Effects of vitamin A deficiency on mitochondrial function in rat liver and heart

Ernesto Estornell\textsuperscript{1}, José R. Tormo\textsuperscript{1}, Pilar Marín\textsuperscript{1}, Jaime Renau-Piqueras\textsuperscript{2}, Joaquín Timoneda\textsuperscript{1} and Teresa Barber\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1}Department de Bioquímica Biologia Molecular, Facultat de Farmàcia, Universitat de València, Spain
\textsuperscript{2}Centro de Investigación, Hospital La Fe, València, Spain

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The aim of this study was to investigate comparative effects of vitamin A deficiency on respiratory activity and structural integrity in liver and heart mitochondria. Male rats were fed a liquid control diet (control rats) or a liquid vitamin A-deficient diet (vitamin A-deficient rats) for 50 days. One group of vitamin-A deficient rats was refed a control diet for 15 days (vitamin A-recovered rats). To assess the respiratory function of mitochondria the contents of coenzyme Q (ubiquinone, CoQ), cytochrome c and the activities of the whole electron transport chain and of each of its respiratory complexes were evaluated. Chronic vitamin A deficiency promoted a significant increase in the endogenous coenzyme Q content in liver and heart mitochondria when compared with control values. Vitamin A deficiency induced a decrease in the activity of complex I (NADH–CoQ reductase) and complex II (succinate–CoQ reductase) and in the levels of complex I and cytochrome c in heart mitochondria. However, NADH and succinate oxidation rates were maintained at the control levels due to an increase in the CoQ content in accordance with the kinetic behaviour of CoQ as an homogeneous pool. On the contrary, the high CoQ content did not affect the electron-transfer rate in liver mitochondria, whose integrity was preserved from the deleterious effects of the vitamin A deficiency. Ultrastuctural assessment of liver and heart showed that vitamin A deficiency did not induce appreciable alterations in the morphology of their mitochondria. After refeeding the control diet, serum retinol, liver and heart CoQ content and the activity of complex I and complex II in heart mitochondria returned to normality. However, the activities of both whole electron transfer chain and complex I in liver were increased over the control values. The interrelationships between physiological antioxidants in biological membranes and the beneficial effects of their administration in mitochondrial diseases are discussed.

Vitamin A deficiency: Coenzyme Q (ubiquinone): Mitochondrial respiratory chain

Vitamin A is a generic term which describes a number of molecules exhibiting the biological activity of retinol, the precursor of naturally-occurring retinoids. Although vitamin A was one of the first vitamins to be discovered, the full range of its activities remains to be defined. Vitamin A (all-trans-retinol) and its natural cis and trans derivatives are involved in important physiological functions: for example, vision and growth, immunity, embryological development and cell differentiation; and also as physiological antioxidants with a great potential role in the prevention of several diseases related with oxidative stress that are in continuous research (Ross, 1992; Livrea & Tesoriere, 1998; Zile, 1998; Palace \textit{et al}. 1999; Semba, 1999).

The antioxidant properties of some retinoids, known for decades, have been reinvestigated in recent years in chemical as well as in biological systems. Its lipid nature and localization within the lipophilic compartment of membranes and lipoproteins make vitamin A effective in reducing lipid peroxidation by acting as a chain-breaking antioxidant. The extremely low concentration of oxidised products of vitamin A, as retinoic acid, and its comparative low antioxidant activity, make it an unlikely factor in modulating cellular oxidative stress, although it is now
known that many of the vitamin A effects are mediated, via retinoic acid isomers, on gene transcription. In fact, antioxidant activities of retinoids have been ranked as retinol ≥ retinal ⇒ retinyl palmitate > retinoic acid (Livrea & Tesoriere, 1998; Palace et al. 1999).

