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Satchell, Leanne and Leake, David (2012) Oxidation of low density lipoprotein by iron at lysosomal pH: implications for atherosclerosis. *Biochemistry*, 51 (18). pp. 3767-3775. ISSN 0006-2960 doi: <https://doi.org/10.1021/bi2017975> Available at <https://centaur.reading.ac.uk/27950/>

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To link to this article DOI: <http://dx.doi.org/10.1021/bi2017975>

Publisher: American Chemical Society

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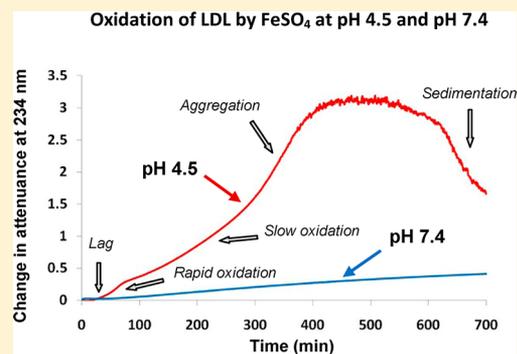
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Oxidation of Low-Density Lipoprotein by Iron at Lysosomal pH: Implications for Atherosclerosis

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ABSTRACT: Low-density lipoprotein (LDL) has recently been shown to be oxidized by iron within the lysosomes of macrophages, and this is a novel potential mechanism for LDL oxidation in atherosclerosis. Our aim was to characterize the chemical and physical changes induced in LDL by iron at lysosomal pH and to investigate the effects of iron chelators and α -tocopherol on this process. LDL was oxidized by iron at pH 4.5 and 37 °C and its oxidation monitored by spectrophotometry and high-performance liquid chromatography. LDL was oxidized effectively by FeSO_4 (5–50 μM) and became highly aggregated at pH 4.5, but not at pH 7.4. The level of cholesteryl esters decreased, and after a pronounced lag, the level of 7-ketocholesterol increased greatly. The total level of hydroperoxides (measured by the triiodide assay) increased up to 24 h and then decreased only slowly. The lipid composition after 12 h at pH 4.5 and 37 °C was similar to that of LDL oxidized by copper at pH 7.4 and 4 °C, i.e., rich in hydroperoxides but low in oxysterols. Previously oxidized LDL aggregated rapidly and spontaneously at pH 4.5, but not at pH 7.4. Ferrous iron was much more effective than ferric iron at oxidizing LDL when added after the oxidation was already underway. The iron chelators diethylenetriaminepentaacetic acid and, to a lesser extent, desferrioxamine inhibited LDL oxidation when added during its initial stages but were unable to prevent aggregation of LDL after it had been partially oxidized. Surprisingly, desferrioxamine increased the rate of LDL modification when added late in the oxidation process. α -Tocopherol enrichment of LDL initially increased the rate of oxidation of LDL but decreased it later. The presence of oxidized and highly aggregated lipid within lysosomes has the potential to perturb the function of these organelles and to promote atherosclerosis.



The accumulation and oxidation of low-density lipoprotein (LDL) in the arterial intima might play an important role in atherosclerosis.¹ There has been an enormous amount of work on the mechanisms by which LDL might be oxidized, but no consensus has emerged. Possible mechanisms involve iron, copper, caeruloplasmin, lipoxygenase, superoxide, peroxynitrite, and myeloperoxidase.²

There is evidence that LDL can be modified by nonoxidative mechanisms in the arterial wall so that it is endocytosed faster by macrophages. These include modification by sphingomyelinase,³ secretory phospholipase A₂,⁴ or cathepsin D.⁵ We have proposed that nonoxidatively modified LDL might be taken up by macrophages in atherosclerotic lesions and oxidized within lysosomes.⁶ Macrophages in culture were capable of taking up acetylated or aggregated LDL and oxidizing it in lysosomes.⁶ Lysosomes are a source of redox-active iron,⁷ and iron is present at elevated levels in atherosclerotic lesions.⁷ Lysosomal LDL oxidation may explain why oxidized LDL is present within lesions despite the apparently strong antioxidant protection within the arterial intima.⁸ Oxidized LDL formed within lysosomes might affect cell function or be released from cells into the interstitial fluid, both with potentially atherogenic consequences.

Oxidation of LDL by copper at pH 7.4 has been extensively characterized,⁹ whereas little is known about the chemical

composition of LDL oxidized by iron under the acidic conditions present in lysosomes (pH ~4.5). We report here the chemical changes in LDL oxidized by iron at lysosomal pH and the surprising effects of ferrous and ferric iron, iron chelators, and α -tocopherol.

MATERIALS AND METHODS

LDL Isolation. LDL ($d = 1.019\text{--}1.063$ g/mL) was isolated by sequential ultracentrifugation of pooled plasma from four healthy adult volunteers.¹⁰

Measurement of Conjugated Dienes. Conjugated diene formation was monitored at 234 nm.¹¹ LDL (50 μg of protein/mL) was oxidized by freshly dissolved FeSO_4 (5 μM) or FeCl_3 (5 μM) at 37 °C in washed Chelex-100-treated 150 mM NaCl/10 mM sodium acetate buffer (pH 4.5) or 150 mM NaCl/10 mM 3-(*N*-morpholino)propanesulfonic acid (MOPS) buffer (pH 7.4), in capped quartz cuvettes, in an automatic six-position (Lambda 2) or eight-position (Lambda Bio 40) spectrophotometer (Perkin-Elmer). The FeSO_4 or FeCl_3 stock solutions for the experiments at pH 4.5 were dissolved in buffer

