No Effect of C-Reactive Protein on Early Atherosclerosis Development in Apolipoprotein E*3-Leiden/Human C-Reactive Protein Transgenic Mice


Objective—C-reactive protein (CRP) has been associated with risk of cardiovascular disease. It is not clear whether CRP is causally involved in the development of atherosclerosis. Mouse CRP is not expressed at high levels under normal conditions and increases in concentration only several-fold during an acute phase response. Because the dynamic range of human CRP is much larger, apolipoprotein E*3-Leiden (E3L) transgenic mice carrying the human CRP gene offer a unique model to study the role(s) of CRP in atherosclerosis development.

Methods and Results—Atherosclerosis development was studied in 15 male and 15 female E3L/CRP mice; E3L transgenic littermates were used as controls. The mice were fed a hypercholesterolemic diet to induce atherosclerosis development. Cholesterol exposure did not differ between E3L/CRP and E3L mice. Plasma CRP levels were on average 10.2±6.5 mg/L in male E3L/CRP mice, 0.2±0.1 mg/L in female E3L/CRP mice, and undetectable in E3L mice. Quantification of atherosclerosis showed that lesion area in E3L/CRP mice was not different from that in E3L mice.

Conclusion—This study demonstrates that mildly elevated levels of CRP in plasma do not contribute to the development of early atherosclerosis in hypercholesterolemic E3L/CRP mice. (Arterioscler Thromb Vasc Biol. 2005;25:0-0.)

Key Words: atherosclerosis ■ C-reactive protein ■ inflammation ■ mouse ■ transgene

Cardiovascular disease attributable to atherosclerosis is a major cause of mortality and morbidity in Western society. In recent years, inflammation has emerged as a key factor in atherosclerosis development.1 The acute phase protein C-reactive protein (CRP) has been shown to predict the risk of cardiovascular events.2 Because the plasma concentration of CRP reflects the inflammatory condition, it has been hypothesized that CRP levels reflect the inflammatory condition of the vascular wall. However, whether CRP itself contributes to atherosclerosis development is still unknown.

CRP is a member of the highly conserved pentraxin family and is produced mainly by hepatocytes in response to infection or inflammation. Its production is stimulated by cytokines such as interleukin-6 (IL-6), IL-1, and tumor necrosis factor-α (TNF-α). CRP binds to phosphatidylcholine in cell membranes and plasma lipoproteins in a Ca2+-dependent manner and has a role in opsonization of infectious agents and damaged cells.3 In vitro studies have reported numerous effects of CRP on endothelial cells, smooth muscle cells, and monocytes. CRP treatment often elicits proinflammatory and proatherosclerotic effects.4 For instance, CRP activates endothelial cells to produce adhesion molecules, induces monocyte chemoattractant chemokine-1 (MCP-1) production facilitating leukocyte adhesion and diapedesis, contributes to the migration of smooth muscle cells, enhances uptake of native low-density lipoprotein by macrophages, and activates complement.5-11 Furthermore, local CRP production by cells in the atherosclerotic lesion has been reported.12 Apolipoprotein E*3-Leiden (E3L) mice exhibit elevated plasma cholesterol and triglyceride levels,13 resembling familial dysbetalipoproteinemia in humans. Plasma cholesterol levels in these mice can easily be titrated by diet.14-16 E3L mice develop various stages of atherosclerosis, varying from mild types I to III foamy lesions to severe type IV to V lesions, depending on plasma cholesterol levels and duration of exposure.14,16 Because CRP is a major acute phase reactant in man but not in mice, the human CRP gene was introduced into E3L mice to enable us to study the contribution of human CRP to the development of early atherosclerosis in hypercholesterolemic mice.

