



Carbohydrate supplementation does not blunt the prolonged exercise-induced reduction of in vivo immunity

Davison, G.; Kehaya, C.; Walsh, N.P.

European Journal of Nutrition

DOI:

[10.1007/s00394-015-0977-z](https://doi.org/10.1007/s00394-015-0977-z)

Published: 11/07/2015

Other version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):

Davison, G., Kehaya, C., & Walsh, N. P. (2015). Carbohydrate supplementation does not blunt the prolonged exercise-induced reduction of in vivo immunity. *European Journal of Nutrition*. <https://doi.org/10.1007/s00394-015-0977-z>

Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 **Carbohydrate supplementation does not blunt the prolonged-exercise induced**
2 **reduction of *in vivo* immunity.**

3

4 *Glen Davison¹, Corinna Kehaya¹, Bethany C. Diment², Neil P. Walsh²*

5 ¹Endurance Research Group, School of Sport and Exercise Sciences, University of Kent, UK

6 ²Extremes Research Group, College of Health and Behavioural Sciences, Bangor University, UK

7

8

9

10

11

12

13 **ADDRESS FOR CORRESPONDENCE**

Dr. Glen Davison

Endurance Research Group, School of Sport and Exercise Sciences,

The Medway Campus, University of Kent,

KENT, ME4 4AG

United Kingdom

Telephone: +44 (0)1634 888994

Fax: +44 (0)1634 888890

Email: G.Davison@kent.ac.uk

14 **Abstract**

15 Carbohydrate (CHO) supplementation during prolonged exercise is widely acknowledged to
16 blunt *in vitro* immunoendocrine responses but no study has investigated *in vivo* immunity.

17 Purpose: To determine the effect of CHO supplementation during prolonged exercise on *in*
18 *vivo* immune induction using experimental contact hypersensitivity (CHS) with the novel
19 antigen Diphenylcyclopropanone (DPCP).

20 Methods: In a double-blind design, 32 subjects were randomly assigned to 120 minutes of
21 treadmill exercise at 60% $\dot{V}O_{2max}$ with CHO (Ex-CHO) or placebo (Ex-PLA)
22 supplementation. Responses were also compared to 16 resting control (CON) subjects from a
23 previous study (for additional comparison with a resting non-exercise condition).

24 Standardised diets (24 h pre-trial) and breakfasts (3.5 h pre-trial) were provided. Subjects
25 received a primary DPCP exposure (sensitisation) 20 min after trial completion and exactly
26 28 d later the strength of immune reactivity was quantified by magnitude of the cutaneous
27 response (skin-fold thickness and erythema) to a low dose-series DPCP challenge. Stress
28 hormones and leukocyte trafficking were also monitored.

29 Results: CHO supplementation blunted the cortisol and leukocyte trafficking responses but
30 there was no difference ($P > 0.05$) between Ex-CHO and Ex-PLA in the *in vivo* immune
31 responses (e.g. both ~46% lower than CON for skin-fold response).

32 Conclusions: CHO supplementation does not influence the decrease of *in vivo* immunity seen
33 after prolonged exercise. The effects with more stressful (or fasted) exercise remain to be
34 determined. However, there appears to be no benefit under the conditions of the present
35 study, which have practical relevance to what many athletes do in training or competition.

36

37 **Key words:** running; immune; contact hypersensitivity; diphenylcyclopropanone; glucose; whole
38 integrated immune response

39

40 **Introduction**

41 It is widely reported that athletes engaged in regular prolonged and/or strenuous exercise, and
42 those in physically demanding occupations (e.g. soldiers), have a higher than normal
43 incidence of upper respiratory tract illness (URTI) symptoms, which may be related to an
44 exercise-induced impairment of immune function (immunodepression) [1, 2]. It has
45 previously been suggested that the primary mechanisms contributing to such exercise-
46 induced immunodepression include the exercise-induced stress responses (i.e. increased
47 stress hormones, in particular cortisol; cytokines; inflammatory responses); and the
48 redistribution of leukocytes and their subsets (e.g. [3–5]). Many nutritional interventions
49 have been investigated as potential countermeasures to exercise-induced immunodepression
50 and acute supplementation with carbohydrate (CHO) is often cited as the most efficacious [6–
51 8]. Supplementation with CHO has been consistently shown to blunt many of the exercise-
52 induced immune and endocrine perturbations (e.g. increased cortisol, cytokine, and leukocyte
53 redistribution responses; decreased neutrophil degranulation and oxidative burst functions,
54 lymphocyte proliferation and functions, natural killer cell function[4–12]) although it is not
55 clear how this may influence infection risk [8, 12]. Such *in vitro* markers provide useful
56 insight into the impact of nutritional interventions but alone they are considered to lack
57 clinical relevance as the extent to which changes in these *in vitro* or *ex vivo* measures are
58 related to increased infection risk is unclear [13, 14]. To date, the vast majority of the
59 supportive evidence for CHO supplementation is based on *in vitro* measures (e.g. [4, 5, 9–
60 11]), with little evidence on URTI and no evidence on *in vivo* immunity. In one study,
61 Nieman et al. [15] studied approximately 100 marathon runners randomly allocated to receive
62 placebo or CHO beverages (providing ~60 g per hour) during a competitive marathon race.
63 Carbohydrate supplementation was associated with higher post-race plasma glucose and
64 insulin concentrations, and lower post-race cortisol and growth hormone concentrations.

65 However, they observed little benefit of CHO, compared to placebo, on the response of a
66 range of salivary immune parameters (including IgA secretion rate, IgA relative to protein,
67 and absolute IgA concentration, which actually decreased less in the placebo group). Nieman
68 et al. [15] were also able to obtain URTI data for the 15-day post-race period from 93 of the
69 participants, and found no difference in URTI incidence between the CHO and placebo
70 groups. However, the validity of using self-reported URTI has been questioned [14].

71

72 The normal immune response (and hence host defence and protection) involves a complex
73 and co-ordinated network of molecules, cells and tissues working in synergy. Hence, *in vivo*
74 immune markers are considered particularly valuable [13, 14]. Cutaneous measures of *in vivo*
75 immunity, such as delayed type hypersensitivity responses to intradermal injection of
76 antigens, or contact hypersensitivity (CHS) responses to epicutaneous application of antigens,
77 represent challenge-type measures, which have recently been suggested to be most useful in
78 immunonutrition studies, when considering biological relevance, sensitivity and feasibility
79 [14]. The clinical relevance of examining cutaneous *in vivo* immunity is supported by studies
80 that have used such measures to monitor immune-competence in HIV-infected patients [16],
81 and studies showing that the magnitude of the responses relate to URTI risk in children [17]
82 or predict mortality in patients with surgical infections [18]. It has been previously
83 demonstrated that the CHS response, using the novel antigen diphenylcyclopropanone
84 (DPCP), is significantly reduced after 2 hours of treadmill running. This includes both the
85 induction of immunity (-53%), in participants with no prior exposure, and the elicitation of
86 immunity (-19%), in participants with well-established immune memory, to DPCP [19]. We
87 have now demonstrated this as a controllable, reproducible, sensitive, and valid *in vivo*
88 marker of exercise-induced immunodepression [19, 20]. Furthermore, we have recently
89 demonstrated no effect of the same exercise (2 h of treadmill running) on the skin's response

90 to the irritant croton oil [20], providing further support for the suggestion that the observed
91 decrease in *in vivo* immune induction to DPCP is an antigen-specific, T cell mediated,
92 response.

