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Hyperlipoproteinemia Enhances Susceptibility to Acute Disseminated Candida albicans Infection in Low-Density-Lipoprotein-Receptor-Deficient Mice

MIHAI G. NETEA,1 PIERRE N. M. DEMACKER,1 NATASJA DE BONT,1 OTTO C. BOERMAN,2 ANTON F. H. STALENHOEF,1 JOS W. M. VAN DER MEER,1 AND BART JAN KULLBERG1*

Division of General Internal Medicine, Department of Medicine,1 and Department of Nuclear Medicine,2 University Hospital Nijmegen, 6500 HB Nijmegen, The Netherlands

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Recent studies have suggested the use of lipoproteins as an adjuvant treatment of lethal gram-negative infections. However, other important microorganisms for the etiology of sepsis, such as Candida species, grow better in lipid-rich environments. We investigated the effect of hyperlipoproteinemia on systemic candidiasis in low-density-lipoprotein-receptor-deficient (LDLR-/-) mice, in which the loss of the receptor results in a seven- to ninefold-higher plasma LDL level than that in their wild-type littermates (C57BL/6J). LDLR-/- mice died earlier, and the outgrowth of Candida albicans in the kidneys and livers of LDLR-/- mice was significantly higher compared with that of controls. After infection, circulating cytokine concentrations were significantly higher in LDLR-/- mice. In vivo, C. albicans grew better in plasma samples of LDLR-/- mice than in control plasma samples and peritoneal macrophages of LDLR-/- mice challenged with heat- killed C. albicans produced more cytokines than did those of controls. This latter phenomenon was probably due to increased binding of yeast cells to macrophages of LDLR-/- mice. These data suggest that hyperlipoproteinemia is deleterious in systemic candidiasis.

1 Corresponding author. Mailing address: Dept. of Medicine (541), University Hospital Nijmegen, P.O. Box 9101, 6500 HB Nijmegen, The Netherlands. Phone: 31-24-3614763. Fax: 31-24-3541734. E-mail: Kullberg@azg.AZN.nl.
The outgrowth of microorganisms from the livers, spleens, and kidneys of animals was quantified on days 1 and 3 after C. albicans infection. For this purpose, the organs were removed aseptically, weighed, and homogenized in sterile saline in a tissue minor (21). The outgrowth of microorganisms in the kidneys and livers of LDLR~ mice was significantly higher (Table 2). No difference in the outgrowth of C. albicans in the spleen was detected between the two mouse strains (Table 2).

Four hours after infection, plasma TNF-α concentrations were below the detection limit and IL-1α concentrations were higher in LDLR~ mice than in controls (140 ± 22 versus 78 ± 48 pg/ml, respectively; P < 0.05). Circulating IL-1β concentrations were similar in both strains (56 ± 29 versus 37 ± 28 pg/ml, respectively; P > 0.05). Plasma TNF-α concentrations were significantly higher in LDLR~ mice compared with those of control animals at both 24 (42 ± 5 versus 18 ± 4 pg/ml, respectively; P < 0.01) and 72 (302 ± 237 versus 98 ± 88 pg/ml, respectively; P < 0.02) h after infection (Fig. 2). No differences in plasma IL-1α and IL-1β concentrations were observed at these time points (Fig. 2).

In vitro cytokine production. We investigated the capacity of peritoneal macrophages of both mouse strains to produce cytokines when stimulated in vitro with heat-killed C. albicans. Compared with those of controls, the TNF-α concentrations in supernatants from macrophages of LDLR~ mice were significantly higher (Fig. 3a). The IL-1α and IL-1β concentrations were only marginally increased (Fig. 3a). The cell-associated IL-1α concentration was significantly increased in macrophages of LDLR~ mice, but the cell-associated TNF-α and

outgrowth in the kidneys of LDLR~ mice was significantly higher compared with that of controls; 3 days after infection, outgrowth of C. albicans was increased in both the kidneys and livers of LDLR~ mice (Table 2). No difference in the outgrowth of C. albicans in the spleen was detected between the two mouse strains (Table 2).

