Antioxidant supplementation preserves antioxidant response in physical training and low antioxidant intake

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The present controlled-training double-blind study (supplemented (S) group, n = 7; placebo (P) group, n = 10) was designed to investigate whether an antioxidant mixture (Se 150 μg, retinyl acetate mg, ascorbic acid 120 mg, α-tocopheryl succinate) would allow overloaded triathletes to avoid adaptation failure in the antioxidant system. Dietary intakes were recorded. The supplement of Se, and vitamins A and E provided 100% of the French RDA. Four weeks of overloaded training (OT) followed 4 weeks of normal training (NT). After NT and OT, biological studies were conducted at rest and after a duathlon test (run 5 km, cycle 20 km, run 5 km). During the 4-week period of NT, blood levels of GSH levels increased in response to supplementation (P<0.05) and remained elevated during OT. Plasma glutathione peroxidase activity was significantly higher in the S group in all situations after NT and OT (P<0.01). The S group had increased erythrocyte Cu,Zn-superoxide dismutase activity in response to OT (P<0.05). Supplementation significantly reduced (P<0.05) the magnitude in duathlon-induced creatine kinase isoenzyme MB mass increase, which tended to be higher with OT (P=0.09).

We conclude that the antioxidant mixture helped to preserve the antioxidant system during an OT-induced stress in subjects with initially low antioxidant intakes. Effects of supplementation during NT and/or OT are shown mostly by the alleviated muscle damage. The effects of the antioxidant mixture were observed for doses that can be provided by a diversified and well-balanced diet. The maintenance of normal nutritional status with regard to the antioxidant intake (Se, vitamins C and E) plays a key role in antioxidant adaptive effects during NT and OT.

Selenium: Ascorbate: α-Tocopherol: Oxidative stress: Physical training

The increase in reactive oxygen species production during physical exercise may disturb intracellular pro-oxidant–antioxidant homeostasis, inducing oxidative stress that initiates oxidative damage of lipid, protein and nucleic acids (Powers & Hamilton, 1999). Cu,Zn-superoxide dismutase (SOD), Se-dependent glutathione peroxidase (GSH-Px), vitamins C and E, and GSH can prevent exercise-induced oxidative stress (Dekkers et al. 1996; Ji, 1999; Powers & Hamilton, 1999). Training-induced upregulation of endogenous antioxidants may reduce the risk of cellular injury during exercise (Powers et al. 1999). To interact with endogenous antioxidants, exogenous antioxidants are provided by the diet. As a result of physical training, adaptive effects of the antioxidant system are known to reduce the magnitude of the exercise-induced stress. Paradoxically, as physical training requires repeated bouts of physical aerobic endurance training, an increase in energy requirement increases O₂ utilization, which in turn increases free radical oxygen-derivative generation by the mitochondria of active muscles (Ji, 1999).

We previously showed that overloaded training (OT) in triathletes increases exercise-induced oxidative stress, lipid peroxidation and muscle damage, and that overloaded triathletes fail to adapt to oxidative exercise-induced stress and cell damage response in exercise conditions (Palazzetti et al. 2003). These outcomes can be attributed to inefficient adaptation (Hinchcliff et al. 2000) or increased antioxidant trace element and vitamin requirements with increased energy expenditure (Clarkson, 1995). Se, and vitamins C and E, play a major and synergistic role as exogenous antioxidants in the regulation of the endogenous antioxidant defence system, and lowers exercise-induced oxidative damage (Goldfarb, 1999).

Abbreviations: GSH-Px, glutathione peroxidase; NT, normal training; OT, overloaded training; P, placebo; POMS, profile of mood states; S, antioxidant-supplemented; SOD, superoxide dismutase; TBARS, thiobarbituric acid-reactive substances.