In a previous work we reported that heart mitochondria from vitamin A-deficient rats showed a defect in the respiratory complex I (NADH–coenzyme Q (CoQ) reductase activity; Estornell et al. 1997), which is the most complex among the proton translocating enzymes of mitochondria and contains the highest number of mitochondrial-encoded subunits. Complex I functional defects are implicated in a number of congenital and acquired pathologies, even the normal ageing process could be associated to them (Schapira, 1998; Wallace, 1999). Mitochondria have been recognised as a major physiological source of reactive oxygen species, which arise as a consequence of oxygen reduction. The presence of several electron carriers and polyunsaturated fatty acid rich membranes makes this organelle highly susceptible to free-radical attack leading to alterations of its structural integrity and functions. In this sense, free-radical mechanisms have also been implicated in the liver mtDNA damage produced in vitamin A-deficient rats (T Barber et al., Free Radical Biology and Medicine, in press).

The aim of this study was to compare the effects of vitamin A deficiency and their reversibility on mitochondrial respiratory activity and mitochondrial structural integrity in two organs with different rates of oxygen consumption, liver and heart.

Materials and methods

Chemicals

Decylubiquinone, rotenone, antimycin A, cytochrome c (from horse heart, type III) and other biochemical reagents were purchased from Sigma Chemical Co. (St. Louis, MO, USA). Salts and solvents were from Merck (Darmstadt, Germany). Diet components were from ICN Biomedicals (Cleveland, OH, USA) and Sigma Chemical Co. Decylubiquinol was formed by reducing decylubiquinone. CoQ analogues and inhibitors were kept as ethanol solutions in the dark, and their titres were determined spectrophotometrically (Lenaz et al. 1995b; Estornell et al. 1993). Ferrous cytochrome c was obtained as described previously (Degli Esposti & Lenaz, 1982).

Animals and diets

Male rats were made deficient in vitamin A by feeding a liquid vitamin A-free diet based on the formulations given previously (Estornell et al. 1994, 1997; Barber et al. 1999) with the recommendations of the American Institute of Nutrition (Reeves et al. 1993), as follows. Five pregnant rats (Charles River, Barcelona, Spain) were housed in individual cages in a room maintained at 22°C with a 12-h light–dark cycle. After pup birth, the dams with their litter were randomly divided into two groups. The first group (two dams with their pups) was fed on a complete semisynthetic liquid diet (Barber et al. 1999) but sunflower oil, which contains less vitamin traces than others, was used as the unique lipid source in order to better control the vitamin A content of the diet (C. Ross, personal communication). The composition of this diet (g/l) was, in distilled deionised water: casein (vitamin-free) 54.5, d3-methionine 0.8, dextrin 162.7, sunflower oil 13.0, AIN-93 vitamin mix 2.6, AIN-93G mineral mix 9.2, choline chloride 0.4, cellulose powder 10.0, xantham gum 2.0. The composition of AIN-93 vitamin mix (g %) was: niacin, 0.300; d-calcium pantothenate, 0.160; pyridoxine HCl, 0.070; thiamine HCl, 0.060; riboflavin, 0.060; folic acid, 0.020; biotin, 0.002; vitamin B12, 0.250; all-trans-retinyl palmitate (250 000 U/g), 0.160; α-tocopherol powder (250 U/g), 5.000; vitamin D3 (400 000 U/g), 0.025; menadione, 0.008; powder sucrose, 95.885. The energy content of this diet was 4.18 MJ/l. The second group (three dams with their pups) was fed on the same diet but devoid of vitamin A. Feeding dams on the vitamin A-free diet during the 21 d of lactation shortens the interval of vitamin A depletion in the pups by reducing its transfer during the suckling period (Pasatiempo et al. 1991). At 21 d eight male pups from mothers fed the complete diet (control group) and thirteen male pups from mothers fed the vitamin A-free diet (deficient group) were weaned into their corresponding mother diet until they were 50 d old. This period was appropriate to induce a severe deficiency in vitamin A without significantly altering the growth of the animals. At the end of the deficiency treatment five male vitamin A-deficient rats were subsequently fed on the complete diet during 15 d to induce a repletion of vitamin A (recovered group). This group was used to study the reversibility of the possible changes caused by the vitamin deficiency. The animals not used in this study were returned to the control diet. All diets were made daily. The amount of food intake was not significantly different between groups.

Sampling procedure

The experiments were performed between 10:00–12:00 a.m. Rats were anaesthetised with pentothal (50 mg/kg body weight, intraperitoneally). Blood was collected from the aorta in heparinised syringes and then liver and heart samples were taken and processed immediately.

