suggests exercise
as a mechanism for the ‘deletion’ of clonally expanded virus-specific T cells, which deleteriously
accumulate with age. The T cell compartment is assumed to be relatively stable or ‘fixed’
because thymic output of naive T cells becomes almost negligible around the time of adolescence
(3). Thus, the ‘immune space’ available for the expansion of memory T cells upon infection with a
novel pathogen is limited, and the relative ‘size’ of the naive T cell pool declines with ageing (1,3).
This narrowing of the T cell repertoire (also known as immune senescence) is associated with lower
antibody responses to vaccination, exacerbated inflammation and an increased susceptibility to
infection (1,3). Simpson (37) suggests that regular exercise might promote apoptotic removal of
some virus-specific T cells by extravasation from blood post-exercise and subsequent exposure to
pro-apoptotic signals (e.g., reactive oxygen species). In support, a cross-sectional study by
Spielmann et al. (38) showed that individuals with a high aerobic fitness (compared to less fit
individuals) had lower proportions of senescent T cells in blood (e.g., CD8⁺TL EMRA cells). In the
present study, athletes undertook a very high training load, which, as with immune senescence, is
also associated with increased susceptibility to infection (12). Subsequently, these athletes showed a
smaller egress of senescent EMRA CD8⁺TLs. Although speculative, our results, interpreted in the
context of the theory proposed by Simpson (37), suggest that fewer senescent cells may be ‘deleted’
from the T cell repertoire during a period of high-intensity exercise training. Thus, the possibility of
delayed immune senescence with regular exercise as suggested by Simpson (37), might not be
gained from excessive volumes of exercise training. Although this is an attractive implication of the
current findings and relevant to infection risk and possible immune senescence in athletes, we
emphasise that our interpretations are speculation at present.

Paragraph 36. It is important to note that the high-intensity exercise training manipulation in the
present study was not designed to improve fitness. Such improvements in fitness might have made
the exercise trial following the high-intensity training condition less demanding. Interestingly, high-
intensity training caused a small reduction in $\dot{V} O_2$ max which is common following very intense
training regimens (14). Thus, it could be argued that the exercise trial following high-intensity training was in fact more demanding, providing further support that the smaller immune-response observed was not caused by an ‘easier’ exercise trial. In support, HR and RPE during maximal exercise were not different between trials. Further, our mediation analyses showed that performance (i.e., exercise duration and power output), physiological (i.e., HR) and psychological (i.e., RPE) variables were not significant covariates in the training-induced reductions in immune cell mobilization with acute exercise. In other words, training-induced alterations in these variables did not confound the observed immunological responses to exercise.

**Paragraph 37.** As well as alterations in the adaptive immune compartment, the present study showed that high-intensity exercise training influenced the response of granulocytes, but not NK cells (cell populations of the innate immune system). Given that similar to the CD8⁺TL EMRA population, NK cells exhibit high adrenergic sensitivity (4), the failure of high-intensity exercise to influence NK cells might seem surprising. However, as NK cells mobilize more than CD8⁺TLs (2), suggesting a greater adrenergic sensitivity or receptor density, it is possible that the relatively small reduction in sympathetic activity with high-intensity training was not enough to affect these highly exercise-sensitive cells. Moreover, although adrenergic activity is just one of the mechanisms behind lymphocytosis (6), as mentioned earlier, other well established processes (e.g., cardiac output and increased shear forces) as well as less investigated processes (e.g., tissue homing and adhesion molecule expression) may play a significant roles in the context of high-intensity training. Unlike NK cells, the mobilization of granulocytes into peripheral blood during exercise was reduced with high-intensity training. These effects observed in the total granulocyte pool were likely driven by neutrophils, an exercise-sensitive sub-population (50-60%) of granulocytes, which exhibit both α- and β-adrenergic receptors (13). These cells are important for the elimination of microbial pathogens (30). Although direct measurements of granulocyte or neutrophil function were
not conducted, our data provide some support for the possibility that innate immune responses
might be impaired following high-intensity exercise training (41).

**Paragraph 38.** When interpreting the results of this study, it should be considered that in humans,
the exact destination of cells leaving peripheral blood post-exercise is unknown. Animal studies
provide strong evidence for exercise-induced leukocyte migration to peripheral tissues such as the
skin, and lungs (6,20). In these models, it is thought that leukocyte tissue migration facilitates the
detection and elimination of antigen. Another consideration is that clinical diagnosis of URTI
episodes were not made in this study. It therefore remains unclear whether altered redistribution
patterns of CD8^+TLs following high-intensity exercise training translates into increased
susceptibility to infection. Future studies are needed to investigate whether altered leukocyte
responses to bouts of intense exercise are predictive of clinically diagnosed infectious disease
episodes in athletes. Functional measures of lymphocytes (e.g., activation, proliferation and
cytokine production) and granulocytes or neutrophils (e.g., chemotaxis, phagocytosis and
superoxide production) might provide useful adjunct measurements for follow-up investigations.

