Estrogen and Progesterone Reduce Lipid Accumulation in Human Monocyte-Derived Macrophages
A Sex-Specific Effect

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Background—Males have an earlier onset and greater prevalence of clinical atherosclerosis than age-matched females, which is consistent with an atheroprotective effect of the female sex steroids, estrogen and progesterone. We therefore examined the effects of estrogen and progesterone on human foam cell formation, a key early event in atherogenesis.

Methods and Results—Monocytes from healthy female and male donors were obtained from white cell concentrates and allowed to differentiate into macrophages over 10 days. These human monocyte-derived macrophages (MDMs) were exposed to either control (0.1% vol/vol ethanol) or estrogen or progesterone treatment on days 3 through 10. Lipid loading was achieved on days 8 through 10 by incubation with acetylated LDL. Lipid from the MDMs was then extracted for analysis of cholesteryl ester (CE) content. 17β-Estradiol at both physiological (2 nmol/L) and supraphysiological (20 and 200 nmol/L) concentrations produced a significant reduction in macrophage CE content (88±3%, 88±2%, and 85±4%, respectively; P<0.02 compared with control). Physiological and supraphysiological levels of progesterone (2, 10, and 200 nmol/L) produced an even more dramatic reduction in CE content (74±9%, 56±10%, and 65±8%, respectively; P<0.002 compared with control). This effect could be abrogated by coincubation with the progesterone receptor antagonist RU486. Neither estrogen nor progesterone produced a reduction in lipid loading in male-donor–derived MDMs. Detailed lipid trafficking studies demonstrated that both estrogen and progesterone altered macrophage uptake and/or processing of modified LDL.

Conclusions—Physiological levels of estrogen and progesterone are associated with a female-sex–specific reduction in human macrophage lipid loading, which is consistent with an atheroprotective effect. (Circulation. 1999;100:2319-2325.)

Key Words: cells ■ atherosclerosis ■ lipoproteins ■ lipids

Premenopausal women have less cardiovascular morbidity and mortality than similarly aged men.1-2 Animal studies have supported a potentially antiatherogenic effect of female sex hormones, with less plaque formation demonstrated in estrogen-treated cholesterol-fed monkeys3 and rabbits,4 an effect also observed with combined administration of estrogen and progesterone.3,5 In humans, estrogen therapy is associated with improved lipoprotein profiles,6,7 vascular reactivity,8 and cardiovascular outcomes9 in postmenopausal women in a number of case control and cohort studies.

The effects of progesterone on atherogenesis and event rates in humans are less well studied. A beneficial effect on smooth muscle cell proliferation has been suggested10; however, several studies have recently found that the addition of progesterone to estrogen replacement may attenuate some of the beneficial effects on lipids,11 fibrinogen,12 and vascular reactivity.13 The Nurses’ Health Study14 recently documented a highly significant reduction in coronary event rates with combined estrogen and progesterone therapy in the setting of primary prevention; however, the recently reported Heart and Estrogen-progestin Replacement Study (HERS)15 suggests that this benefit may not be observed in women with established coronary disease. Few data exist, however, on the effects of these hormones on basic atherogenic processes in humans.

Foam cell formation is a key event in the early development of atherosclerosis and is largely due to the uptake of modified lipoproteins by monocyte-derived macrophages (MDMs) in the arterial wall.16,17 We therefore examined the effects of the principal female sex steroids, 17β-estradiol and progesterone, on macrophage lipid loading and the mechanisms of the observed effects in primary human cells.

Methods

Isolation of Human Monocytes

White cell concentrates (Red Cross Blood Bank) were obtained from the peripheral blood of healthy human volunteers. All female donors...
were premenopausal (aged 18 to 40 years) with no significant negative medical history. Male donors (n=8) were also healthy and were aged 21 to 58 years. Monocytes were removed within 24 hours of collection by density gradient separation of the white cells on Lymphoprep (Nycomed Pharma) followed by centrifugation at 20°C, as previously described by our group,18 by use of a Beckman J2-21 M/E centrifuge equipped with a JE-6B elutriation rotor and a 4.2-mL elutriation chamber (Beckman Instruments, Inc.). The elutriation buffer was HBSS without calcium or magnesium (Sigma) supplemented with EDTA (0.1 g/L) and 1% heat-inactivated human serum. The system and tubing were rinsed with 250 mL each of 70% ethanol, endotoxin-free water, 6% hydrogen peroxide, endotoxin-free water, and elutriation buffer in that order before the Lymphoprep-derived mononuclear cell fraction was loaded at 9 mL/min into the elutriation rotor chamber (2020 rpm at 20°C). Flow rate was increased by 1 mL/min increments every 10 minutes, and monocytes were typically eluted between 16 and 17 mL/min. Collected fractions were examined by use of a Cytospin system (Shandon) and Wright’s stain (Dif-Quik, Laboratory Aids). Monocyte purity of >90% and viability of >95% by trypan blue exclusion were confirmed by light microscopy.