Retinoid and tocopherol determination

Serum vitamin A concentration was determined by the spectrofluorimetric method of Selvaraj & Susheela (1970) using retinol palmitate as standard. The different forms of vitamin A (retinol, retinoic acid and retinyl esters), β-carotene and tocopherols were measured in serum and tissues following the method described by Barua & Olson (1998).

Mitochondria isolation

Liver and heart mitochondria were isolated as described previously (Johnson & Lardy, 1967; Smith, 1967).
Coenzyme Q assay

The CoQ content of homogenates and mitochondrial membranes was measured according to Kröger with minor modifications (Kroger, 1978). Liver and heart homogenates and isolated mitochondria were diluted to 1 ml in sucrose (250 mM), Tris–HCl buffer (10 mM; pH 7-4), and they were extracted with methanol–light petroleum (60:40 v/v). After collection of the upper layers, the residues were re-extracted twice with light petroleum. The combined extracts were evaporated under nitrogen stream and the dry residues were dissolved in ethanol. The CoQ content was determined in the ethanolic solutions by recording the absorbance at 280 nm minus the absorbance at 289 nm caused by reduction with K-borohydride and by oxidation in the presence of KOH (ε = 8.88 mM per cm).

Respiratory chain enzymatic activity determination

Individual and integrated enzymatic activities were assayed at 22°C in potassium phosphate buffer, (50 mM; and pH 7.4), EDTA (1 mM). When appropriate, potassium cyanide (2 mM) was added. Isolated liver and heart mitochondria were diluted to 15–25 μg/ml in the cuvette after freezing and thawing, which was found to completely remove the permeability barrier to NADH without significant damage to the respiratory enzyme activities (Lenaz et al. 1995a; Genova et al. 1995). Quinones and inhibitors were added in ethanol in a solution at a maximum of 2 % ethanol in the assay mixture.

Integrated aerobic NADH oxidation and NADH–CoQ reductase activity (complex I) were assayed as previously described (Estornell et al. 1993). The soluble saturated-long chain decylubiquinone was used as ubiquinone analogue. Succinate–CoQ reductase (complex II) and succinate–cytochrome c reductase (integrated complex II and III) were assayed as described previously (Degli Esposti & Lenaz, 1982; Estornell et al. 1992; Lenaz et al. 1995b) after 10 min preincubation with succinate (1.25 mM) to activate complex II. Ubiquinol–cytochrome c reductase (complex III) and cytochrome c oxidase (complex IV) activities were measured as have been previously reported (Degli Esposti & Lenaz, 1982). Additionally, complex I and II activities were indirectly estimated from the application of the pool equation of Kröger and Klüggenberg, which has been found to be a more reliable estimation of their activity than the direct specific measurement (Lenaz et al. 1995a; Genova et al. 1995; Estornell et al. 1997).

Respiratory enzyme and cytochrome contents in mitochondria

The cytochrome content was measured in mitochondrial samples diluted at 2–3 mg/ml in potassium phosphate buffer (50 mM; pH 7-4), EDTA (1 mM), deoxycholate (1 %), according to Vanneste (1966) and Nicholls (1976). NADH–ferricyanide reductase activity was used to estimate the content of active complex I in mitochondria (Estornell et al. 1997). The amount of complex III was obtained by dividing cytochrome b content by two and that of complex IV from the cytochrome aa3 content (Genova et al. 1995).

Ultrastuctural studies

Rat tissues were processed for electron microscopy as described by Sancho-Tello et al. (1987). The sample fragments were immediately prefixed in ice cold glutar-aldehyde (1.5 %) and formaldehyde (1 %) in cacodylate buffer (0.1 M; pH 7-4) for 15 min, cut into smaller fragments (about 1 mm2) and fixed for 2 h. After washing in cacodylate buffer (0.1 M; pH 7-4), samples were sequentially postfixed in ice-cold solution of OsO4 (1 %) and potassium ferricyanide (0.8 %) for 1 h, in tannic acid (1 %) for 1 min and in uranyl acetate (5 %) for 45 min. Fixed samples were dehydrated in gradual concentrations of ethanol and embedded in Epon. Ultrathin sections were obtained with an LKB ultramicrotome (Leica, Barcelona, Spain) and examined under a Zeiss EM 10-C electron microscope (Zeiss-Germany, Ober Kochen, Germany).

