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JAMES T. DODGE,† GERALD COHEN, HERBERT J. KAYDEN,‡ AND GERALD B. PHILLIPS §

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Summary. The effect of peroxidative stress on tissue was studied by exposure of red blood cells (RBC) from patients with abetalipoproteinemia to minute amounts of H₂O₂ in vitro. Red blood cells from untreated patients showed a marked sensitivity to H₂O₂, as evidenced by hemolysis and lipid peroxidation (peroxidative hemolysis).

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Substances that prevented lipid peroxidation also prevented hemolysis; in addition, lipid peroxidation appeared to precede hemolysis. These observations suggested that hemolysis was a consequence of lipid peroxidation.

Introduction

Lipids extracted from human red blood cells are highly susceptible to autoxidation (2). The possibility of a comparable lipid alteration occurs.

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† This work was done during the tenure of an Advanced Research Fellowship of the American Heart Association.

‡ Recipient of U. S. Public Health Service Career Research Development Award K3 HE-14-828.
§ Recipient of Lederle Medical Faculty Award. Address requests for reprints to Dr. Gerald B. Phillips, Roosevelt Hospital, 428 W. 59th St., New York, N. Y. 10019.

ring in the intact cell has been suggested by the appearance of substances reactive with 2-thiobarbituric acid when RBC from vitamin E-deficient animals were exposed in vitro to hydrogen peroxide (3-6) or dialuric acid (3, 7), or in vivo to hyperbaric oxygen (8). Indeed, lipid peroxidation has been implicated as a mechanism for some of the manifestations of vitamin E deficiency in

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experimental animals (3, 4, 7, 9, 10) and man (5, 11, 12). Recently, Kayden and Silber reported that patients with abetalipoproteinemia (acanthocytosis) were deficient in vitamin E; in fact, the serum tocopherol levels were the lowest reported for man (13). These patients presented a unique opportunity to investigate lipid oxidation in intact human RBC. Rats with experimental vitamin E deficiency were also studied. Red blood cells were exposed to minute amounts of H$_2$O$_2$ as a stressing agent; hemolysis and lipid peroxidation (peroxidative hemolysis) resulted. This report is the first description of alterations in the RBC phospholipid fatty acids that characterize peroxidative hemolysis of RBC from patients or experimental animals with vitamin E deficiency. Moreover, evidence suggests that these lipid alterations portend hemolysis.

**Methods**

Each of the four following patients with abetalipoproteinemia has been included in previous investigations: A.V. (13), a girl born in 1957; and R.B. (13-17), M.S. (13, 16-18), and R.I. (15, 19-21), boys born in 1956, 1954, and 1953, respectively. Control subjects were healthy males and females between the ages of 20 and 40 who were taking no medication. Vitamin E deficiency was produced in male and female Wistar rats by feeding a "tocopherol-deficient diet"\(^1\) from weaning until the age of 6 months, when this study was performed.

We determined plasma tocopherol levels by a micro-method using the Emmerie–Engle reaction (22). The autohemolysis test was performed by sterile incubation of defibrinated blood at 37° C for 48 hours essentially as described by Young, Izzo, Altman, and Swisher (13, 23); samples were run in duplicate and average values reported.

*Exposure of RBC suspensions to H$_2$O$_2$ vapor.* Heparinized\(^2\) venous blood was stored between 0 and 4° C for up to 18 hours before the RBC were isolated by centrifugation, washed three times in an equal volume of isotonic saline at room temperature, and studied. A 10% suspension of the washed RBC in isotonic saline-phosphate buffer, pH 7.4 (24), was prepared; 4.5-ml samples were placed in 25-ml Warburg flasks and exposed to minute amounts of H$_2$O$_2$ by the method of Cohen and Hochstein (25, 26). The 0.3 ml of 30% H$_2$O$_2$ that was placed in the center well diffused into the RBC suspension at a rate of approximately 2.3 µmoles per hour\(^3\) while the flasks were shaken in a Dubnoff metabolic incubator 90 to 100 times a minute at 37° C. In order to facilitate lipid extraction in later experiments in which phospholipid and fatty acid analyses were performed, we increased the hematocrit of the RBC suspension to between 30 and 40%.

