Interaction between vitamins C and E affects their tissue concentrations, growth, lipid oxidation, and deficiency symptoms in yellow perch (*Perca flavescens*)

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We have conducted studies with juvenile yellow perch (*Perca flavescens*) over a period of 20 weeks to address the question of the interaction between water- and lipid-soluble antioxidant vitamins. Fish (2.25 ± 0.14 g) were divided into twelve groups, and triplicate groups were fed one of four casein-based, semi-purified diets formulated to contain low or high vitamin E levels of either 5 or 160 mg/kg without or with vitamin C supplementation (250 mg/kg). Diets were designated as –C–E, –C+E, +C–E, or +C+E, respectively. The fish fed the +C+E diet showed significantly higher weight gain, feed intake, and feed efficiency than the groups fed vitamin C-deficient diets. Total ascorbate concentrations of liver were significantly higher in fish fed vitamin C-supplemented diets than in fish fed the vitamin C-deficient diet after 16 and 20 weeks. The liver α-tocopherol concentrations were increased by supplemental vitamin C in vitamin E-deficient dietary groups which indicates a sparing or regenerating effect of vitamin C on vitamin E. Fish fed vitamin C-deficient diets (–C–E and –C+E) exhibited severe deficiency symptoms, such as scoliosis, lens cataracts, anorexia, and haemorrhages. The cumulative mortality was significantly higher in the –C–E groups. The thiobarbituric acid-reactive substances value was significantly higher in blood plasma of fish fed a diet unsupplemented with both vitamins. The findings in the present study with yellow perch support the hypothesis that vitamin C regenerates and/or spares vitamin E in vivo.

**Yellow perch: Vitamin C: Vitamin E: Thiobarbituric acid-reactive substances: Deficiency symptoms**

Vitamins C and E play important roles in numerous biological conditions, such as ageing, cataracts, DNA damage, atherosclerosis, diabetes, neurodegenerative diseases, cardiovascular diseases, and cancers. The major beneficial actions of vitamin C and E are due to their antioxidant properties that scavenge reactive oxygen species in biological fluid (Frei et al. 1990) and membranes (Burton et al. 1983). Tappel (1968) hypothesized that vitamin C might reduce tocopheroxyl radicals formed in vivo and numerous studies have been done to demonstrate this phenomenon (Packer et al. 1979; Niki et al. 1982; McCay, 1985; Chan, 1993). The interaction between the two vitamins occurs at the membrane–cytosol interface (Buettner, 1993), and vitamin C functions as a reducing agent of the membrane-bound oxidized vitamin E.

Diets with supplemental vitamin C resulted in higher vitamin E concentrations in tissues compared with those without supplemental vitamin C in rats (Igarashi et al. 1991; Ho & Chan, 1992), guinea-pigs (Bendich et al. 1984; Liu & Lee, 1998), and human subjects (Wantanowicz et al. 1984; Jacob et al. 1988; Stoyanovsky et al. 1995; Hamilton et al. 2000). However, results showing no effects of sparing or regenerating vitamin E by vitamin C have also been reported in rats (Chen, 1981), guinea-pigs (Burton et al. 1990), and human subjects (Jacob et al. 1996).

The interaction of the two vitamins was also examined in fish, such as rainbow trout (*Oncorhynchus mykiss*; Wahli et al. 1998), Atlantic salmon (*Salmo salar*; Hamre et al. 1997), and lake sturgeon (*Acipenser fulvescens*; Moreau et al. 1999). Hamre et al. (1997) found that a diet deficient in vitamin C resulted in significantly decreased liver vitamin E concentrations. The authors proposed that there would be two different interaction mechanisms: a synergistic effect of simultaneous protection in the water and lipid phases.

**Abbreviation:** TBARS, thiobarbituric acid-reactive substances.

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against oxidation, and a regenerating effect of vitamin C on tocopheroxyl radicals.

Pathological changes resulting from deficiencies of the two vitamins were studied in rainbow trout juveniles (Frischknecht et al. 1994; Wahli et al. 1998). In the study by Frischknecht et al. (1994), a significant increase in mortality, severe muscular dystrophy and splenic haemosiderosis were observed in the fish fed a diet deficient in both vitamins after 8–12 weeks. Fish fed a diet deficient in vitamin C but high in vitamin E exhibited the typical deficiency symptoms of vitamin C after 16–20 weeks, such as retarded growth rate, haemorrhages, gill alterations, and severe vertebral column deformations.