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For overloaded subjects, the efficacy of antioxidant micronutrients, either individually or in combination, has not been established by randomized clinical trial. We hypothesized that the antioxidant system downregulation and its consequences would be avoided, at least in part, by the ingestion of a supplement of antioxidant nutrients. The present study was designed to test the efficacy of a micronutrient daily supplementation with antioxidant vitamins (ascorbic acid, α-tocopherol, retinyl acetate) and Se, at nutritional doses, in reducing the effects of OT-induced oxidative stress and damage.

**Methods**

**Subjects**

Twenty well-trained male triathletes (age 32.9 (SD 9.9) years, height 1.754 (SD 0.070) m, body mass 69.4 (SD 5.3) kg, body fat 11.4 (SD 3.7)%, maximal \( V_{O2max} \) 65.0 (SD 6.1) ml/min per kg) participated in this 8-week double-blind study. During the first 4-week period, normal training (NT) was conducted; during the second 4-week period, training was overloaded by qualitative and quantitative increase in swimming, cycling and running loads (Table 1). Training loads were defined for each subject, quantitatively by collecting personal data about past training, and qualitatively by functional assessments as described by Palazzetti et al. (2003). Individual training loads were quantified by a modified version of the method of Morton et al. (Palazzetti et al. 2003). Total training load was increased by 42% during OT. The 4-week OT induced an overloaded state shown by a significant decrease in duathlon performance capacity and \( V_{O2max} \) during running. Triathletes were randomly assigned in blind fashion to an antioxidant-supplemented (S, \( n \) 10) or placebo (P, \( n \) 10) group. After 5 weeks, three triathletes in the S group dropped out because of injuries and for personal reasons. Triathletes were long-distance competitors who managed social, occupational, family and sporting activities. Experimental procedures were approved by the Local Committee for the Protection of Persons in Biomedical Research (no. 99002), and all triathletes gave written informed consent after having been explained the purpose, possible risks and stress associated with the study. All triathletes were non-smokers, had no history of medical disorders and had not taken antioxidant supplements for at least 6 months before the study. They were instructed to refrain from making any drastic changes in diet and to abstain from anti-inflammatory or analgesic drugs throughout the study.

**Experimental procedures**

Referring to the competition program of long-distance triathletes, training was overloaded for 4 weeks following a 4-week NT phase. Maximal functional assessments in swimming, cycling and running were performed by each triathlete before NT (Palazzetti et al. 2003). After NT and OT, the triathletes completed a duathlon test (run 5 km, cycle 20 km, run 5 km) at 84 (SD 2)% \( V_{O2max} \) preceded 2 d before by a maximal treadmill test. Each functional assessment before NT or duathlon was separated by 1 day off and performed at the same time of day. Before each functional assessment, body mass was measured with a calibrated balance. The % body fat was determined from the skinfold thicknesses measured at four sites (biceps, triceps, subscapular, suprailiac), as described by Durnin & Rahaman (1967). Venous blood samples were collected in basal conditions at the start of the study and after NT and OT, and in post-exercise conditions after NT and OT.

**Supplementation**

The S group consumed two tablets of an antioxidant complex preparation per d: Selenium A-C-E® (Richelet Laboratories, Paris, France); each containing 75 µg organic Se, mg retinyl acetate, 60 mg ascorbic acid and mg D-α-tocopheryl succinate). The P group received a placebo preparation that was identical in form and taste, and the same amount of tablets as the S group. Before the study, triathletes were told to take one tablet before breakfast and one tablet before lunch during NT and OT phases.

**Nutritional status**

Dietary records were kept each day of the study for each meal. All triathletes were instructed on proper nutritional recording, including estimating portion sizes. Data acquisition was made in grams and daily nutritional consumption was quantified by the CIQUAL database (Regal micro Windows 9x, NT version 1.2; Max Feinberg, Paris, France). Nutritional status was assessed by reference to the French RDA for sportsmen, based on additional needs for daily energy expenditure exceeding 9.207 MJ, recently been established by the French Food Agency of Sanitary Security (Guillard et al. 2001).