*Analysis of the incubation suspension.* The per cent hemolysis was calculated from the hemoglobin concentration, which was determined by a cyanometmethemoglobin method (26) on the supernatant of the incubation suspension after centrifugation and appropriate dilution. The value for 100% hemolysis was obtained by measurement of hemoglobin concentration in a sample of the RBC suspension lysed in the saline-phosphate buffer diluted to be equivalent to 0.1% saline.

The TBA test was performed on a trichloroacetic acid extract of a sample of the incubation suspension with absorbency measurement at 532 mµ (7). This test provides an index of lipid peroxidation by determination of the malondialdehyde released on acid hydrolysis (27, 28).

*Analysis of RBC lipid.* Lipids were extracted at room temperature from 3.0 ml of the 10% suspension of RBC. After centrifugation at 3,000 X g and aspiration of the supernatant, about 0.3 ml of packed RBC (or ghosts) remained, and this amount was taken as 1 vol for calculation of the quantity of reagents used. One vol of methanol that contained the antioxidant 2,6-di-tert-butyl 4 methyl phenol (BHT),\(^5\) 5.5 mg per 100 ml, and 9 vol of methanol alone were added, mixed, and allowed to stand for 30 minutes. Ten vol of chloroform\(^7\) was added, mixed, and allowed to stand for an additional 30 minutes.

\(^3\) Approximately 5.5 X 10\(^{-6}\) µmole of H$_2$O$_2$/RBC per hour.

\(^4\) Approximately 2 X 10\(^{-8}\) µmole of H$_2$O$_2$/RBC per hour.

\(^5\) "Ionol, CP," a gift from the Shell Chemical Co., New York, N. Y.

\(^6\) Approximately one part BHT per 100 parts of total lipid, by weight. This amount of BHT was approximately 10 times more than was necessary to prevent autoxidation of dried lipid extracts of normal human RBC (2). As a result of our first experiments with RBC from patients with abetalipoproteinemia in which an antioxidant was not employed, we found it necessary to add BHT in order to prevent the artificial development of large amounts of lipid peroxides in the extract. BHT did not appear to reduce lipid peroxides, specifically hydroperoxides, once they developed. This conclusion was based on studies of cod liver oil during various stages of autoxidation, which showed that the peroxide value, determined by an iodometric method, did not decrease when BHT was added after autoxidation had occurred. Because BHT has a characteristic absorbence in the ultraviolet region of the spectrum (29), absorbency data were corrected for its presence.

\(^7\) Chloroform was purified by distillation in an all glass system and stabilized with methanol 1:50 (vol/vol).
After centrifugation at 3,000 x g for 5 minutes, the supernatant was collected and 10 vol of chloroform followed by 6 of 0.05 M KCl was added, mixed, and allowed to stand overnight at -25°C. When warmed to room temperature, the phases separated cleanly. The lower phase was collected and evaporated in vacuo at 40°C. Complete exclusion of the upper phase was essential for reproducible ultraviolet light absorbancy measurements. The lipid extract was dissolved in 5 vol of chloroform and analyzed the same day. In experiments where the hematocrit of the incubation suspension was between 30 and 40%, lipids were extracted without prior centrifugation from a 2.0-ml sample that was taken as 1 vol for calculation of the quantity of reagents.

The absorbancy at 234 and 208 ma of the lipid extract dissolved in methanol provides a convenient index of peroxidation of the RBC lipids (2), as conjugated dienes and conjugated trienes that absorb at these wavelengths, respectively, are intermediates during autoxidation and peroxidation of polyunsaturated fatty acids (30). The extinctions were expressed in terms of the molar concentration of lipid phosphorus. To determine lipid phosphorus, an adaptation of Marinetti's modification of Bartlett's method was used (31).

We determined the RBC phospholipid distribution by thin-layer chromatography (TLC) on silica gel HR, 0.5 mm thick, with the developing solvent chloroform-methanol-glacial acetic acid-water 25:15:4:2 (vol/vol) (32) to which we added BHT at a concentration of 50 mg per 100 ml to prevent autoxidation during chromatography (33). The spots were made visible in ultraviolet light by spraying with a dichlorofluorescein solution, and the phosphorus content of each spot was analyzed (31).

