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Original Contribution

IMPAIRED RESISTANCE TO OXIDATION OF LOW DENSITY LIPOPROTEIN IN CYSTIC FIBROSIS: IMPROVEMENT DURING VITAMIN E SUPPLEMENTATION

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Abstract—Antioxidants such as vitamin E protect unsaturated fatty acids of LDL against oxidation. In the ex vivo model used, LDL was exposed to Cu²⁺ ions, a potent prooxidant capable of initiating the oxidation of LDL. The lag time, indicating the delay of conjugated diene formation in LDL due to antioxidant protection, was measured in 54 cystic fibrosis (CF) patients with plasma α-tocopherol levels below (Group A, n = 30) or above (Group B, n = 24) 15.9 mg/ml (mean ± 2 SD of Swiss population). Patients were reevaluated after 2 months on 400 IU/d of oral RRR-α-tocopherol. In group A, α-tocopherol concentrations in LDL increased significantly from 3.2 ± 1.6 mg/mol LDL to 8.2 ± 2.8 mg/mol (P < 0.001) and lag times increased from 79 ± 33 min to 126 ± 48 min (P < 0.001), whereas in the vitamin E sufficient group B no further increase neither in LDL α-tocopherol concentrations or in lag times was observed. LDL oleic acid concentrations were higher, and linoleic acid concentrations were lower in patients than in controls. After efficient vitamin E supplementation, lag times were positively related to LDL α-tocopherol (P < 0.01) and negatively to LDL linoleic and arachidonic acid content (P < 0.001). The maximum rate of oxidation correlated positively with linoleic and arachidonic acid concentrations, as did the maximum conjugated diene absorbance. These results indicate that LDL resistance to oxidation is impaired in vitamin E deficient CF patients but can be normalized within 2 months when α-tocopherol is given in sufficient amounts. Linoleic and arachidonic acid content exhibit a major influence on the LDL resistance to oxidation.

Keywords—α-Tocopherol, Low density lipoprotein, Oxidation resistance, Linoleic acid, Arachidonic acid, Cystic fibrosis, Free radicals

INTRODUCTION

As a consequence of fat malabsorption due to exocrine pancreatic insufficiency,1 subclinical vitamin E deficiency is a frequent finding in patients with cystic fibrosis (CF). In contrast, symptomatic vitamin E deficiency is a rare event.2 To prevent and treat vitamin E deficiency, oral vitamin E supplementation has become part of the therapeutic management of CF patients.3 However, vitamin E deficiency is not always reversed by routine vitamin E supplementation.1,4

Thus far, data on the biological significance of subclinical vitamin E deficiency in CF patients are limited. Chronic lung inflammation is suggested to cause an increased release of oxygen-derived free radicals in the presence of antioxidant deficiencies due to fat malabsorption, and the resulting oxidant—antioxidant imbalance could lead to an enhanced free radical attack of polyunsaturated fatty acids (PUFAs) of biomembranes and lipoproteins and, consequently, to tissue injury.5 Data on the occurrence of lipid peroxidation in CF patients is available from determinations of in vitro peroxide induced red cell hemolysis,6 thiobarbituric acid reactive substances,7 and hydrocarbon gas exhalation.8,9

The aim of this study was to determine the significance of subclinical vitamin E deficiency on the LDL resistance to in vitro oxidative stress and the effects
of correcting this deficiency in CF patients. In addition, relationships between the LDL resistance to oxidation and the fatty acid content of LDL were analyzed.

SUBJECTS

Patients

Fifty-four CF patients under long-term care in the CF outpatient clinics of 10 different hospitals in Switzerland, Austria, and Germany were enrolled. Their ages ranged from 3 months to 34 years (median 9 years). The diagnosis of CF had been established by typical clinical symptoms and elevated sweat electrolytes. All patients exhibited exocrine pancreatic insufficiency and were treated with pancreatic enzymes. Twenty-four patients were on long-term oral vitamin E supplementation in dosages of 50 to 800 IU/d prior to study entry. Shwachman scores, indicating the clinical disease status, were 77 ± 19. No changes were introduced in the therapeutic management during the study period, except for intermittent antibiotic treatment of acute pulmonary exacerbations. Patients were considered vitamin E deficient and assigned to group A if they had plasma α-tocopherol concentrations below mean − 2 SD of the Swiss population (15.9 μmol/l)\(^1\); accordingly, those with plasma α-tocopherol concentrations > 15.9 μmol/l were assigned to group B.