**Culture of Human MDMs**

Monocytes isolated by elutriation were resuspended in phenol red–free RPMI (Life Technologies), plated onto 24-mm-diameter tissue culture wells, and allowed to adhere for ≥1.5 hours at 37°C under 5% CO₂ in air. The media were then removed and the adherent monocytes washed twice gently with PBS before the addition of phenol red–free RPMI containing 10% postmenopausal female human serum, penicillin G (50 U/mL), and streptomycin (50 μg/mL). Media changes occurred every 2 to 3 days, and the various treatments were added from days 3 through 10 with each media change. Treatment conditions included 17β-estradiol (2, 20, and 200 nM; Sigma), progesterone (2, 10, and 200 nM; Fluka), RU 486 (100 nM/L; Sigma), and ethanol (0.1% vol/vol) as control (used to dissolve the hormones). Each experiment used at least triplicate cultures for each condition. In addition, experiments were performed to compare the effects of the above hormones in male- and female-donor MDMs propagated in either male serum or postmenopausal female serum to ensure that any effects observed were not merely nonspecific perturbations due to removal of the cells from their usual hormonal environment (for example, androgen withdrawal in the male MDMs).

Macrophage differentiation occurred over the 10-day period, and lipid loading was achieved on days 8 through 10 during a 48-hour incubation with 50 μg/mL acetylated LDL (AcLDL) in phenol red–free RPMI containing 10% (vol/vol) lipoprotein-deficient human serum (d=1.25). Cell viability for each treatment condition was established by trypan blue exclusion, with viability levels of 90% to 94%.

Monocyte to macrophage differentiation was similar in all treatment groups as assessed by cell-surface expression of CD16 (FcγRII) (Sigma) by use of an ELISA technique involving a second antibody of sheep anti-mouse antibody/horseradish peroxidase conjugate (Amersham International) and ABTS substrate (Kirkegaard and Perry Laboratories).19 At 4, 7, 10, and 12 days, CD16 expression was measured under control conditions from extremely low levels of 0.09±0.02 on day 3 (OD at 405 nm) to 0.17±0.02 on day 10 (OD at 405 nm), and 0.36±0.02 at days 7, 10, and 12, respectively (n=3). There was no significant difference in CD16 antigen expression in these control cells and those exposed to estrogen 2 nmol/L or progesterone 10 nmol/L during days 3 through 12 of differentiation (P>0.3). Similarly, nonspecific binding (assessed by use of isotype mouse IgG) was not significantly different between conditions for each time point.

**Preparation of LDL**

LDL (1.05–d<1.02 g/mL) was isolated from plasma of healthy, normolipidemic fasting subjects by 2-step centrifugation at 10°C with a Beckman L8-M centrifuge and Ti70 rotor at 50 000 rpm (242 000g) for 24 hours. The LDL was dialyzed 4 times against 1L of deoxygenated PBS (calcium and magnesium free; Flow Laboratories) containing 0.1 mg/mL chloramphenicol (Boehringer Mannheim) and 1.0 mg/mL EDTA. The LDL was stored in the dark at 4°C and used within 2 weeks.

**Acetylation of LDL**

LDL was acetylated at 4°C by a modification of a previous method20 with 6 μL of acetic anhydride per 1 mg of LDL protein. After acetylation, LDL was again dialyzed 4 times in 1 L of PBS containing chloramphenicol (0.1 g/L) and EDTA (1 mg/mL) over 16 hours to remove excess saturated sodium acetate and acetic anhydride, filtered (0.45 μm/L), and stored in the dark at 4°C to be used within 1 week. Adequate acetylation of LDL was confirmed before use by observation of a relative electrophoretic mobility of ≥2.5 for AcLDL compared with native LDL on 1% Universal agarose gels (Ciba-Corning) in Tris-barbitone buffer (pH 8.6) at 90 V for 45 minutes.