To prepare RBC total phospholipid fatty acid methyl esters, we employed TLC of the lipid extract on silica gel HR. 0.5 mm thick, in hexane-diethyl ether-glacial acetic acid 70:30:1 (vol/vol) containing BHT at a concentration of 50 mg per 100 ml. The phospholipid, which remained at the origin, was scraped into an ampul, and boron trifluoride-methanol reagent* was added; the ampul was flushed with nitrogen, sealed, and heated in boiling water for 90 minutes according to the method of Morrison and Smith (34). Four ml of pentane* and 1.0 ml of water were added and mixed, and the fatty acid methyl esters were recovered in the pentane phase. Long chain hydroxy fatty acid methyl esters, if present, were not recovered quantitatively by the single extraction with pentane (34).

Methyl esters of RBC total lipid fatty acids were prepared without prior lipid extraction as follows: A 1.0-ml sample of the incubation suspension was hydrolyzed in 5.0 ml of aqueous 2 N HCl, which contained 25 μg of dl-a-tocopherol1, 11 and 12 μg of BHT, in a sealed tube at 110°C for 18 hours. The fatty acids were ex-
III, IV, V) does indicate a loss in palmitic acid with peroxidation, presumably because some peroxidized phosphatidyl ethanolamine and phosphatidyl serine, which contain palmitic acid but almost no 24:0 (31), were not in the extract.

**Results**

RBC from the untreated patients with abetalipoproteinemia showed a marked sensitivity to H₂O₂ (Figure 1). Seventy-nine to 95% of the cells from two untreated patients lysed during 4 to 6 hours of exposure to minute amounts of H₂O₂, whereas less than 3% of the RBC from normal subjects lysed during 10 hours, and less than 7% during 21 hours of exposure.

Evidence was found for lipid peroxidation in the RBC from untreated patients with abetalipoproteinemia after exposure to H₂O₂ in vitro (Table 1). This evidence consisted of striking increases in the TBA reaction (malondialdehyde) on the trichloroacetic acid extracts of the cell suspensions and increases in the absorbencies at 234 and 268 mμ (conjugated dienes and conjugated trienes, respectively) of the lipid extracts. Since it appears that certain peroxidized lipids may be lost, in part, during the RBC extraction procedure (see below), the ultraviolet absorbency measured may underestimate the degree of peroxidation that has occurred. Addition of dl-α-tocopherol,12 glucose, or sodium nitrite to the incubation solution prevented hemolysis as well as increase

12 Calbiochem, Los Angeles, Calif.

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**TABLE I**

**Effect of H₂O₂ in vitro on red blood cells (RBC) from untreated patients with abetalipoproteinemia**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Analyses after incubation of RBC with H₂O₂ diffusion*</th>
<th>Absorbency of total lipid†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analyses of suspension</td>
<td>TBA test</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>moles × 10⁻⁸</td>
</tr>
<tr>
<td>Not incubated</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Incubated in air</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Incubated with H₂O₂ diffusion‡</td>
<td>87.0</td>
<td>13.9</td>
</tr>
<tr>
<td>+ Glucose, 200 mg per 100 ml</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>+ NaNO₂, 28 mg per 100 ml</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>+ CO, 10 ml per 100 ml of atmosphere</td>
<td>5.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>

* Data are averaged from two experiments with RBC from patient A.V. and one experiment with RBC from patient R.B. The hematocrit of the RBC suspension was 10%. Exposure time was 4 to 6 hours.
† Lipids were extracted without 2,6-di-tert-butyl 4 methyl phenol.
‡ In all of the samples incubated with H₂O₂ diffusion alone, hemolysis was >79.0%, 2-thiobarbituric acid (TBA) >12.3, and absorbency at 234 μM >3.5 and at 268 μM >1.9. Values for normal controls are shown in Table II.
tocopherol-treated specimen was protected (TBA = 1.3 × 10⁻⁸ mole of malonaldehyde per ml RBC, hemolysis = 10%), but the glucose-treated specimen had exhibited peroxidative hemolysis (TBA = 7.2 × 10⁻⁸ mole, hemolysis = 84%).