Immediately after the baseline evaluation, patients without supplements (n = 30) or with dosages ≤ 400 IU/d (n = 12) were switched to 400 IU/d of RRR-α-tocopherol, given in a single dose during breakfast. Patients who were already taking vitamin E supplements in dosages of 400 IU/d (n = 9), 600 IU/d (n = 1), and 800 IU/d (n = 2) continued to do so.

Forty-seven of 54 patients had a second evaluation after 2 months on vitamin E. Drop-outs were due to death (n = 2), movement to another country (n = 2), or vacation (n = 3). In two patients, either LDL α-tocopherol concentrations at baseline or lag time values at 2 months were missing. Thus, a complete set of data for statistical analysis was available from 53 patients at baseline and 46 patients at 2 months.

Controls

Twenty-three clinically healthy normolipidemic nonsmoking staff members aged 26 ± 7 years from the Departments of Pediatrics, University of Zurich (n = 21), and University of Innsbruck (n = 2) served as controls because it was ethically not acceptable to draw the necessary amounts of blood from healthy children. None of the controls was taking vitamin supplements or medications other than oral contraceptives (n = 6). All were on a regular diet. Controls had a single evaluation including the same parameters as assessed in patients to allow, by comparison, validation of baseline values and evaluation of treatment efficacy.

The study protocol was approved by the Ethical Committee of the Department of Pediatrics, University of Zurich, and informed consent was obtained from the patients or their parents and from controls.

METHODS

Immediately after blood was drawn after an overnight fast, EDTA (0.1% final) plasma was prepared and protected from light with aluminum foil by the same investigator (B.M.W.R.) in all CF centers.

Determination of LDL antioxidants and LDL resistance to oxidation

The freshly prepared plasma samples (3 to 4 ml) were shipped on wet ice by overnight courier to the Institute of Biochemistry, University of Graz. LDL was isolated by ultracentrifugation in a discontinuous potassium bromide gradient containing 0.1% EDTA using a Beckman SW 41 Ti-rotor, as described previously.\(^13\) The LDL band was quantitatively collected and diluted with PBS to give the same volume as the centrifuged plasma sample (3 to 4 ml). The total cholesterol concentrations of the LDL stock solutions were determined with the CHOD-PAP kit from Boehringer Mannheim. Based on this analysis, the LDL concentration was calculated as mg LDL mass/ml and μmol LDL/l, respectively, assuming an LDL cholesterol content of 31.6 wt % and a molecular weight of 2500 kDa both for CF patients and healthy subjects. An aliquot of the LDL stock solution was stored at 4°C for not longer than 6 h for the determination of antioxidants. Another aliquot was used immediately for the oxidation assay. For the latter, EDTA and salt were removed using prepacked Biogel P6 columns. Oxidation was then performed under standardized conditions\(^13\) with 0.1 μM LDL in PBS (equal to 0.25 ml LDL mass/ml) and 1.66 μM CuCl\(_2\). The oxidation of LDL was monitored spectrophotometrically by measuring the conjugated diene (CD) absorbance at 234 nm. The oxidation indexes derived from the CD versus time curves are lag time, maximum rate of oxidation (dA/min), and maximum increase in CD absorbance (A\(_{234}\)). This oxidation assay has proved to be reproducible with CV for multiple analyses of the same LDL sample of 1.85%\(^1\) and multiple analyses of LDL from a single donor of 8.8%.\(^1\)

Antioxidants in LDL were determined as described...
Table 1. Tocopherol and Carotenoid Concentrations in Plasma and in LDL at Baseline and After 2 Months of Vitamin E Supplementation in Group A (Plasma α-Tocopherol < 15.9 μmol/l) and Group B (Plasma α-Tocopherol > 15.9 μmol/l) as Well as in Controls