**Iodination of AcLDL**

AcLDL was iodinated with 125I (carrier-free sodium iodide, activity 200 MBq) by the iodine monochloride method.21 The 125I-labeled AcLDL was passed through a PD-10 column (Sephadex G-25M, Pharmacia), to remove unreacted iodide and then dialyzed 4 times against 1 L of PBS/EDTA/chloramphenicol, filtered (0.45 μm/L), and stored at 4°C to be used within 1 week. Specific activity was assessed before use and ranged between 250 and 750 counts/min per 1 ng of LDL protein.

**Preparation of Macrophage Cell Extracts**

After the human MDMs were washed 3 times with ice-cold PBS, cells were lysed with 0.6 mL of cold 0.2 mol/L NaOH at 4°C for 15 minutes. From the lysate, 0.2 mL was used for cell protein estimation, and the remaining 0.4 mL was added to 0.6 mL of ice-cold PBS and immediately extracted into methanol (2.5 mL) and hexane (5 mL), in the presence of 20 μmol/L butylated hydroxytoluene (Sigma) and 2 nmol/L EDTA. Samples were stored after extraction at −80°C until analysis for free cholesterol (FC) and cholesteryl ester (CE) was performed, usually within 7 days.

**Analysis of Cholesterol and CEs**

Cholesterol and CEs were separated by reverse-phase high-performance liquid chromatography at room temperature on a C-18 column (Supelco) as described previously.22 CEs were analyzed with an eluent of acetonitrile/isopropanol (30:70 vol/vol), whereas FC values were assessed with acetonitrile/isopropanol/water (44:54:2 vol/vol), with detection at 210 nm absorbance for both parameters (Action UV-200 absorbance detector).

Cholesterol and CEs were quantified by the derivation of standard curves by use of commercially available standards (Sigma). The curves expressed a linear relation between the chromatographic peak areas and the mass of the standard, which enabled us to quantify individual cholesterol compounds in nanomoles per milligram of cell protein.

**Protein Estimation**

All protein estimations were performed by the bicinchoninic acid method (Sigma) with BSA used as a standard. Samples were incubated for 60 minutes at 60°C before measurement of absorbance at 562 nm.

**125I-Labeled AcLDL Trafficking Experiments**

For all of the following lipoprotein trafficking experiments, MDMs were treated as described previously. Instead of AcLDL loading on day 8, cells were treated with 125I-labeled AcLDL to assess lipid-handling mechanisms.

**Cell-Surface Lipoprotein Binding at 4°C**

After 8 days of propagation, cells were washed twice with PBS and cooled to 4°C for 20 minutes, and cell-surface–bound AcLDL was determined after a 4-hour incubation at 4°C with 125I-AcLDL (1, 2,
5, 8, 10, 20, 30, and 40 µg/mL) with and without a 30-fold excess of unlabeled AcLDL to assess specific and nonspecific binding. Each condition was performed in triplicate cultures. After incubation, macrophages were washed 5 times with ice-cold PBS containing 2 mg/mL BSA, then washed 3 times with PBS as described by Goldstein et al.\textsuperscript{23} Cells were lysed with 0.2 mol/L NaOH, and lysates were assessed for protein content and cell-associated (cell surface) radioactivity. Binding parameters were analyzed by the LIGAND computer program.\textsuperscript{24}

**Incubation at 37°C Followed by Surface Binding at 4°C**

Macrophages were incubated at 37°C for 4 hours with 20 µg/mL unlabeled AcLDL and washed as described previously at 4°C, and the media were replaced with RPMI (containing 2 mg/mL BSA and 20 µg/mL \textsuperscript{125}I-AcLDL) for an additional 4 hours at 4°C to reassess surface binding–site availability after metabolism of AcLDL at 37°C.