We provided further evidence for the importance of lipid peroxidation in the hemolysis observed on exposure of RBC from patients with abetalipoproteinemia to H₂O₂ in vitro by studying the effect of vitamin E therapy in four patients (Table II). The RBC from two patients, A.V. and R.B., were studied before and during the administration of vitamin E (d-α-tocopheryl polyethylene glycol succinate) ¹⁸ equivalent to 750 mg of α-tocopherol daily by mouth. Protection of the RBC against autohemolysis, but not H₂O₂, was noted after 1 week of therapy. After 8 weeks, the RBC were fully protected for at least 7 hours of exposure to H₂O₂. Maintenance of this improvement was documented for patient A.V. after 12 weeks of treatment. Two patients, R.I. and M.S., had received vitamin E in a variety of dosage forms when these tests were first performed. Their RBC gave normal responses to H₂O₂ in this system on incubation for 7 and 10 hours, respectively. Patient M.S. dis-

* Estimated by visual comparison.
† Normal values in this laboratory are <4.5%.
‡ Averaged from two normal subjects; one was A.V.’s mother.
§ Average ± standard deviation from six normal subjects.

TABLE II

<table>
<thead>
<tr>
<th>Patient</th>
<th>Treatment duration</th>
<th>Autohemolysis test</th>
<th>Incubation time</th>
<th>Hemolysis</th>
<th>TBA test</th>
<th>Absorbeny of lipid extract</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>weeks</td>
<td>%</td>
<td>hr</td>
<td>%</td>
<td>moles × 10⁻⁴</td>
<td>per ml RBC</td>
</tr>
<tr>
<td>A.V.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>55</td>
<td>4.0</td>
<td>95</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>6.4</td>
<td>4.5</td>
<td>&gt;80*</td>
<td>2.1</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>7.2</td>
<td>7.0</td>
<td>2.1</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>6.8</td>
<td>4.0</td>
<td>2.1</td>
<td>1.2</td>
<td>0.4</td>
</tr>
<tr>
<td>R.B.</td>
<td></td>
<td>58</td>
<td>4.5</td>
<td>91</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>7.5</td>
<td>4.5</td>
<td>&gt;80*</td>
<td>2.7</td>
<td>1.2</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>5.8</td>
<td>7.0</td>
<td>2.1</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>R.I.</td>
<td></td>
<td>3.6</td>
<td>7.0</td>
<td>2.1</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>M.S.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off 5 weeks</td>
<td>6.0</td>
<td>22.0</td>
<td>16</td>
<td></td>
<td>19.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Off 20 weeks</td>
<td>5.6</td>
<td>4.0</td>
<td>94</td>
<td></td>
<td>2.1 ± 0.2§</td>
<td>0.9 ± 0.1§</td>
</tr>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>†</td>
<td>6.5</td>
<td>11</td>
<td></td>
<td>2.1 ± 0.2§</td>
<td>0.9 ± 0.1§</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.0</td>
<td>14 ± 0.2§</td>
<td></td>
<td>2.1 ± 0.2§</td>
<td>0.9 ± 0.1§</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td>2†</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>20.5</td>
<td>4†</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

18 Provided by Dr. Stanley Ames, Distillation Products Industries, Rochester, N. Y.

continued vitamin E therapy, and his RBC exhibited sensitivity to H₂O₂ when tested several months later; however, at that time his autohemolysis test was not strikingly abnormal.

The fatty acid and phospholipid distribution of the RBC from these patients during vitamin E therapy (38) was similar to that reported previously for untreated patients with abetalipoproteinemia (15, 18, 39), suggesting that the protective effect of vitamin E in these studies was not due to correction of the abnormal RBC lipid distribution. Vitamin E administered orally in a water–soluble form protected the RBC, even though tocopherol could not be determined in the plasma. This discrepancy may be explained either by increased plasma levels that were still below the useful range of the method employed (< 0.08 mg per 100 ml) or by increased tissue levels not reflected in the plasma because of the absence of beta lipoprotein, where most of the plasma tocopherol is found normally; tissue levels were not determined.

