Effect of resveratrol, tyrosol and β-sitosterol on oxidised low-density lipoprotein-stimulated oxidative stress, arachidonic acid release and prostaglandin E₂ synthesis by RAW 264.7 macrophages

Marta Vivancos and Juan J. Moreno*
Department of Physiology, Faculty of Pharmacy, University of Barcelona, Avda. Joan XXIII s/n, E-08028, Barcelona, Spain

(Received 4 June 2007 – Revised 29 October 2007 – Accepted 30 October 2007 – First published online 17 December 2007)

Oxidation of LDL is hypothesised as an early and critical event in atherogenesis. Oxidised LDL (oxLDL) favour the transformation of macrophages into foam cells, an important cell involved in atherosclerosis. Furthermore, oxLDL cause multiple changes in macrophage functions. Thus, oxLDL induces certain genes, suppresses others and alters cell lipid metabolism. Consumption of a Mediterranean diet is associated with a low incidence of atherosclerotic disease, but data about the specific dietary constituents involved and mechanisms conferring cardioprotection are still sparse. The aim of the present study was to determine the effect of representative minor components of wine and olive oil on reactive oxygen species and eicosanoid synthesis induced by oxLDL-stimulated macrophages. We observed that exposure to non-toxic oxLDL concentrations leads to the production of H₂O₂ by RAW 264.7 macrophages and this effect was reverted by apocynin, a NADPH oxidase inhibitor. Moreover, oxLDL induced arachidonic acid (AA) release, cyclo-oxygenase-2 overexpression and subsequent PGE₂ release. We observed that resveratrol and tyrosol revert H₂O₂ production induced by oxLDL as well as AA release and PGE₂ synthesis and that these effects were not as a consequence of these compounds interfering with the oxLDL binding to their receptors. Interestingly, β-sitosterol presence enhances these polyphenol actions. Thus, we found a synergistic action of polyphenols of olive oil and wine and β-sitosterol of olive oil led to the modulation of the effects of oxLDL on oxidative stress and PGE₂ synthesis.

Mediterranean diet: Olive oil: Wine: Reactive oxygen species: Prostaglandins

Oxidation of LDL is accepted as an early and critical event in atherogenesis[19]. Thus, high levels of oxidised LDL (oxLDL) correlate with the severity of acute coronary events[9] and are considered a biochemical marker for CHD[3]. Macrophages keep taking up oxLDL which induce the release of pro-inflammatory cytokines and promote the recruitment of monocytes and accumulation of lipid-laden macrophages named foam cells[4], which are the most predominant cell type in the earliest atherosclerotic lesions called fatty streaks[5]. Thus, a vicious circle of oxidation, modification of lipoproteins and further inflammation can be maintained in the artery by the presence of oxLDL. In this way, the levels of circulating oxLDL have been related to intima media thickness and plaque occurrence[6] as well as with the progress of atherosclerosis[7]. The role of foam cells in the initiation and progression of atherosclerotic lesions is also extensively documented[8,9] and these cells have been shown to predispose atherosclerotic plaque to fissuring and rupture[10]. OxLDL cause multiple changes in cellular functions distinct from the effects of native LDL. Thus, oxLDL induce certain genes[11], suppress others[12] and alter cellular lipid metabolism[13]. As well as promoting atherogenesis, oxLDL affect many aspects of macrophage function linked to the inflammatory response of these cells[10]. Macrophages, when activated by inflammatory stimuli, synthesise and secrete several mediators such as reactive oxygen species (ROS), cytokines, prothrombotic substances and eicosanoids, which cause, at least in part, the clinical manifestations and acute complications of atherosclerosis[15]. Thus, it has been shown that oxLDL stimulate the release of arachidonic acid (AA) and PG by murine peritoneal macrophages[13] and RAW 264.7 macrophages[10].