**Table 1.** Calculated total training loads and training volumes per week for swimming, cycling and running in triathletes (Mean values and standard deviations for seventeen subjects)

<table>
<thead>
<tr>
<th></th>
<th>NT</th>
<th>OT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Total training load (AU)</td>
<td>648</td>
<td>172</td>
</tr>
<tr>
<td>Cycling (km per week)</td>
<td>5.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Running (km per week)</td>
<td>174</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>10</td>
</tr>
</tbody>
</table>

NT, normal training; OT, overloaded training; AU, arbitrary units. Mean values were significantly different from those of NT. *\( p < 0.05; *** p < 0.001 \).
coefficient was assigned from a corresponding physical activity level (Vernorel et al. 2001). The relationship between activity duration and physical activity level enabled calculation of a mean energy expenditure (kJ) for each activity. During training sessions, the heart rate was recorded by a telemetric system (Polar Accurex Plus; Polar Electro Oy, Kempele, Finland) and the energy expenditure was calculated from the relationship between O₂ consumption and heart rate established individually for swimming, cycling and running. The total energy expenditure was the sum of energy expenditure calculated for each activity.

Profile of mood states

Every week, each triathlete completed the profile of mood states questionnaire (POMS) (McNair et al. 1992). The relationship between physiological, biochemical disturbances, and behaviour and/or psychological indices is well documented. Originally, POMS was devised to indicate the occurrence of these disturbances in pathological situations. POMS is now widely used as one of the tools for identifying overloaded state. In our present study, POMS was administered to quantify the influence of training loads on mood state.

Functional assessments

Identical series of measurements were repeated by all triathletes after NT and after OT. Each test was performed at the same time of day.

Maximal treadmill test. Triathletes performed a continuous incremental running test on a motorized treadmill (2500 ST; GYMROL, Andrieux Boutheon, France). The test began with a warm-up at 10 km/h (2 % slope) for 5 min; running speed was then increased by 2 km/h every 2 min up to 14 km/h and by 1 km/h to exhaustion. During treadmill tests, ventilatory and gas exchange responses were measured on a breath-by-breath basis using an automatic spiroergometric system (Vmax 29; Sensor Medics, Rungis, France). Heart rate was monitored continuously and recorded using an electrocardiograph monitor (SMS 182; HELLIGE, Freibourg in Breisgau, Germany) and a telemetric system (Polar Accurex Plus; Polar Electro Oy). The criteria used for determining VO₂max were a plateau in VO₂max, despite an increase in running speed, a respiratory exchange ratio >1.1 and an heart rate >90 % of the predicted maximal heart rate.

Duathlon test. All duathlon tests took place outdoors between March and April in Nice, France. Outside temperature ranged from 17 to 22°C. Triathletes performed all tests under the same equipment conditions and drank the same energy-providing beverage. Before each duathlon test (run 5 km, cycle 20 km, run 5 km), all triathletes warmed-up for 30 min by alternate jogging and stretching. Running trials were performed on a flat circuit alternating lawn and asphalt. Cycling was performed on an exercise bike (EliteTravel, Fontaniva, Italy), over which was positioned the personal bike of triathletes. Duathlon tests were performed at 84 (SD 2) % VO₂max.

Blood sampling

Venous blood samples were collected at the start of the study (baseline), after NT and after OT in resting and post-duathlon conditions. Subjects reported to the laboratory after a day off and an overnight fast. The time of day for basal blood test was standardized to within 30 min for each subject, and all samples were taken between 06.00 and 08.00 hours. Post-exercise venous blood samples were obtained immediately after the duathlon tests, which took place the same day at the end of afternoon. Blood samples were collected by venepuncture from an antecubital vein of each subject. Whole blood (400 µl) for glutathione analysis was immediately treated as described later. The blood samples were centrifuged (4000 rpm, 4°C, 10 min), and plasma or serum were divided into portions and frozen in liquid N₂ before storage at −80°C until assay.