93

94 Challenging the skin using novel antigens permits the investigation of the influence of
95 stressors on *in vivo* immune induction and allows rigorous control of both the dose and
96 timing of sensitisation [19]. We are not aware of any previous study that has utilised such an
97 *in vivo* marker to determine the effects of nutritional interventions such as CHO
98 supplementation on exercise-induced immunodepression. To date, the most supportive
99 evidence for a nutritional strategy to limit the exercise-induced immune perturbations is for
100 CHO supplementation, but no study has investigated *in vivo* immunity. Therefore, the aim of
101 the present study was to determine the effects of acute CHO ingestion, before, during and
102 after prolonged exercise, on induction of the CHS response to DPCP. We hypothesised that
103 CHO supplementation would blunt the prolonged exercise-induced decrease of CHS
104 induction.

105

106 **Experimental Methods**

107 This study was conducted according to the guidelines laid down in the Declaration of
108 Helsinki (2008, including 2013 amendments) and all procedures were approved by the local
109 University Research Ethics Committee. Written informed consent was obtained from all
110 subjects. Subjects also completed a pre-exercise screening questionnaire (Physical Activity
111 Readiness Questionnaire: PAR-Q) before participating in each exercise test.

112

113 Subjects

114 Thirty two men were included in this study (age 28.8 ± 8.1 years, body mass 76.2 ± 10.1 kg,
115 maximal oxygen uptake, $\dot{V}O_{2\max}$, 58.3 ± 6.4 mL \cdot min $^{-1}\cdot$ kg $^{-1}$; means \pm standard deviation for
116 all 32 subjects; values for individual groups are summarised in Table 1). All participants were
117 healthy, non-smoking, and recreationally active (familiar with running) with no previous
118 history of exposure to DPCP. Subjects were excluded if they were taking any medication or
119 dietary supplements, had a history of atopy or any other immune-related or inflammatory
120 dermatological or relevant medical conditions. Other exclusion criteria included current (or
121 within two weeks of recovery from) an infection prior to the study, having any vaccinations
122 in the 2 months preceding the study, and donating blood in the four weeks before the study.
123 Participants were asked to abstain from strenuous exercise in the 24 hours before and 48
124 hours following each trial (exercise/sensitisation and elicitations). Participants were asked to
125 abstain from the consumption of alcohol or caffeinated drinks 48 hours ahead of each trial.

126

127 Study design

128 In the current study, 32 subjects were randomly assigned to either 120 minutes of treadmill
129 exercise at 60% $\dot{V}O_{2\max}$ with CHO supplementation (Ex-CHO, n = 16), or 120 minutes of
130 treadmill exercise at 60% $\dot{V}O_{2\max}$ with placebo (Ex-PLA, n = 16). As a point of reference
131 for the normal response in rested individuals, we also statistically compared the Ex-CHO and
132 Ex-PLA groups' *in vivo* immune induction responses to the control group (CON, n = 16, who
133 completed 120 minutes of seated rest) from Diment et al. [20]. Subjects were allocated
134 randomly into either the Ex-CHO or Ex-PLA groups after being matched for physical
135 characteristics, speed at gas exchange threshold (GET) and speed at $\dot{V}O_{2\max}$ (and hence
136 relative exercise intensity in the main trials). The PLA and CHO conditions were
137 administered in a double-blind manner. All subjects undertook two preliminary tests
138 ($\dot{V}O_{2\max}$ determination and familiarisation) and one main trial.

139

140 Determination of maximal oxygen uptake ($\dot{V}O_{2max}$)

141 $\dot{V}O_{2max}$ was determined by an incremental exercise test on a motorised treadmill

142 (H/P/Cosmos Sport and Medical, Nussdorf-Traunstein, Germany) in accordance with the

143 methods of Diment et al. [20]. The test began at a treadmill speed of $5 \text{ km}\cdot\text{h}^{-1}$, with a 1%

144 incline, for 3 minutes. The speed was then increased by $1 \text{ km}\cdot\text{h}^{-1}$ every minute until a speed

145 of $18 \text{ km}\cdot\text{h}^{-1}$ was attained and then further increases were achieved by increasing the gradient

146 by 1% every minute until volitional exhaustion. Heart rate was recorded throughout using a

147 short range telemetry heart rate monitor (Polar 810i, Polar Electro, Kempele, Finland); rating

148 of perceived exertion (RPE) was recorded at the end of each minute [21]; breath-by-breath

149 gas exchange was recorded using an online system (Cortex Metalyser 3B, Cortex Biophysik,

150 GmbH, Leipzig, Germany) throughout the duration of the test. The gas analysis system was

151 calibrated prior to use according to the manufacturer's guidelines using a calibration gas of

152 known composition and a three-litre syringe (Hans Rudolf Inc, Kansas, USA). $\dot{V}O_{2max}$ was

153 recorded as the highest average $\dot{V}O_2$ over any 30 second period of the test. The speed required

154 to elicit 60% $\dot{V}O_{2max}$ was estimated from the linear part of the $\dot{V}O_2$ - speed relationship, and

155 later verified in the familiarisation trial. The intensity at 60% $\dot{V}O_{2max}$ was also expressed as a

156 percentage of the difference between GET and $\dot{V}O_{2max}$ (% Δ) in accordance with the

157 methods of Lansley et al. [19], to verify that the relative intensity (and hence relative

158 physiological stress) were equal between exercise groups.

159

160 Familiarisation

161 Subjects completed a familiarisation session one week prior to the main trial. Participants

162 completed a warm-up for 5 minutes at $5 \text{ km}\cdot\text{h}^{-1}$ and 1% gradient on the same treadmill used

163 for the $\dot{V}O_{2max}$ test. This was immediately followed by a 60 minute run at a speed equivalent

164 to 60% $\dot{V}O_{2\max}$ to familiarise subjects to the main trial exercise procedures and confirm
165 accuracy of the calculated speed (to elicit 60% $\dot{V}O_{2\max}$). Minor speed adjustments were made
166 during the first 15 min if necessary to attain the target 60% $\dot{V}O_{2\max}$. Subjects were provided
167 with 5 ml·kg⁻¹ body mass water bolus 20 min before exercise commencement and on trial
168 completion and 2 ml·kg⁻¹ was provided every 15 min during the trial to familiarise subjects
169 with the fluid provision schedule to be followed in the main trials. Heart rate and RPE were
170 recorded every 5 min.