Materials and Methods

The detailed materials and methods used in this study are described in the online supplement (available at http://atvb.ahajournals.org). E3L11/CRP17 mice were obtained by cross-breeding female E3L mice13-16 with heterozygous male CRP transgenic mice.17-19
Four groups of mice (15 male and 15 female E3L/CRP transgenic mice and 15 male and 15 female E3L transgenic littermates [controls]) were used. Mice were matched on the basis of age (average 14 weeks) and plasma cholesterol level. The institutional animal care and use committee approved all animal experiments.

Females were fed a semisynthetic diet supplemented with 0.5% (wt/wt) cholesterol (Table I, available online at http://atvb.ahajournals.org); males were fed a diet supplemented with 1% cholesterol and 0.05% sodium cholate (wt/wt; Table I). In addition, fructose was added to the drinking water of male mice, which resulted in an additional plasma cholesterol increase of ~3 mmol/L. Female and male mice were kept on these diets for 25 and 30 weeks, respectively. Body weight and food intake were monitored every 4 weeks.

Body weight (Table) and food intake (data not shown) of E3L/CRP mice at any time point.

**Results**

**Body Weight and Food Intake**

Body weight (Table) and food intake (data not shown) of E3L/CRP mice did not differ significantly from body weight and food intake of E3L mice at any time point.

**Inflammation Markers**

CRP could only be detected in the plasma of E3L/CRP transgenic mice. Plasma CRP levels were on average 10.2±6.5 mg/L in male mice. In female E3L/CRP mice, plasma CRP levels were much lower at 0.2±0.1 mg/L (Table).

Data on SAA and plasma vWF levels are shown in the Table. SAA levels were considerably higher in male mice compared with female mice. Even although the SAA levels were lower in the E3L/CRP transgenic mice compared with the gender-matched E3L mice, these differences were not statistically significant. vWF was significantly higher in the male mice compared with the females, but there were no significant differences between E3L/CRP mice and E3L mice. CRP levels were not significantly correlated with either SAA or vWF levels.

**Plasma Cholesterol Levels, Cholesterol Exposure, and Lipoprotein Composition**

Plasma cholesterol levels, as measured at 8 time points (t=3), were on average 13.3±3.8 mmol/L for female E3L/CRP mice, 13.6±3.1 mmol/L for female E3L mice, 17.2±6.2 mmol/L for male E3L/CRP mice, and 14.7±5.7 mmol/L for male E3L mice (Table). There was no significant difference in cholesterol exposure (plasma cholesterol×weeks of exposure) between the 2 male groups, nor between the 2 female groups (Table; Figure 1A). Thus, the presence of the human CRP gene did not modify plasma cholesterol levels in E3L mice.

Triglyceride levels did not differ significantly between the female groups, but the male E3L/CRP mice had higher triglyceride levels than male E3L mice (Table). Lipoprotein profiles at 20 weeks of high-cholesterol feeding did not differ between groups of the same sex (Figure 1B).

Initially, ALAT activities in plasma were 350 U/L, presumably because of the use of 0.05% cholate in the diet.

In the female groups, plasma ALAT levels gradually increased to ~150 U/L at the end of the study. In the male groups, plasma ALAT levels increased more, to final values of ~350 U/L, presumably because of the use of 0.05% cholate in the diet.

**Atherosclerosis Development**

Atherosclerotic lesion area and the severity (types I to V) of the lesions were quantified in 4 cross-sections of the aortic
valve area for each individual mouse. Representative photomicrographs of atherosclerotic lesions present in the 4 groups are shown in Figure 2.

No significant differences in average lesion size were observed between the E3L/CRP and E3L mice, either in male or female mice (Table; Figure 3A). In the male mice, there was no correlation between lesion size and plasma CRP concentration ($r_s=0.56$; NS).

Lesions were somewhat larger in female mice (with minimal expression of CRP) than in male mice (which did express CRP), despite a larger cholesterol exposure in the male groups. This sex difference, which differs from that in most strains of mice, is in agreement with previous observations in this strain of mice and with observations in unpublished studies (J.J. Emeis) that lesion development in males is slower than in females in E3L mice.