Biochemical analysis

Oxidized and reduced glutathione. Immediately after venepuncture, 400 µl whole blood was transferred into a tube containing 3600 µl metaphosphoric acid (60 ml/l water). The contents was mixed and centrifuged for 10 min at 4°C. Acidic protein-free supernatant fractions were stored at −80°C until analysis. Glutathione level was determined using enzymatic cycling of GSH by means of NADPH and glutathione reductase coupled with 5,5′-dithiobis(2-nitrobenzoic acid). We estimated GSSG level according to the method of Akerboom & Sies (1981), slightly modified by Emonet et al. (1997). For this, we masked GSH by adding 10 µl 2-vinyl-pyridine to 500 µl deproteinized extract adjusted to pH 6 with triethanolamine. The mixture was allowed to stand for 60 min. The fraction of GSH was calculated as:

\[
\text{GSH} = \text{total glutathione} - (2 \times \text{GSSG})
\]

Mass of creatine kinase isoenzyme MB. The mass of creatine kinase isoenzyme MB, determined in plasma by immunoassay using the ELISA sandwich principle with fluorogenic marker, was used to evaluate exercise-induced muscle damage.

Single-cell gel electrophoresis assay. The single-cell electrophoresis assay (or comet assay), a sensitive technique for the measurement of DNA breakage in individual cells, was performed as described by Singh et al. (1988) with minor modifications by Emonet et al. (1998). One hundred and fifty µl agarose (5 g/l) diluted in Ca- and Mg-free PBS buffer was added to fully frosted microscope slides (Touzart et Matignon, Paris, France), immediately covered with coverslips, and kept for 10 min in a refrigerator to solidify. Next, the coverslips were removed and 5 µl whole blood mixed with 60 µl low-melting-point agarose (6 g/l; Biozym, Hessisch Oldendorf, Germany) diluted in Ca- and Mg-free PBS buffer (60 µl) was added. The slides were covered again with a coverslip and kept in the refrigerator for another 10 min to solidify the low-melting-point agarose. After removal of the coverslips, the slides were immersed in a jar containing cold lysing solution
Statistical analysis

All values are expressed as means and standard deviations. To determine training main effect, one-way ANOVA test (supplementation) with repeated measures (NT, OT) was used to estimate daily energy intake, energy expenditure and macronutrient intake and to evaluate body mass, body fat and BMI. Differences between energy intake and energy expenditure were analysed by two-way ANOVA (supplementation, training) with repeated measures (energy intake, energy expenditure). To compare estimated daily micronutrient intakes and French RDA in NT and OT, we used Student’s t test for paired values. A one-way ANOVA test (supplementation) with repeated measures (NT, OT) was applied to determine supplementation main effect on estimated dietary intake. Physiological and psychological data were pooled and Student’s t test for paired values was applied. Biochemical data were analysed by two-way ANOVA test (supplementation, training) with repeated measures (preduathlon, post-duathlon) to determine: (1) interaction effects between supplementation, training and duathlon (supplementation × training × duathlon); supplementation and training (supplementation × training); supplementation and duathlon (supplementation × duathlon); (2) main effects (supplementation, training or duathlon). When significant changes were observed in ANOVA tests, Fisher’s protected least significant difference post hoc test was applied to locate the source of significant differences. Statistical significance level was set at \( P<0.05 \).

Results

A decrease in duathlon performance capacity (68·3 (sd 7·9) v. 71·2 (sd 10·4) min; \( n=17, P<0.05 \)) and in running \( V_{\text{oxygen max}} \) (4·516 (sd 0·433) v. 4·386 (sd 0·370) l/min; \( n=17, P<0.05 \)), and an increase in total POMS score (108·3 (sd 21·8); \( n=17, P<0.05 \)) showed that the 4-week OT induced an overloaded state in the triathletes. Nutritional analysis in both groups show that energy intake, energy expenditure and macronutrient intake were increased in response to OT, and that energy intake was significantly lower (\( P<0.01 \)) than energy expenditure in NT and OT (Table 2). On the other hand, the S and P groups did not differ in food antioxidant intakes (Table 2). The observance of the supplementation (supplementation provided:effective intake ratio) was 97·9 %.