171

172 Main trials

173 *Standardisation and pre-exercise preparation of subjects:* Dietary intake was controlled
174 during the 24 h before the main experimental trial by providing subjects with 35 mL·kg⁻¹·d⁻¹
175 water and food from a standard food list to meet their estimated daily energy requirement
176 (11.4 ± 1.5 MJ·d⁻¹, which was comprised of 15%, 60%, and 25% of energy from protein,
177 CHO and fat respectively, and was equivalent to ~1.3, 5.4 and 1.0 g·kg⁻¹ body mass,
178 respectively). They were also provided with a standard breakfast at 07:30 on the morning of
179 the main trial to provide ~0.03 MJ·kg⁻¹ (equivalent to 2.4 ± 0.3 MJ, comprised of ~0.2, 1.0
180 and 0.2 g·kg⁻¹ of protein, CHO and fat, respectively). To further standardise dietary intake
181 subjects were also provided with lunch after the final blood sample collection (see timings
182 below), to provide ~0.02 MJ·kg⁻¹ (equivalent to 1.6 ± 0.2 MJ, comprised of ~0.2, 1.0 and 0.2
183 g·kg⁻¹ of protein, CHO and fat, respectively).

184

185 Experimental procedures

186 Subjects were provided with breakfast (as detailed above) at 07:30 before beginning the 120
187 min exercise (Ex-CHO and Ex-PLA) at 11:00. They were also provided with a quantity of
188 water for the 3 h period between 07:30 and 10:30 proportional to their daily requirement but

189 *pro rata* for this period (based on their calculated requirement for the prior 24 h, equating to
190 approximately 6.6 mL·kg⁻¹). During this period they were required to be restful but were
191 allowed to undertake light activities such as reading or using a computer. They were then
192 required to sit for 10 min with minimal movement before resting blood samples were
193 collected. Subjects received a bolus of 5 mL·kg⁻¹ of their respective drink (CHO or PLA) 20
194 min before and immediately after exercise and 2 mL·kg⁻¹ every 15 min during exercise.
195 Exercise commenced at 11:00 and immediately after the trial, post-exercise blood samples
196 were collected, then subjects showered and returned to the laboratory within 15 minutes of
197 completion for patch application at exactly 20 min post-exercise (i.e. 13:20) to sensitise
198 subjects to DPCP (details below). A final blood sample was also obtained 1 h post-exercise.
199 During exercise, expired gas was analysed during minutes 10, 20, 40, 50, 70, 80, 100, and
200 110 of exercise using the Douglas bag method. Gas was analysed using a gas analyser
201 (Servomex, Crowborough, UK) and a dry gas meter (Harvard Apparatus, Edenbridge, UK).
202 The gas analyser was calibrated prior to use according to the manufacturer's guidelines using
203 calibration gasses of known composition. Heart rate and RPE were recorded every 15 min
204 during exercise. Elicitation was then performed (details below) exactly 28 days after this trial.
205
206 *Drink composition:* The CHO drink was prepared with a lemon flavoured CHO-based sports
207 drink powder (Go Energy, Science in Sport, Nelson, UK) according the manufacturer's
208 instructions (to give a CHO concentration of 10% w/v). The placebo was CHO-free and
209 prepared from sugar-free, artificially sweetened lemon flavoured drink concentrate (Tesco,
210 Dundee, UK) diluted 4 parts water to 1 part concentrate. The concentrations were determined
211 so that drinks were taste matched as closely as possible. Even though this may not be
212 necessary with the between groups design employed here, we taste matched drinks as closely
213 as possible to avoid potential loss of blinding (i.e. subjects discussing their drinks outside of

214 the study/laboratory). A laboratory technician, independent of the study, was responsible for
215 the drink preparation to maintain double-blind procedures. The drinking schedule provided
216 approximately 60 g CHO per hour during exercise (in addition to the pre- and post-exercise
217 boluses of ~40 g each) for an average sized subject.

218

219 Induction of contact sensitivity (sensitisation)

220 Subjects were sensitized to DPCP at 13:20, exactly 20 min post-exercise (to ensure cutaneous
221 blood flow had returned to baseline) in accordance with the methods of Harper Smith et al.
222 [19] and Diment et al. [20]. Sensitisation was achieved by the application of an occluded
223 patch, constituting a 12 mm aluminium Finn chamber (Epitest Oy, Tuusula, Finland) on
224 scanpor hypoallergenic tape containing an 11 mm filter paper disc. The disc was soaked in
225 22.8 μl of 0.125 % DPCP in acetone and allowed to dry for 5 minutes before being applied to
226 the skin on the lower back, for exactly 48 h. This provides a dose of $30 \mu\text{g}\cdot\text{cm}^{-2}$ DPCP on the
227 patch.

228

229 Elicitation

230 The magnitude of *in vivo* immune responsiveness was quantified by measuring the responses
231 elicited by secondary exposure to the same antigen, also in accordance with the methods of
232 Harper Smith et al. [19] and Diment et al. [20]. Exactly 28 days after the initial sensitisation
233 to DPCP, all subjects received a challenge with a low concentration dose-series of DPCP on
234 individual patches, each comprising an 8 mm aluminium Finn chamber on scanpor
235 hypoallergenic tape containing a 7 mm filter paper disc. Patches were applied to the inner
236 aspect of the upper arm in the following doses of DPCP per patch: $1.24 \mu\text{g}\cdot\text{cm}^{-2}$; $1.98 \mu\text{g}\cdot\text{cm}^{-2}$;
237 $3.17 \mu\text{g}\cdot\text{cm}^{-2}$; $5.08 \mu\text{g}\cdot\text{cm}^{-2}$; $8.12 \mu\text{g}\cdot\text{cm}^{-2}$ and an additional acetone only control patch for
238 background subtraction. Patches were applied in randomly allocated order at the local site in

239 order to minimize any anatomical variability in responses. This pattern was matched between
240 subjects in each of the groups however (i.e. for every allocation pattern used in one group
241 there was an equivalent identical pattern used in the other). Elicitation patches were removed
242 after precisely 6 h and the strength of immune reactivity was assessed as cutaneous responses
243 at 48 h post-application. This method allows the magnitude of *in vivo* immune
244 responsiveness to be quantified (e.g. establishment of immune memory) following
245 sensitisation during the post-exercise period.