Diet is an important element of CVD prevention[17]. Mediterranean diets are associated with a low incidence of atherosclerotic disease[18], but data about the specific dietary constituents involved and mechanisms conferring cardioprotection are still sparse. Olive oil is the main source of fat in Mediterranean diets. We observed that an olive oil diet reduces AA release and subsequent metabolism through the cyclo-oxygenase-2 (COX-2) pathway in phorbol ester-stimulated macrophages[19]. Moreover, olive oil consumption offers an additional beneficial effect by increasing NO/superoxide anion rate release by macrophages[19]. The beneficial effects of extra-virgin olive oil have been linked to both MUFA and polyphenols[20]. However, we must consider that

Abbreviations: AA, arachidonic acid; COX-2, cyclo-oxygenase-2; DCPIP, 2,6-dichlorophenolindophenol; Dil, 1,1′-dioctadecyl-3,3,3′,3′-tetramethylindocarbocyanine; oxLDL, oxidised LDL; PLA₂, phospholipase A₂; ROS, reactive oxygen species; TBARS, thiobarbituric acid-reactive substance.

*Corresponding author: Dr Juan J. Moreno, fax +34 93 4035901, email jjmoreno@ub.edu
other minor compounds such as β-sitosterol, α-tocopherol, terpenoids or squalene could also be contributing to these effects. Tyrosol and hydroxytyrosol are the main olive oil phenolic compounds present in extra-virgin olive oil as free or conjugated forms (21) up to 800 mg/kg, and in olives (about 2 g/100 g dry weight) (22). These compounds show several anti-atherogenic activities, such as the inhibition of LDL oxidation (23) as well as the modulation of foam cell formation (24). Recently, we observed that tyrosol and β-sitosterol, a phytosterol present in olive oil, are synergistic with phorbol esters (25). It is proposed that β-sitosterol effects were the consequence of the induction of antioxidant enzymes such as glutathione peroxidase and Mn superoxide dismutase (26).

Moderate wine consumption is another characteristic element of the Mediterranean diet. Resveratrol, present in high levels in grapes and wine (1·5–7 mg/l in red wine) (28), has been reported to protect against atherosclerosis by modulating LDL oxidation (27) and inhibiting platelet aggregation and the production of pro-atherogenic eicosanoids by platelets and neutrophils (29). Furthermore, we observed that the antioxidant action of resveratrol affects AA release, COX-2 induction and PGE2 synthesis induced by lipopolysaccharide or phorbol ester-stimulated macrophages (30). Recently, Delmas et al. (31) reported how the regulation of ROS and pro-inflammatory mediators formation by resveratrol can lead to a prevention of vascular diseases.

The aim of the present study was to determine the effect of representative minor components of wine and olive oil on ROS and eicosanoid synthesis induced by oxLDL-stimulated macrophages. Furthermore, we are interested to study the synergistic effects of these compounds.

Materials and methods

Materials and chemicals

[5,6,8,9,11,12,14,15-3H]AA (7 399 000–8 879 000 GBq (200–240 Ci)/mmol) was from American Radiolabeled Chemicals Inc. (St Louis, MO, USA). Resveratrol, β-sitosterol from soybeans, 2,6-dichlorophenolindophenol (DCPIP), allopurinol, rotenone, fucoidan, ethidium bromide, acridine orange, catalase from human erythrocytes and superoxide dismutase from beef erythrocytes, malondialdehyde, and 1,1,3,3,3′,3′′-tetramethoxypropane (DiI) were obtained from Sigma Chemical Co. (St Louis, MO, USA). Tyrosol (4-hydroxyphenylethanol) was from Aldrich (Milwaukee, WI, USA). Apocynin was from Calbiochem (Darmstadt, Germany). Dulbecco’s modified Eagle’s medium, heat-inactivated fetal bovine serum, penicillin G, streptomycin and trypsin/EDTA were from Bio Whittaker Europe (Verviers, Belgium). All other reagents were of analytical grade.

Culture of RAW 264.7 macrophages

Murine RAW 264.7 macrophages (TIB-71) from American Type Culture Collection (Manassas, VA, USA) were grown in Dulbecco’s modified Eagle’s medium containing 10% fetal bovine serum, penicillin (100 U/ml) and streptomycin (100 μg/ml) in a 95% air–5% CO2 humidified atmosphere at 37°C. Cells were scraped off and passed to tissue culture in 60 mm or 100 mm dishes (Costar, Cambridge, MA, USA) for experimental purpose. Ethidium bromide–acridine orange staining was used to assess cell viability.