Supplementation

The supplementation induced changes in circulating concentrations in Se after the first 4 weeks (Table 3). The changes in serum \( \alpha \)-tocopherol were significant (\( P<0.05 \))
when the complete duration of the study was taken into account (Table 3), and concentrations of retinol did not change with supplementation. An interaction effect of supplementation × training was observed for ascorbic acid (P < 0.05; Table 3). From the beginning of the study during NT, blood GSH levels increased in response to supplementation (Fig. 2) and remained high during OT. During OT the levels tended to be still higher with supplementation (P = 0.09). In all situations after NT and OT, plasma GSH-Px activity was significantly higher (P < 0.05) in the S group than in the P group (Table 4).

Supplementation × training effect

There were no effects of antioxidant supplementation on plasma TBAR levels or on GSH:GSSG ratio at rest.

Table 2. Estimation of energy intake, energy expenditure, macronutrient and micronutrient intakes/d, and evaluation of body mass, body fat, and BMI in normal and overloaded training for supplemented and placebo group triathletes

<table>
<thead>
<tr>
<th></th>
<th>S group (n 5)</th>
<th>P group (n 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NT</td>
<td>OT</td>
</tr>
<tr>
<td>Energy intake (MJ/d)</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Energy expenditure</td>
<td>13-8††</td>
<td>3-1</td>
</tr>
<tr>
<td>Carbohydrate (g/d)</td>
<td>425</td>
<td>80</td>
</tr>
<tr>
<td>Lipid (g/d)</td>
<td>119</td>
<td>39</td>
</tr>
<tr>
<td>Protein (g/d)</td>
<td>125</td>
<td>32</td>
</tr>
<tr>
<td>β-Carotene (µg RE/d)</td>
<td>625</td>
<td>244</td>
</tr>
<tr>
<td>Vitamin C (mg/d)</td>
<td>168</td>
<td>82</td>
</tr>
<tr>
<td>Vitamin E (mg TE/d)</td>
<td>11-0</td>
<td>3-6</td>
</tr>
<tr>
<td>EDI Se (µg/d)</td>
<td>245</td>
<td>13</td>
</tr>
<tr>
<td>FRDA Se (µg/d)</td>
<td>102†††</td>
<td>10</td>
</tr>
<tr>
<td>EDI β-carotene (µg RE/d)</td>
<td>625</td>
<td>244</td>
</tr>
<tr>
<td>FRDA β-carotene (µg RE/d)</td>
<td>633</td>
<td>55</td>
</tr>
<tr>
<td>FRDA Vitamin C (mg/d)</td>
<td>288</td>
<td>82</td>
</tr>
<tr>
<td>FRDA Vitamin E (mg TE/d)</td>
<td>250</td>
<td>33</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>69-1</td>
<td>4-1</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>12-4</td>
<td>3-9</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22-4</td>
<td>1-5</td>
</tr>
</tbody>
</table>

S, antioxidant supplemented; P, placebo; NT, normal training; OT, overloaded training; EDI, estimated dietary intake (including antioxidant supplementation (sele- nium A–C–E†; Richelet Laboratories, Paris, France)); FDRA, French recommended dietary allowance (Guilland et al. 2001); RE, retinol equivalents; TE, toco- pherol equivalents.

Mean values were significantly different from those of NT: *P < 0.05, **P < 0.01, ***P < 0.001.

Mean values were significantly different from EDI: †P < 0.05, ††P < 0.01, †††P < 0.001.