Yellow perch (Perca flavescens) is one of the most valuable fish species in North America, particularly in the Midwest as an aquaculture species (Stickney, 1993; Brown et al. 1996; Twibell & Brown, 2000; Twibell et al. 2000). Little nutritional information is available for this species, and no clinical deficiency symptoms of vitamins have been reported yet. The present study, therefore, was designed to investigate the interactions between vitamins C and E on growth, feed utilization, and deficiency symptoms in juvenile yellow perch. The interactions of the two vitamins, in terms of the sparing effects of vitamin C on vitamin E and synergism of their antioxidant actions, were also examined in the present study by determining the concentrations of each vitamin in the liver and thiobarbituric acid-reactive substances (TBARS) in blood plasma as a criterion for the lipid peroxidation.

**Materials and methods**

**Design and diets**

Four casein-based semi-purified diets were formulated to contain no vitamin C and low vitamin E (5 mg/kg; –C–E), no vitamin C and high vitamin E (160 mg/kg; –C+E), high vitamin C (250 mg/kg) and low vitamin E (+C–E), and high vitamin C and high vitamin E (+C+E). The composition of the basal diet for the four experimental diets is provided in Table 1. The basal diet was formulated to be isonitrogenous and isoenergetic according to previous work (Moreau & Dabrowski, 1996) in juvenile lake Sturgeon. In the basal diet, vitamin C was not detected and vitamin E (sum of α-, β-, γ-, and δ-tocopherols) concentration was 4.8 mg/kg. The detected vitamin E concentration of n-3 highly unsaturated fatty acid concentrate and fish-protein hydrolysate (Table 1). Ascorbyl-2-monophosphate-Mg (Phospitan C; Showa Denko America, Inc., NY) and all-rac-α-tocopheryl phosphate-Na (Showa Denko America, Inc., NY) were used as the vitamin C and E sources, respectively. For the different levels of vitamins in experimental diets, cellulose was replaced by each vitamin. Five percent of fish-protein concentrate (CPSP 90; Sopropeche S. A., Boulogne-Sur-Mer, France) was supplemented in the diets to enhance palatability of the semi-purified diet to the juvenile yellow perch. The diets were cold-pelleted (2.0 mm diameter) with distilled water, freeze-dried to have less than 5% moisture, crushed into desirable particle size (0.4–2.0 mm), and stored at –20°C until use.

**Table 1. Composition of the basal semi-purified diet (no vitamin C and low vitamin E; –C–E)**

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Concentration (g/kg dry diet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casein (vitamin-free)*</td>
<td>360</td>
</tr>
<tr>
<td>Dextrin*</td>
<td>150</td>
</tr>
<tr>
<td>Maize starch†</td>
<td>105</td>
</tr>
<tr>
<td>Fish-protein hydrolysate‡</td>
<td>50</td>
</tr>
<tr>
<td>Egg white*</td>
<td>50</td>
</tr>
<tr>
<td>Gelatin*</td>
<td>40</td>
</tr>
<tr>
<td>Maize oil (tocopherol-stripped)*</td>
<td>60</td>
</tr>
<tr>
<td>Lard (tocopherol-stripped)*</td>
<td>50</td>
</tr>
<tr>
<td>n-3 Highly unsaturated fatty acid concentrate§</td>
<td>5</td>
</tr>
<tr>
<td>Vitamin mixture</td>
<td></td>
</tr>
<tr>
<td>Mineral mixture¶</td>
<td>30</td>
</tr>
<tr>
<td>Choline chloride*</td>
<td>1</td>
</tr>
<tr>
<td>Carboxymethylcellulose*</td>
<td>20</td>
</tr>
<tr>
<td>L-methionine*</td>
<td>5</td>
</tr>
<tr>
<td>Cellulose*</td>
<td>34</td>
</tr>
</tbody>
</table>

*†‡CPSP 90, Sopropeche S. A., Boulogne-Sur-Mer, France.
†DHASCO and ARASCO (1:1, v/v), Martek Biosciences Corporation, Columbia, MD.
‡Roche Performance Premix composition (per g vitamin mixture): vitamin A, 794 µg; vitamin D₃, 5.5 µg; vitamin B₁₂, 13 µg; riboflavin, 13.2 mg; niacin, 61.7 mg; d-pantothenic acid, 22.1 mg; menadione, 1.32 mg; folic acid, 1.76 mg; pyridoxine, 4.42 mg; thiamin, 7.95 mg; d-biotin, 0.31 mg; Hoffman-La Roche, Inc., Nutley, NJ.
¶Se (5 mg) in the form of sodium selenite per kg Bernhart Tomarelli salt mixture (ICN Pharmaceuticals Inc., Costa Mesa, CA).