Received: December 7, 2011

Revised: April 11, 2012

Published: April 11, 2012

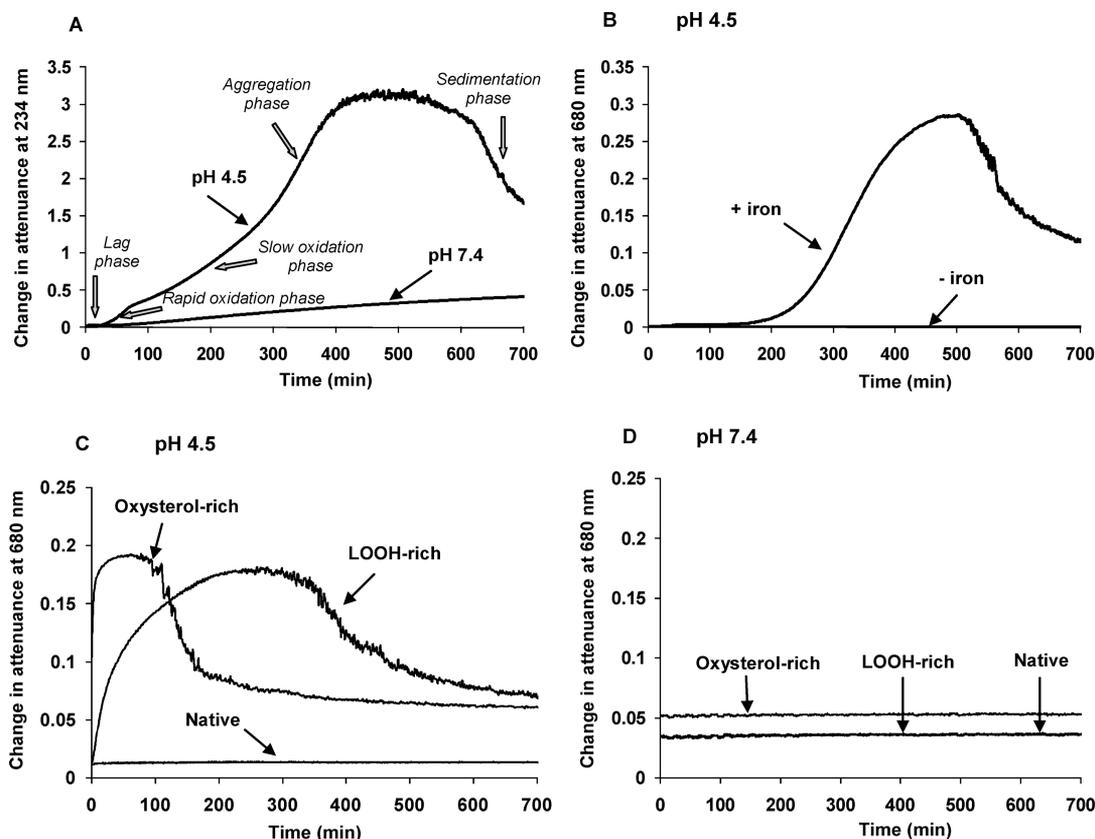


Figure 1. Oxidation of LDL by FeSO_4 at pH 4.5 or 7.4. (A) LDL (50 μg of protein/mL) in NaCl/sodium acetate buffer (pH 4.5) or NaCl/MOPS buffer (pH 7.4) was incubated with 5 μM FeSO_4 at 37 $^\circ\text{C}$ in quartz cuvettes, and oxidation was monitored by measuring the change in attenuation at 234 nm against appropriate reference cuvettes. (B) LDL (50 μg of protein/mL) in NaCl/sodium acetate buffer (pH 4.5) was incubated with or without 5 μM FeSO_4 at 37 $^\circ\text{C}$ in quartz cuvettes, and aggregation was monitored by measuring light scattering at 680 nm against appropriate reference cuvettes. Please note that the line without FeSO_4 lies over the abscissal axis. (C and D) Oxysterol-rich or lipid hydroperoxide (LOOH)-rich oxidized LDL or native LDL (all 50 μg of protein/mL) was incubated at 37 $^\circ\text{C}$ (in the absence of iron) in quartz cuvettes in either NaCl/sodium acetate buffer (pH 4.5) (C) or NaCl/MOPS buffer (pH 7.4) (D). Aggregation was monitored by measuring light scattering at 680 nm against appropriate reference cuvettes. The lines for native LDL and LOOH-rich LDL at pH 7.4 lie on top of each other. For the sake of clarity, the attenuation at time zero was subtracted from the data in panels A and B but not in panels C and D. These data are representative examples of at least three independent experiments.

at pH 4.5, rather than in water, to prevent the rapid oxidation of ferrous ion that occurs at higher pH values.¹² The change in attenuation at 234 nm was measured every minute at 37 $^\circ\text{C}$, against reference cuvettes lacking LDL. The attenuation at time zero was subtracted from all values, except where stated.

Measurement of LDL Aggregation. LDL aggregation was monitored by continuously measuring light scattering¹³ at 680 nm and 37 $^\circ\text{C}$ in the spectrophotometers mentioned above.

LDL Oxidation for Compositional Analysis. LDL (250 μL at a concentration of 2 mg of protein/mL) was oxidized with freshly dissolved FeSO_4 (50 μM) at 37 $^\circ\text{C}$ in NaCl/sodium acetate buffer (pH 4.5). At various times over 48 h, the oxidation was stopped by addition of butylated hydroxytoluene (BHT, final concentration of 80 μM , from a 2 mM stock solution in ethanol) and EDTA (final concentration of 4 mM).

Preparation of Lipid Hydroperoxide-Rich and Oxysterol-Rich LDL. Lipid hydroperoxide-rich LDL and oxysterol-rich LDL were produced by oxidizing LDL with CuSO_4 (10 μM) at 4 and 37 $^\circ\text{C}$, respectively, in 150 mM NaCl/10 mM MOPS buffer (pH 7.4), followed by dialysis in the presence of EDTA overnight to remove copper.¹⁴

Total Hydroperoxide Content. Hydroperoxides (ROOH) were measured using a triiodide method.¹⁵

Relative Electrophoretic Mobility. The relative electrophoretic mobility (REM) of oxidized LDL was measured using a Paragon Lipogel electrophoresis system (Beckman Instruments), according to the manufacturer's instructions, with 3 μL of LDL (2 mg of protein/mL) applied to the origin and run at 100 V for 40 min. The distance that the samples migrated was divided by the distance migrated by native LDL.