Mean values were significantly different from those of the S group: ‡P < 0.05.

Mean values were significantly different from energy expenditure: §§P < 0.01.

† Values do not include antioxidant supplementation.

Fig. 1. Food and supplement vitamin C and E and selenium intakes/d relative to the French RDA (FRDA; Guilland et al. 2001) in supplemented (n 5) and placebo (n 7) group triathletes during overloaded training. □, Placebo group; ●, supplemented group; ‡, supplement contribution. For details of subjects and procedures, see p. 92. Mean values were significantly different from those of the P group: *P < 0.05. Mean values were significantly different from those of the FRDA: †P < 0.05.
No effect of OT on creatine kinase isoenzyme MB mass was observed at rest (Fig. 3). The S group had an increase in erythrocyte Cu,Zn-SOD activity in response to OT ($F_{5\cdot1}, P_{0\cdot05}$) (Fig. 4). Supplementation did not modify a decrease in erythrocyte GSH-Px activity at rest in response to OT (Table 4). In both groups, OT induced an increase in leucocyte-DNA damage (S group 12·0 (SD 13·6) $v.$ 2 0·1 (SD 6·9), $P_{0\cdot05}$; P group 10·4 (SD 5·9) $v.$ 23·0 (SD 8·4), $P_{0\cdot05}$) and in plasma GSH-Px activity (Table 4). After NT, plasma GSH-Px activity decreased in the P group (412·9 (SD 65·9) $v.$ 358·1 (SD 63·0) U/l, $P_{0\cdot05}$), and there was smaller change in the S group (460·8 (SD 78·0) $v.$ 444·0 (SD 72·9) U/l, $P_{0\cdot05}$).

Supplementation $\times$ duathlon effect

Antioxidant supplementation significantly reduced ($P_{0\cdot05}$) the magnitude of duathlon-induced creatine kinase isoenzyme MB mass increase, an effect that tended to be greater with OT ($P_{0\cdot09}$, Fig. 3). The increase in plasma GSH-Px activity pre- and post-duathlon was not modified by supplementation (Table 4). There was no interaction effect of OT $\times$ duathlon or supplementation $\times$ duathlon on the increase in erythrocyte GSH-Px activity (Table 4). Supplementation did not prevent a decrease in blood GSH in response to the duathlon (Fig. 2).

Supplementation $\times$ training $\times$ duathlon

No interaction effect of supplementation $\times$ training $\times$ duathlon was observed for the all biochemical variables analysed.

Discussion

We hypothesized that an antioxidant supplementation at physiological doses would partially avoid antioxidant system downregulation and consequently lower chronic and/or acute exercise-induced oxidative damage to lipids or DNA in overloaded triathletes. Based on French RDA for energy expenditure, the increase in energy expenditure in the triathletes with OT induced an increase in theoretical micronutrient need. Spontaneous nutritional intakes did

Table 3. Antioxidant status in supplemented and placebo group triathletes at baseline after NT and OT†

<table>
<thead>
<tr>
<th></th>
<th>S group (n 7)</th>
<th>P group (n 10)</th>
<th>Statistical significance of effect (ANOVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Supplemented $\times$ Training</td>
</tr>
<tr>
<td>Serum Se ($\mu mol/l$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>0·98 (0·13)</td>
<td>1·06 (0·13)</td>
<td>$P_{&lt;0\cdot001}$ NS</td>
</tr>
<tr>
<td>After NT</td>
<td>1·37† (0·16)</td>
<td>1·03*** (0·15)</td>
<td></td>
</tr>
<tr>
<td>After OT</td>
<td>1·35† (0·16)</td>
<td>1·08*** (0·12)</td>
<td></td>
</tr>
<tr>
<td>Serum ascorbic acid ($\mu mol/l$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>57·6 (16·4)</td>
<td>70·0 (19·4)</td>
<td></td>
</tr>
<tr>
<td>After NT</td>
<td>65·5 (10·9)</td>
<td>61·1 (18·0)</td>
<td>$P_{&lt;0\cdot05}$ NS</td>
</tr>
<tr>
<td>After OT</td>
<td>69·6 (8·6)</td>
<td>56·9 (18·1)</td>
<td></td>
</tr>
<tr>
<td>Serum $\alpha$-tocopherol ($\mu mol/l$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>27·0 (5·8)</td>
<td>24·1 (4·1)</td>
<td></td>
</tr>
<tr>
<td>After NT</td>
<td>30·1 (5·6)</td>
<td>24·6* (6·1)</td>
<td>$P_{&lt;0\cdot05}$ NS</td>
</tr>
<tr>
<td>After OT</td>
<td>28·1 (4·8)</td>
<td>23·7* (4·9)</td>
<td></td>
</tr>
</tbody>
</table>