**Fish and feeding trial**

Juvenile yellow perch averaging 2.25 ± 0.14 g initial weight were used as an experimental fish and the feeding trial was conducted in the Aquaculture Laboratory at the Ohio State University. Before the feeding trial, the fish were fed the basal diet (–C–E) for 2 weeks to adjust to the casein-based semi-purified experimental diet and to reduce possible body reserves of vitamin C. A total of 240 fish were randomly distributed into groups of twenty; three groups per treatment. Each experimental diet was fed to triplicate groups of fish with the feeding rates ranging from 4.0% of fish weight at the beginning to 1.5% at the end of the feeding trial. The feeding trial was conducted for 20 weeks in 40 litre glass aquaria, supplied with u.v.-irradiated and filtered semi-circulated water at a flow rate of 1.0–1.5 litres/min. All procedures and handling of animals were conducted in compliance with the guidelines of the Institutional Laboratory Animal Care and Use Committee, the Ohio State University. The fish were fed twice daily, 7 d per week. Supplemental aeration was also provided to maintain dissolved O₂ levels near saturation. The diurnal light–dark cycle was regulated at 12h–12h. Total fish weight in each tank was determined every 2 weeks to monitor their growth and to adjust the feeding rate. Feeding was stopped 24 h before weighing. The insides of the aquaria were scrubbed once per week in addition to the daily siphoning of faeces to minimize algae and fungal growth, which could provide a source of vitamin C.

**Sample collection and analyses**

At the end of the feeding trial all fish were weighed to measure growth rate and feed conversion ratio (dry feed
consumed/body weight gain), and cumulative survival was calculated. For the vitamin analyses, three fish were randomly selected from each group (total of nine fish per dietary treatment) and killed to collect livers. Blood was obtained from the caudal vein of fish randomly selected from each group (total of six fish per treatment) with heparinized syringes. Blood was stored on ice and then centrifuged at 1500 g for 10 min. Five fish per group (a total of fifteen fish per dietary treatment) were killed for the whole-body proximate analyses. Analyses of proximate compositions (crude protein, ash, and moisture) were performed by standard procedures (Association of Official Analytical Chemists, 1995).

Total and dehydro-ascorbic acid were analysed in liver samples by the dinitrophenylhydrazine colorimetric method with modifications for interfering substances (Dabrowski & Hinterleitner, 1989). Vitamin E (α-, β-, γ-, and δ-tocopherols) concentrations in diets and α-tocopherol in liver tissue were determined by HPLC (Cort et al. 1983; Zaspel & Csallany, 1983). TBARS in blood plasma were determined by the HPLC method of Tatum et al. (1990) with a slight modification. Before starting extraction of thiobarbituric acid–malonaldehyde adducts in plasma, samples were first mixed with 0·62 M-TCA (1:1, v/v) for deproteinization and followed by the method of Tatum et al. (1990). As a standard, 1,1,3,3-tetramethoxy-propane (Sigma Chemical, St Louis, MO) was used.

For the feed utilization, an instantaneous meal intake test was conducted three times during the 10th week, and once during the 16th and 20th week by feeding fish ad libitum. The respective experimental diets were fed to fish groups (three replicate tanks) as the morning meal on days 72, 114, and 140. The average feed amount that fish were fed ad libitum at a time was calculated from triplicate groups (from three tanks for each diet).

**Statistical analysis**

Each experimental diet was fed to three groups (tanks) of fish by a completely randomized design. Two-way ANOVA was conducted three times during the 10th week, and once during the 16th and 20th week by feeding fish ad libitum. The respective experimental diets were fed to fish groups (three replicate tanks) as the morning meal on days 72, 114, and 140. The average feed amount that fish were fed ad libitum at a time was calculated from triplicate groups (from three tanks for each diet).