Thiobarbituric Acid Reactive Substances (TBARS). TBARS were assessed as described previously.¹⁶

HPLC Analysis. Lipids were extracted from oxidized LDL for HPLC analysis using methanol and hexane.¹⁷ The upper hexane layer was dried under a stream of nitrogen and redissolved in 200 μL of an acetonitrile/2-propanol/water mixture (44/54/2, by volume). Lipid species were separated by reverse phase HPLC in a Capital C18 column (250 mm \times 4.6 mm, 5 μm particle size, 5 μm guard column) with a Perkin-Elmer 200 series HPLC system. Cholesterol and cholesteryl esters were detected at 210 nm using an acetonitrile/2-propanol/water mobile phase (44/54/2, by volume) and a flow rate of 1.5 mL/min. 7-Ketocholesterol and cholesteryl linoleate hydroperoxide were detected at 234 nm using an acetonitrile/2-propanol/water mobile phase (50/48.8/1.2, by volume) and a flow rate of 1.2 mL/min. The identities of the peaks were

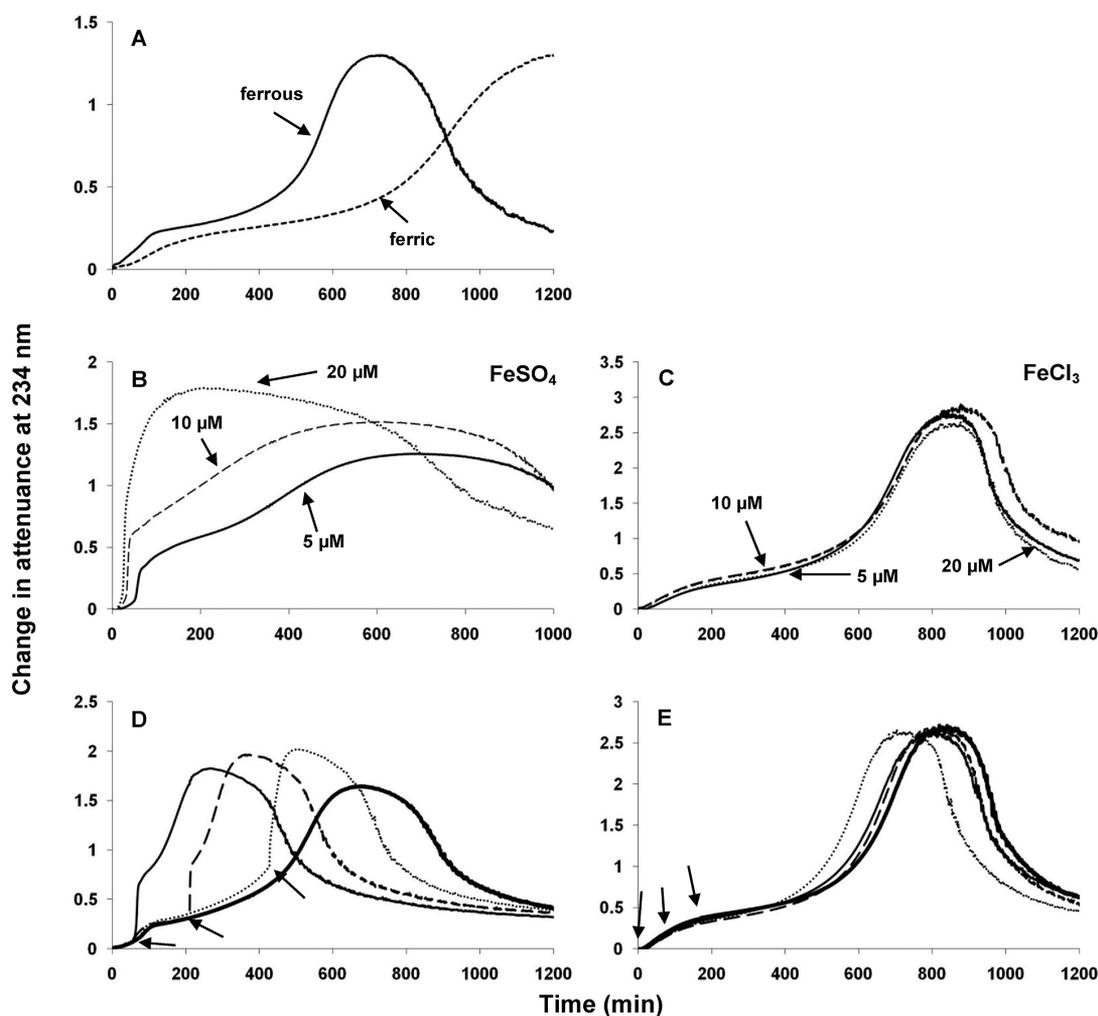


Figure 2. Comparison of the oxidation of LDL by FeSO_4 and FeCl_3 at pH 4.5. (A) LDL ($50 \mu\text{g}$ of protein/mL) in NaCl/sodium acetate buffer (pH 4.5) was incubated with $5 \mu\text{M}$ FeSO_4 (—) or $5 \mu\text{M}$ FeCl_3 (---) at 37°C in quartz cuvettes. (B and C) LDL was incubated at pH 4.5 and 37°C with FeSO_4 (B) or FeCl_3 (C) at iron concentrations of $5 \mu\text{M}$ (—), $10 \mu\text{M}$ (---), or $20 \mu\text{M}$ (···). (D) LDL was incubated at pH 4.5 and 37°C with $5 \mu\text{M}$ FeSO_4 (thick solid line), and additional FeSO_4 (to give a final concentration of $10 \mu\text{M}$) was added during the rapid oxidation phase (thin solid line), during the slow oxidation phase (---), or at the beginning of the aggregation phase (···), as indicated by the arrows. (E) LDL was incubated at pH 4.5 and 37°C with $5 \mu\text{M}$ FeCl_3 (thick solid line), and additional FeCl_3 (to give a final concentration of $10 \mu\text{M}$) was added at the start of the reaction (thin solid line), during the rapid oxidation phase (---), or during the slow oxidation phase (···), as indicated by the arrows. Oxidation was monitored by measuring the change in attenuation at 234 nm against appropriate reference cuvettes. These data are representative examples of at least three independent experiments.

confirmed by mass spectrometry (data not shown), and the lipids were quantified using commercially available standards.

Enrichment of LDL with α -Tocopherol. Blood was centrifuged at $1500g$ for 30 min at 4°C in the presence of 3 mM Na_2EDTA . The plasma was incubated at 37°C for 3 h with α -tocopherol (1 mM) dissolved in dimethyl sulfoxide (1% of the plasma volume) or with dimethyl sulfoxide alone (1% of the plasma volume).¹⁸ LDL was then isolated from the plasma.¹⁰ The α -tocopherol content of the LDL was measured by HPLC¹⁹ after extraction using methanol and hexane¹⁷ and drying the hexane using nitrogen. The extract was redissolved in ethanol and injected into the column described above. The mobile phase consisted of 99% methanol and 1% water (v/v), with a flow rate of 1 mL/min and detection at 298 nm.