Sequential measurements of lysis and lipid peroxidation during exposure to H₂O₂ diffusion were carried out on the RBC of patient M.S., who had not received vitamin E for 6 months. The results from the two experiments done 4 weeks apart (experiments A and B) are shown in Table III. The
TABLE III

Sequential changes during exposure of RBC from an untreated patient* with abetalipoproteinemia to H\textsubscript{2}O\textsubscript{2} in vitro

<table>
<thead>
<tr>
<th></th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incubation time with H\textsubscript{2}O\textsubscript{2} diffusion (hours)</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td>dl-\alpha-Tocopherol added (\mu g per ml RBC suspension)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemolysis (%)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2-Thiobarbituric acid test (moles \times 10\textsuperscript{-4} malonylaldehyde/ml RBC)</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Absorbeny of total lipid (\epsilon \times 10\textsuperscript{-3})</td>
<td>234 \textmu \text{m}</td>
<td>0.88</td>
</tr>
<tr>
<td>268 \textmu \text{m}</td>
<td>0.33</td>
<td>0.35</td>
</tr>
<tr>
<td>Fatty acid distribution in total phospholipid† (weight %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16:0</td>
<td>20.2</td>
<td>20.2</td>
</tr>
<tr>
<td>18:0 + 18:1 aldehyde§</td>
<td>16.1</td>
<td>16.3</td>
</tr>
<tr>
<td>18:1</td>
<td>10.7</td>
<td>10.4</td>
</tr>
<tr>
<td>18:2</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>20:3\omega6 + 22:0</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>20:4\omega6 + 22:1¶</td>
<td>14.5</td>
<td>12.7</td>
</tr>
<tr>
<td>24:0</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>22:4\omega6 + 24:1‖</td>
<td>13.2</td>
<td>12.6</td>
</tr>
<tr>
<td>22:5\omega6</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>24:2</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>22:5\omega3</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>22:6\omega3 + 26:0**</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Sum of 10 minor peaks</td>
<td>5.8</td>
<td>4.5</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>95.2</td>
</tr>
<tr>
<td>Phospholipid distribution†† (molar %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphatidyl ethanolamine + polyglycerolphosphatide‡‡</td>
<td>30.4</td>
<td></td>
</tr>
<tr>
<td>Phosphatidyl serine</td>
<td>16.8</td>
<td></td>
</tr>
<tr>
<td>Phosphatidyl inositol†‡</td>
<td>0.2</td>
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<tr>
<td>Phosphatidyl choline</td>
<td>18.7</td>
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<tr>
<td>Sphingomyelin</td>
<td>33.7</td>
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<tr>
<td>Lyso phosphatidyl choline</td>
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</tr>
<tr>
<td>Origin</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

* Patient M.S., who had not received vitamin E for 6 months before experiment A and 7 months before experiment B.
† In this abbreviation of the fatty acids, the first two digits state the number of carbon atoms, the third digit states the number of double bonds, and the digit after the omega states the end carbon chain length.
‡‡ The fatty acid percentages in these incubated samples were recalculated by means of the factor that made the per cent of palmitic acid equal to its value in the control sample.
§ The dimethyl acetel was eluted with this peak and accounted for 12% of the area in control samples; this component remained after exposure to H\textsubscript{2}O\textsubscript{2}.
¶ 24:1 accounted for 55% of this peak in control samples.
‖ 26:0 accounted for 9% of this peak in control samples.
** Based on the per cent of phosphorus in each spot on thin layer chromatography. Only 80.4% of the lipid phosphorus of the control RBC was obtained in the lipid extract of cells that were exposed to H\textsubscript{2}O\textsubscript{2}.
†† Not positively identified.

Data from experiment A suggest that lipid changes preceded lysis, as 1) the relative amount of arachidonic acid (20:4\omega6) was decreased 12% after 1.5 hours of incubation, although no abnormal hemolysis was evident; and 2) the TBA reaction was increased 58% of the maximal value after 2.5 hours, when hemolysis was only 7%. The temporal relationship between parameters of lipid peroxidation and hemolysis for experiment A is diagrammed in Figure 2. In experiment B, lysis had already proceeded too far at 2.8 hours, and the temporal relationship could not be determined.