Table 2 provides the results of growth, feed utilization performance, and cumulative survival after 20 weeks of feeding. The fish fed the +C+E diet showed significantly higher weight gain and increased feed efficiency than the fish groups fed vitamin C-deplete diets (–C–E and –C+E). Significantly higher meal intake was found in the +C+E group than in –C+E and –C–E groups. Survival was significantly lower in fish fed the diet deficient in both vitamin C and E than in fish fed diets supplemented with either vitamin C or E. However, no significant difference was found in hepatosomatic index between the treatments. A two-way ANOVA test (Table 4) showed that weight gain was significantly affected by either vitamin C (P=0·006) or E (P=0·046), but there was no significant interaction between the two vitamins (P=0·16). Feed conversion ratio and instantaneous meal intake were significantly affected by dietary vitamin C, but not by vitamin E (P<0·05).

In liver (Table 3), total ascorbic acid (sum of reduced and dehydro-ascorbic acid) concentration was significantly higher in fish fed vitamin C-supplemented diets after 16 and 20 weeks. The liver vitamin C concentration was not affected by dietary vitamin E. Liver α-tocopherol concentration was not significantly affected by dietary supplementation of either vitamin C or E after 20 weeks (Table 4). However, a Student’s t test showed that α-tocopherol concentration was significantly (P<0·05) elevated by approximately 140 % (from 10·4 (SD 3·50) to 25·2 (SD 5·56) nmol/g liver) in vitamin E-deficient dietary groups.

### Table 2. Weight gain, feed conversion ratio, instantaneous meal intake, hepatosomatic index and survival of yellow perch juveniles fed four experimental diets for 20 weeks*

<table>
<thead>
<tr>
<th>Diet</th>
<th>–C–E</th>
<th>–C+E</th>
<th>+C–E</th>
<th>+C+E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Initial body wt (g)†</td>
<td>2.30</td>
<td>0.08</td>
<td>2.28</td>
<td>0.19</td>
</tr>
<tr>
<td>Final body wt (g)‡</td>
<td>16.6g</td>
<td>0.66</td>
<td>17.3g</td>
<td>2.26</td>
</tr>
<tr>
<td>Feed conversion ratio</td>
<td>1.27a</td>
<td>0.08</td>
<td>1.29b</td>
<td>0.05</td>
</tr>
<tr>
<td>Instantaneous meal intake [g/100g body wt]§</td>
<td>1.47a</td>
<td>0.28</td>
<td>1.34a</td>
<td>0.21</td>
</tr>
<tr>
<td>Hepatosomatic index (%)</td>
<td></td>
<td>1.80</td>
<td>0.06</td>
<td>1.88</td>
</tr>
<tr>
<td>Survival (%)</td>
<td>82.2a</td>
<td>4.6</td>
<td>95.8a</td>
<td>7.2</td>
</tr>
</tbody>
</table>

* Means values within a row with unlike superscript letters were significantly different (P<0·05).
† For details of diets and procedures, see Table 1 and p. 590.
‡ Feed weight (% = (final weight – initial weight) x 100/initial weight.
§ Means of three separate tests.
|| Hepatosomatic index (%) = liver weight x 100/body weight.
but not significantly elevated in vitamin E-supplemented dietary groups after 16 weeks. Also, increases of the liver \(\alpha\)-tocopherol concentrations by approximately 150 and 40% were observed by vitamin C supplementation in vitamin E-devoid and -supplemented dietary groups, respectively, after 20 weeks, although they were not significant (\(P < 0.05\)).

Vitamin E isomers, such as \(\alpha\)-tocopherol, \(\beta\)–\(\gamma\)-toco-pherols, \(\delta\)-tocopherol, and tocopheryl phosphates (dietary source) were determined in diets and liver. However, the concentrations of \(\beta\)–\(\gamma\)-toco-pherols, and \(\delta\)-tocopherol were very low in the diets (ranged from 0.01 to 0.5 mg/g diet). Concentrations in the liver of fish after 16 and 20 weeks were much lower than those in diets or not detectable.

The TBARS value was significantly lower in blood plasma of fish fed diets supplemented with either vitamin C or E and with both vitamins compared with that of fish fed the diet deficient in both vitamins C and E (Table 3). Plasma TBARS concentration was significantly affected by dietary supplementation of vitamin C (\(P = 0.001\)) and E (\(P = 0.008\)). The interaction between the two vitamins was also significant (\(P < 0.001\)), showing a positive effect of either supplemental vitamin C or E (Table 4). However, no synergistic effect of the two vitamins on TBARS value was found.