Statistical Analysis. The mean and the standard error of the mean (SEM) of n independent experiments are given. Where appropriate, results were evaluated using a paired t test or one-way ANOVA, with a Dunnett's post-hoc test.

RESULTS

Oxidation of LDL by Ferrous Iron at pH 4.5. To compare the oxidation of LDL by iron at lysosomal pH with the oxidation at pH 7.4, LDL ($50 \mu\text{g}$ of protein/mL) was oxidized in NaCl/sodium acetate buffer (pH 4.5) or NaCl/MOPS buffer (pH 7.4) at 37°C in the presence of ferrous iron (FeSO_4 , $5 \mu\text{M}$). The oxidation was followed by measuring the formation of conjugated dienes, which absorb UV radiation at 234 nm. In agreement with previous results,⁶ LDL was oxidized effectively at pH 4.5 and much less so at pH 7.4 (Figure 1A). At pH 4.5, following a lag phase, conjugated diene formation proceeded rapidly and then more slowly. There was then a second rapid increase in attenuation (absorbance of UV plus UV scattering) with rapid minor fluctuations, consistent with UV scattering by aggregates, as the aggregates move in and out of the UV beam. This was followed by a decrease in attenuation, caused by the LDL aggregates, which were clearly visible by eye, sedimenting below the beam of UV radiation. Inverting the cuvette gently to

resuspend the aggregates increased the attenuation. Light scattering was also measured by continuously measuring the attenuation at 680 nm. Light scattering increased rapidly at ~200 min, corresponding with the second rapid phase at 234 nm, and decreased at ~500 min (Figure 1B). There was no light scattering in the absence of iron, showing that LDL aggregation and sedimentation were due to LDL oxidation (Figure 1B).

LDL Aggregation at pH 4.5. We tested if oxidized LDL would spontaneously aggregate at pH 4.5, regardless of whether iron was present. LDL that had previously been oxidized with CuSO_4 to give a species rich in lipid hydroperoxides (LOOH) or oxysterols followed by removal of the CuSO_4 ¹⁴ was incubated at pH 4.5 or 7.4 and 37 °C. Both oxidized forms of LDL aggregated rapidly at pH 4.5, whereas native LDL did not (Figure 1C). Oxysterol-rich LDL aggregated even more rapidly than LOOH-rich LDL, indicating that the extent to which the LDL was oxidized affected its aggregation rate. In contrast, none of the lipoprotein species aggregated at pH 7.4 (Figure 1D).

Oxidation of LDL by Ferrous or Ferric Iron. It has been reported that phagolysosomes in macrophages contain ferrous iron and probably ferric iron.²⁰ Iron will cycle between the two forms during LDL oxidation, and it was therefore of interest to examine the oxidation of LDL with ferrous and ferric iron. LDL was oxidized at pH 4.5 and 37 °C in the presence initially of ferrous iron ($5 \mu\text{M FeSO}_4$) or ferric iron ($5 \mu\text{M FeCl}_3$) (Figure 2A). The oxidation reaction proceeded at a faster rate with ferrous iron than with ferric iron. The time taken to reach an attenuation of 0.1 was 27 ± 6 min in the presence of ferrous iron compared with 79 ± 6 min in the presence of ferric iron ($p < 0.05$; paired t test; $n = 9$ independent experiments). Increasing the concentration of ferrous iron to 10 or 20 μM at the start of the oxidation caused an increase in attenuation attained during the rapid phase (Figure 2B), whereas increasing the concentration of ferric iron surprisingly had no effect on the oxidation kinetics (Figure 2C).

We postulated that the rapid phase of the oxidation reaction with ferrous iron was caused predominantly by ferrous iron and the slower phase was caused when most of the ferrous iron had been converted to ferric iron. This theory was investigated via addition of further iron at different times during the oxidation reaction and examination of the effects on the kinetics of LDL oxidation. When additional $5 \mu\text{M}$ ferrous iron was added to LDL oxidized by FeSO_4 at various time points, there was an immediate rapid burst of oxidation (Figure 2D). In contrast, adding additional $5 \mu\text{M FeCl}_3$ to LDL oxidized by ferric iron had little effect on the rate of oxidation (Figure 2E).

Effects of Iron Chelators. To assess the dependency of the various phases of the oxidation process on the presence of iron, the iron chelators diethylenetriaminepentaacetic acid (DTPA) and desferrioxamine were added during the different phases and the effect on the attenuation was observed. DTPA ($10 \mu\text{M}$), added to LDL at the start of the incubation or during the rapid phase, caused almost complete inhibition of the oxidation (Figure 3A). Addition of DTPA during the slow phase of oxidation caused the rate of oxidation to decrease, but the LDL was still able to aggregate and later sediment. Adding DTPA during the aggregation phase did not greatly affect the aggregation or sedimentation. These data suggest that iron catalyzes oxidation of LDL during the lag, rapid, and slow phases and that when LDL is oxidized sufficiently it is able to