246

247 Assessment of cutaneous responses

248 Skin oedema (inflammatory swelling) is considered the key measure of CHS elicitation
249 responses [19]. This was assessed as mean skin-fold thickness from triplicate measurements
250 at each elicitation site using modified spring-loaded skin callipers (Harpenden Skin-fold
251 Calliper, British Indicators, England), to the nearest 0.1 mm (measuring skin-fold only: i.e.
252 no subcutaneous fat) as described previously [19, 20]. Skin erythema was determined from
253 triplicate measurement at each patch site using an erythema meter (ColorMeter DSM11,
254 Cortex Technology, Hadsund, Denmark) as previously described [19, 20]. Mean background
255 values were determined from triplicate measurements at the acetone only control patch site
256 for thickness and erythema. In order to determine the increase in thickness and erythema in
257 response to DPCP, the value from the acetone only control site was subtracted from each
258 patch site value. The values for increase in skin-fold thickness, and erythema over all the
259 doses were summed to give a representative measure of the overall reactivity of each subject
260 to DPCP [19, 20]. The dose-response curve was also used to conduct sensitivity analyses (i.e.
261 identify the minimal dose required to elicit a positive response, for the skin-fold measure) in
262 accordance with the methods of Harper Smith et al. [19].

263

264 Blood samples

265 Blood samples were obtained by venepuncture, with minimal stasis, from an antecubital vein
266 and collected into vacutainer (Becton Dickinson, Oxford, UK) tubes (containing lithium
267 heparin or K₃EDTA). All blood samples were obtained while subjects were in the seated
268 position. Subjects were asked to sit without changes of posture and minimal movement for 10
269 min before all blood samples were drawn, except the Post-Ex sample, which was drawn as
270 soon as possible after completing the exercise (within 5 min). A small aliquot was taken from
271 the K₃EDTA tube for haematological analysis and then all samples were centrifuged
272 immediately at 1500 × g for 10 minutes at 4°C. Aliquots of plasma were stored -80°C for
273 later analysis.

274

275 Analytical methods

276 Haematological analysis was performed on the K₃EDTA treated blood aliquot using
277 automated haematology analysers (Gen-S, Beckman Coulter, High Wycombe, UK; ABX
278 Pentra 60C+, Horiba Medical, France).

279

280 *** *Please insert table 1 near here* ***

281

282 Glucose concentration was determined in heparinised plasma using an automated analyser
283 (YSI 2300 Stat Plus, Yellow Springs, OH, USA). Plasma cortisol concentration in
284 heparinised plasma was determined using a commercially available enzyme linked
285 immunosorbent assay (ELISA) kit (DRG, Germany; Biomerica, Ca, USA). Plasma
286 epinephrine and norepinephrine concentrations in K₃EDTA plasma were determined using a
287 commercially available CatCombi ELISA (IBL International, Hamburg, Germany). All
288 plasma samples were thawed only once prior to analysis.

289

290 Data analysis

291 Statistical analyses were carried out using SPSS (IBM SPSS Statistics for Windows, Version
292 21.0, Armonk, NY: IBM Corp.). Values were compared between groups using 1-way
293 independent ANOVA or, for variables with repeated measures, 2-way mixed ANOVA. If
294 data were not normally distributed they were first normalised with log transformation using
295 the natural log (training hours, $\% \Delta @ 60\% \dot{V}O_{2\max}$, neutrophil count, neutrophil-to-
296 lymphocyte ratio, adrenaline, noradrenaline summed skin-fold responses), or $1/x^2$ (total
297 leukocyte count) transformations. Post hoc Holm-Bonferroni corrected paired (for within
298 groups comparisons) or independent (for between groups) t-tests were applied where
299 appropriate. All results are presented as mean \pm standard deviation unless otherwise stated.

300

301 **Results**

302 Participants were well matched for physical characteristics with no significant differences for
303 any of the physical parameters except $\dot{V}O_{2\max}$, (Table 1). However, exercise responses were
304 similar between groups (Table 2) and, importantly, there was no difference in the trial relative
305 exercise intensity (this holds true whether expressing relative intensity as $\% \dot{V}O_{2\max}$ during
306 the trial or $\% \Delta$, whereby exercise intensity is expressed relative to the individual GET and
307 $\dot{V}O_{2\max}$).

308

309 *** *Please insert Table 2 near here* ***

310

311 CHS responses to DPCP

312 *Oedema responses:* For the skin-fold responses, 1-way independent ANOVA (including
313 comparison to the CON group from [20]) showed a main effect of group ($F_{2,45} = 3.370$, $P =$

314 0.043). There was no difference between the Ex-CHO or Ex-PLA groups (post hoc analysis:
315 between Ex-PLA and Ex-CHO, $P = 0.460$; mean difference 1.04 mm, 95% confidence
316 intervals 0.45 to 2.41 mm) but there was a difference between the CON and Ex-PLA ($P =$
317 0.026 , mean difference 2.29 mm, 95% confidence intervals 1.11 to 4.71 mm) and between
318 CON and Ex-CHO ($P = 0.036$, mean difference 2.38 mm, 95% confidence intervals 1.13 to
319 5.02 mm, see Figure 1). The exercise trials were both ~46% lower ($P < 0.05$) than the CON
320 responses reported by Diment et al. [20]. Sensitivity analysis revealed the average threshold
321 dose for a response to DPCP was $0.45 \mu\text{g}\cdot\text{cm}^2$ for the CON group but a dose ~3-fold higher
322 was required (2.81-fold for PLA and 2.88-fold for CHO, see Figure 1) in order to elicit a
323 positive response in the exercise groups.

324

325 *** Please insert Figure 1 near here ***

326

327 *Erythema responses*: One-way independent ANOVA (including comparison to the CON
328 group from [20]) showed a main effect of group ($F_{2,45} = 3.219$, $P = 0.049$). There was no
329 difference between the Ex-CHO or Ex-PLA groups (post hoc analysis: between Ex-PLA and
330 Ex-CHO, $P = 0.290$, mean difference 4.22 AU, 95% confidence intervals -11.16 to 19.60 AU;
331 between CON and Ex-PLA, $P = 0.070$, mean difference 14.29 AU, 95% confidence intervals
332 -1.25 to 29.83 AU; between CON and Ex-CHO, $P = 0.036$, mean difference 18.51 AU, 95%
333 confidence intervals 2.6 to 34.41 AU, see Figure 2).