From the 13th week, fish began to show some deficiency symptoms, and at the 20th week the fish fed the diets deficient only in vitamin C (–C–E and –C+E) exhibited severe deficiency symptoms, such as haemorrhages (Fig. 1 (A)), scoliosis (Fig. 1 (B); vitamin C-specific), anor-exia, and lens cataracts (Fig. 1 (C)). The cumulative percentages of fish showing deficiency symptoms by the 20th week were 28.3 (SD 5.77) and 16.7 (SD 2.89) for diets –C–E and –C+E, respectively. The above deficiency symptoms were not found in fish fed vitamin C-supplemented diets (+C–E and +C+E), regardless of vitamin E status.

### Table 3. Total ascorbate (TAA), dehydroascorbate (DHAA), and \(\alpha\)-tocopherol concentrations in liver of yellow perch fed four experimental diets for 16 and 20 weeks*

<table>
<thead>
<tr>
<th>Diet...</th>
<th>–C–E</th>
<th>–C+E</th>
<th>+C–E</th>
<th>+C+E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>16 weeks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAA (nmol/g)</td>
<td>18.2</td>
<td>10.2</td>
<td>12.0</td>
<td>3.0</td>
</tr>
<tr>
<td>DHAA (nmol/g)</td>
<td>11.2</td>
<td>0.73</td>
<td>13.4</td>
<td>3.40</td>
</tr>
<tr>
<td>(\alpha)-Tocopherol (nmol/g)</td>
<td>10.4</td>
<td>3.50</td>
<td>39.4</td>
<td>32.6</td>
</tr>
<tr>
<td>20 weeks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAA (nmol/g)</td>
<td>12.4</td>
<td>3.60</td>
<td>11.2</td>
<td>9.02</td>
</tr>
<tr>
<td>DHAA (nmol/g)</td>
<td>9.36</td>
<td>3.08</td>
<td>7.81</td>
<td>12.1</td>
</tr>
<tr>
<td>(\alpha)-Tocopherol (nmol/g)</td>
<td>11.1</td>
<td>6.36</td>
<td>34.3</td>
<td>13.9</td>
</tr>
<tr>
<td>TBARS (pmol/ml)</td>
<td>29.1</td>
<td>8.29</td>
<td>18.8</td>
<td>5.93</td>
</tr>
</tbody>
</table>

TBARS, thiobarbituric acid-reactive substances.

*a,bMean values within a row with unlike superscript letters were significantly different (\(P < 0.05\)).

* For details of diets and procedures, See Table 1 and p. 590.

### Table 4. Statistical results by two-way ANOVA test showing the main effect of dietary vitamin C or E, and their interaction with each dependent variable* (\(P\) values and F ratios)

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Error between subject effects</th>
<th>Statistical results by ANOVA†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F ratio</td>
<td>P value</td>
</tr>
<tr>
<td>Final weight</td>
<td>22-3</td>
<td>0.006</td>
</tr>
<tr>
<td>FCR</td>
<td>0-04</td>
<td>0.002</td>
</tr>
<tr>
<td>IMI</td>
<td>1-83</td>
<td>0.01</td>
</tr>
<tr>
<td>Survival</td>
<td>483-7</td>
<td>0.019</td>
</tr>
<tr>
<td>TAA</td>
<td>697-2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DHAA</td>
<td>837-5</td>
<td>0.002</td>
</tr>
<tr>
<td>(\alpha)-Tocopherol</td>
<td>2312-8</td>
<td>NS</td>
</tr>
<tr>
<td>TBARS</td>
<td>211-1</td>
<td>0.001</td>
</tr>
<tr>
<td>TAA (16 weeks)</td>
<td>179-9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DHAA (16 weeks)</td>
<td>31-3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>(\alpha)-Tocopherol (16 weeks)</td>
<td>2931-2</td>
<td>NS</td>
</tr>
</tbody>
</table>

FCR, feed conversion ratio; IMI, instantaneous meal intake; TAA, total ascorbic acid; DHAA, dehydro-ascorbic acid; TBARS, thiobarbituric acid-reactive substances.

* For details of diets and procedures, see Table 1 and p. 590.

†Degree of freedom was 1 in each case.
The present study showed a typical growth trend in which growth rate is higher in the fish fed vitamin C-supplemented diets than in fish fed a diet devoid of vitamin C. The vitamin C level in the supplemented diets in the present study was approximately six times higher than the recommended requirement level in other fish species (National Research Council, 1993). The increased growth rates and feed efficiency in several fish species fed diets containing high levels of vitamin C highlight the importance of adequate vitamin C supplementation in fish nutrition.