<table>
<thead>
<tr>
<th></th>
<th>Group A Baseline</th>
<th>Group B Baseline</th>
<th>Group A Baseline vs. Group B Baseline</th>
<th>Group A After 2 Months</th>
<th>Group B After 2 Months</th>
<th>Group A After 2 Months vs. Group B After 2 Months</th>
<th>Controls After 2 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma (μmol/l)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>α-tocopherol</td>
<td>9.0 ± 4.2</td>
<td>28.3 ± 9.3</td>
<td>&lt; 0.0001</td>
<td>27.8 ± 8.1</td>
<td>35.3 ± 9.0</td>
<td>&lt; 0.05</td>
<td>26.9 ± 5.1^d</td>
</tr>
<tr>
<td>γ-tocopherol</td>
<td>0.76 ± 0.6</td>
<td>0.48 ± 0.43</td>
<td>NS</td>
<td>0.34 ± 0.33</td>
<td>0.25 ± 0.17</td>
<td>&lt; 0.01</td>
<td>1.59 ± 0.61</td>
</tr>
<tr>
<td>α-carotene</td>
<td>0.02 ± 0.05</td>
<td>0.06 ± 0.11</td>
<td>&lt; 0.05</td>
<td>0.03 ± 0.07</td>
<td>0.03 ± 0.10</td>
<td>NS</td>
<td>0.18 ± 0.08</td>
</tr>
<tr>
<td>β-carotene</td>
<td>0.09 ± 0.11</td>
<td>0.22 ± 0.33</td>
<td>&lt; 0.05</td>
<td>0.10 ± 0.15</td>
<td>NS</td>
<td>0.21 ± 0.40</td>
<td>NS</td>
</tr>
<tr>
<td>Lycopene</td>
<td>0.03 ± 0.03</td>
<td>0.06 ± 0.06</td>
<td>&lt; 0.05</td>
<td>0.05 ± 0.05</td>
<td>0.09 ± 0.07</td>
<td>&lt; 0.01</td>
<td>0.54 ± 0.28</td>
</tr>
<tr>
<td>LDL (mol/mol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>α-tocopherol</td>
<td>3.2 ± 1.6^a</td>
<td>8.5 ± 3.1^b</td>
<td>&lt; 0.0001</td>
<td>8.2 ± 2.8^c</td>
<td>9.4 ± 3.5^d</td>
<td>NS</td>
<td>5.0 ± 0.8^d</td>
</tr>
<tr>
<td>γ-tocopherol</td>
<td>0.27 ± 0.19</td>
<td>0.16 ± 0.15</td>
<td>&lt; 0.01</td>
<td>0.12 ± 0.13</td>
<td>0.05 ± 0.06</td>
<td>&lt; 0.001</td>
<td>0.32 ± 0.14</td>
</tr>
<tr>
<td>α-carotene</td>
<td>0.003 ± 0.005</td>
<td>0.02 ± 0.03</td>
<td>NS</td>
<td>0.008 ± 0.02</td>
<td>NS</td>
<td>0.02 ± 0.04</td>
<td>NS</td>
</tr>
<tr>
<td>β-carotene</td>
<td>0.04 ± 0.06</td>
<td>0.09 ± 0.18</td>
<td>&lt; 0.05</td>
<td>0.04 ± 0.04</td>
<td>NS</td>
<td>0.12 ± 0.25</td>
<td>NS</td>
</tr>
<tr>
<td>Lycopene</td>
<td>0.02 ± 0.04</td>
<td>0.04 ± 0.05</td>
<td>&lt; 0.05</td>
<td>0.04 ± 0.03</td>
<td>0.05 ± 0.05</td>
<td>NS</td>
<td>0.31 ± 0.15</td>
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<tr>
<td>Lutein/Zeaxanthine</td>
<td>0.02 ± 0.01</td>
<td>0.03 ± 0.02</td>
<td>&lt; 0.01</td>
<td>0.02 ± 0.01</td>
<td>NS</td>
<td>0.03 ± 0.02</td>
<td>NS</td>
</tr>
<tr>
<td>Cryptoxanthine</td>
<td>0.009 ± 1.01</td>
<td>0.009 ± 0.01</td>
<td>NS</td>
<td>0.01 ± 0.01</td>
<td>NS</td>
<td>0.01 ± 0.02</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

Values are mean ± SD. Identical superscripts indicate significant differences for α-tocopherol between patients and controls.