334

335 *** Please insert Figure 2 near here ***

336

337 Blood leukocyte counts

338 It was not possible to obtain a blood sample at every time point for some individuals (for
339 example, if a post-exercise sample could not be obtained within 5 min it was abandoned to
340 avoid delays in patch application, as the CHS responses were of primary importance). For
341 this reason the sample sizes for these measures were $n = 12$ for the Ex-PLA group and $n = 11$
342 for the Ex-CHO group. Significant main effects for ANOVA comparisons (group, time and
343 group \times time) were evident for most leukocyte parameters (total leukocyte count, neutrophil
344 count, lymphocyte count, and neutrophil-to-lymphocyte ratio) with the exception of no
345 significant group effects for total leukocyte count, lymphocyte count, and neutrophil-to-
346 lymphocyte ratio (detailed in Table 3). Post hoc analysis on the time effect (in each group
347 separately, owing to the observed interactions) showed that significant leukocyte trafficking
348 was evident in Ex-PLA at Post-Ex ($P < 0.001$) and 1 h Post-Ex ($P < 0.001$) and Ex-CHO at
349 Post-Ex ($P = 0.002$) and 1 h Post-Ex ($P < 0.001$) but counts were significantly lower at both
350 post-exercise ($P = ???$) and 1 h Post-Ex ($P = ???$) times in the Ex-CHO compared to Ex-PLA
351 group (see Table 3). Significant neutrophil trafficking was evident in Ex-PLA at Post-Ex ($P <$
352 0.001) and 1 h Post-Ex ($P < 0.001$) and Ex-CHO at Post-Ex ($P < 0.001$) and 1 h Post-Ex ($P =$
353 0.004) but counts were significantly lower at both post-exercise ($P = ???$) and 1 h Post-Ex (P
354 $= ???$) times in the Ex-CHO compared to Ex-PLA group (see Table 3). A significant time
355 effect was evident for lymphocyte count (trafficking) and a significant group \times time
356 interaction indicates that this pattern differs between groups. Post hoc comparison did not
357 reveal any between group differences at any of the time points (Table 3) but there was a
358 significant increase in Ex-PLA at Post-Ex ($P = 0.006$) but no change over time in the Ex-
359 CHO group ($P = 0.262$). The neutrophil-to-lymphocyte ratio increased significantly in Ex-
360 PLA at Post-Ex ($P < 0.001$) and 1 h Post-Ex ($P < 0.001$) and Ex-CHO at Post-Ex ($P = 0.028$)
361 and 1 h Post-Ex ($P = 0.020$) but neutrophil-to-lymphocyte was significantly lower at 1 h Post-
362 Ex in the Ex-CHO compared to Ex-PLA group (see Table 3).

363

364 *** *Please insert Table 3 near here* ***

365

366 Stress hormones and glucose

367 For stress hormones and glucose n = 12 for the Ex-PLA group and n = 11 for the Ex-CHO

368 group. Significant main effects of group, time and group × time interaction were evident for

369 plasma glucose, which was significantly higher at post-exercise and 1 h post-exercise in the

370 Ex-CHO group compared to Ex-PLA (Table 4). Post hoc analysis on the time effect (in each

371 group separately, owing to the observed interaction) revealed a significant decrease below

372 Pre-Ex concentration at 1 h Post-Ex in the Ex-PLA group (P = 0.032) and a significant

373 increase at Post-Ex (P < 0.001) and 1 h Post-Ex (P = 0.011) in the Ex-CHO group.

374

375 Significant main effects of time, and group × time interaction were evident for plasma

376 cortisol, which was significantly lower post-exercise and 1 h post-exercise in the Ex-CHO

377 compared to the Ex-PLA group (Table 4). Post hoc analysis on the time effect (in each group

378 separately, owing to the observed interaction) revealed no differences in the Ex-PLA group

379 (P > 0.05) and a significant decrease at Post-Ex (P < 0.001) and 1 h Post-Ex (P < 0.001) in

380 the Ex-CHO group (in line with the normal expected diurnal pattern).

381

382 Significant main effects of time were evident for both adrenaline and noradrenaline (i.e. an

383 exercise response) but there were no differences between Ex-CHO and Ex-PLA groups

384 (interactions P > 0.05, Table 4). Post hoc analysis on the time effect (both groups considered

385 together, owing to the lack of interaction) revealed a significant increase in plasma adrenaline

386 concentration (P = 0.013) and noradrenaline concentration (P < 0.001) at Post-Ex.

387

388 *** Please insert table 4 near here ***

389

390 Discussion

391 The aim of the present study was to determine the effects of acute CHO ingestion, before,
392 during, and after prolonged exercise, on the *in vivo* immune response (CHS) to the novel
393 contact antigen DPCP. The main findings were that despite CHO ingestion blunting the
394 cortisol and leukocyte trafficking responses to prolonged treadmill running, there was no
395 effect on *in vivo* immune response to DPCP. When comparing to the resting CON group from
396 Diment et al. [20] *in vivo* immune induction (oedema assessed by skin-fold thickness) in the
397 present study was significantly lower (-46%). Sensitivity analysis also revealed that the
398 threshold dose for a response to DPCP was ~3-fold higher (2.81-fold for PLA and 2.88-fold
399 for CHO) in order to elicit a positive response. Previous research has consistently
400 demonstrated that prolonged exercise (2 h treadmill running at 60% $\dot{V}O_{2max}$) reduces *in vivo*
401 immune induction as assessed by this method [19, 20]. The exercise groups in the present
402 study exhibited similar responses to the exercise groups in both of these previous studies [19,
403 20]. This, in conjunction with direct statistical comparison with the CON group of Diment et
404 al. [20], shows that the prolonged exercise in the present study reduced *in vivo* immune
405 induction. However, the present study suggests that this decrease is not altered by acute CHO
406 supplementation.

407

408 Challenging the skin using novel antigens permits the investigation of the influence of
409 stressors on *in vivo* immune induction and allows rigorous control of both the dose and
410 timing of sensitisation [19]. However, we are not aware of any previous study that has
411 utilised *in vivo* immune induction of CHS to determine the effects of nutritional interventions
412 on exercise-induced immunodepression. Despite the large body of research showing CHO

413 supplementation to blunt the prolonged exercise-induced responses for a wide array of
414 immune markers (e.g. [4, 5, 9–11]), there is a lack of evidence on the effects of CHO
415 supplementation on *in vivo* immune function and/or clinically relevant outcomes. The
416 findings of the present study, that CHO supplementation did not benefit *in vivo* immunity
417 post-exercise, is broadly in line with Nieman et al. [15] who compared placebo or CHO
418 beverage-supplemented runners during a competitive marathon race. In that study Nieman et
419 al. [15] observed CHO supplementation (approximately 60 g per hour) to be associated with
420 higher post-race plasma glucose and insulin concentrations, and lower post-race cortisol and
421 growth hormone concentrations. However, there was no difference between the CHO and
422 placebo groups in salivary IgA responses (considered high value markers in relation to URTI
423 risk, [14]) or URTI incidence in the 15-day post-race period. However, as this was a field-
424 based study in which subjects were racing, it is possible that performance would have
425 differed (relative to each individual's current potential performance or fitness) or that the
426 CHO could have ergogenic effects meaning it is difficult to confirm whether subjects were
427 exposed to the same relative stress (both physiological and psychological) in each group.
428 Hence, in the present study we investigated *in vivo* immune function using the CHS
429 'challenge-test' with otherwise standardised diet and exercise conditions. Given the outcomes
430 previously reported for immune markers, with CHO supplementation, we hypothesised that
431 CHO would protect against the exercise-induced decrease of *in vivo* immunity. However,
432 contrary to our original hypothesis, and despite significant blunting of the leukocyte (and
433 leukocyte subset) trafficking and cortisol responses, there was no difference between the Ex-
434 CHO and Ex-PLA groups in *in vivo* immune function. Therefore, these results suggest that
435 CHO supplementation does not protect against prolonged exercise-induced
436 immunodepression when assessed using an *in vivo* immune marker, which we [19, 20] and
437 others [14] propose to be of clinical relevance in an exercise immunology context.