Statistics

Values in the tables are presented as means and standard errors for the number of animals indicated. For Table 4 significance of differences with respect to the control group was evaluated by the unpaired t test and accepted when P < 0.05. For Tables 1–3, a one-way ANOVA was performed. The null hypothesis was accepted for all values of those sets in which F was non-significant at the level of P < 0.05 and the sets of data in which F was significant were examined by the Dunnett’s multiple comparison test at P < 0.05. The CV for any of the different analytical procedures employed was not higher than 5 %. The CV for each measurement within any experimental group ranged from 4 to 50 %, with the exceptions of serum retinol in vitamin A-deficient group and NADH oxidase in recovered group, which were 63 % and 55 %, respectively.

Results

Retinoid and tocopherol concentrations in plasma and tissues

The concentration of retinol in serum from control, vitamin A-deficient and vitamin A-recovered rats is shown in Table 1. Rats fed on vitamin A-free diet from their birth (through the dam’s milk) to 50 d old (vitamin A-deficient rats) showed less than 20 % of control serum vitamin A concentration. When vitamin A-deficient rats were refed a control diet over 15 d (recovered rats) retinol values were significantly lower than in the control group, which were 63 % and 55 %, respectively.
Retinyl palmitate levels in vitamin A-deficient liver and heart. Control diet refed animals recovered even higher tissue retinyl palmitate levels than the control group, especially in liver (data not shown). Plasma tocopherol levels did not change between the experimental groups as deeply as retinoids did. Although moderate variations in the amount of plasma and tissue \( \alpha \)-tocopherol between groups were observed, the differences did not appear significant under our sample number and assay conditions (data not shown).

Coenzyme Q content in liver and heart

The amount of CoQ in whole liver was 60% higher in vitamin A-deficient rats than in control rats. CoQ content increased twofold in liver mitochondria of vitamin A-deficient rats when compared with control rats. Vitamin A deficiency also induced an increase on the CoQ concentration in heart mitochondria; however, values in whole tissue were similar to those found in control rats as previously described (Estornell et al. 1997). The amount of CoQ was restored to control levels when deficient rats were refed a control diet (Table 1).

Respiratory chain activities in liver and heart mitochondria

Table 2 and 3 show the individual and integrated respiratory activities in liver and heart mitochondria, respectively. It is important to note that the direct assays of complex I and complex II with externally added ubiquinone analogues often underevaluate their activities. In our study, both specific activities showed non-significant differences between control and vitamin A-deficient rats (results not shown). Instead, possible changes are better assessed by the indirect calculation based on the CoQ behaviour as an homogeneous pool suggested previously (Lenaz et al. 1995a; Genova et al. 1995). Therefore, we have given in the tables those values that take the advantage of a more reliable estimation of the activity of these respiratory complexes in both liver (Lenaz et al. 1995a) and heart mitochondria (Estornell et al. 1997).

As shown in Table 2 the integrity of the respiratory chain was maintained in the liver of vitamin A-deficient rats with non-significant changes in the enzymatic activities measured. Complex I and NADH oxidase (integrated aerobic oxidation) activities were increased in liver mitochondria from recovered rats. Data from heart mitochondria (Table 3) showed that complex I and complex II were decreased in vitamin A-deficient rats when compared with control rats. Other respiratory chain activities were not changed. The recovered group showed normal respiratory activities.

Respiratory enzyme and cytochrome c contents in liver and heart mitochondria

In order to better define the alterations in the respiratory

<table>
<thead>
<tr>
<th>Activity</th>
<th>Control Mean</th>
<th>Deficient Mean</th>
<th>Recovered Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>NADH oxidase</td>
<td>44</td>
<td>43</td>
<td>56*</td>
</tr>
<tr>
<td>NADH-CoQ reductase**</td>
<td>70</td>
<td>62</td>
<td>97*</td>
</tr>
<tr>
<td>Succinate-CoQ reductase†</td>
<td>74</td>
<td>75</td>
<td>67</td>
</tr>
<tr>
<td>Succinate-cytochrome c reductase</td>
<td>90</td>
<td>95</td>
<td>82</td>
</tr>
<tr>
<td>Ubiquinol-cytochrome c reductase</td>
<td>240</td>
<td>245</td>
<td>246</td>
</tr>
<tr>
<td>Cytochrome c oxidase</td>
<td>352</td>
<td>350</td>
<td>379</td>
</tr>
</tbody>
</table>