The distribution of the individual phospholipids was analyzed in experiment B (Table III). The lipid phosphorus content of the extract of incubated RBC was only 80.4% of the control value. This finding along with the low values for phosphatidyl ethanolamine (PE) and phosphatidyl...
TREATED PATIENT WITH H₂O₂ IN A. EXPERIMENT cent cent of (PS) decreased interpretation was removed was and plate. represented probably the that fatty acid RBC effect. The related was decrease of The extract lipid The loss of acid of (18:0), z 2. FIG. 2. EFFECTS OF EXPOSURE OF RBC FROM AN UNTREATED PATIENT WITH ABETALIPOPROTEINEMIA (M.S.) TO H₂O₂ IN VITRO, DIAGRAMMED FROM DATA IN TABLE III, EXPERIMENT A. Per cent TBA reaction refers to per cent of 2-thiobarbituric acid reaction at 4.5 hours, and per cent arachidonic acid to per cent of value at 0 time.

serine (PS) suggested that most of the missing PE and PS was not extracted from the RBC or was removed by the washing procedure. This interpretation was supported by the observation of a decreased amount of Ninhydrin staining on the TLC plate. A small amount of Ninhydrin staining in the region of phosphatidyl inositol indicated that the apparent increase shown for that moiety probably represented peroxidized “cephalin” that trailed during chromatography. Large decreases were observed in the relative concentrations of the polyunsaturated fatty acids (Table III). The large amount of arachidonic acid normally present in RBC made it the most useful polyunsaturated fatty acid to quantify as an index of the H₂O₂ effect. The relative concentration of stearic acid (18:0), however, also showed a large decrease. The decrease of this saturated fatty acid probably was related to the decreased phospholipid in the lipid extract after exposure of the RBC to H₂O₂. The stearic acid of human RBC is found mainly in PE and PS and is by far the most abundant fatty acid in the latter phospholipid (31, 40, 41); loss of cephalin from the lipid extract, therefore, may account for a decrease of stearic acid.

Because the decreased extraction of peroxidized phospholipid may influence results of fatty acid analyses of lipid extracts, the fatty acid composition of the total lipid in the incubation suspension was determined without prior extraction. This was accomplished by acid hydrolysis of the RBC suspension, conversion of the fatty acids to methyl esters, and GLC of these derivatives. The results indicated that mainly the polyunsaturated fatty acids were affected by exposure of the RBC to H₂O₂ (Table IV). The decrease of a given fatty acid moiety appeared to be related to the number of double bonds that it contained. The decrease of the peak that contained the polyunsaturated fatty acid 22:4ω6 probably would have been larger if the peak did not also contain a large amount of nervonic acid (24:1). By this method of analysis, stearic acid (18:0) was decreased only 7%.

To assess further the role of vitamin E deficiency in the RBC alterations observed, the RBC from vitamin E-deficient rats were tested in the same manner. The RBC changes that occurred (Table V) were similar to those seen with RBC

<table>
<thead>
<tr>
<th>TABLE IV</th>
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<tbody>
<tr>
<td>The effect of H₂O₂ exposure on the RBC total lipid fatty acid distribution determined without prior extraction*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Incubation time exposed to H₂O₂</th>
<th>0.0</th>
<th>4.0 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemolysis (%)</td>
<td>&gt;80†</td>
<td></td>
</tr>
<tr>
<td>Fatty acid distribution in total lipid‡ (weight %)</td>
<td>16:0</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>18:0</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>18:1</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>18:2</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>20:3ω6 + 22:0</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>20:4ω6 + 22:1</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>24:0</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>22:4ω6 + 24:1</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>22:5ω6</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>24:2</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>22:5ω3</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>22:6ω3 + 26:0</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Sum of 10 minor peaks</td>
<td>5.0</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>80.2</td>
</tr>
</tbody>
</table>

* The RBC were from patient M.S., who had not received vitamin E for 7 months before this study.
† Estimated by visual comparison.
‡ Fatty acid methyl esters were prepared by aqueous HCl hydrolysis of the incubation suspension followed by methylation of the extracted fatty acids (see text). Explanation for abbreviations of the fatty acids is given in footnote to Table III.
§ The fatty acid percentages in the incubated sample were recalculated to make the per cent of palmitic acid equal to that of the control sample.
from the patient with abetalipoproteinemia. Lipid peroxidation again appeared to precede hemolysis; at 0.7 hour the TBA reaction was elevated, but hemolysis was not increased significantly. Considerable hemolysis was evident, however, before H₂O₂ exposure, and the hemolysis proceeded at a more rapid rate.