Assessment of lesion severity (scored as type I to V lesions) showed that in female mice, 69% of the lesions found were mild (type I to III lesions), and 29% were more severe (type IV and V lesions; Figure 3B; Table II, available online at http://atvb.ahajournals.org). In the male mice, 83% of the lesions found were of type I to III and 17% of types IV to V. No differences in lesion severity distribution were observed between E3L/CRP mice and E3L mice of the same sex, nor between male and female mice (Figure 3B; Table II).

Characterization of Vessel Wall and Lesions
Because no differences in lesion area had been observed, we sought to determine whether CRP was associated with any differences in the composition of the lesions. This was determined by assessment of endothelial activation (ie, ICAM staining) by assessing the number of adhering monocytes and by the determination of the macrophage-containing area of the lesion.

The endothelium of the vessel wall was found to be ICAM positive. However, no differences in staining intensity of ICAM-1 in the lesions were observed whether mice expressed CRP or not, either in male or in female mice.

The number of monocytes adhering to the endothelium was counted in the same slides used for quantification of athero-
develop lesions more slowly. However, more severe lesions in male mice were smaller than lesions in female mice, in agreement with earlier stages of lesion development. Also, lesions in male mice studied by Paul et al.23 were also present in male and female mice, demonstrating that these mice have the potential to develop more extensive and more complex lesions, as we have also observed in other studies (compare also van Vlijmen et al20). Lesion severity did not differ between male and female mice, nor between E3L and E3L/CRP mice (Table II).

Inflammation has been implicated in atherosclerosis development, and plasma levels of inflammatory markers can be used as predictors of the risk for cardiovascular events.26,27 Therefore, we measured, in addition to CRP, also SAA and vWF at the end point of the study, with vWF serving as a marker of endothelial cell activation. SAA was used as a second, general murine inflammation marker because it is present in all mice. There were no significant differences in SAA and vWF levels between the E3L/CRP and E3L mice. Male mice had higher levels of SAA and vWF than the females. This is probably a result of the cholate, which had been added to the diet of the males only, and may produce inflammatory responses.28,29 The difference in plasma CRP level between male and female mice is attributable to the testosterone dependence of CRP synthesis in this species.19 Therefore, there was no evidence of a difference in inflammation status between the 2 male study groups or between the 2 female study groups.

Recently, Paul et al23 reported a significant increase in lesion size in CRP/apolipoprotein E knockout mice. They also detected CRP in the atherosclerotic lesions, in which it was associated with increased complement C3 deposition, suggesting that CRP stimulated activation of complement within these lesions. Paul et al concluded that CRP has a proatherogenic role in vivo. However, the plasma levels of CRP in these mice were extremely high, with a basal expression of 120±77 mg/L. In the general population, presymptomatic, baseline plasma CRP levels >3 mg/L are associated with an increased risk of heart attack and stroke.30 Among patients with acute coronary syndromes, CRP values >3 mg/L are associated with increased risk of coronary events. However, CRP values >10 mg/L can reflect a wide range of pathologies, and therefore, if patients are presenting with CRP levels >10 mg/L, CRP can no longer be used in the prediction of risk of atherothrombotic events. In the study reported here, the plasma CRP level in the male mice was ≈10 mg/L, much lower than the very high CRP levels in the mice studied by Paul et al.23

We were not able to demonstrate the presence of CRP in the atherosclerotic lesions using the same antibody technique as described by Paul et al.23

**Discussion**

Although numerous in vitro studies have suggested a possible causal involvement of CRP in atherosclerosis, in vivo evidence for a proatherogenic role of CRP is scarce. In the present study, we demonstrated that in E3L mice, the presence of CRP in the blood did not modify the extent nor the severity of atherosclerosis development. Also, the effect of CRP on ICAM-1 expression observed in vitro7 could not be confirmed in vivo in the present study.