438

439 For consistency between groups, we were careful to control diet and CHO intake before (i.e.
440 on the day before and the morning of) the main trials and during the period of sensitisation so
441 that the only difference between groups was CHO content of drinks consumed acutely before,
442 during, and after the prolonged exercise. Many previous studies required subjects to exercise
443 following an overnight fast and it is possible, therefore, that immune alterations would be
444 more pronounced in these circumstances. We chose to provide a standard breakfast in order
445 to replicate what many athletes often do in training and competition and, as such, our results
446 have practical relevance to such athletes. This presents the possibility that CHO
447 supplementation during exercise would be more beneficial if exercise was commenced in the
448 fasted state, which may be used by some athletes in certain sessions (e.g. see reference [20]
449 for a recent review on the practice of training with low CHO availability). However,
450 consuming a CHO-containing beverage would be counterproductive to any athlete wishing to
451 practice this ‘train low’ method (as it would negate the fundamental principle of training
452 low). As such, our approach for determining the effect of acute CHO ingestion on the *in vivo*
453 immune responses to prolonged exercise in the fed state seems the most valid and of practical
454 relevance for athletes. In the current study, the fact that we still observed notable differences,
455 between the Ex-CHO and Ex-PLA conditions, in plasma glucose, leukocytosis and a number
456 of stress markers typically associated with exercise and/or CHO ingestion demonstrates that
457 there was a meaningful difference between the Ex-CHO and Ex-PLA groups in terms of the
458 stress response to exercise. We suggest, therefore, that the lack of difference between CHO
459 and PLA conditions in the present study cannot be explained by the fact that subjects were
460 fed a standard breakfast 3.5 h before the exercise trials. These findings are in line with
461 previous studies showing that *in vivo* immune responses to DPCP are unrelated to stress
462 hormone responses induced by exercise [20] or altitude [21]. Taken together, this offers a

463 feasible explanation for the lack of effect of CHO supplementation on DPCP responses,
464 despite a blunting of many of the stress response markers typically proposed to be responsible
465 for the immunodepressive effects associated with prolonged and strenuous exercise. Induction
466 of CHS is dependent upon dendritic cell activation at the skin, dendritic cell migration from
467 the skin to the regional lymph nodes and subsequent clonal expansion of specific T cells [22],
468 and represents an *in vivo* measure of the whole integrated immune response. As we have
469 demonstrated no effect of CHO supplementaiton on this *in vivo* immune measure, and since
470 the stress hormone (particularly cortisol) response does not seem to be implicated [20], it is
471 now necessary to further explore the mechanisms responsible for the exercise-induced
472 decrease in *in vivo* immunity and suitable nutritional countermeasures.

473

474 Limitations

475 The results for erythema responses were generally in line with the oedema responses but
476 when comparing to the CON data of Diment et al. [20] the summed response was
477 significantly lower in the Ex-CHO condition (~41%) but there was only a trend for lower
478 responses in the Ex-PLA group (~32%). Importantly, however, there was no difference
479 between the Ex-PLA and Ex-CHO groups (if anything the response was lower in the CHO
480 group). Since the use of erythema may suffer from interference at sites of a strong response,
481 where yellow vesicles can interfere with the erythema readings [19, 20] the oedema results of
482 this study should be taken as the primary indication of CHS. Importantly, even if using the
483 erythema data, the overall conclusion would remain the same, that acute CHO ingestion
484 before, during and after prolonged exercise does not benefit *in vivo* immunity.

485

486 We recognise a limitation of the current study is that we did not concurrently measure any of
487 the previously reported functional *in vitro* markers (e.g. neutrophil function, lymphocyte

488 proliferation, stimulated cytokine production) for comparison with *in vivo* responses.
489 However, it is well-established and consistently reported that CHO supplementation blunts
490 many of the prolonged-exercise-induced alterations in *in vitro* immune measure (e.g. [4, 5, 9–
491 11]). Our current results do not suggest that subjects' responses were any different from
492 those typically observed in such studies: we observed the typical exercise-induced increases
493 of stress hormones and leukocyte trafficking which were blunted by CHO ingestion. This
494 study therefore supports the recent findings of Diment et al. [20] that the induction of
495 immune memory is decreased by prolonged exercise but the circulating stress hormone
496 responses do not appear to be responsible. This also agrees with Oliver et al. [21] who
497 showed that reduced CHS responses after ascent to altitude were not related to the stress
498 hormone response. The current study does support the previously reported effects of CHO
499 supplementation on blunting of stress and leukocytosis responses to prolonged exercise (e.g.
500 [4, 5, 9, 11]) but it does not support the use of CHO as an acute nutritional intervention of
501 benefit to *in vivo* immunity. This also seems to support the notion that *in vitro* measures do
502 not sufficiently capture the whole integrated immune response and as such, are not
503 representative of *in vivo* host defence. As a result, it would be beneficial for future studies to
504 include *in vivo* measures in order to test the utility of proposed nutritional countermeasures
505 for immune impairment after prolonged exercise.

506

507 We also recognise that the CHS response to DPCP is benign, and the clinical significance of
508 the response, with specific regard to URTI in athletes, has not yet been established [20].
509 Nevertheless, the clinical relevance of *in vivo* cutaneous immune measures has been
510 demonstrated in other contexts e.g. relationships with the progression of immunodeficiency;
511 progression of acute to persistent diarrhoea; and URTI risk in children [14, 26–28]. In the
512 current study, we have used the CHS response as a marker of *in vivo* immune function but do

513 acknowledge that future research must confirm the relationship between this and illness (e.g.
514 URTI) risk in athletes.