Alpha-tocopherol, when added to the incubation medium before exposure to H₂O₂, prevented all of the changes observed in the RBC of patients with abetalipoproteinemia (Tables I and III) and of rats with vitamin E deficiency (Table V).  

**Discussion**

The present study demonstrates the striking vulnerability to H₂O₂ of RBC from untreated patients with abetalipoproteinemia, as evidenced by lipid peroxidation and hemolysis (peroxidative hemolysis). The lipid peroxidation was similar to that seen in spontaneously autoxidized lipid extracts from normal human RBC (2). Vitamin E deficiency appeared to be responsible for this vulnerability, as 1) the patients were shown to be deficient in vitamin E, 2) vitamin E is a major biologic lipid antioxidant, 3) administration of vitamin E to the patients or addition to the RBC in vitro prevented peroxidative hemolysis, and 4) the RBC damage in response to H₂O₂ could be duplicated in RBC from vitamin E–deficient rats.

Rose and György were the first to describe the increased hemolysis of RBC from vitamin E–de-
ficient rats upon exposure to H2O2 added directly in vitro; administration of the vitamin in vivo or addition to the RBC suspension in vitro, furthermore, prevented hemolysis (42). Slight modifications of their method for H2O2 exposure have been used for evaluation of vitamin E levels in premature infants (43, 44), newborn full-term infants (44, 45), and children and adults in a variety of clinical circumstances that includes dietary alterations (5, 11, 44, 46) and malabsorption syndromes (12, 44, 46). In the present study, minute amounts of H2O2 were added by continuous diffusion into a suspension of RBC during incubation as described by Cohen and Hochstein (25, 26); this method provides an approximation to the continuous formation of H2O2 as it might occur under physiologic conditions. The amount of H2O2 required for hemolysis in this system was approximately three orders of magnitude smaller than in the direct H2O2 addition test described by Rose and György (42). The low levels of H2O2 provided by the diffusion system have helped to elucidate the importance of the enzyme glutathione peroxidase as a primary defense mechanism of RBC against the minute amounts of H2O2 that may arise in vivo from the action of certain hemolytic drugs (26, 47-49). This H2O2 diffusion system was employed in these studies of patients with abetalipoproteinemia to demonstrate the possible consequences of deficiency of vitamin E, another primary biologic defense against peroxidative stress.

Previous studies have shown that hemolysis on exposure to H2O2 of RBC from vitamin E–deficient man (5) and animals (4, 6) is accompanied by an increase in the TBA reaction of the lysate. It was also shown that replacement of vitamin E in vivo by oral or parenteral routes, or addition of the vitamin to the incubation suspension before exposure to H2O2, prevented the increase in the TBA reaction as well as the hemolysis (4-6). The protection afforded by vitamin E appears to be based on its antioxidant properties, because lipid-soluble antioxidants that are not of biologic origin protect vitamin E–deficient RBC during exposure to H2O2 in vitro (5). These lines of evidence have suggested that peroxidation of lipids may be an important factor in the hemolysis of vitamin E–deficient RBC on exposure to H2O2.

Evidence for lipid peroxidation in the present study is based on analyses of the ultraviolet light absorbancy and the fatty acid composition of lipid extracts of the incubation suspension, as well as on the results of the TBA test and the protective effect of vitamin E in vitro and in vivo. Increases in ultraviolet light absorbancy paralleled the increase in the TBA reaction. The increased absorbencies at 234 and 268 nm are consistent with the appearance of conjugated dienes and conjugated trienes, respectively, which are well-established intermediate structures formed during autooxidation of polyunsaturated fatty acids (30). Fatty acid analyses showed a decrease in unsaturated moieties that appeared to be proportional to their number of double bonds. The rates of fatty acid autooxidation have been reported to be many times greater for polyunsaturated than for saturated moieties (50). A similar hierarchy for the susceptibility of tissue lipids based on their degree of unsaturation was shown for heme-catalyzed peroxidation (9, 51).