The E3L transgenic mice are an established model for diet-induced atherosclerosis and a useful model for drug-induced effects on lesion formation.24,25 The lesions found in this study were mostly mild because we wanted to study the earlier stages of lesion development. Also, lesions in male mice were smaller than lesions in female mice, in agreement with previous (unpublished) observations that male E3L mice develop lesions more slowly. However, more severe lesions were also present in male and female mice, demonstrating that these mice have the potential to develop more extensive and more complex lesions, as we have also observed in other studies (compare also van Vlijmen et al20). Lesion severity did not differ between male and female mice, nor between E3L and E3L/CRP mice (Table II).
whereas significant effects were generally observed only at CRP levels >10 mg/L.

Another point of uncertainty in the in vitro experiments relates to the purity of the CRP preparations used. Nagoshi et al.33 have shown that even recombinant CRP preparations can be contaminated with endotoxin. Removal of endotoxin blocked the ability of recombinant CRP to induce the secretion of IL-6 and MCP-1 by human coronary artery endothelial cells. In vivo, this problem obviously plays no role.

The results reported here do not support a role of CRP in atherosclerosis development in the E3L mouse. However, the association between CRP and cardiovascular disease (CVD) is well established because elevated CRP levels do predict future cardiovascular risk.2,3,4,5 Possibly, CRP is implicated in other processes than atherosclerosis development that contribute to the incidence of CVD, such as thrombosis or revascularization after ischemia.32,36–38 worsening the prognosis of CVD through these mechanisms. Danenberg et al.36 used human CRP transgenic mice to investigate whether CRP has a prothrombotic effect. They demonstrated that at 4 weeks after transmural wire injury, 75% of the femoral arteries were occluded in CRP transgenic mice compared with 17% in wild-type mice.36 However, these results can only be extrapolated to the human situation with care because CRP levels in these mice (18 ± 6 mg/L at baseline to 56 ± 5 mg/L after surgery) were higher than in humans.

CRP has been found to be deposited in the infarcted area together with complement.39 Griselli et al.40 demonstrated in an animal model that human CRP and complement activation are major mediators of ischemic myocardial injury. In rats injected with CRP, infarct size was increased by 40% compared with mice not injected with CRP. So although CRP does not appear to be involved in atherosclerosis directly, it may well have other effects that may adversely influence the outcome of a cardiovascular event.

Also, protective functions for CRP in atherosclerosis have been reported recently in in vitro studies. On incubation with CRP, endothelial cells from human coronary artery or human saphenous vein show increased expression of complement inhibitory factors.41 However, again, the issue of possible artifacts attributable to contamination of the CRP preparation used is raised because van den Berg and Taylor demonstrated that removal of azide from the CRP preparations used inhibited the CRP-induced DAF expression reported by Li et al.42 CRP was also reported to protect cells against assembly of the terminal complement complex,43,44 and native CRP (but not monomeric CRP) was shown to inhibit platelet activation.45,46 However, in the present study, we could not demonstrate a protective effect of CRP.

In conclusion, the present study does not support a direct role of CRP in atherosclerosis development in E3L transgenic mice. No differences in lesion area or lesion severity could be observed between mice with and mice without CRP in this study. We conclude that moderately increased levels of plasma CRP do not affect the development of atherosclerosis in hypercholesterolemic E3L/CRP transgenic mice.

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References

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Materials and Methods

Mice

CRP transgenic mice\textsuperscript{17,18} carry a 31-kb fragment of human genomic DNA, containing the CRP gene and flanking sequences, on a C57Bl/6 background. E3L\textsuperscript{+/+}/CRP\textsuperscript{+/+} mice were obtained by crossbreeding female E3L mice\textsuperscript{13,14,15,16} with heterozygous male CRP transgenic mice. Non-CRP transgenic littermates were used as controls. E3L mice are also bred on a C57Bl/6 background.