S, antioxidant supplemented; P, placebo; NT, normal training; OT, overloaded training. Mean values were significantly different from those of the S group; $^* P_{<0\cdot05}$, $^{***} P_{<0\cdot001}$.

Mean values were significantly different from those at baseline: $^{†} P_{<0\cdot05}$.

† For details of subjects, training loads, supplements and procedures, see Table 1 and pp. 92–94.
not enable any of the athletes to reach the French recommendations for intakes of Se, and vitamins C and E. With regard to energy expenditure, it has to be emphasized that for Se, and vitamins C and E, the supplement was administered at physiological doses and allowed the subjects to reach 100% of the French recommendations without reaching the non-observable adverse effect level. The 97.9% observance of the supplement intake had an effect on Se, α-tocopherol and ascorbic acid plasma concentrations.

As lipoperoxidation (and muscle damage) may be greater in trained than in sedentary subjects (Kanter et al. 1993; Marzatico et al. 1997), it was possible that poorly conducted training or OT led to a lack of the expected protective adaptations to training, especially if combined with a decreased density of antioxidant intakes provided by food. From the beginning of the study and during NT, blood GSH levels increased with supplementation and remained elevated during OT. During OT, the levels tended to be still higher with supplementation ($P<0.05$).

GSH is a component of the antioxidant system and its efficiency depends on the synergic effects of the components in the system. Some of them are reinforced, for example, by exogenous supplementation. In our present study,
GSSG could have been spared from oxidation because of the increase in ascorbic acid and α-tocopherol. This effect could have been reinforced by training, which is known to increase GSSG concentrations (Margaritis et al. 1997). Moreover, upregulation of the endogenous antioxidant system by supplementation was shown by the increase in erythrocyte Cu,Zn-SOD activity in the S group.

The rapid exercise-induced increase in activity of plasma GSH-Px after the duathlon can be seen as an acute response to exercise-induced oxidative stress; indeed, acute stress is observed under other conditions. Acute exposure to such a situation could increase antioxidant activity during and/or after exercise to anticipate and/or respond to the free radical overproduction that occurs during reperfusion of kidney. As plasma GSH-Px is quickly released from the kidney in the case of oxidative stress (Nadif et al. 1998), its release may be the anticipated response to the oxidative stress. OT induced an increase in plasma GSH-Px activity at rest in both groups. This increase appears to be an adaptive effect over longer periods to repetitive stress induced by exercise. Plasma GSH-Px activity was significantly higher in the S group in all situations after NT and OT. Greater tissue GSH-Px activity due to the increase in circulating Se levels (as a consequence of supplementation) caused an increased release by the kidneys in response to repetitive stress.