\* Mann-Whitney tests, two tailed.

\^ Wilcoxon signed ranks test.

Values are mean ± SD. Identical superscripts indicate significant differences between patients and controls.

\* Mann-Whitney tests, two tailed.

\^ Wilcoxon signed ranks test.

Determination of fatty acids in LDL

The freshly prepared EDTA plasma samples (2.5 to 3.0 ml) were immediately frozen at −80°C and kept at this temperature for not longer than 2 months until analysis. LDL was prepared from the freshly thawed samples by 2 h ultracentrifugation using a single-step discontinuous gradient in a Beckman NVT65 rotor (note that this rotor, which allows isolation of LDL within 2 h, was not yet available at the time when LDL oxidation experiments were performed). The plasma volume after centrifugation was in the range of 2.5 to
Fig. 1. Lag times of 53 CF patients are plotted against baseline LDL \(\alpha\)-tocopherol concentrations. One patient is not included due to LDL \(\alpha\)-tocopherol value missing.

![Graph showing lag times versus baseline LDL \(\alpha\)-tocopherol concentrations.](image)

Fig. 2. Changes in lag times during vitamin E supplementation are plotted against changes in LDL \(\alpha\)-tocopherol concentrations in 45 patients. One patient who completed the study is not included due to LDL \(\alpha\)-tocopherol value missing at baseline.

![Graph showing changes in lag times versus changes in LDL \(\alpha\)-tocopherol concentrations.](image)
As there were no differences between groups A and B except for C22:6n-3 (P < 0.05), groups A and B baseline were combined for comparison with controls. DB = Double bonds. Units are mol/mol; values are Mean ± SD.

Table 4. Results of Regression Analyses for Indexes of the LDL Oxidizability and LDL α-Tocopherol and Fatty Acid Content

<table>
<thead>
<tr>
<th></th>
<th>α-Tocopherol</th>
<th>C18:2n-6</th>
<th>C20:4n-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>P = 0.0001</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Lag time</td>
<td>NS</td>
<td>P = 0.0003</td>
<td>NS</td>
</tr>
<tr>
<td>Oxidation rate</td>
<td>NS</td>
<td>P = 0.0001</td>
<td>P = 0.006</td>
</tr>
<tr>
<td>Maximum CD absorbance</td>
<td>NS</td>
<td>P = 0.00005</td>
<td>P = 0.0001</td>
</tr>
</tbody>
</table>

2 Months

<table>
<thead>
<tr>
<th></th>
<th>α-Tocopherol</th>
<th>C18:2n-6</th>
<th>C20:4n-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lag time</td>
<td>P = 0.002</td>
<td>P = 0.0002</td>
<td>P = 0.0006</td>
</tr>
<tr>
<td>Oxidation rate</td>
<td>NS</td>
<td>P = 0.0003</td>
<td>P = 0.0001</td>
</tr>
<tr>
<td>Maximum CD absorbance</td>
<td>P = 0.000005</td>
<td>P = 0.00001</td>
<td>P = 0.0001</td>
</tr>
</tbody>
</table>
DISCUSSION

This study documents that LDL resistance to oxidation is impaired in vitamin E deficient CF patients but can be normalized within 2 months of oral α-tocopherol supplementation. Thus far, data on LDL resistance to oxidation comprised, with one exception, healthy subjects with a sufficient vitamin E status before and after vitamin E supplementation or with variations in dietary fatty acid intake, but not a larger cohort of vitamin E deficient subjects and, in particular, not of CF patients. Whereas lag times correlated poorly with LDL α-tocopherol concentrations in healthy subjects, the study patients, exhibiting a wide range of LDL α-tocopherol values, showed a significant positive correlation. Interestingly, a few patients had unexpectedly long lag times despite a low LDL α-tocopherol content (Fig. 1), an observation in agreement with that of Kleinveld et al. but lacking a final explanation.