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TABLE 1. Plasma cholesterol and triglyceride concentrations before and 4 h after C. albicans infection in LDLR~ and C57BL/6J mice

<table>
<thead>
<tr>
<th>Mouse strain</th>
<th>Time</th>
<th>Mean concn (mmol/liter) ± SD</th>
<th>Cholesterol</th>
<th>Triglycerides</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDLR~</td>
<td>Before</td>
<td>9.55 ± 1.11*</td>
<td>1.25 ± 0.33*</td>
<td>6.76 ± 0.92, **</td>
</tr>
<tr>
<td>C57BL/6J</td>
<td>Before</td>
<td>2.25 ± 0.45</td>
<td>0.65 ± 0.12</td>
<td>1.84 ± 0.09**</td>
</tr>
</tbody>
</table>

a Mice were infected i.v. with 10^6 CFU of C. albicans. Each group consisted of five mice.

b P < 0.01 for comparison between results for LDLR~ and control mice;

c P < 0.05 for comparison between results before and after C. albicans infection.

FIG. 1. Survival during C. albicans infection. LDLR~ mice (closed symbols) infected with either 10^6 (triangles) or 10^7 (circles) CFU of C. albicans died significantly earlier than did C57BL/6J mice (open symbols) (P < 0.05; Kaplan-Meyer log rank test). The data are pooled results of two experiments with at least 15 animals per group.
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strains (Fig. 3b).

decreased compared with that of control plasma, as shown by after 5, 10, and 30 min of incubation. The binding of yeast cells bated radioiodinated ratio) and determined the amounts bound to macrophages V o l DLR-/-(shaded bars) mice at 4, 24, and 72 h after the injection of 10^6 CFU of C. Jium) of LDLR mice and controls. The capacity of 4 ronment, we compared the in vitro growth of 10^6 CFU of C. 65, 1997 65, 1997

TABLE 2. Outgrowth of C. albicans in the organs of LDLR-/– and C57BL/6J mice after infection with 10^6 CFU of C. albicans

<table>
<thead>
<tr>
<th>Mouse strain</th>
<th>Organ</th>
<th>Day</th>
<th>Log CFU/g of tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDLR-/-</td>
<td>Kidney</td>
<td>1</td>
<td>6.3 ± 0.5*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>7.4 ± 0.3*</td>
</tr>
<tr>
<td></td>
<td>Liver</td>
<td>1</td>
<td>4.8 ± 0.3**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.2 ± 0.2**</td>
</tr>
<tr>
<td></td>
<td>Spleen</td>
<td>1</td>
<td>4.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.1 ± 0.5</td>
</tr>
<tr>
<td>C57BL/6J</td>
<td>Kidney</td>
<td>1</td>
<td>5.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>6.5 ± 0.3</td>
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<td>Spleen</td>
<td>1</td>
<td>5.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5.0 ± 0.2</td>
</tr>
</tbody>
</table>

* Data are means ± standard deviations of pooled data from two experiments with 10 animals per group. *, P < 0.01; **, P < 0.05.

IL-1β concentrations did not differ between the two mouse strains (Fig. 3b).

C. albicans binding. To investigate the total binding of C. albicans to macrophages from the two mouse strains, we incubated radioiodinated C. albicans cells with macrophages (5:1 ratio) and determined the amounts bound to macrophages after 5, 10, and 30 min of incubation. The binding of yeast cells to macrophages of LDLR-/– mice was increased and more rapid compared to that of control macrophages (Fig. 4).

Growth of C. albicans in vitro. To investigate whether the outgrowth of C. albicans in the organs of LDLR-/– mice is due to enhanced growth of yeast cells in a lipoprotein-rich environment, we compared the in vitro growth of 10^6 CFU of C. albicans in plasma samples (diluted 1:1 with Sabouraud medium) of LDLR-/– mice and controls. The capacity of LDLR-/– plasma to inhibit the outgrowth of C. albicans was decreased compared with that of control plasma, as shown by the growth of C. albicans in the two types of plasma samples after 12 [(7.2 ± 2.4) × 10^5] versus (2.4 ± 1.5) × 10^5 CFU/ml, respectively; P < 0.05] and 24 [(4.2 ± 1.6) × 10^5] versus (1.5 ± 1.0) × 10^5 CFU/ml, respectively; P < 0.05] h of incubation.

FIG. 2. In vivo cytokine concentrations during C. albicans infection. Shown are circulating concentrations of proinflammatory cytokines in control (open bars) and LDLR-/– (shaded bars) mice at 4, 24, and 72 h after the injection of 10^6 CFU of C. albicans. *, P < 0.05.

DISCUSSION

The main conclusion from the present study is that hyperlipoproteinemia has deleterious effects on the outcome of severe C. albicans infection, in contrast to gram-negative bacterial infections. We have shown that LDLR-/– mice, with seven- to nine-times-higher LDL levels, are more susceptible to C. albicans infection than are their wild-type littermates. The earlier mortality of LDLR-/– mice was associated with increased outgrowth of C. albicans in their organs, and these mice produced significantly more proinflammatory cytokines than did control mice.