**Retroendocytosis Studies**

Previous studies in the THP-1 cell line have shown that estrogen action in reducing macrophage lipoprotein metabolism is independent of lysosomal degradation of AcLDL.\textsuperscript{25} We therefore explored the possibility that estrogen and progesterone might affect the membrane traffic of AcLDL in human macrophages. A role for sex steroid hormone modulation of cellular lipoprotein-receptor pathways has been demonstrated in the estrogen-mediated increase in hepatocyte LDL transcytosis via the asialoglycoprotein receptor.\textsuperscript{26} In macrophages, internalized lipoprotein-scavenger receptor complex dissociates in the acidic environment of the endosome, with the receptor recycling to the cell surface and the majority of the AcLDL proceeding to lysosomal degradation.\textsuperscript{27} A shift in the balance between degradation and retroendocytosis of intact AcLDL would contribute to a reduction in net uptake of modified lipoprotein. We examined rates of retroendocytosis by internalizing labeled AcLDL 4 times between 15 minutes and 2 hours and then measuring the release of intact AcLDL to the extracellular media over 60 minutes. At 8 days, cells were incubated with 20 µg/mL \textsuperscript{125}I-AcLDL at 37°C for either 15, 30, or 120 minutes. At each time point, the respective wells were rapidly cooled to 4°C to inhibit additional intracellular transport and washed as described previously\textsuperscript{28} with the exception of an acid wash (0.2 mol/L acetic acid, 0.5 mol/L NaCl, pH 2.4) to remove surface-bound \textsuperscript{125}I-AcLDL, followed by the final 3 PBS washes. By removing ≥80% of the specific surface-bound AcLDL at acid washing\textsuperscript{29} before the chase incubation, these studies ensured that the intact AcLDL in the TCA-treated media was derived largely from inside the cell rather than from dissociation of labeled ligand from surface receptors. These experiments were also performed in the presence of 30 times excess cold AcLDL to account for nonspecific binding.

The chase incubation involved the addition of fresh RPMI (containing 2 mg/mL BSA and 100 µg/mL of unlabeled AcLDL) at 37°C for 1 hour. The media were then collected and precipitated with TCA, and the radioactivity of the pellet was measured (intact AcLDL released into the media from inside cells). In addition, a separate chase of only 15 minutes was performed on the cells that received a 2-hour pulse, to preferentially measure retroendocytosis from organelles close to the surface (eg, early endosomes). Viability after each trafficking experiment was assessed by the trypan blue exclusion method and confirmed to be >90%.

**Statistical Analysis**

Results are expressed as mean±SEM of ≥3 wells per condition per donor, with n = 11 for female-donor MDMs and n = 8 for male-donor MDMs. Because of individual donor variability, results for each donor have been expressed as a percentage of control values, and individual experimental results (in percent of control values) have been pooled to give the final results for male and female-donor cells under control and hormone-treated conditions. Statistical significance was analyzed by a 1-way ANOVA and post hoc pairwise testing between conditions. Statistical significance was inferred at a 2-sided P value <0.05.

**Results**

**Effects of Estrogen and Progesterone on Macrophage Lipid Loading**

\textsuperscript{17β}-Estradiol produced a significant reduction in human macrophage CE content compared with controls. This effect was independent of the classic estrogen receptor (ie, effect not abrogated by estrogen receptor antagonist ICI 182780 [ICI] or reproduced by estrogen receptor agonist diethylstilbestrol [DES]). Results are expressed as percentage of control values and are from 11 female donors. *P < 0.02 control vs E2nM. There was no significant difference between physiological (E2nM) and supraphysiological levels (E20nM, E200nM) of estradiol. B, Progesterone (P) treatment produced marked reduction in CE content. Progesterone effect could be abrogated by coinubcation with progesterone receptor antagonist RU 486. Results are expressed as percentage of control values and are from 11 female donors. \textsuperscript{*}P < 0.002 control vs P2nM. There was no significant difference between physiological (P2nM and P10nM) and supraphysiological (P200nM) progesterone doses.