During supplementation with 400 IU/d of RRR-α-tocopherol, plasma and LDL α-tocopherol concentrations increased about threefold in the vitamin E deficient, but not in the vitamin E sufficient group, with plasma and LDL α-tocopherol concentrations higher than in healthy controls. This is in contrast to data suggesting that LDL α-tocopherol concentrations can be increased during vitamin E supplementation without saturation in vitamin E sufficient healthy subjects and perhaps indicates a plateau effect due to low LDL content of plasma in CF patients. However, because a high proportion of patients in the vitamin E sufficient group had already been on vitamin E supplements prior to study entry and the increase in the dosage was small compared to that in the vitamin E deficient group, final conclusions cannot be drawn for a ceiling effect from this study.

The maximum rate of oxidation and CD absorbance did not differ between vitamin E deficient and sufficient patients and healthy controls, and vitamin E supplementation had no effect on these indexes. In contrast, healthy subjects showed significantly lower propagation rates after vitamin E supplementation compared with baseline. CD absorbance was positively related to the LDL α-tocopherol content only after vitamin E supplementation in the present study, suggesting that α-tocopherol does exert this particular

Fig. 3. The maximum CD absorbance after 2 months of vitamin E supplementation is plotted against the LDL α-tocopherol content for 46 patients who completed the study.

At baseline, no differences were observed in the maximum rate of oxidation and the maximum CD absorbance, neither between the two patient groups nor between patients and controls. During vitamin E supplementation, the maximum rate of oxidation and the maximum CD absorbance did not change in group A, but the maximum CD absorbance increased in group B ($P = 0.02$) (Table 2).

Concentrations of saturated and monounsaturated fatty acids in LDL, such as palmitic (C16:0), palmitoleic (C16:1n-7), stearic (C18:0), and oleic acid (C18:1n-9), were higher and those of linoleic acid (C18:2n-6) and docosahexaenic acid (C22:6n-3) were lower in patients compared with controls; no differences were observed in α-linolenic (C18:3n-3) and arachidonic acid content (C20:4n-6) (Table 3). During the study period, arachidonic acid concentrations increased in group A and those of docosahexaenoic acid decreased in both groups, whereas palmitic acid concentrations decreased in group B (Table 3). There was a significant correlation between LDL linoleic (but not arachidonic) acid and LDL α-tocopherol concentrations ($r = 0.38, P = 0.009$).

In Table 4, the results of regression analyses for indexes of the LDL oxidizability and α-tocopherol and fatty acid content of LDL are summarized. Lag times (Fig. 1) and the maximum CD absorbance (Fig. 3) correlated positively with LDL α-tocopherol concentrations, whereas the maximum rate of oxidation did not. Lag times were negatively, and both the maximum rate of oxidation and the maximum CD absorbance were positively related to LDL linoleic and arachidonic acid concentrations (Fig. 4).
protective action only at relatively high levels, as achieved after 2 months of supplementation. Recently, LDL of vitamin E deficient patients with fat malabsorption has been found less susceptible to oxidation compared with controls.\textsuperscript{20} However, these patients also showed a low LDL content of linoleic acid, a major substrate for CD formation.

The fatty acid content of LDL had a major impact

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Correlations between indexes of LDL oxidizability and LDL linoleic and arachidonic acid concentrations after 2 months of supplementation. Lag times (A, D), maximum rate of oxidation (B, E), and maximum conjugated diene (CD) absorbance (C, F) are plotted against LDL linoleic acid concentrations (left) and arachidonic acid concentrations (right) for 46 patients who completed the study.}
\end{figure}
on the resistance to oxidation: Lag times were negatively and rate of oxidation and CD absorbance were positively related to linoleic and arachidonic acid concentrations. This is in line with data from healthy subjects focusing on LDL linoleic acid. It is not surprising and rate of oxidation and CD absorbance were positively related to linoleic and arachidonic acid concentrations. This is in line with data from healthy subjects and easily undergoes oxidation. However, this study shows for the first time a significant effect of arachidonic acid content on the LDL resistance to oxidation.