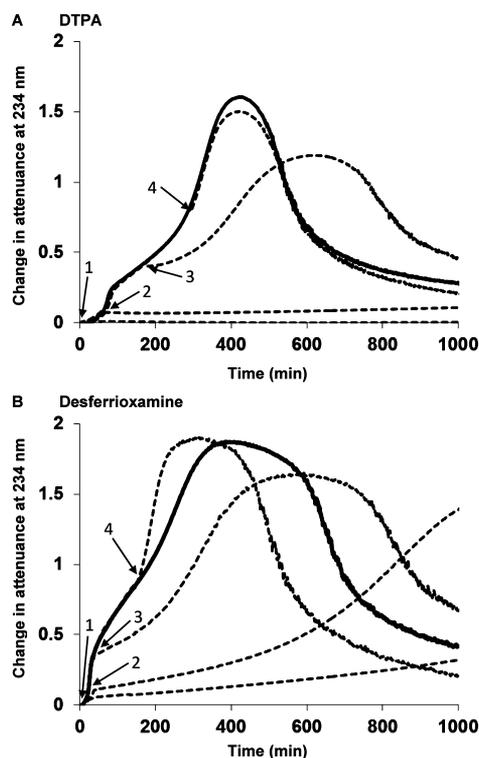


Figure 3. Effect of the iron chelators DTPA and desferrioxamine (both obtained from Sigma-Aldrich) on oxidation of LDL by FeSO_4 at pH 4.5. LDL ($50 \mu\text{g}$ of protein/mL) in NaCl/sodium acetate buffer (pH 4.5) was incubated with $5 \mu\text{M FeSO}_4$ at 37 °C in quartz cuvettes. DTPA (A, final concentration of $10 \mu\text{M}$) or desferrioxamine (B, final concentration of $100 \mu\text{M}$) was added to the cuvettes at the start of the incubation (arrow 1), during the rapid oxidation phase (arrow 2), during the slow oxidation phase (arrow 3), or during the aggregation phase (arrow 4). Oxidation and UV scattering were monitored by measuring the change in attenuation at 234 nm against appropriate reference cuvettes. These data are representative examples of four independent experiments.

aggregate in the absence of iron, which is consistent with the results shown in Figure 1C.

Unlike DTPA, addition of desferrioxamine ($100 \mu\text{M}$) at the start of the incubation or during the rapid phase partially inhibited the oxidation but did not fully inhibit it (Figure 3B). Addition of desferrioxamine at the start of the slow phase of oxidation caused the rate of the reaction to decrease, but the LDL was able to aggregate and then sediment. Interestingly, adding desferrioxamine at the start of the aggregation phase actually caused a faster increase in attenuation ($p < 0.05$; $n = 3$ independent experiments). These data agree with the DTPA data in that the lag, slow, and rapid oxidation phases are dependent on iron. It appears that desferrioxamine is less able than DTPA to inhibit LDL oxidation and may actually promote LDL modification when LDL is sufficiently oxidized.

Effect of α -Tocopherol Enrichment on the Oxidation of LDL by Iron. α -Tocopherol can inhibit^{18,21} or sometimes promote²² LDL oxidation. We therefore investigated its effect on the oxidation of LDL by iron at pH 4.5. LDL was enriched with α -tocopherol via addition of α -tocopherol to plasma and isolation of the LDL.¹⁸ The α -tocopherol content was increased ~4.5 times from 6.5 ± 4.4 to 29.5 ± 9.1 nmol/mg of protein ($p < 0.005$; $n = 6$ independent experiments). As expected, α -tocopherol enrichment increased the length of the lag phase of oxidation of LDL by $5 \mu\text{M CuSO}_4$ at pH 7.4 (Figure 4). The

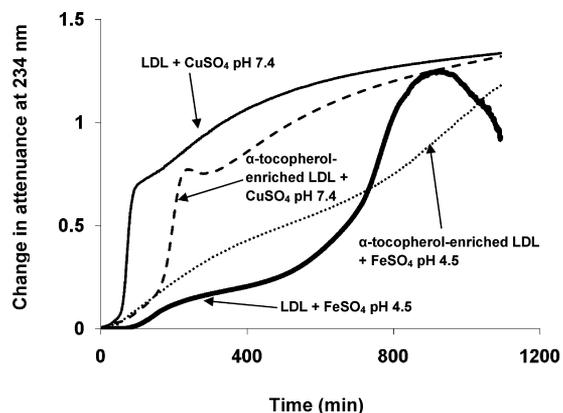


Figure 4. Comparison of the oxidation of α -tocopherol-enriched LDL by FeSO_4 at pH 4.5 and CuSO_4 at pH 7.4. Control LDL ($50 \mu\text{g}$ of protein/mL) was incubated with NaCl/sodium acetate buffer (pH 4.5) containing $5 \mu\text{M}$ FeSO_4 (thick solid line) or NaCl/MOPS buffer (pH 7.4) containing $5 \mu\text{M}$ CuSO_4 (thin solid line) at 37°C in quartz cuvettes. LDL enriched with α -tocopherol was incubated in the same experiment with NaCl/sodium acetate buffer (pH 4.5) containing $5 \mu\text{M}$ FeSO_4 (\cdots) or NaCl/MOPS buffer (pH 7.4) containing $5 \mu\text{M}$ CuSO_4 ($---$). Oxidation was monitored by measuring the change in attenuation at 234 nm against appropriate reference cuvettes. These data are representative examples of at least three independent experiments.

time taken to increase the attenuation at 234 nm by 0.1 increased from 37 ± 9 to 153 ± 28 min ($p < 0.05$; $n = 4$ independent experiments). Very different results were obtained when $5 \mu\text{M}$ FeSO_4 at pH 4.5 was used. The oxidation of α -tocopherol-enriched LDL started immediately with no lag period and was initially faster than that of nonenriched LDL, which had a lag period followed by a rapid phase of oxidation (Figure 4). The oxidation of the nonenriched LDL overtook the oxidation of the α -tocopherol-enriched LDL later in the experiment.

Chemical Characteristics of LDL Oxidized by Iron at pH 4.5. Establishing the lipid composition of LDL oxidized by iron at lysosomal pH might help us to assess the atherogenicity of the oxidized LDL formed in this manner. LDL (2 mg of protein/mL) was oxidized in the presence of FeSO_4 ($50 \mu\text{M}$) at 37°C in NaCl/sodium acetate buffer (concentrations of LDL and FeSO_4 were higher than those used for spectrophotometry because of sensitivity issues). There was a trend for the nonesterified cholesterol levels measured by HPLC to decline during the oxidation, but this was not statistically significant (Figure 5A). The levels of the major polyunsaturated cholesteryl esters in LDL, cholesteryl linoleate (CL) and cholesteryl arachidonate (CA), declined greatly during oxidation by iron (Figure 5C,D). As expected, the levels of CA declined somewhat more rapidly than those of CL, which is probably due to the increased number of double bonds making it more susceptible to free radical attack.²³

The level of the cholesterol oxidation product, 7-ketocholesterol, increased greatly after a long lag period from 0.24 ± 0.14 to 101 ± 21 nmol/mg of LDL protein after oxidation for 48 h (Figure 5B). Cholesteryl linoleate hydroperoxide (CLOOH) levels increased to 457 ± 86 nmol/mg of LDL protein after oxidation for 24 h and then appeared to decrease during the next 24 h (Figure 5E). Total hydroperoxide levels, as determined using a triiodide assay, peaked at 697 ± 91 nmol/mg of LDL protein after oxidation for 24 h (Figure 5F).