Isolation of low-density lipoprotein

LDL (density = 1·03–1·053) were prepared by sequential ultracentrifugation from pooled, citrated human plasma from healthy normolipidaemic volunteers, according to the method of Chung et al. (32). Finally, LDL were dialysed, filtered through a 0·45 μm filter and stored at 4°C. The protein concentration was determined by the Lowry method modified by Peterson’s method (33).

LDL (1 mg protein/ml) were oxidised with 1·66 μM-CuSO4 at 37°C for 24 h (34). Native and oxLDL were screened for lipopolysaccharide concentration by a Limulus lysate assay. All the LDL prepa-
by 0·5 ml Dulbecco’s modified Eagle’s medium containing 0·1 % fatty acid-free bovine serum albumin and 0·003699 MBq (0·1 μCi) [3H]AA for 24 h. Cells were then washed three times with medium containing 0·5 % bovine serum albumin-containing medium to remove unincorporated radioactivity. After a study period, the medium was removed to determine the amount of radioactivity released and the cells overlaid with 1 % Triton X-100, and then scraped off the dishes. The amount of [3H]AA released into the medium was expressed as a percentage of cell incorporated which was determined in solubilised cells\(^{(31)}\). The background release from untreated cells (11 (SEM 2) % of [3H]AA incorporated) was subtracted from all data.

A sample of culture medium (0·25 ml) was acidified with 1 ml of 1 % formic acid, PGE\(_2\) was extracted in ethyl acetate (5 ml) and, after discarding the aqueous phase, the organic phase was evaporated under a stream of N\(_2\). PGE\(_2\) levels were determined by monoclonal enzyme immunoassay kits (Cayman Chemical Co., Ann Arbor, MI, USA) following the manufacturer’s protocol.

**Western blot analysis of cyclo-oxygenase-2**

RAW 264.7 cells were washed twice in ice-cold PBS, scraped off into PBS containing 2 mM-EDTA and pelleted. Cell pellets were sonicated in PBS containing 2 mM-EDTA, phenylmethylsulfonyl fluoride (2 μg/ml), aprotinin (20 μg/ml), leupeptin (20 μg/ml) and dimethylthiocarbamic acid (200 μg/ml) and were separated by SDS-PAGE and blotted onto a nitrocellulose membrane using a MiniProtean II system (Bio-Rad, Hercules, CA, USA). Finally, the membranes were blocked and COX-2 was immunodetected\(^{(38)}\) using a rabbit polyclonal antiserum (Cayman Chemical Co., Ann Arbor, MI, USA). Thus, COX-2 expression was normalised to the β-actin expression. All blots were developed using an enhanced chemiluminescence kit (Supersignal West Dura extended Duration Substrate) from Pierce (Rockford, IL, USA).

**Assay for binding and/or uptake of oxidised low-density lipoprotein**

OxLDL was labelled using the fluorescent probe DiI according to the methodology described by Innerarity et al.\(^{(39)}\). OxLDL (1 mg protein/ml) was incubated overnight with DiI (30 μg/ml) at 37°C and, finally, DiI-labelled oxLDL was isolated by ultracentrifugation. Macrophages (1 × 10\(^{6}\)) were treated and stimulated with DiI-labelled oxLDL (10 or 50 μg protein/ml) or unlabelled oxLDL (50 μg protein/ml) for 3 h. After being washed three times with PBS, cells were lysed with 0·1 % Triton X-100, and then scraped off the dishes. The amount of [3H]AA produced which was determined in solubilised cells\(^{(31)}\). The background release of [3H]AA from untreated cells (11 (SEM 2) % of [3H]AA incorporated) was subtracted from all data.