\begin{figure}[h]
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\caption{A. \textsuperscript{17β}-estradiol (E) treatment produced a significant reduction in human macrophage CE content compared with controls. This effect was independent of the classic estrogen receptor (ie, effect not abrogated by estrogen receptor antagonist ICI 182780 [ICI] or reproduced by estrogen receptor agonist diethylstilbestrol [DES]). Results are expressed as percentage of control values and are from 11 female donors. *P < 0.02 control vs E2nM. There was no significant difference between physiological (E2nM) and supraphysiological levels (E20nM, E200nM) of estradiol. B, Progesterone (P) treatment produced marked reduction in CE content. Progesterone effect could be abrogated by coinubcation with progesterone receptor antagonist RU 486. Results are expressed as percentage of control values and are from 11 female donors. \textsuperscript{*}P < 0.002 control vs P2nM. There was no significant difference between physiological (P2nM and P10nM) and supraphysiological (P200nM) progesterone doses.}
\end{figure}
between concentrations). This effect could not be reversed by coinoculation with the estrogen receptor antagonist ICI 182780 (shown in Figure 1A). Furthermore, MDMs exposed to the potent nonsteroidal estrogen receptor agonist diethylstilbestrol did not show a significant reduction in CE content (95±4%; \( P < 0.1 \) compared with controls), which further suggests that the effect of 17β-estradiol occurred independently of the classic estrogen receptor known to be present in these cells.

Physiological levels of progesterone produced an even more dramatic reduction in CE accumulation (74±9%, 56±10%, and 65±8% for 2, 10, and 200 nmol/L progesterone, respectively; \( P < 0.002 \) for each concentration compared with control but no significant difference between concentrations) (Figure 1A). This reduction in cellular CE content with progesterone could be abrogated by coinoculation with the progesterone receptor antagonist RU 486 (112±8% and 91±13% for 2 nmol/L progesterone per 100 nmol/L RU 486 and 10 nmol/L progesterone per 100 nmol/L RU 486, respectively; \( P > 0.5 \) compared with controls) (Figure 1). RU 486 treatment alone was not significantly different from controls (93±8%, \( P = 0.1 \)).

Intracellular FC levels were also reduced in the estrogen-treated female-donor MDMs (86±4%, 88±3%, and 85±6% for 2, 20, and 200 nmol/L estrogen, respectively; \( P < 0.02 \) for each concentration compared with controls) but not in progesterone-treated MDMs (108±8%, 105±8%, and 117±11% for 2, 10, and 200 nmol/L progesterone, respectively; \( P > 0.1 \) compared with controls).

By contrast, CE accumulation in MDMs from male donors was not decreased by either 17β-estradiol or progesterone (for example, 105±9% and 115±8% for estrogen 200 nmol/L and progesterone 10 nmol/L, respectively; \( P > 0.05 \) compared with controls). Similarly, FC levels in male-donor MDMs were not significantly influenced by either female hormone (data not shown).

These sex-specific effects of estrogen and progesterone were also observed when the male- and female-donor MDMs were propagated in phenol red–free RPMI supplemented with 10% male serum (as opposed to 10% postmenopausal female serum). There was no significant effect of 17β-estradiol or progesterone on lipid loading of male-donor MDMs compared with controls (data not shown), but there was a persistent reduction in lipid loading in female-donor MDMs exposed to female hormones in the presence of male or postmenopausal female serum in the growth media. For example, cellular CE and FC values (expressed as nmol/mg cell protein) for MDMs from the same female donor, maintained in RPMI containing 10% postmenopausal female serum compared with 10% male serum, were not significantly different from each other for each of the treatment conditions (control 277±12 versus 301±3, \( P = 0.1 \); estrogen 200 nmol/L 233±9 versus 264±12, \( P = 0.1 \); progesterone 10 nmol/L 221±18 versus 245±15, \( P = 0.4 \)).

**Estrogen and Progesterone Action on Macrophage Uptake and Processing of Modified LDL**

To understand the effects of estrogen and progesterone on AcLDL loading, we conducted binding and intracellular processing studies of radiolabeled AcLDL in premenopausal female-donor macrophages, in which there were significant hormonal effects on intracellular lipid loading.

**Surface Binding Studies**

Surface binding studies performed at 4°C over a range of concentrations for radiolabeled AcLDL with or without a 30-fold excess of unlabeled ligand showed no significant difference in binding between control cells and cells treated with estrogen (Figure 2A) or progesterone (Figure 2B). When specific and nonspecific binding kinetics were analyzed by the LIGAND computer program, scavenger receptor affinity and binding-site numbers were not significantly different between treatment groups (\( K_s \) values 1.0×10^{-8}, 9.7×10^{-9}, and 9.6×10^{-9} mol/L for control, estrogen 2 nmol/L, and progesterone 10 nmol/L, respectively; \( P > 0.9 \); receptor site concentrations 8.8×10^{-11}, 7.1×10^{-11}, and 7.1×10^{-11} mol/L for control, estrogen 2 nmol/L, and progesterone 10 nmol/L, respectively, \( P > 0.4 \)).