* Significant differences compared with controls \( P < 0.05 \).
† See the text for details of the assay of each activity.
‡ Activities calculated from the CoQ pool equation (Lenaz et al. 1995a).
chain promoted by the vitamin A deficiency, the respiratory-enzyme content and the amount of cytochrome c were evaluated in liver and heart mitochondria (Table 4). Vitamin A-deficient rats preserved these respiratory components in liver mitochondria, although the content of complex I showed a tendency to descend. However, complex I and cytochrome c contents were decreased in heart mitochondria from vitamin A-deficient rats when compared with control rats. This decrease in the level of cytochrome c could be a limiting factor for the overall rate of respiration by slowing the electron-transfer rate between complex III and IV. The complex I deficiency found in heart mitochondria was well correlated with the diminished respiratory-enzyme content and the amount of cytochrome c in liver mitochondria, although the content of cytochrome c was not affected.

Ultrastructural studies

Some structures similar to the multivesicular lysosomes described by Leo et al. (1983) were found in the vitamin-deficient liver by electron microscopy. However, no appreciable difference was observed between control and vitamin A-deficient rats in the ultrastructural morphology of liver and heart mitochondria. Therefore, it appeared that the changes induced by our period of vitamin A deficiency in the respiratory chain function and composition were not reflected yet in the structure of the mitochondria. This could partially justify the reversibility of the alterations detected in the respiratory chain.

Discussion

Among the different properties of vitamin A, the antioxidant role of some of their compounds, known for decades, has been reinvestigated in recent years in chemical as well as in biological systems. Its hydrophobic chain of polyene units can stabilize peroxyl radicals, neutralize thyl radicals and quench singlet oxygen. In the lipophilic compartment of membranes and lipoproteins where lipid soluble vitamins are localised, retinol can act as an effective peroxyl radical scavenger. In fact, it has been shown in model phosphatidylcholine liposomes that the relative antioxidant efficiency of retinol is similar to that of tocopherol, whose antioxidant activity is well documented (Packer & Landvik, 1990; Burton, 1994; Traber & Packer, 1995), when radicals are generated inside a lipophylic environment. Possibly the shorter polyene chain of retinol supplies it with higher mobility to interact with radicals.

In a previous work we reported that the deficiency of vitamin A induced a decrease in both the activity and the amount of the respiratory complex I (NADH: CoQ reductase) (Estornell et al. 1997) in heart mitochondria. Complex I is the largest proton-translocating enzyme of mitochondria and it contains the highest number of mitochondrial-encoded subunits. Mitochondria have been recognised as a major physiological source and target for reactive oxygen species, which arise as a consequence of oxygen reduction. The presence of several electron carriers and polyunsaturated fatty acid rich membranes makes this organelle highly susceptible to changes in the levels of physiological antioxidants (i.e. retinol, tocopherol, etc.) and to free-radical attack leading to alterations of its structural integrity and function.

### Table 3. Specific respiratory chain activities in heart mitochondria from control, vitamin A-deficient and recovered rats†

(Data are means and standard errors of triplicate determinations from eight control rats, eight vitamin A-deficient rats and five recovered rats)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Specific activity (nmol/min/mg)</th>
<th>Control</th>
<th>Deficient</th>
<th>Recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>NADH oxidase</td>
<td>153</td>
<td>23</td>
<td>149</td>
<td>26</td>
</tr>
<tr>
<td>NADH–CoQ reductase‡</td>
<td>349</td>
<td>30</td>
<td>230*</td>
<td>33</td>
</tr>
<tr>
<td>Succinate–CoQ reductase‡</td>
<td>187</td>
<td>10</td>
<td>121*</td>
<td>6</td>
</tr>
<tr>
<td>Succinate–cytochrome c reductase</td>
<td>222</td>
<td>16</td>
<td>208</td>
<td>24</td>
</tr>
<tr>
<td>Ubiquinol–cytochrome c reductase</td>
<td>618</td>
<td>37</td>
<td>756</td>
<td>60</td>
</tr>
<tr>
<td>Cytochrome c oxidase</td>
<td>739</td>
<td>74</td>
<td>757</td>
<td>96</td>
</tr>
</tbody>
</table>

* Significant differences compared with controls P < 0.05.