**Results**

**Oxidised low-density lipoprotein-induced hydrogen peroxide production**

OxLDL (40 μg protein/ml) induced time-dependent and concentration-dependent formation of H\(_2\)O\(_2\), with maximum H\(_2\)O\(_2\) levels reached 20–30 min after stimulation using 80–160 μg protein/ml oxLDL (Fig. 1). We observe no cell toxicity using this range of concentrations of oxLDL (data not shown). The exogenous addition of superoxide dismutase or catalase decreased H\(_2\)O\(_2\) production over time despite the presence of oxLDL (Table 1). Addition of the NADPH oxidase inhibitor, apocynin (100 μM)\(^{(41)}\), reduced the rate of H\(_2\)O\(_2\) production induced by oxLDL, whereas allopurinol (100 μM) that inhibits xanthine oxidase\(^{(42)}\) or rotenone (5 μM), a mitochondrial respiratory chain complex inhibitor\(^{(43)}\), did not have any significant effects (Table 1).

**Statistical analysis**

Results are expressed as mean values with their standard errors. Differences between non-treated and treated cells were tested by Student’s t test followed by the least significant difference test, as appropriate.
Furthermore, we examined the effects of resveratrol, tyrosol and β-sitosterol on the binding and uptake of oxLDL using DiI-labelled oxLDL. As shown in Fig. 5, incubation of RAW 264.7 cells with DiI-labelled oxLDL (10 or 50 μg protein/ml) resulted in a marked increase in fluorescence intensity, while autofluorescence of the sample, prepared from cells stimulated with unlabelled oxLDL, was less than 10 units. Under these conditions, resveratrol (30 μM), tyrosol (100 μM) and β-sitosterol (100 μM) did not modify fluorescence intensity induced by DiI-labelled oxLDL, whereas fucoidan (10 μg/ml), a polyanionic polysaccharide effective competitor for oxLDL in studies of receptor binding (44), prevented the increase in fluorescence intensity.

Discussion

Our findings show that exposure to low, non-toxic levels of oxLDL leads to the production of \( \text{H}_2\text{O}_2 \) by RAW 264.7 cells as was previously reported by Masella et al. (45). Interestingly, this effect was observed when we employed oxLDL concentrations capable of transforming macrophages into foam cells (46–48). A more detailed analysis has revealed that exogenous addition of superoxide dismutase, catalase or apocynin, a potent and selective inhibitor of the NADPH oxidase system through interfering with the translocation of an essential cytosolic protein, p47phox (41), modulate these events. This suggests that NADPH oxidase is involved in \( \text{H}_2\text{O}_2 \) production. Recent studies have reported by Rouhani-zadeh et al. (49) who observed that oxidised components of LDL induce NADPH oxidase and superoxide anion production by vascular endothelial cells.

The redox state of the cell may act as a molecular switch that regulates the activity of many enzymes and genes in concert. AA is released from cellular phospholipids by phospholipase A2 (PLA2) in response to a variety of physiological stimuli, which is the rate-limiting step in subsequent metabolism by cyclo-oxygenase pathway. We found that ROS such as \( \text{H}_2\text{O}_2 \) are involved in Ca\(^{2+}\)-dependent PLA2 activation and subsequent AA release in RAW 264.7 macrophages (50,51). On the other hand, we observed that ROS production could activate an early-immediate gene leading to new synthesis of COX-2 in macrophages and subsequent PGE\(_2\) synthesis (52). Recently, Lupo et al. (53) reported that oxLDL induced Ca\(^{2+}\)-dependent PLA2 and Ca\(^{2+}\)-independent PLA2.

Table 1. Effect of oxidised low-density lipoprotein (oxLDL) on hydrogen peroxide and prostaglandin E\(_2\) production by murine RAW 264.7 macrophages†‡

<table>
<thead>
<tr>
<th>Treatment</th>
<th>(\text{H}_2\text{O}_2) (mm)</th>
<th>PGE(_2) (pg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (no LDL or oxLDL)</td>
<td>0.21 ± 0.05</td>
<td>5.1 ± 0.10</td>
</tr>
<tr>
<td>LDL</td>
<td>0.35 ± 0.03</td>
<td>4.9 ± 0.08</td>
</tr>
<tr>
<td>oxLDL</td>
<td>1.83 ± 0.21</td>
<td>21.6 ± 0.22</td>
</tr>
<tr>
<td>oxLDL + SOD</td>
<td>1.13 ± 0.17</td>
<td>ND</td>
</tr>
<tr>
<td>oxLDL + catalase</td>
<td>0.76 ± 0.09</td>
<td>ND</td>
</tr>
<tr>
<td>oxLDL + apocynin</td>
<td>0.63 ± 0.11</td>
<td>7.5 ± 0.14</td>
</tr>
<tr>
<td>oxLDL + apocynin + (\text{H}_2\text{O}_2)</td>
<td>– ± 0.00</td>
<td>24.2 ± 0.19</td>
</tr>
<tr>
<td>oxLDL + allopurinol</td>
<td>1.68 ± 0.12</td>
<td>ND</td>
</tr>
<tr>
<td>oxLDL + rotenone</td>
<td>1.75 ± 0.09</td>
<td>ND</td>
</tr>
</tbody>
</table>