Further, in light of the present results, mechanistic studies are now warranted to better understand
how high-intensity exercise training influences lymphocytosis and lymphocytopenia. For example,
relevant to lymphocytosis, cyclic-adenosine monophosphate (cAMP) assays on isoproterenol
stimulated T-cell subsets could be conducted *in vitro* to examine whether β2 adrenergic receptors
are indeed desensitized. Relevant to lymphocytopenia, adhesion and tissue homing molecule
expression could be investigated *ex vivo* with athletes undertaking very large volumes of exercise.
Similar analyses could be made in *vitro*, examining lymphocyte cell-surface molecule expression in
response to cortisol exposure.
Paragraph 39. We recently showed that CD8$^+$TL mobilization and egress in response to exercise was amplified in CMV$^+$ individuals (39). The within-subjects study design employed in the present study negates the possibility that CMV status confounded our observation of a blunted mobilization and egress of CD8$^+$TL sub-populations in response to high-intensity exercise training. However, investigations into possible interactions between lymphocyte responses to acute exercise, high-intensity exercise training, and CMV serostatus is justified. For example, it might be hypothesized that compared to CMV$^-$ individuals, CMV$^+$ individuals would exhibit a smaller ‘blunting’ effect of high-intensity training because they exhibit exaggerated lymphocyte responses to exercise.

Paragraph 40. In summary, we show that the redistribution of CD8$^+$TLs in response to a standardized bout of exercise was reduced by a period of high-intensity training. Although the mechanism(s) behind this observation remains unclear, it is possible that aspects of immune-surveillance might be impaired with very large volumes of exercise training.

Acknowledgments

DSM Food Specialities, Delft, The Netherlands funded this study. Leila Anane, Natalie Riddell and John Campbell provided technical assistance with flow cytometry analysis.

The results of the present study do not constitute endorsement by ACSM.

Conflict of Interest Statement: All authors declare that there are no conflicts of interest.


Table captions

Table 1: Total leukocyte and leukocyte sub-population responses to exercise following normal- and high-intensity training.

Supplementary table: Physiological and psychological responses to exercise following normal- and high-intensity training.
Figure legends

Figure 1: Total CD8^{\text{TL}} responses to exercise following normal- and high-intensity exercise training. A) changes in cell number over time; B) mobilization of cells expressed as incremental area curve (iAUC) during exercise; C) egress of cells 1 hour post-exercise. SM: sub-maximal exercise, MAX: maximal exercise, Post 1 h: 1 hour following maximal exercise. Values are means ± SEM (n = 8). †significantly different from baseline in corresponding training period (p < 0.05). *significantly different from normal-intensity training (p < 0.05).

Figure 2: CD45RA^{+} effector memory CD8^{\text{TL}} (EMRA) responses to exercise following normal- and high-intensity exercise training. A) changes in cell number over time; B) mobilization of cells expressed as incremental area curve (iAUC) during exercise; C) egress of cells 1 hour post-exercise. SM: sub-maximal exercise, MAX: maximal exercise, Post 1 h: 1 h following maximal exercise. Values are means ± SEM (n = 8). †significantly different from baseline in corresponding training period (p < .05). *significantly different from normal-intensity training (p < 0.05).

Figure 3: Naïve (NA) CD8^{\text{TL}} (CD45RA^{+}CD27^{+}) responses to exercise following normal- and high-intensity exercise training. A) changes in cell number over time; B) mobilization of cells expressed as incremental area curve (iAUC) during exercise; C) egress of cells 1 hour post-exercise. SM: sub-maximal exercise, MAX: maximal exercise, Post 1 h: 1 hour following maximal exercise. Values are means ± SEM (n = 8). †significantly different from baseline in corresponding training period (p < .05). *significantly different from normal-intensity training (p < 0.05).

Figure 4: Neuroendocrine responses to exercise following normal- and high-intensity exercise training. A) Plasma epinephrine; B) plasma cortisol. Concentrations expressed as pg/ml and ng/ml.
respectively. SM: sub-maximal exercise, MAX: maximal exercise, Post 1 h: 1 hour following maximal exercise. Values are means ± SEM (n=8). †significantly different from baseline in corresponding training week (p < .05). *significantly different from normal-intensity training at corresponding time-point (p < 0.05).
Table 1

Total leukocyte and leukocyte sub-population responses to exercise following normal- and high-intensity training.