Despite this apparent upregulation of endogenous circulating antioxidant response by the antioxidant mixture, there was no effect on plasma TBARS, a finding which is consistent with a previous and independent epidemiological study in sedentary subjects (Preziosi et al. 1998). Lipid peroxidation and muscle damage were reduced with supplementation with mg vitamin E/d for 5 weeks in subject previously moderately trained before an OT period (Itoh et al. 1999). The same effects were observed with lower doses (330 mg/d) after intensive aerobic training in cyclists (Rokitzi et al. 1994a). The question of the level of dose administered seems to be important. Administration of 68-5mg vitamin E/d and 200 mg ascorbic acid/d for 4-5 weeks to marathon runners had no effect on lipid peroxidation (Rokitzi et al. 1994b). In our present study, the doses of α-tocopheryl succinate and ascorbic acid were lower (20 mg/d and 120 mg/d respectively). The 150 μg Se added did not cause a synergistic effect of the mixture components. Moreover, we cannot dismiss the possibility that the increase in clearance of TBARS in well-trained subjects before the study could have blinded the increase in lipid peroxidation products.

DNA is probably the most biologically significant target of oxidative attack (Halliwell, 2000). Some studies dealing with exercise and oxidative stress have shown an increase in leucocyte-DNA damage due to intensive aerobic exercise (Hartmann et al. 1994; Tsai et al. 2001). Training status (Niess et al. 1996; Radlak et al. 1999; Sato et al. 2003) or vitamin E supplementation (Hartmann et al. 1995) seemed to protect against this damage. There was no effect of the antioxidant mixture on the extent of leucocyte-DNA damage after OT in our present study. The mechanisms of oxidative leucocyte-DNA damage induced either by acute exercise, and of reinforcement of endogenous antioxidant by the supplement and the expected protective effect on leucocyte-DNA, are not necessarily identical. Independent of an exercise effect, there have been mixed results on the effect of supplement complexes containing vitamins C and E on leucocyte-DNA damage (Duthie et al. 1996; Prieme et al. 1997; Huang et al. 2000). The lack of carotenoids or closely associated substances available from fruits and vegetables (Collins, 1999) in our administered antioxidant complex may also explain the lack of expected protective effects.

Myocellular enzyme release due to increased sarcolemmal and lysosomal membrane permeability is easily estimated by circulating activities and/or concentrations. Even if muscle damage has several origins, in our present study this effect was largely attributable to membrane peroxidation. The magnitude of exercise-induced muscle damage increase, which tended moreover to be higher with OT, was significantly decreased with supplementation. This decrease suggests that supplementation has a protective effect despite the lack of effect on exercise-induced increase in lipid peroxidation markers. The same decrease in oxidative damage after exercise has already

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**Fig. 4.** Erythrocyte Cu,Zn-superoxide dismutase (SOD) activity in antioxidant-supplemented (n 7; †) and placebo (n 10; ‡) group triathletes on baseline, pre-duathlon (¶) and post-duathlon (§), after normal training (NT) and overloaded training (OT). For details of subjects, supplements, training and procedures, see Table 1 and pp. 92–94. Values are means with their standard deviations shown by vertical bars. Mean value was significantly different from that pre-duathlon after NT: *P<0.05 (Fisher’s protected least significant difference post hoc analysis).
been shown, but at higher supplementation with vitamin E (Meydani et al. 1993) or vitamin C (Alessio et al. 1997). Our present results show that even at a lower dose of supplementation and at higher training level, antioxidants provide a protective effect against exercise-induced muscle damage.

Conclusion
The effects of antioxidant supplementation during NT and/or OT are shown mostly through alleviation of acute exercise-induced muscle damage. Whatever the mechanisms involved, the antioxidant mixture helped to preserve the antioxidant system during OT-induced stress in subjects with initially low antioxidant intakes. Most of the studies did not attempt to define an optimal dose for protection (McCall & Frei, 1999). The current results are still inadequate to define the optimal dose for protection of OT subjects. In the present study the effects of the antioxidant mixture were observed for doses that can be provided by a diverse and well-balanced diet. Hence, maintaining a normal nutritional status with regard to antioxidant intake (Se, and vitamins C and E) plays a key role in antioxidant adaptive effects during NT and OT.

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