SOD, superoxide dismutase; ND, not determined.
† Mean value is significantly different from that of the LDL condition (\(P<0.05\)).
‡ Cells were incubated with LDL or oxLDL (50 μg protein/ml) for 30 min at 37°C in the presence of apocynin (100 μM), allopurinol (100 μM), rotenone (5 μM), SOD (50 units/ml) or catalase (1000 units/ml). \(\text{H}_2\text{O}_2\) was added to 2 mM.

When \(^{[\text{H}]\text{AA}}\) labelled RAW 264.7 cells were incubated with oxLDL (40 μg protein/ml), a time-dependent (Fig. 2 (A)) and concentration-dependent enhancement of \(^{[\text{H}]\text{AA}}\) release was observed (Fig. 2 (B)). On the other hand, macrophages incubated with native LDL showed low levels of COX-2, whereas exposure to oxLDL (40 μg protein/ml) induced an appreciable COX-2 overexpression (Fig. 3). These effects of oxLDL on AA release and COX-2 levels could be responsible for the time-dependent (Fig. 2 (C)) and concentration-dependent (Fig. 2 (D)) increase in PGE\(_2\) synthesis induced by oxLDL. Furthermore, we observed that PGE\(_2\) release induced by oxLDL was inhibited by apocynin and that \(\text{H}_2\text{O}_2\) added exogenously reverted the effect of apocynin on PGE\(_2\) synthesis (Table 1). These results presented in Figs. 1 and 2 were carried out to select the conditions at which LDL and oxLDL were assayed in the rest of the study.

Resveratrol, tyrosol and β-sitosterol modulate hydrogen peroxide production and arachidonic acid release and prostaglandin E\(_2\) synthesis induced by oxidised low-density lipoprotein

The present results show that resveratrol (30 μM) or tyrosol (100 μM) markedly decreased \(\text{H}_2\text{O}_2\) levels induced by oxLDL, whereas lower concentration of resveratrol (3 μM) or tyrosol (10 μM) did not induce any significant effect (Fig. 4 (A)). However, these low concentrations of resveratrol (3 μM) together with tyrosol (10 μM) reduced significantly \(\text{H}_2\text{O}_2\) production by oxLDL-stimulated RAW 264.7 cells. Furthermore, we observed that low concentrations of both polyphenols or tyrosol (10 μM) did not modify \(\text{H}_2\text{O}_2\) levels induced by oxLDL (Fig. 4 (A)).

Similarly, we found that resveratrol (30 μM) and tyrosol (100 μM) significantly inhibited \(^{[\text{H}]\text{AA}}\) release and PGE\(_2\) synthesis (Fig. 4 (B) and (C)). Interestingly, low concentrations of resveratrol (3 μM) and tyrosol (10 μM) incubated together also impaired AA release and PGE\(_2\) synthesis induced by oxLDL. Similar effects were obtained when we used tyrosol (10 μM) together with β-sitosterol. The effect of these compounds on PGE\(_2\) synthesis could be related to the inhibition of the COX-2 overexpression induced by oxLDL (Fig. 3). Furthermore, the incubation of the low concentration of both polyphenols in the presence of β-sitosterol induced an additional appreciable inhibition of AA mobilisation and PGE\(_2\) levels induced by oxLDL (Fig. 4 (B) and (C)).