Evidence was obtained supporting a hypothesis that peroxidation of membrane lipids is the basis for hemolysis on exposure to H2O2 in vitro of RBC from patients with abetalipoproteinemia and vitamin E deficiency. A time sequence study showed a decrease in the relative amount of phospholipid arachidonic acid before abnormal hemolysis occurred and a large increase in the TBA reaction when hemolysis was starting. Similar TBA changes were observed in the RBC from vitamin E–deficient rats. All procedures tested that prevented peroxidation in vitro (i.e., addition to the incubation system of tocopherol, glucose, nitrite, or carbon monoxide) also prevented hemolysis. Finally, after treatment of the patients with vitamin E, their RBC showed increased resistance to H2O2 in vitro. This effect was presumably due to the antioxidant properties of the vitamin rather than to some possible secondary influence of the vitamin, such as a change in the abnormal distribution of phospholipids and fatty acids in their RBC, because detailed analyses of RBC lipids performed concurrently with this study showed no correction of the altered lipid distribution as a result of treatment with vitamin E (38).

Heme-containing compounds have been recognized as important catalysts of lipid peroxidation in various animal tissues (9). Lipid peroxidation in RBC from patients with abetalipoproteinemia...
appeared to be catalyzed primarily by either oxy-
or deoxyhemoglobin, because nitrite and carbon
monoxide, which produced methemoglobin or
carboxyhemoglobin, respectively, inhibited peroxi-
dation. These findings were in agreement with
those of Goldstein and Cohen on RBC from vita-
im E–deficient rats (6).

The partial protection of RBC from patients
with abetalipoproteinemia by addition of glucose
to the incubation suspension may be explained by
the action of glutathione peroxidase, which cata-
yzes the destruction of \( \text{H}_2\text{O}_2 \) after it diffuses into
the cell (24). In the absence of glucose, the pro-
tective glutathione is lost by oxidation; in the
presence of glucose, the NADPH required for
reduction of oxidized glutathione is derived from
hexose monophosphate shunt activity. Tocoph-
erol, however, protected for a longer incubation
time than glucose, in agreement with similar ob-
servations with RBC from vitamin E–deficient
rats (6). These findings indicate that tocopherol
provides a primary biologic defense against
peroxidative hemolysis.

Anemia is not generally found in patients with
abetalipoproteinemia; however, Simon and Ways
(16) and Farquhar and Ways (52) have pre-
sented evidence and have summarized the work
of others that strongly suggests that intermittent
hemolysis may occur. Although the causes of this
hemolysis have not been defined, \( \text{H}_2\text{O}_2 \) formed
in vivo, such as by Mycoplasma pneumoniae or
M. laidlawii (53, 54), 8-aminoquinoline antimarial-
larials (47), or menadione (47, 48), may be re-
sponsible. Aspirin, phenacetin, and sulfonamides
are examples of other drugs that have, in theory,
this same capability (47). In addition, exposure
of vitamin E–deficient animals to hyperbaric oxy-
gen causes a hemolytic response (4), which ap-
pears from recent evidence to be based on peroxi-
dation of membrane lipids (8). Therefore, treat-
ment of patients with abetalipoproteinemia with
\( \text{H}_2\text{O}_2 \)-producing drugs or hyperbaric oxygen
should be approached with caution.

Should peroxidative changes occur in the lipids
of RBC in vivo, the clinical manifestations may
be tempered by that cell’s considerable capacity
for replacement. In contrast, the nervous system
exhibits greater functional differentiation with
limited regenerative capacity and has low levels
of the protective enzymes glutathione peroxidase
and catalase (55). Lipid peroxidation of this
tissue may be expected to produce diverse and
cumulative changes. Indeed, vitamin E deficiency
in laboratory animals is associated with charac-
teristic neurological and neuropathological find-
ing (56–58). A major disability in abetalipopro-
teinemia is a progressive neurologic disorder (52,
59). The possibility arises, therefore, that the
neurologic as well as other clinical manifestations
in patients with abetalipoproteinemia may result
from lipid peroxidation.

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