515

516 Conclusion

517 Based on the results of this study, acute CHO ingestion before, during and after exercise does
518 not blunt the decrease of *in vivo* immunity observed following 2 h of moderate exercise in the
519 fed state (exercise commencing 3.5 h after breakfast). It remains to be determined, however,
520 whether there would be any benefit with exercise that places a greater stress on CHO
521 availability (e.g. longer duration and/or in the fasted state), or during periods of intensified
522 training. However, we propose that the current design is relevant to what many athletes
523 actually do in training and competition ~~and would expect similar findings if repeated during~~
524 ~~regular training~~, although the effects of more chronic CHO supplementation (i.e. during
525 regular training for weeks or months) require further investigation.

526

527 **Acknowledgments**

528 No external funding was received for this study. On behalf of all authors, the corresponding
529 author states that there is no conflict of interest.

530

531 **Ethical standards**

532 All procedures within this study were first approved by the University local research ethics
533 committee and were carried out in accordance with the Declaration of Helsinki (including
534 2013 amendments). All study participants gave written informed consent prior to their
535 inclusion in the study.

536

537 **References**

- 538 1. Gleeson M (2007) Immune function in sport and exercise. *J Appl Physiol* 103:693–9.
539 doi: 10.1152/jappphysiol.00008.2007
- 540 2. Walsh NP, Gleeson M, Shephard RJ, et al. (2011) Position statement. Part one:
541 Immune function and exercise. *Exerc Immunol Rev* 17:6–63.
- 542 3. Robson PJ, Blannin AK, Walsh NP, et al. (1999) Effects of exercise intensity, duration
543 and recovery on in vitro neutrophil function in male athletes. *Int J Sports Med* 20:128–
544 35. doi: 10.1055/s-2007-971106
- 545 4. Davison G, Gleeson M (2005) Influence of acute vitamin C and/or carbohydrate
546 ingestion on hormonal, cytokine, and immune responses to prolonged exercise. *Int J*
547 *Sport Nutr Exerc Metab* 15:465–79.
- 548 5. Lancaster GI, Khan Q, Drysdale PT, et al. (2005) Effect of prolonged exercise and
549 carbohydrate ingestion on type 1 and type 2 T lymphocyte distribution and
550 intracellular cytokine production in humans. *J Appl Physiol* 98:565–71. doi:
551 10.1152/jappphysiol.00754.2004
- 552 6. Gunzer W, Konrad M, Pail E (2012) Exercise-induced immunodepression in
553 endurance athletes and nutritional intervention with carbohydrate, protein and fat-what
554 is possible, what is not? *Nutrients* 4:1187–212. doi: 10.3390/nu4091187
- 555 7. Walsh NP, Gleeson M, Pyne DB, et al. (2011) Position statement. Part two:
556 Maintaining immune health. *Exerc Immunol Rev* 17:64–103.

- 557 8. Gleeson M (2006) Can nutrition limit exercise-induced immunodepression? *Nutr Rev*
558 64:119–31. doi: 10.1301/nr.2006.mar.119
- 559 9. Henson DA, Nieman DC, Blodgett AD, et al. (1999) Influence of exercise mode and
560 carbohydrate on the immune response to prolonged exercise. *Int J Sport Nutr* 9:213–
561 228.
- 562 10. Scharhag J, Meyer T, Gabriel HHW, et al. (2002) Mobilization and oxidative burst of
563 neutrophils are influenced by carbohydrate supplementation during prolonged cycling
564 in humans. *Eur J Appl Physiol* 87:584–587. doi: 10.1007/s00421-002-0642-0
- 565 11. Scharhag J, Meyer T, Auracher M, et al. (2006) Effects of graded carbohydrate
566 supplementation on the immune response in cycling. *Med Sci Sports Exerc* 38:286–
567 292. doi: 10.1249/01.mss.0000191437.69493.d4
- 568 12. Moreira a, Kekkonen R a, Delgado L, et al. (2007) Nutritional modulation of exercise-
569 induced immunodepression in athletes: a systematic review and meta-analysis. *Eur J*
570 *Clin Nutr* 61:443–60. doi: 10.1038/sj.ejcn.1602549
- 571 13. Albers R, Antoine J-M, Bourdet-Sicard R, et al. (2005) Markers to measure
572 immunomodulation in human nutrition intervention studies. *Br J Nutr* 94:452–81.
- 573 14. Albers R, Bourdet-Sicard R, Braun D, et al. (2013) Monitoring immune modulation by
574 nutrition in the general population: identifying and substantiating effects on human
575 health. *Br J Nutr* 110 Suppl:S1–30. doi: 10.1017/S0007114513001505
- 576 15. Nieman DC, Henson DA, Fagoaga OR, et al. (2002) Change in salivary IgA following
577 a competitive marathon race. *Int J Sports Med* 23:69–75. doi: 10.1055/s-2002-19375
- 578 16. Levis WR, Holzer AM, Leonard LK (2006) Topical diphenylcyclopropenone as a
579 measure of immune competence in HIV-seropositive subjects. *J Drugs Dermatol*
580 5:853–858.
- 581 17. Zaman K, Baqui AH, Yunus M, et al. (1997) Malnutrition, cell-mediated immune
582 deficiency and acute upper respiratory infections in rural Bangladeshi children. *Acta*
583 *Paediatr* 86:923–927. doi: 10.1111/j.1651-2227.1997.tb15171.x
- 584 18. Poenaru D, Christou N V (1991) Clinical outcome of seriously ill surgical patients
585 with intra-abdominal infection depends on both physiologic (APACHE II score) and
586 immunologic (DTH score) alterations. *Ann Surg* 213:130–136. doi:
587 10.1097/00000658-199102000-00007
- 588 19. Harper Smith AD, Coakley SL, Ward MD, et al. (2011) Exercise-induced stress
589 inhibits both the induction and elicitation phases of in vivo T-cell-mediated immune
590 responses in humans. *Brain Behav Immun* 25:1136–1142. doi:
591 10.1016/j.bbi.2011.02.014
- 592 20. Diment BC, Fortes MB, Edwards JP, et al. (2014) Exercise Intensity and Duration
593 Effects on In Vivo Immunity. *Med Sci Sport Exerc* 1. doi:
594 10.1249/MSS.0000000000000562