Resveratrol, tyrosol and β-sitosterol did not modify oxidised low-density lipoprotein uptake by RAW 264.7 macrophages
PLA2 gene expression. Muroya et al.\(^{(54)}\) reported that oxLDL induced NF\(\kappa\)B signalling, a redox-sensitive transcription factor involved in the regulation of COX-2 expression, in RAW 264.7 macrophages. Considering all together, the present results suggest that H2O2 production induced by oxLDL is involved in the AA release, COX-2 overexpression and PGE2 release by RAW 264.7 macrophages. Several authors have reported similar effects of oxLDL on ROS production\(^{(44)}\) or on PGE2 synthesis\(^{(13,55)}\). However, to our knowledge, the present study is the first to have related the effect of oxLDL on oxidative stress, AA release, COX-2 expression and the subsequent PGE2 synthesis.

In the context of the Mediterranean diet and CVD, it has also been shown that extra-virgin olive oil and wine polyphenols increase the resistance of LDL to oxidation, both in vitro and ex vivo\(^{(23,56)}\). Furthermore, Covas et al.\(^{(57)}\) demonstrated that wine consumption reduces postprandial LDL oxidation. They also reported that olive oil ingestion reduces postprandial LDL oxidation\(^{(58)}\). Thus, although several authors reported that olive oil or wine polyphenols modulate LDL oxidation, the present results are the first to compare quantitatively the effect of minor compounds of olive oil and wine on AA cascade activation induced by oxLDL. Our findings show that olive oil and wine polyphenols such as tyrosol and resveratrol modulate H2O2 production and COX-2 overexpression induced by oxLDL as well as AA release and PGE2 synthesis. Considering that oxLDL uptake and foam cell formation take place via scavenger receptors\(^{(59)}\), and that Miles et al.\(^{(60)}\) observed that an olive oil diet decreased macrophage uptake of oxLDL though the down regulation of scavenger receptors, we attempted to explore whether polyphenols such as tyrosol and/or resveratrol influence oxLDL interaction with macrophage receptors in our experimental conditions.
The present results demonstrated that the above effects were not the consequence of these compounds interfering with oxLDL binding to their receptors. Perhaps the more interesting findings of the present study were that we observed an additive effect for the co-incubation of both polyphenols. Thus, resveratrol (3 μM) or tyrosol (10 μM) concentrations reached in plasma after wine or olive oil consumption were not significantly effective on ROS and PGE₂ synthesis induced by oxLDL. However, both together were markedly effective on these events under our experimental conditions. In addition, the presence of β-sitosterol, a characteristic olive oil phytosterol, enhances tyrosol and tyrosol/resveratrol actions. These synergistic effects of the phytosterol could be related to the fact that β-sitosterol activates antioxidant enzymes such as Mn superoxide dismutase and glutathione peroxidase and consequently modulates the cellular redox state though a different mechanism from tyrosol or resveratrol. Thus, it seems that the simultaneous action of polyphenols of olive oil and wine and phytosterols of olive oil could result in an additional atheroprotective effect through the modulation of the AA cascade induced by oxLDL. Most relevantly, such effects occurred at olive oil/wine minor compound concentrations within the range expected after nutritional intake from a Mediterranean diet.

Fig. 4. Effect of resveratrol, tyrosol and β-sitosterol on H₂O₂ production (A), [³H]arachidonic acid (AA) release (B) and PGE₂ synthesis (C) induced by oxidised LDL (oxLDL). RAW 264.7 macrophages were incubated with resveratrol (3–30 μM) or tyrosol (10–100 μM) for 1 h or with β-sitosterol (10 μM) for 1 or 3 h, and then stimulated with oxLDL (50 μg protein/ml) for 3 h. Finally, H₂O₂ levels, [³H]AA release and PGE₂ levels were measured. Data are the means of three experiments performed in duplicate, with standard errors represented by vertical bars. * Mean value is significantly different from that of the control (LDL) cells (P<0.05). † Mean value is significantly different from that of the non-treated oxLDL cells (P<0.05).

LDL
OxLDL
Resveratrol (3 μM)
Resveratrol (30 μM)
Tyrosol (10 μM)
Tyrosol (100 μM)
β-sitosterol (10 μM)
β-sitosterol (10 μM, 3 h)
Olive oil/wine and arachidonic acid cascade

1205