Because of the previously reported temperature-sensitive nature of the scavenger receptor ligand-binding domain, binding at 4°C may not be representative of in vivo binding. We therefore incubated the MDMs with unlabeled AcLDL for 4 hours at 37°C and then rapidly cooled the cells to 4°C before challenging them with a single concentration of

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**Figure 2.** There was no significant difference in surface binding at 4°C between conditions at any concentration of AcLDL (\( P > 0.1 \)). These data are representative of 3 equivalent experiments.
radioactive ligand and excess AcLDL. In this protocol, binding represents the steady state, with unoccupied receptor sites remaining at the surface during uptake at 37°C. Compared with controls, estrogen- and progesterone-treated macrophages were able to bind a significantly greater proportion of labeled AcLDL (114±6% for estrogen 2 nmol/L and 161±6% for progesterone 10 nmol/L versus 100±4% control, \( P < 0.05 \) and \( P < 0.001 \), respectively) (Figure 3). This suggests that at physiological temperatures, estrogen and progesterone reduce scavenger receptor occupancy and therefore subsequent internalization of ligand-receptor complexes.

**Retroendocytosis Studies**

Progesterone significantly increased the amount of intact AcLDL that had undergone retroendocytosis under all conditions tested \( (P < 0.008) \) (Figure 4). Furthermore, the fractions of intact ligand that had undergone retroendocytosis after 15 minutes of labeling (Figure 4, A), 30 minutes of labeling (B), and a 2-hour labeling period (C) were similar. Because early endosomes would be filled by the 15-minute time point, this suggests that retroendocytosis predominantly occurs from the early endosomal compartment. Release of AcLDL from the cells was also rapid, with the majority occurring during the first 15 minutes of the 60-minute chase (Figure 4, D). This observation is also consistent with the recycling time of lipids from an early endosomal compartment. Retroendocytosis in estrogen-treated macrophages was not significantly different from control cells.

**Discussion**

In this study, we found that physiological concentrations of both 17\( \beta \)-estradiol and progesterone decreased CE formation in human MDMs. This effect was sex specific, being observed in female- but not male-donor cells. The estrogen effect was not mediated via the classic estrogen receptor and was due predominantly to an effect on scavenger receptor occupancy and therefore lipoprotein uptake. The progesterone effect, in contrast, was receptor mediated and due to changes in both lipoprotein uptake and intracellular processing, in particular to increased retroendocytosis of modified LDL. Both estrogen and progesterone receptors are known to exist in macrophages.

Previous studies have suggested other potentially antiatherogenic effects of estrogen, including beneficial effects on the lipid profile, coagulation factors, cell adhesion molecule expression, arterial plaque size, and cellular proliferation. In an immortalized cell line that does not express estrogen receptors, supraphysiological doses of 17\( \beta \)-estradiol have been shown to decrease lipid uptake by macrophages; however, the effects of physiological levels of estrogen and its antagonists on foam cell formation and the mechanism of lipoprotein uptake in female and male primary macrophages have not been studied previously. Our observation of an uptake-mediated, receptor-independent reduction in macrophage lipid loading in female cells only is consistent with other recently published work that has also noted sex-specific effects of sex steroid hormones on atherosclerotic processes.

Few previous studies have examined the effect of progesterone on basic atherogenic processes. The mechanism for the observed benefit of progesterone on MDM lipid loading in the present study most likely relates to both reduced modified LDL internalization at 37°C and greater retroendocytosis of undegraded lipoprotein to the surface. Time-course experiments (Figure 4) suggested that retroendocytosis must occur from early endosomal compartments of the cell, because it is close to its maximal value after 15 minutes, which is approximately twice the \( t_{1/2} \) (8 minutes) of passage through this compartment in Chinese hamster ovary cells. The precise effects on the endosome remain uncertain. Altered endosomal acidification affecting receptor-ligand dissociation is one plausible explanation, although previously reported effects with estrogen in hepatocytes were small.

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**Figure 3.** Surface receptor occupancy for modified LDL at 37°C was significantly lower for both 17\( \beta \)-estradiol (E) and progesterone (P) vs controls as assessed by subsequent surface binding of \(^{125}\text{I}\)-AcLDL at 4°C. These results were representative of 3 equivalent experiments. *\( P < 0.05 \); **\( P < 0.001 \).