Experimental design

Four groups of mice were used. Fifteen male E3L/CRP mice (group I) and 15 female E3L/CRP (group II) were used. As controls, 15 male (group III) and 15 female (group IV) E3L transgenic littermates were used. The presence of the E3L transgene was assessed by an ELISA for human apoE.\textsuperscript{16} The presence of the hCRP gene was assessed by PCR genotyping.

Since testosterone is required for constitutive expression of CRP in mice,\textsuperscript{18} only males have detectable levels of CRP in their plasma. However, both male and female E3L/CRP transgenic mice will produce human CRP upon stimulation with LPS.

At the start of the study mice were matched on the basis of age (average: 14 weeks) and cholesterol levels. The Institutional Animal Care and Use Committee had approved all animal experiments.

Diets

Before the start of the study, animals were kept on a standard murine chow diet (Hope Farms, Woerden, the Netherlands). At the start of the experiment the diet of the female mice was changed to a semi-synthetic cholesterol-raising diet supplemented with 0.5\% (\textit{w/w}) cholesterol (Table 1). Since gender has been shown to affect hyperlipidemia and atherosclerosis development in the E3L mouse model\textsuperscript{20}, male mice were fed a diet supplemented with 1\% cholesterol and 0.05\% sodium cholate (\textit{\%w/w}) (Table 1). In addition, fructose was added to the drinking water of male mice, which results in an additional plasma cholesterol increase of about 3 mmol/L. Female and male mice were kept on these diets for 25 and 30 weeks, respectively, because male E3L mice develop atherosclerosis more slowly than the females.
All animals had free access to water and food. Body weight and food intake were monitored every 4 weeks.

**Analysis of blood parameters**

Blood samples were obtained at baseline, at \( t = 3, 8, 12, 16, 20, 24, 28 \) weeks and at sacrifice from each mouse by tail incision after a 4-hour fast. Blood samples were collected into pre-cooled EDTA-coated tubes, and centrifuged at 2000 x g for 10 min at 4°C to obtain plasma. Total plasma cholesterol and triglyceride levels were measured enzymatically [kit # 236691 (Roche Diagnostics, Almere, the Netherlands) and kit # 337-B (Sigma, St Louis, MI), respectively].

Lipoprotein distribution was determined for each group in a pooled plasma sample by fast protein liquid chromatography, using the ÄKTA system (Amersham-Pharmacia, Stockholm, Sweden).

Human CRP concentrations in plasma were measured using a high-sensitivity in-house enzyme immunoassay using rabbit anti-human-CRP IgG (DakoCytomation, Glostrup, Denmark) as capture and tagging antibody. Human CRP Standard (Dade Behring, Marburg, Germany) was used as a calibrator. The lower limit of sensitivity was 0.05 mg/L.

Plasma alanine aminotransferase (ALAT) activities were measured enzymatically (Reflotron kit # 745 138, Roche).

Serum amyloid A (SAA) was determined by ELISA, as prescribed by the manufacturer (Biosource International, Nivelles, Belgium).

Endothelial activation was assessed by determination of the plasma levels of von Willebrand factor (vWF) by ELISA, using antisera from DakoCytomation, essentially as described by Ingerslev, and using pooled normal plasma for calibration.

**Assessment of atherosclerosis**

After 25 or 30 weeks of diet feeding, mice were sacrificed under general fentanyl / fluanison / midazolam anaesthesia, the hearts were dissected, stored overnight in phosphate-buffered 3.8% formalin, embedded in paraffin, and sectioned. Serial cross-sections were obtained from the aortic root area, and stained with haematoxylin-phloxin-saffron (HPS). For each mouse, 4 sections (5 \( \mu \)m thick) at intervals of 50 \( \mu \)m, representing that stretch of the aortic root where the aortic valves are clearly visible, were used for quantification and typing of atherosclerotic lesions. Total lesion area was determined using the Leica Qwin image analysis software. For each mouse, the average lesion area
per cross-section was calculated. To determine the severity of atherosclerosis, the lesions were classified into five categories as described before\textsuperscript{14,16}: type I) early fatty streak, type II) regular fatty streak, type III) mild plaque, type IV) moderate plaque, and type V) severe plaque.