Hence, at the peak level of hydroperoxides, cholesteryl linoleate hydroperoxide accounted for most of the hydroperoxides. Other cholesteryl ester hydroperoxides and phospholipid, triacylglycerol, and protein hydroperoxides have not been measured here and may account for the remainder of the total hydroperoxides. Interestingly, in contrast to apparent CLOOH levels, total hydroperoxide levels did not decline much between 24 and 48 h.

The level of TBARS, which consist mainly of malondialdehyde,²³ increased to 23.9 ± 2.9 nmol/mg of LDL protein at 24 h and subsequently decreased at 48 h (Figure 5G).

The electronegativity of the oxidized LDL was also assessed as a measure of the extent of LDL protein oxidation (Figure 5H). The REM of the LDL, measured in agarose gels at pH 8.6, increased slightly as the duration of oxidation increased, reaching 1.3 ± 0.07 after 6 h. LDL oxidized for ≥ 12 h could not be loaded onto the gel effectively because the LDL was highly aggregated.

DISCUSSION

Lysosomal iron is a candidate for catalyzing the oxidation of LDL in vivo. Redox-active iron has been shown to be present in lysosomes,²⁴ probably because of the degradation of ferritin, the turnover of iron-containing organelles or the phagocytosis of erythrocytes. Most of the labile iron in cells is present in lysosomes,²⁵ and the concentration of chelatable iron in some endosomes/lysosomes is $\sim 16 \mu\text{M}$.²⁶ The concentration of redox-active iron in lysosomes is therefore probably above $5 \mu\text{M}$. We have used a concentration of FeSO_4 of $5 \mu\text{M}$ for the spectrophotometry studies and $50 \mu\text{M}$ for the HPLC studies (as the LDL concentration needed to be much higher for the HPLC studies, because of sensitivity issues, and we therefore needed to increase the FeSO_4 concentration, as well). These concentrations of FeSO_4 might be broadly consistent with the concentrations of redox-active iron in lysosomes (although the nature of the redox-active iron and its ligands in lysosomes are unclear).

In agreement with work conducted previously in this laboratory,⁶ LDL was oxidized effectively by $5 \mu\text{M}$ FeSO_4 at lysosomal pH (pH 4.5) but was not oxidized effectively at the pH of plasma or normal interstitial fluid (pH 7.4) (Figure 1A). In contrast, CuSO_4 oxidized LDL effectively at pH 7.4, but not so well at pH 4.5.¹⁶ Acidity increases the solubility of iron and should allow it to oxidize LDL more effectively. Extracellular fluids have a high antioxidant capacity, with the oxidation of LDL by transition metals being inhibited greatly by just a few percent of serum or interstitial fluid.⁸ Oxidation of LDL by iron within lysosomes might help to explain why LDL can be oxidized in atherosclerotic lesions in the presence of strong antioxidant protection in the interstitial fluid of the arterial intima.

The lipid composition of LDL oxidized by iron at lysosomal pH over time has been characterized (Figure 5). The levels of cholesteryl linoleate and arachidonate decreased greatly, mainly because of the oxidation of their polyunsaturated fatty acid (PUFA) moieties.²⁷ PUFA are oxidized via a free radical chain reaction, which is initiated by the abstraction of a hydrogen atom by a free radical at a bisallylic methylene group. As expected, cholesteryl arachidonate was oxidized somewhat more rapidly than cholesteryl linoleate, because of its increased number of double bonds. The levels of the cholesteryl linoleate oxidation product, cholesteryl linoleate hydroperoxide (CLOOH), increased significantly for periods of oxidation of