† See the text for details of the assay of each activity.

‡ Activities calculated from the CoQ pool equation (Lenaz et al. 1995a).

### Table 4. Complex III, complex IV and cytochrome c contents (pmol/mg) in liver and heart mitochondria from control and vitamin A-deficient rats

(Data are means and standard errors of duplicate determinations from eight control rats and eight vitamin A-deficient rats)

<table>
<thead>
<tr>
<th>Comp</th>
<th>Control Mean</th>
<th>Control SE</th>
<th>Deficient Mean</th>
<th>Deficient SE</th>
<th>Recovered Mean</th>
<th>Recovered SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver Complex I</td>
<td>8.4</td>
<td>1.0</td>
<td>6.7</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex III</td>
<td>110</td>
<td>17</td>
<td>119</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex IV</td>
<td>108</td>
<td>10</td>
<td>97</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cytochrome c</td>
<td>248</td>
<td>24</td>
<td>176*</td>
<td>13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant differences compared with controls P < 0.05.
Our study shows that the respiratory-chain integrity in heart mitochondria is highly dependent on vitamin A. The vitamin A deficiency promoted a damage in the respiratory chain at different levels, being its flavin-dehydrogenase complexes the most affected. The defect in complex II shown here and also the reduced cytochrome c content, which acts as mobile electron carrier between complex III and IV, must be added to the defective complex I previously described (Estornell et al. 1997). The damage induced by vitamin A deficiency in heart mitochondria, however, was not seen in liver mitochondria which preserved the integrity of its electron transfer components in the absence of vitamin A. This is in concordance with the fact that heart is a more aerobic tissue than the liver and thus, it is more exposed to oxidative injuries. Other authors have also reported tissue-different responses to damage induced by vitamin A deficiency, the liver being less affected than proliferating epithelial tissues (Evarts et al. 1995). Moreover, several oxidative treatments induced lipid membrane peroxidation in vivo in different tissues (i.e. brain, heart, etc.) but not in liver, suggesting that it has more effective antioxidant systems than the other tissues (Ciaccio et al. 1993). However, the lack of changes in respiratory chain in liver after vitamin A depletion does not imply that other manifestations related to oxidative stress could not be found in this tissue. In fact, we have found that free-radical mechanisms appear to be implicated in the mtDNA damage, mitochondrial glutathione depletion and the fall in mitochondrial membrane potential induced by vitamin A deficiency in rat liver (Barber T et al., Free Radical Biology and Medicine, in press).

Interestingly, the increase in the CoQ content that we have found in the heart mitochondria of vitamin A-deficient rats could maintain their overall rate of aerobic NADH oxidation and counteract the defects seen in the different components of their respiratory chain. This is in accordance with our previous data and with the kinetic behaviour of the CoQ pool. In kinetic terms, it is possible to increase respiratory-chain activity from NADH oxidation by increasing CoQ content over the normal level due to its lack of saturation for enzyme activities (Estornell et al. 1992). Thus, partial enzyme deficiencies can be counteracted by higher CoQ levels (Lenaz et al. 1995b; Estornell et al. 1997). An increase in mitochondrial CoQ concentration has also been described in other situations with reduced mitochondrial activity such as liver-induced cirrhosis in human and rats as a compensatory response of mitochondrial respiratory assembly for maintaining liver function (Morimoto et al. 1985; Kraehenbuhl & Reichen, 1992).