Fig. 1. Deficiency symptoms of vitamin C and/or E in yellow perch fed one of four casein-based semi-purified diets. The diets were formulated to contain low and high vitamin E levels of 5 and 160 mg/kg without or with vitamin C supplementation (250 mg/kg) designated as diets –C–E, –C+E, +C–E, or +C+E, respectively. (A), Growth depression and haemorrhages (▲) on fins of fish fed –C–E diet (upper) and normal growth of fish fed +C+E diet (lower). (B), The broken vertebrae (scoliosis) of fish fed diets –C–E (upper) and –C+E (middle) and normal shape of fish fed +C+E diet (lower). (C), Extreme close-up of lens cataract (●) of fish fed –C–E diet for 20 weeks.

Discussion

The present study showed a typical growth trend in which growth rate is higher in the fish fed vitamin C-supplemented diets than in fish fed a diet devoid of vitamin C. The vitamin C level in the supplemented diets in the present study was approximately six times higher than the recommended requirement level in other fish species (National Research Council, 1993). The increased growth rates and feed efficiency in several fish species fed diets...
sufficient in vitamin C are well documented elsewhere (Dabrowski et al. 1990, 1996; Lee et al. 1998; Shiau & Hsu, 1999). In the present study, the effects of supplemental vitamin C and E on how fish respond to the diets in terms of feed acceptance were tested. The results of the tests (Table 2; instantaneous meal intake) revealed that yellow perch are more affected by vitamin C than E, in terms of feed acceptance. This might mean that sufficient dietary vitamin C can increase the palatability to yellow perch that subsequently results in increased feed intake and enhanced appetite. The lower survivals in both vitamin C and E-deficient groups were due to the deficiency symptoms of the two vitamins that resulted in impaired metabolism.

In the present study, total ascorbate concentration in the liver increased in response to the dietary vitamin C supplementation (Table 3). There were no signs of dietary vitamin E effects on the liver total ascorbate or dehydroascorbate concentrations. Similar results were found in lake sturgeon (Moreau et al. 1999). Moreau et al. (1999) found that ascorbate concentrations in the liver and posterior kidney were correlated with dietary vitamin C regardless of dietary vitamin E level. However, there are other works that have reported elevated ascorbate concentration in liver of Atlantic salmon (Hamre et al. 1997) and rats (Tanaka et al. 1997), and human plasma (Hamilton et al. 2000) by supplementation of vitamin E.

Numerous studies have been carried out on vitamin C and E and their interactions in mammals (McCay, 1985). However, there are several inconsistent results in terms of the sparing effect of vitamin C on vitamin E in human and animal models (Chen, 1981; Bendich et al. 1984; Wantanowicz et al. 1984; Jacob et al. 1988, 1996; Burton et al. 1990; Igarashi et al. 1991; Stoyanovsky et al. 1995; Hamilton et al. 2000). In fish, literature is scarce on the interactions of the two vitamins (Gatlin et al. 1986; Hamre et al. 1997; Wahl et al. 1998; Moreau et al. 1999). In Atlantic salmon, Hamre et al. (1997) reported that liver vitamin E concentrations were not affected by vitamin C except in the vitamin C-deficient dietary group. Vitamin E data in yellow perch liver (Table 3) are well supported by Hamre et al. (1997) and Wahl et al. (1998). In the present study, α-tocopherol concentrations in liver were elevated by approximately 150% by the supplementation of vitamin C in vitamin E-deficient dietary groups after 16 and 20 weeks. Therefore, the hypothesis that vitamin C regenerates vitamin E by reducing the tocopheroyl radical in vivo (Tappel, 1968; McCay, 1985; Mukai et al. 1991) may be supported in yellow perch. The findings in the present study suggest that the sparing or regenerating effects of vitamin C on vitamin E in fish may possibly be conditional depending on the vitamin E status in tissues. This phenomenon, which showed conditional sparing effects of vitamin C depending on vitamin E status, was found in other studies in fish (Hamre et al. 1997; Wahl et al. 1998; Moreau et al. 1999). Moreau et al. (1999) also found the sparing effect of vitamin C for vitamin E in liver of juvenile lake sturgeon fed diets similar to those used with the yellow perch except for a five times higher dose of vitamin C. In that study (Moreau et al. 1999), dietary vitamin C supplementation (1250 mg/kg diet) increased liver α-tocopherol by 46% in vitamin E-supplemented groups. In the vitamin E-deficient groups, however, vitamin C decreased liver α-tocopherol significantly, and the authors discussed that the decreased level was attributed to the pro-oxidant effect of high vitamin C dose in the diet. Yellow perch, a teleost, cannot synthesize vitamin C in vivo, unlike lake sturgeon (Dabrowski, 1990, 1994; Moreau & Dabrowski, 1998), which can synthesize vitamin C in vivo due to the presence of gulonolactone oxidase (EC 1.1.3.8), an enzyme involved in ascorbic acid synthesis. The negative effects of a high dose of vitamin C in the juvenile lake sturgeon were then explainable. In the present study, however, we did not find any negative effect of vitamin C. This result was in agreement with Hamre et al. (1997) who used a teleost, Atlantic salmon, which cannot synthesize vitamin C in vivo.