In general, mortality after infection may be due to lethal cytokinemia or to functional impairment by the growth of microorganisms in the organs of an animal. The increased susceptibility of LDLR-/– mice to C. albicans is likely to be due to the latter mechanism, because C. albicans did not induce an impressive cytokinemia. The hypothesis that cytokines are not responsible for the deaths of animals during C. albicans infection is in agreement with studies showing that the stimulation of neutrophils and macrophages by TNF and IL-1 enhanced their capability to kill C. albicans cells (6, 29), whereas anti-TNF antibodies (26) or pharmacologic inhibition of proinflammatory cytokines proved to be deleterious during severe C. albicans infection (20). Thus, proinflammatory cytokines seem to play a beneficial rather than a deleterious role in the defense against C. albicans. It should be noted that despite the greater cytokine response, LDLR-/– mice were not protected against C. albicans infection, probably due to the overwhelming outgrowth of yeast cells in their organs.

It may be hypothesized that the enhanced outgrowth of C. albicans in the organs of LDLR-/– mice is due to elevated lipoprotein concentrations. Normal serum has a candidicidal effect (22), and as shown by in vitro growth experiments, this property was significantly decreased in plasma samples from LDLR-/– mice. This effect may be due to the use of lipoproteins as a nutrition factor by C. albicans, as has been suggested by earlier studies showing increased growth of C. albicans in lipid-containing parenteral solutions compared with that in formulations without lipid contents (5, 9, 16). Another possible mechanism by which lipoproteins could influence C. albicans growth is interaction with other plasma factors. We cannot
exclude the possibility that plasma candidicidal factors, such as platelet microbicidal protein (32) and the calprotectin complex (19), are bound and inactivated by lipoproteins.

The higher cytokine concentrations during infection in LDLR⁻/⁻ mice, compared with those of controls, were probably at least in part a response of the host against enhanced C. albicans outgrowth in the organs of LDLR⁻/⁻ mice. However, surprisingly, stimulated in vitro with heat-killed C. albicans, macrophages of LDLR⁻/⁻ mice produced significantly more TNF-α and IL-1α than macrophages of control mice did. Most likely, this was due to the observed increased binding of C. albicans to macrophages of LDLR⁻/⁻ mice compared with that of control macrophages. This phenomenon may be explained by the influence of constitutively increased lipoprotein concentrations in LDLR⁻/⁻ mice on the Candida-binding proteins on macrophage. It has been shown previously that hypercholesterolemia is able to modify the number and clustering of other receptors, such as the LPS receptor CD14 (7, 25). Earlier, we observed similar higher binding of radiolabelled LPS to macrophages of LDLR⁻/⁻ mice, followed by higher cytokine production (21). Thus, similar changes in the number and/or clustering of Candida-binding proteins may facilitate the binding of C. albicans to macrophages of LDLR⁻/⁻ mice, with a subsequent increase in cytokine production. Hyperlipoproteinemia could also modify the hydrophobicity of cells, which may also influence the adherence of C. albicans to macrophages, as has been shown for endothelial cells (10). Which of these mechanisms is responsible for the observed increase in cytokine production by macrophages of LDLR⁻/⁻ mice is under study.

An alternative desirable experiment to our model in order to investigate the influence of hyperlipoproteinemia in C. albicans infection would have been to infuse lipoproteins into animals before and during infection. However, an infusion of lipoproteins into mice is not possible and other models of lipoprotein infusion in rabbits (11) and rats (24) are short-term models that are not suitable for sustained lipid infusion during systemic candidiasis. Therefore, the genetically modified mouse model is a good alternative for studying the in vivo effects of hyperlipoproteinemia in models of sustained infection.

In conclusion, hyperlipoproteinemia has deleterious effects on the course of acute disseminated C. albicans infection, in contrast to its beneficial effect in gram-negative infection. Although no epidemiological studies have been done to show a relationship between hyperlipoproteinemia and increased susceptibility to C. albicans, an infusion of lipoproteins into a patient with disseminated candidiasis under the presumptive diagnosis of gram-negative sepsis may prove deleterious. These divergent effects of hyperlipoproteinemia should be taken into account when the use of lipoproteins as an adjuvant treatment of sepsis is considered.

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REFERENCES