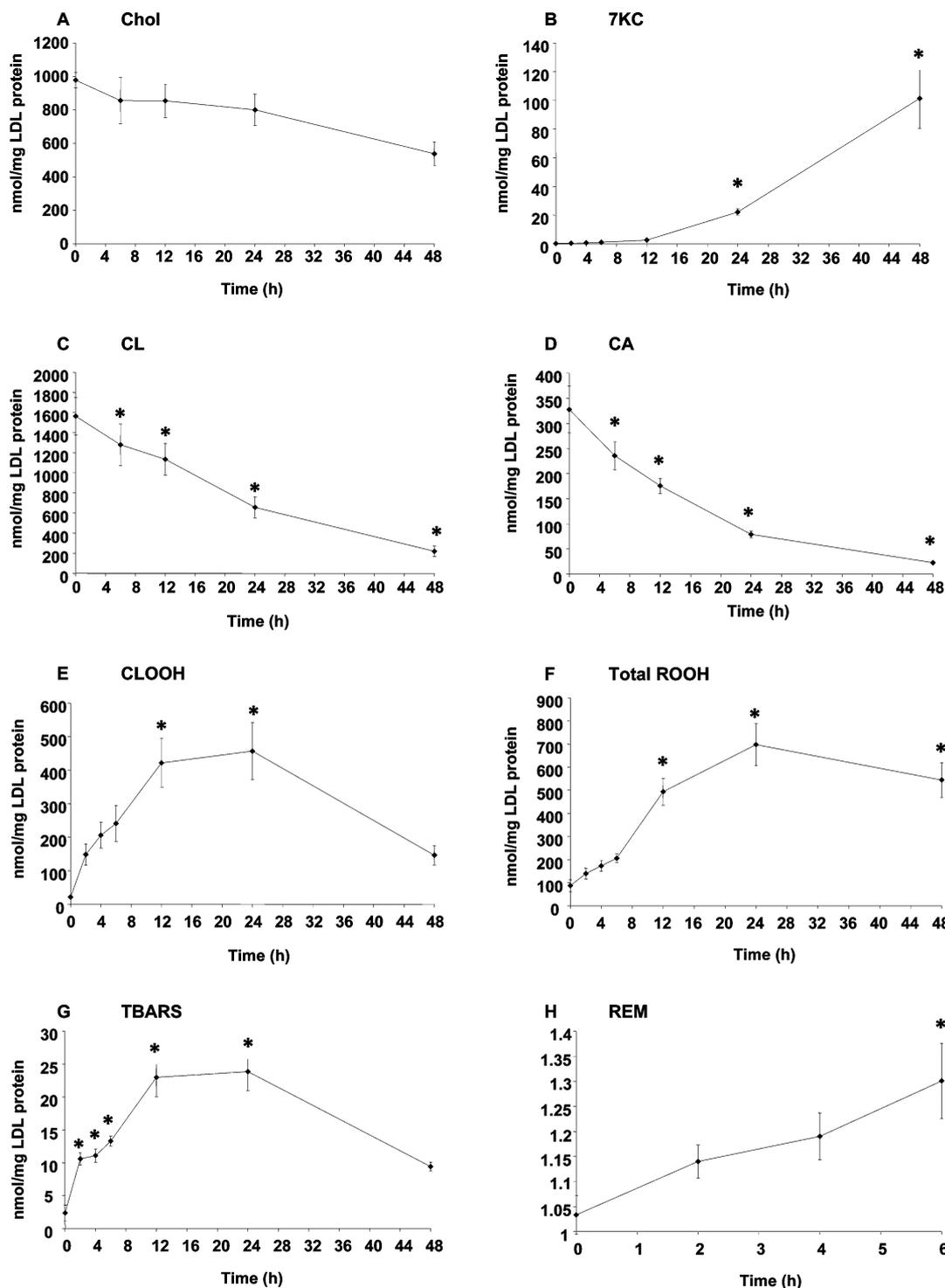


Figure 5. Chemical characteristics of LDL oxidized by FeSO₄ at pH 4.5. LDL (2 mg of protein/mL) was oxidized with FeSO₄ (50 μM) at 37 °C in buffer at pH 4.5. At various time points up to 48 h, LDL oxidation was stopped by addition of EDTA (4 mM) and BHT (80 μM). LDL was assayed by reverse-phase HPLC for nonesterified cholesterol [Chol (A)], 7-ketocholesterol [7KC (B)], cholesteryl linoleate [CL (C)], cholesteryl arachidonate [CA (D)], and cholesteryl linoleate hydroperoxide [CLOOH (E)]. LDL was assayed for total hydroperoxides by a triiodide assay [ROOH (F)], for thiobarbituric acid-reactive substances [TBARS (G)], and for relative electrophoretic mobility [REM (H); note the different time scale]. Graphs represent the mean ± the SEM of at least three independent experiments. Differences between values at each time point and the zero time point were determined by ANOVA and a Dunnett's post-hoc test. **p* < 0.05.

≤24 h and then appeared to decrease again. The total level of hydroperoxides was measured using a triiodide assay and also increased up to 24 h. It then decreased only slowly over the next 24 h. During LDL oxidation, lipid hydroperoxides may decompose to form aldehydes, such as malondialdehyde²⁸ and

epoxy lipids.²⁹ This decomposition probably accounted for the slow decrease in the total level of hydroperoxides after oxidation for 24 h. The levels of CLOOH may have declined faster after 24 h than the levels of total hydroperoxides because CLOOH might have become oxidized also on its cholesterol

moiety, causing its HPLC retention time to change, although it may have retained the hydroperoxide group on its fatty acyl moiety and been detected in the triiodide assay.

When LDL is oxidized with copper at 37 °C and pH 7.4, lipid hydroperoxides are formed during the propagation phase of oxidation and then decompose fairly rapidly.^{11,14} In contrast, when LDL is oxidized by iron at 37 °C at acidic pH, the net hydroperoxide levels fall only slowly between 24 and 48 h (Figure 5F), in agreement with our previous work.³⁰ The lipid composition of LDL oxidized by iron at pH 4.5 and 37 °C for 12 h (Figure 5) was similar to that of LDL oxidized by copper at pH 7.4 and 4 °C for 12 h,¹⁴ i.e., rich in hydroperoxides but low in oxysterols. The high levels of lipid hydroperoxides present in LDL oxidized by iron at lysosomal pH may confer atherogenic properties to the LDL, which differ from those of copper-oxidized LDL. Kritharides et al.³¹ showed that treatment of murine peritoneal macrophages with acetylated or aggregated LDL, subjected to mild oxidation, led to a lysosomal or prelysosomal accumulation of CLOOH and CLOH, which impaired the breakdown of cholesteryl esters. The accumulation of lipid hydroperoxides within the lysosome might therefore compromise lysosomal function. Furthermore, data presented here show that oxidized LDL aggregates spontaneously and rapidly at lysosomal pH (Figure 1C). This may weaken the ability of lysosomal enzymes to degrade it effectively. Atherosclerosis has previously been described as having features of a lysosomal storage disorder, whereby engagement of lysosomes with lipids impairs their function,³² and our data lend further support to this concept.

A wide variety of aldehydes are formed from the decomposition of lipid hydroperoxides. A major aldehyde formed is malondialdehyde.²⁸ The levels of TBARS (mainly malondialdehyde) increased after oxidation for ≤ 24 h by iron at pH 4.5 and then decreased (Figure 5G). The decrease might be explained by the further reaction of malondialdehyde with amino groups of the lysyl residues of apolipoprotein B-100, which would abolish the positive charge of these residues.²³

The level of the cholesterol oxidation product 7-ketocholesterol remained very low for some time but then increased greatly (Figure 5B). The level of 7-ketocholesterol was also increased in macrophages when they oxidized LDL in their lysosomes,⁶ and 7-ketocholesterol is present in much larger amounts in human atherosclerotic lesions than in normal arteries.³³

A slight increase in REM at pH 8.6 was detected after oxidation for ≤ 6 h (Figure 5H). LDL oxidized for ≥ 12 h could not be loaded onto an agarose gel, because of its high level of aggregation, but it is possible that the net negative charge of LDL continued to increase. The isoelectric point of native LDL has been reported to be 5.1–5.8,^{34,35} so at pH 5.1–5.8, LDL will have no net charge. At pH 7.4 or 8.6 (the pH at which electrophoresis was conducted), LDL would have a net negative charge, but at the pH of lysosomes, ~ 4.5 , it would have a net positive charge. The LDL particles would therefore repel each other; however, as oxidation proceeds and the net positive charge becomes smaller (Figure 5H), the repulsion would weaken, and this may favor the aggregation of the LDL particles.