TBARS has been the most frequently used indicator for determination of protective actions of the two antioxidant vitamins against lipid peroxidation (Harats et al. 1990; de Zwart et al. 1999). Our result in yellow perch showed similar trends easily found in studies of human and animal models (Harats et al. 1990; Sakuma et al. 1997; Liu & Lee, 1998; Naidoo & Lux, 1998). In the present study, TBARS in plasma of fish fed the diet deficient in both vitamins C and E was 12-fold greater (P<0.05) than that of fish fed diets supplemented with either vitamin C or E, or both (Table 3). Also, TBARS concentration was more affected by dietary vitamin C (P=0.001) than by vitamin E (P=0.008) (Table 4). This result is in agreement with the study of Naidoo & Lux (1998) that showed the reduction of TBARS in human blood plasma by combined administration of both vitamin C and E, or vitamin C alone. Tanaka et al. (1997) also reported a trend of TBARS level similar to that found in yellow perch plasma and liver tissues of rats suggesting that vitamin C deficiency can increase oxidative stress in vivo more than vitamin E deficiency. However, there were also reports of negative (pro-oxidant) or unclear effects of vitamin C or both vitamins by other fish species (National Research Council, 1993; Dabrowski, 2001). Other deficiency symptoms, such as anorexia and haemorrhages, were also reported as the deficiency signs of either vitamin C or E, or both vitamins by other fish species (National Research Council, 1993; Dabrowski, 2001). We also found that a dietary deficiency of vitamin C can cause lens cataracts in yellow perch (Fig. 1 (C)). The eye abnormalities caused by vitamin C deficiency were previously reported in fish species, such as rainbow trout (Halver et al. 1975), red drum (Collins et al. 1993), and oscar (Fracalossi et al. 1998). Dabrowski & Wieser (1990) also discussed that a high concentration of vitamin C in the fish eye reflects the importance of vitamin C in this organ and demonstrated that dietary vitamin C deficiency in cyprinid
fish resulted in significant depletion of ascorbate concentrations in all eye compartments; retina, lens, and humour.

In the present study, supplemental dietary vitamin C protected yellow perch against vitamin E-deficiency symptoms, such as poor growth, anorexia, and haemorrhages, which were observed in the groups fed diets deficient in both vitamin C and E. These results are well supported by the other studies in rainbow trout (Frischknecht et al. 1994; Wahl et al. 1998) and Atlantic salmon (Hamre et al. 1997). The liver vitamin C has been used as an indicator of vitamin C deficiency in fish (Hilton et al. 1977; Lim & Lovell, 1978; Hardie et al. 1991; Fournier et al. 2000). Overt deficiency symptoms were found in fish that had vitamin C concentrations less than 170 and 114 nmol/g liver in channel catfish and rainbow trout, respectively (Hilton et al. 1977; Lim & Lovell, 1978). In the present study, the fish groups that showed deficiency symptoms also exhibited very low concentrations of liver vitamin C (9.84 nmol/g liver; Table 3).

In conclusion, our findings in yellow perch may support the hypothesis that vitamin C spares and/or regenerates vitamin E in vivo. Supplemental vitamin C and/or E reduce lipid peroxidation in vivo. However, there were no synergistic effects of both vitamins. The deficiency symptoms of vitamin E, with respect to antioxidant properties may be reduced or prevented by dietary supplementation of vitamin C. These findings need to be considered in further studies of the dietary requirement for the two vitamins in fish, especially in yellow perch.

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