CF patients have long been known to exhibit essential fatty acid deficiency; however, the mechanisms involved are not precisely known. In the present study, linoleic and docosahexaenoic acid concentrations in LDL were lower only in the vitamin E deficient but not in the vitamin E sufficient group, compared with controls, and LDL linoleic (but not arachidonic acid) and α-tocopherol content were related to each other, indicating either a similarity in the underlying pathophysiological mechanism of fat malabsorption with subsequent alterations in the vitamin E and fatty acid status or a direct protective effect of α-tocopherol on the loss of LDL linoleic acid. The latter mechanism is further supported by an increase in arachidonic acid concentrations in the vitamin E deficient group during supplementation. However, there was a decrease in docosahexaenoic acid during supplementation in both groups that does not support this mechanism.

The effect of LDL α-tocopherol concentrations on lag times, but not on the rate of oxidation and CD absorbance, and the influence of linoleic acid and arachidonic acid content on the latter two indexes can at least in part be explained by the concept that, in the model of copper-induced LDL oxidation, α-tocopherol and other endogenous antioxidants are consumed during the lag phase and will therefore no longer be available for affecting the rate of oxidation or CD absorbance. The PUFA content of LDL, particularly of linoleic and arachidonic acid, as the substrate for oxidation will then become the major determinant of the LDL oxidizability.

In summary, this study documents that subclinical vitamin E deficiency in CF patients exerts a significant effect on the LDL resistance to oxidation in vitro. Impaired LDL resistance to oxidation of vitamin E deficient patients can be normalized within 2 months of 400 IU/d of RRR-α-tocopherol supplementation. We hypothesize that impaired resistance to oxidation of PUFAs is not confined to lipoproteins but might affect several tissues and, particularly, surfactant lipids in the lung of CF patients. Hence, efficient vitamin E supplementation of CF patients is recommended as part of the therapeutic regime. However, dietary supplementation with unsaturated fatty acids may increase the oxidizability of lipids and, consequently, increase the vitamin E demands of CF patients for an efficient protection of PUFAs against oxidation.

Acknowledgements—The authors gratefully acknowledge the excellent cooperation of the CF outpatient clinics of the University Hospital in Zurich, Switzerland (Professor E. Russi), the Children's Hospitals in Luzern (Dr. J. Spullinger), Aarau (Dr. P. Kirnzi), Chur (Dr. D. Visehe), St. Gallen (Dr. F. Semnhuser), and the Department of Internal Medicine, Kantonsspital Winterthur (Dr. A. Musil), all Switzerland, who allowed us to investigate their patients, as well as the determinations of plasma tocopherols and carotenoids in the Vitamin Research Department of Hoffmann-La Roche Ltd. (Basel, Switzerland) and plasma LDL cholesterol determinations in the Institute of Clinical Chemistry and Hematology, St. Gallen, Switzerland (Professor W. Riesen). We thank Trudi Blau for expert technical assistance and Dorothea Stoessel, Irene Tanner, and Johanna Spuler for their assistance in the enrollment of patients and controls. This work was supported by grants from Swiss National Science Foundation, 32-33914, Austrian Science Foundation, MO 15 (Habilitationsstipendium of B. M. W. R.) and S07102-MED (Institute of Biochemistry, University of Graz), and Nestlé AG, Switzerland.

REFERENCES


**ABBREVIATIONS**

CD—conjugated dienes
CF—cystic fibrosis
EDTA—ethylene-diamine-tetraacetic acid
GC—gas chromatography
HPLC—high-performance liquid chromatography
LDL—low density lipoprotein
MDA—malondialdehyde
PBS—phosphate-buffered saline
PUFAs—polyunsaturated fatty acids