Oxidation of LDL by ferrous iron at lysosomal pH proceeds with lag, rapid oxidation, slow oxidation, aggregation, and sedimentation phases (Figure 1A), in agreement with our earlier findings.⁶ The pattern of oxidation with ferric iron was similar to that with ferrous iron; however, there was a decrease

in the rates of the rapid and slow phases of oxidation and aggregation (Figure 2A). Kuzuya et al.³⁶ found that ferrous iron oxidized LDL faster than did ferric iron in an unbuffered NaCl solution initially at pH 7.4. There is evidence that lysosomes contain cysteine and therefore have a reducing environment³⁷ (but this is controversial³⁸), and this would favor the ferrous oxidation state of iron. In fact, the phagolysosomes of macrophages are known to contain ferrous (and probably ferric) iron.²⁰

Iron may be able to initiate the oxidation of LDL by reacting with preexisting lipid hydroperoxides in the LDL particle.²³



Fe^{2+} is believed to react faster with lipid hydroperoxides (reaction 1) than does Fe^{3+} (reaction 2), as the rate constant for the analogous reaction of Fe^{2+} with H_2O_2 is $68 \text{ M}^{-1} \text{ s}^{-1}$ whereas that for Fe^{3+} with H_2O_2 is $\sim 4 \times 10^{-6} \text{ M}^{-1} \text{ s}^{-1}$.³⁹ This may explain why the oxidation of LDL is slower with Fe^{3+} . Interestingly, adding higher concentrations of Fe^{2+} shortened the lag phase and increased the rates of the rapid, slow, and aggregation phases (Figure 2B), but adding a higher concentration of Fe^{3+} had little effect (Figure 2C). This suggests that it is the concentration of Fe^{2+} , rather than Fe^{3+} , that determines the rate-limiting step in the oxidation of LDL. The results shown in panels D and E of Figure 2 are consistent with this suggestion. Adding extra Fe^{2+} at various times when the oxidation was already underway caused an immediate rapid burst of oxidation, whereas adding extra Fe^{3+} had little effect. These results suggest that the rapid phase of oxidation is mediated by the reaction of Fe^{2+} with LDL and the slow phase occurs when the levels of Fe^{3+} predominate.

DTPA is a metal ion chelator with a high affinity for iron and is able to bind both ferrous and ferric iron.⁴⁰ Adding this chelator at the start of the oxidation or during the rapid oxidation phase caused great inhibition of LDL oxidation with iron at pH 4.5 (Figure 3A). When DTPA was added during the slower oxidation phase, the rate of change of attenuation was decreased substantially, but the LDL was still able to aggregate, as indicated by the aggregation and sedimentation phases. These data suggest that the rapid and slower oxidation phases of LDL modification are iron-dependent and that LDL is able to aggregate only after it has been oxidized to a certain extent, corresponding to the slow oxidation phase. The aggregation phase can proceed in the absence of iron.

Adding another iron chelator, desferrioxamine, at the start of LDL oxidation or during the rapid or slow phases of oxidation caused a partial inhibition of LDL oxidation but was less effective than adding DTPA (Figure 3B). Desferrioxamine binds Fe^{2+} within seconds or less above pH 7.0 but requires many minutes at pH 4.5.⁴¹ Surprisingly, when desferrioxamine was added at the beginning of the aggregation phase of LDL modification, the rate of the modification was actually increased. Pro-oxidant effects of desferrioxamine have been reported.⁴² It might be argued that desferrioxamine was acting by pulling the equilibrium in eq 1 over to the right, as it binds Fe^{3+} with a higher affinity than Fe^{2+} ,⁴¹ and accelerating the breakdown of LOOH. Arguing against this is the fact that there is a rapid burst of LDL oxidation when Fe^{2+} is added to partially oxidized LDL in the absence of an added iron chelator (Figure 2D). The reason for the different behaviors of desferrioxamine and DTPA is unknown but may be related

to their different stability constants for Fe^{2+} and Fe^{3+} , their different standard reduction potentials,⁴⁰ or the electron donating ability of desferrioxamine,⁴³ which might reduce Fe^{3+} to Fe^{2+} and promote reaction 1.

Desferrioxamine injections inhibited atherosclerosis in cholesterol-fed rabbits.⁴⁴ Desferrioxamine inhibits intralysosomal iron redox chemistry⁴⁵ and inhibits the lysosomal oxidation of LDL in macrophages.⁶ Targetting iron chelators to lysosomes might be a potential strategy for slowing the lysosomal oxidation of LDL, if toxicity issues could be overcome.

α -Tocopherol enrichment of LDL had complex effects on the oxidation of LDL by iron at pH 4.5, whereas its antioxidant effects on oxidation of LDL by copper at pH 7.4 were as expected (Figure 4). There was initially a pro-oxidant effect of α -tocopherol enrichment on the oxidation of LDL by iron, followed by an antioxidant effect. The initial pro-oxidant effect might possibly be explained by tocopherol-mediated peroxidation, in which an α -tocopheroxyl radical abstracts a hydrogen atom from a polyunsaturated fatty acyl group.²² There may later have been a net antioxidant effect of α -tocopherol enrichment. Large clinical trials have shown that α -tocopherol supplementation does not usually decrease the risk of cardiovascular disease.^{46,47} The absence of an initial antioxidant effect of α -tocopherol enrichment on oxidation of LDL by iron at lysosomal pH might possibly be relevant to this lack of protection.

These data lend support to the finding that LDL can be oxidized within lysosomes. High levels of lipid hydroperoxides and 7-ketocholesterol can be formed in LDL by iron at lysosomal pH, and the LDL becomes highly aggregated and may therefore be difficult to degrade with lysosomal hydrolases. This suggests that lysosomal oxidation of LDL might lead to lysosomal lipid engorgement and lysosomal dysfunction in atherosclerosis.

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Funding

We are grateful to the British Heart Foundation for a Ph.D. studentship (grant number FS/05/040/18863) (L.S.).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank Ms. Helen A. Oakley and Ms. Jessica del Rio for skilfully isolating LDL and the volunteer blood donors from the University of Reading.

ABBREVIATIONS

CA, cholesteryl arachidonate; CL, cholesteryl linoleate; CLOOH, cholesteryl linoleate hydroperoxide; DTPA, diethylenetriaminepentaacetic acid; HPLC, high-performance liquid chromatography; LDL, low-density lipoprotein; MOPS, 3-(*N*-morpholino)propanesulfonic acid; REM, relative electrophoretic mobility; TBARS, thiobarbituric acid-reactive substances.

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