**Figure 4.** Retroendocytosis of undegraded AcLDL was significantly greater in progesterone-treated human MDMs than in control and estrogen-treated cells (*\( P < 0.008 \)). Fraction of undegraded ligand that was retroendocytosed was similar for early and late time points, implying a predominant effect on early stages of intracellular lipid trafficking. These data are pooled from 3 separate experiments, with results expressed as a percentage of control.
Modulation of receptor affinity and sorting are other possible methods of sex steroid action. Previous studies\(^6\) in the mouse cell line J774 have suggested that progesterone inhibits FC translocation from the plasma membrane, leading to decreased CE accumulation in foam cell macrophages. This mechanism was not observed in the present study, in which decreased intracellular CE levels in progesterone-treated MDMs were not accompanied by significant increases in FC concentration. A reduction in acyl-CoA:cholesterol acyltransferase (ACAT) activity may also lead to reduced cellular CE content; however, progesterone has been shown to be only a weak inhibitor of ACAT activity in previous studies in mouse peritoneal macrophages.\(^{37}\)

Competitive ligand-receptor–binding experiments at 4°C did not reveal altered scavenger receptor binding kinetics between treatment groups; however, our data showing less ligand-receptor occupancy at 37°C with estrogen and progesterone treatment could be attributed to a change in ligand-receptor affinity at 37°C. Hence, 4°C binding data may not be representative of in vivo hormone effects, consistent with the previously described temperature-sensitive nature of the scavenger receptor ligand-binding domain.\(^{30,38}\) The progesterone- and estrogen-related increase in radiolabeled AcLDL surface binding at 4°C after a 37°C incubation could be due to (1) reduced cell-surface scavenger receptor occupancy with modified LDL at 37°C or (2) an increase in cell-surface scavenger receptor numbers. The latter explanation is unlikely, because our data showed no treatment differences in cell-surface binding site number in MDMs exposed to hormones for 6 days at 37°C until just before the 4°C binding experiments. A plausible explanation is that estrogen and progesterone decrease receptor affinity for AcLDL at 37°C, leading to an overall decrease in ligand binding and internalization at this temperature. We attempted to examine receptor-ligand affinity at 37°C indirectly using receptor occupancy as a marker because of the inadequacy of Scatchard binding kinetics at this temperature and the limitations imposed by inhibitors of internalization such as N-ethylmaleimide, whose broad-specificity alkylating potential could also modify sulfhydryl groups in the scavenger receptor, potentially confounding interpretation of binding data.

Sex-specific reduction in lipid loading under the influence of the female sex steroids, estrogen and progesterone, occurs in the presence of either male or postmenopausal female serum. This suggests that the sex differences are unlikely to be related to nonspecific perturbations in the cell environment but rather to specific cellular characteristics. One plausible explanation would be a difference in sex steroid hormone receptor levels or hormonally responsive cellular pathways between the sexes; this possibility requires additional study.

Foam cell formation is intimately involved in early atherosclerosis\(^{9,40}\) and has been studied extensively in mouse and more recently in immortalized human cell lines.\(^{41,42}\) The methods used to purify primary monocytes from healthy donors have enabled the study of macrophage lipoprotein uptake with primary human cells from both males and females. This might be expected to reflect the in vivo situation more closely than could previously be accomplished. The presence of sex steroid receptors in these primary cells\(^{43–45}\) has been demonstrated recently and is important in an examination of sex steroid modulation of lipoprotein metabolism. The use of AcLDL is well established as a standard form of modified lipoprotein in foam cell experiments, because it is specific for the scavenger receptor pathway for lipoprotein uptake.\(^{46}\) The probable importance of this pathway in contributing to atherosclerosis has been confirmed in several animal studies.\(^{47}\)

In summary, the present study has shown that physiological levels of estrogen and progesterone are associated with reduced foam cell formation in a primary human cell culture system. Our data demonstrate that sex steroid hormones might influence macrophage lipoprotein metabolism by changing ligand-receptor interactions and membrane traffic. These results are consistent with a role for both estrogen and progesterone in the atheroprotection conferred by female premenopausal status and the observed sex difference in atherosclerosis development.

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References


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