<table>
<thead>
<tr>
<th>Cells × 10⁹/L</th>
<th>Normal-intensity training</th>
<th>High-intensity training</th>
<th>Main effect of time (both normal- and high-intensity training)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Submaximal-cycling</td>
<td>Maximal-cycling</td>
</tr>
<tr>
<td></td>
<td>(120 min)</td>
<td>(~45 min)</td>
<td></td>
</tr>
<tr>
<td>Leukocytes</td>
<td>4.8±1.0</td>
<td>8.2±1.9†</td>
<td>12.8±3.6†</td>
</tr>
<tr>
<td>Lymphocytes</td>
<td>2.0±0.4</td>
<td>2.8±0.6†</td>
<td>4.0±0.5†</td>
</tr>
<tr>
<td>Granulocytes</td>
<td>2.5±2.4</td>
<td>4.8±1.3</td>
<td>8.5±3.1†</td>
</tr>
<tr>
<td>Monocytes</td>
<td>0.4±0.1</td>
<td>0.6±0.2†</td>
<td>0.7±0.2†</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. Main effect of time combines both normal- and high-intensity training values. †significantly different from baseline in corresponding training week (p < .05). *significantly different from Normal-intensity training in corresponding time-point (p < .05).
Supplementary table: Physiological and psychological responses to exercise following normal- and high-intensity training.

Power output and performance time during maximal-cycling was reduced following high-intensity training despite no significant differences in heart rate and perceived effort. None of these variables mediated or confounded the reduced immunological response to exercise.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal-intensity training</th>
<th>High-intensity training</th>
<th>Main effect of time (both normal- and high-intensity training)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Submaximal-cycling</td>
<td>Maximal-cycling</td>
</tr>
<tr>
<td>Exercise duration (min:sec)</td>
<td>-</td>
<td>120:0±00:00</td>
<td>42:35±02:45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42:35±02:45</td>
<td>48:13±04:59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>Power output (watts)</td>
<td>-</td>
<td>177±14</td>
<td>267±47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>267±47</td>
<td>237±46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F_{(1,7)} = 41.6; p &lt; 0.05</td>
</tr>
<tr>
<td>RPE</td>
<td>-</td>
<td>11±1</td>
<td>18±1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13±1*</td>
<td>18±1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F_{(1,7)} = 56.7; p &lt; 0.05</td>
</tr>
<tr>
<td>HR (beats·min^{-1})</td>
<td>50±6</td>
<td>128±8†</td>
<td>159±4†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125±10†</td>
<td>153±5†</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F_{(1,7)} = 575.4; p &lt; 0.05</td>
</tr>
</tbody>
</table>

Values are means ± SD. Data were not collected 1h post-exercise. Main effect of time combines data from normal- and high-intensity training and shows increased physiological demand between baseline (HR only), submaximal and maximal-cycling. HR is an average of measurements made continuously during submaximal and maximal cycling. RPE during submaximal-cycling is an average from 20, 40, 60, 80, 100 and 120 min. RPE during maximal cycling is an average from 25, 50, 75 and 100% of task completion. VO2 and RER were measured at the same periods as RPE during sub-maximal cycling: no differences were observed between trials (data not shown for clarity). †significantly different from baseline in corresponding training week (p < .05). *significantly different from Normal-intensity training at corresponding time-point (p < .05).
Figure 1

A

CD8^+TL count
(cells/µL)

Baseline  SM  MAX  Post 1 h

Normal  High

B

CD8^+TL during exercise
(AUC, cells/µL*~165 min)

Normal  High

p = .09

C

CD8^+TL egress post-exercise (cells/µL)

Normal  High

*
Figure 2

A. Graph showing EMRA CD8+TL (cells/µL) over time with baseline, SM, MAX, and Post 1 h conditions. The graph shows a significant increase in EMRA CD8+TL during exercise with an AUC of ~165 min.

B. Bar graph comparing EMRA CD8+TL during exercise (AUC, cells/µL * 165 min) between Normal and High conditions. The graph shows a statistically significant increase in the High condition.

C. Bar graph comparing EMRA CD8+TL egress post-exercise (cells/µL) between Normal and High conditions. The graph shows a trend towards a decrease in the High condition with a p-value of 0.06.
Figure 3

A

\[ \text{NA CD8}^+ \text{TL} (\text{cells/µL}) \]

- Normal
- High

B

\[ \text{NA CD8}^+ \text{TL during exercise (AUC, cells/µL * ~165 min)} \]

- Normal
- High

C

\[ \text{NA CD8}^+ \text{TL egress post-exercise (cells/µL)} \]

- Normal
- High

*
Figure 4

A. Plasma epinephrine concentration (pg/mL)

- Normal
- High

B. Plasma cortisol concentration (ng/mL)

- Normal
- High