The changes in the respiratory function of mitochondria induced by vitamin A deficiency were not manifested in alterations of their structure as observed at the electron microscope. One reason for that could be that the deficiency period was not long enough for the functional deficiencies being translated in rearrangements of mitochondrial morphology. Alternatively, the impairment of the function could not be severe enough. In this sense, no morphological changes were observed at light microscope level despite a 60% inhibition of complex I activity in an animal model with induced mitochondrial myopathy (Cooper et al. 1988). However, Thomas et al. (1993) in a neuromuscular myopathy induced by feeding rats on a vitamin E-deficient diet (vitamin E is a known membrane antioxidant) for 1 year, found decreases of 60 and 50% in complex I and IV activities respectively, together with non-specific degenerative changes of muscle mitochondria and disorganisation of their cristae. In agreement with our study, Leo et al. (1983) did not find any change in the structure of liver mitochondria after feeding rats on a vitamin A-deficient diet for 60 d and Morre et al. (1981) described modifications of the Golgi apparatus as the only consistent ultrastructural response in liver to changes in vitamin A status. The lack of structural degeneration in our condition of vitamin A deficiency probably facilitates the complete restoration of the functional changes after refeeding on the control diet.

It is known that a variety of key events in apoptosis focus on mitochondria and include changes in electron transport activity, decreased cytochrome c content inside mitochondria, increased release of cytochrome c to the cytosol and altered cellular oxidation–reduction status (Liu et al. 1996; Green & Reed, 1998). It is also known that vitamin A and its metabolites are inhibitors of apoptosis (Sembä, 1994; Maden et al. 1998). In our work, vitamin A deficiency impaired the integrity of heart mitochondrial function in association with a decreased cytochrome c content and changes in the levels of CoQ, a physiological antioxidant in mitochondrial membrane. Moreover, in a recent work (Barber T et al., Free Radical Biology and Medicine, in press) we have shown that vitamin A deficiency induced oxidative stress, accompanied with an increase in malondialdehyde and 8-oxo-dihydro-2′-deoxyguanosine (which indicate damage to mtDNA) and a drop in the mitochondrial membrane potential. All of these parameters are different signals described on the pathway in physiological cell death (Green & Reed, 1998) and agree with data reported previously by others on vitamin A deficiency. In testis from vitamin A-deficient rats most of the germ cells from seminiferous tubules degenerated by apoptosis (Akmal et al. 1998) and, in a rat model, maternal vitamin A deficiency was correlated with placental apoptosis and perturbed fetal development (Lea et al. 1999). Moreover, in regenerating rat liver vitamin A deficiency leads to a widespread activation of nuclease activity and the administration of vitamin A to these animals enhanced the capacity of the liver to regenerate by preventing apoptosis and necrosis cell death (Evarts et al. 1995). The functional alterations found in our study may represent a pre-apoptotic stage before morphological changes become manifest. However, the mechanistic aspects of mitochondrial involvement in cell death are extremely complex and require understanding the integration of numerous mitochondrial responses that cannot be dissected easily and escapes the aim of our work.

The functional and compositional differences between the three experimental groups found in our work seem to result from the changes in retinoids rather than from those in α-tocopherol. This suggestion is based on quantitative variations in retinoids being much more important than those in α-tocopherol. In fact, the levels of retinyl palmitate diminished around 95 and 70% in the liver and heart of...
vitamin A-deficient animals whereas the changes in α-tocopherol were not significant.

The present study has raised some interesting questions concerning the therapeutic use of retinol because of the high dependence for the heart mitochondrial integrity. Our results are in accordance with many experimental and epidemiological studies that are supportive of the beneficial effects of retinol as an important antioxidant for heart integrity, which is highly susceptible for free-radical attack. In fact, numerous reports have provided the basic structural and metabolic characteristics of vitamin A as well as information about its potential as physiological antioxidant for mitigating and defending against heart injury (for review see Palace et al. 1999). Another question is the beneficial effect of the CoQ to treat respiratory-chain diseases and also to preserve the mitochondrial integrity in ageing (Schapira, 1998; Wallace, 1999). Assuming that it is possible to incorporate CoQ into the mitochondrial membranes by external administration to patients, it could contribute to preserve the bioenergetic function in damaged mitochondria, at least if the respiratory chain complex deficiencies are not highly severe. This short-term effect of CoQ could be important in addition to the long-term effects due to its well-known antioxidant role (Shi et al. 1999). This idea opens the possibility of a combined therapeutic use of both CoQ and retinol to improve some of the heart mitochondrial diseases.

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