**Immunohistochemistry**

We performed immunohistochemistry using primary antibodies specific for ICAM-1 (monoclonal anti-mouse-ICAM-1, 1:100, R&D, Minneapolis, MN), monocytes and macrophages (AIA31240, 1:1000, Accurate Chemical and Scientific) and CRP (anti-CRP clone 8, 1:500, Sigma). 5 µm thick sections were deparaffinized and rehydrated, and endogenous peroxidase activity was eliminated by treatment with 0.3% H\textsubscript{2}O\textsubscript{2} for 15 min. After washing with PBS, sections were heated in 0.01 M citric acid (pH 6.0) for 10 min (when staining for ICAM-1), and incubated with 5% BSA in PBS for 15 min at room temperature. Sections were then incubated overnight with the primary antibody at 4°C. Subsequently, the sections were incubated with a biotinylated secondary antibody. Avidin-biotin conjugated HRP (DakoCytomation) and NovaRed substrate (Vector Laboratories, Burlingame, CA) were used to visualize the antibody complex. Sections were counterstained with haematoxylin.

**Statistics**

All data are presented as mean ± SD, or median (95% confidence interval). For statistical analysis SPSS 10.0 for Windows was used. Effects of the CRP transgene were tested statistically for female and male mice separately. Parametric and non-parametric tests were used as indicated. To analyze the differences between groups the Mann-Whitney rank sum test was used. P values less than 0.05 were regarded as significant. Spearman's correlation coefficient was used for calculating correlations.
### Table I. Summary of diet characteristics.  

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weeks on diet</strong></td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td><strong>Diet containing:</strong></td>
<td>15% cacao butter</td>
<td>15% cacao butter</td>
</tr>
<tr>
<td></td>
<td>40.5% sucrose</td>
<td>40.5% sucrose</td>
</tr>
<tr>
<td></td>
<td>10% corn starch</td>
<td>10% corn starch</td>
</tr>
<tr>
<td></td>
<td>1% corn oil</td>
<td>1% corn oil</td>
</tr>
<tr>
<td></td>
<td>20% casein</td>
<td>20% casein</td>
</tr>
<tr>
<td></td>
<td>5.45% cellulose</td>
<td>5.45% cellulose</td>
</tr>
<tr>
<td></td>
<td>5.1% mineral</td>
<td>5.1% mineral</td>
</tr>
<tr>
<td></td>
<td>1% choline chloride</td>
<td>1% choline chloride</td>
</tr>
<tr>
<td></td>
<td>0.2% methionine</td>
<td>0.2% methionine</td>
</tr>
<tr>
<td><strong>Supplemented with:</strong></td>
<td>0.5% cholesterol</td>
<td>1% cholesterol</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05% cholate</td>
</tr>
<tr>
<td><strong>Drinking water</strong></td>
<td>tap water</td>
<td>10% fructose in tap water</td>
</tr>
</tbody>
</table>
Table II. Lesion severity in male and female E3L and E3L/CRP mice.

<table>
<thead>
<tr>
<th>Lesion type</th>
<th>E3L/CRP males</th>
<th>E3L males</th>
<th>E3L/CRP females</th>
<th>E3L females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I-III</td>
<td>71</td>
<td>94</td>
<td>42</td>
<td>63</td>
</tr>
<tr>
<td>Type IV and V</td>
<td>18</td>
<td>21</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>

The table indicates the absolute number of lesions of type I-III (fatty spots, fatty streaks and capped fatty lesions) and lesions type IV and V (complicated lesions with and without media involvement). There is no significant difference in the distribution of lesion types between the four groups (Chi-square = 3.67, df = 3, p = 0.230). By Fischer's exact test not differences were found either between the two female groups (p=0.850), nor the two male groups (p=0.724), nor between the two male groups combined versus the two female groups combined (p=0.073).