- 595 21. Borg GA (1982) Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*
596 14:377–81.
- 597 22. Lansley KE, Dimenna FJ, Bailey SJ, Jones AM (2011) A new method to normalise
598 exercise intensity. *Int J Sports Med* 32:535–541. doi: 10.1055/s-0031-1273754
- 599 23. Bartlett JD, Hawley J a, Morton JP (2015) Carbohydrate availability and exercise
600 training adaptation: Too much of a good thing? *Eur J Sport Sci* 15:3–12. doi:
601 10.1080/17461391.2014.920926
- 602 24. Oliver SJ, Macdonald JH, Harper Smith AD, et al. (2013) High altitude impairs in vivo
603 immunity in humans. *High Alt Med Biol* 14:144–9. doi: 10.1089/ham.2012.1070
- 604 25. Toebak MJ, Gibbs S, Bruynzeel DP, et al. (2009) Dendritic cells: Biology of the skin.
605 *Contact Dermatitis* 60:2–20. doi: 10.1111/j.1600-0536.2008.01443.x
- 606 26. Azim T, Islam LN, Sarker MS, et al. (2000) Immune response of Bangladeshi children
607 with acute diarrhea who subsequently have persistent diarrhea. *J Pediatr Gastroenterol*
608 *Nutr* 31:528–535. doi: 10.1097/00005176-200011000-00014
- 609 27. Blatt SP, Hendrix CW, Butzin CA, et al. (1993) Delayed-type hypersensitivity skin
610 testing predicts progression to AIDS in HIV-infected patients. *Ann Intern Med*
611 119:177–184.
- 612 28. Gordin FM, Hartigan PM, Klimas NG, et al. (1994) Delayed-type hypersensitivity skin
613 tests are an independent predictor of human immunodeficiency virus disease
614 progression. Department of Veterans Affairs Cooperative Study Group. *J Infect Dis*
615 169:893–7.
- 616
- 617

618

619 Figure legends

620

621 **Figure 1.** CHS response to DPCP elicitation 28 d after sensitisation: Summed increase in skin-fold
622 thickness (left panel, values are mean \pm SD) and full dose-series response (right panel, values are mean \pm
623 SEM), 48 h post elicitation.

624 *#note: Responses were also compared to 16 resting control (CON) subjects from Diment et al. [20] for additional
625 comparison with a resting non-exercise condition (n = 16, 120 minutes of seated rest).*

626 ** Indicates significantly different to CON (P < 0.05). There were no differences between Ex-PLA and Ex-CHO*

627

628

629

630 **Figure 2.** CHS response to DPCP elicitation 28 d after sensitisation: Summed increase in erythema (left
631 panel, values are mean \pm SD) and full dose-series response (right panel, values are mean \pm SEM), 48 h
post elicitation.

*#note: Responses were also compared to 16 resting control (CON) subjects from Diment et al. [20] for additional
comparison with a resting non-exercise condition (n = 16, 120 minutes of seated rest).*

** Indicates significantly different to CON (P < 0.05). There were no differences between Ex-PLA and Ex-CHO*

Table 1. Subject demographics

	PLA-Ex (n = 16)	CHO-Ex (n = 16)	t-test P value
Height (m)	1.79 (0.05)	1.78 (0.05)	0.489
Weight (kg)	76.4 (10.4)	76.0 (10.0)	0.916
BMI (kg·m ⁻²)	23.8 (3.0)	24.0 (2.6)	0.827
Age (years)	29 (8)	29 (8)	0.864
Training (h)	7 (3)	6 (2)	0.721
$\dot{V}O_{2\max}$ (ml·kg ⁻¹ ·min ⁻¹)	55.7 (6.1)	60.9 (5.6)	0.017

Values are mean (SD)

Table 2. Exercise responses during main trial

	PLA-Ex	CHO-Ex	t-test P value
% Δ @ 60% $\dot{V}O_{2\max}$	39.6 (28.7)%	38.8 (36.4)%	0.622
Mean % $\dot{V}O_{2\max}$	59.6 (4.9)%	58.2 (4.7)%	0.432
HR (bpm)	140 (15)	138 (12)	0.686
RPE	11 (2)	11 (2)	0.182

636 *Values are mean (SD)*

Table 3. Leukocyte responses to exercise

		Pre-Ex	Post-Ex	1 h Post-Ex	ANOVA main effects (group; time; trial × time)
Leukocyte count (×10 ⁹ .l ⁻¹)					0.313 ; <0.001 ; <0.001
	Ex-PLA	5.1 (1.2)	10.4 (2.9)	10.2 (2.7)	
	Ex-CHO	5.6 (0.8)	7.1 (1.3) ^{aa}	6.2 (0.6) ^{aa}	
Neutrophil count (×10 ⁹ .l ⁻¹)					0.005 ; <0.001 ; <0.001
	Ex-PLA	3.2 (1.0)	7.6 (2.6)	7.9 (2.1)	
	Ex-CHO	3.2 (0.6)	4.7 (1.2) ^{aa}	4.1 (0.8) ^{aa}	
Lymphocyte count (×10 ⁹ .l ⁻¹)					0.830 ; <0.001 ; 0.037
	Ex-PLA	1.4 (0.4)	1.8 (0.7)	1.3 (0.5)	
	Ex-CHO	1.6 (0.5)	1.7 (0.4)	1.4 (0.4)	
N:L ratio					0.053 ; <0.001 ; <0.001
	Ex-PLA	2.5 (1.2)	4.9 (2.7)	6.5 (2.3)	
	Ex-CHO	2.2 (1.0)	2.9 (0.9)	3.2 (1.2) ^{aa}	

N:L ratio: Neutrophil-to-Lymphocyte ratio. *Values are mean (SD)*;

Post hoc (between groups): Significantly different to Ex-PLA ^a (P <0.05), ^{aa} (P <0.01). Post hoc results for significant time effects are described in the text of results section but not shown in above table.

Table 4. Glucose and stress hormone responses to exercise

	Pre-Ex	Post-Ex	1 h Post-Ex	ANOVA main effects (group; time; trial × time)
Plasma Glucose (mmol.l ⁻¹)				0.002 ; 0.007 ; <0.001
Ex-PLA	4.5 (0.8)	4.2 (0.6)	3.8 (0.9)	
Ex-CHO	4.2 (0.8)	5.9 (0.9) ^{aa}	5.1 (1.1) ^{aa}	
Cortisol (nmol.l ⁻¹)				0.263 ; 0.037 ; 0.001
Ex-PLA	367 (187)	431 (218)	398 (175)	
Ex-CHO	488 (159)	259 (98) ^a	269 (81) ^a	
Adrenaline (nmol.l ⁻¹)				0.961 ; 0.002 ; 0.857
Ex-PLA	0.37 (0.27)	0.96 (1.26)	0.45 (0.44)	
Ex-CHO	0.37 (0.28)	0.62 (0.31)	0.31 (0.09)	
Noradrenaline (nmol.l ⁻¹)				0.949 ; <0.001 ; 0.701
Ex-PLA	3.15 (1.53)	4.71 (2.02)	3.30 (1.19)	
Ex-CHO	2.96 (1.14)	4.98 (1.19)	3.18 (0.77)	

Values are mean (SD);

Post hoc (between groups): Significantly different to Ex-PLA ^a (P <0.05), ^{aa} (P <0.01). Post hoc results for significant time effects are described in the text of results section but not shown in above table.