Cholesterol Metabolism and Efflux in Human THP-1 Macrophages

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Abstract—This study has investigated in detail factors regulating accumulation, esterification, and mobilization of cholesterol in human THP-1 macrophages. Human THP-1 monocytes were differentiated into macrophages and then cholesterol enriched by exposure to acetylated LDL (AcLDL), together with [3H]free cholesterol (FC). Although THP-1 macrophages accumulated FC and esterified cholesterol (EC), assessed by both mass and radioactivity, cellular EC always demonstrated a much lower specific activity (cpm/μg) than did cellular FC, and several potential causes of this finding were investigated. Inhibition of acyl-CoA:cholesterol acyltransferase (ACAT) during loading decreased cellular [3H]EC by 95±1.4% but decreased cell EC mass by only 66.0±4.0%, indicating that some intracellular undegraded AcLDL-derived EC was present in these cells. Esterification of [3H]oleate to EC in THP-1 cells loaded with AcLDL was 2.0 nmol·mg⁻¹·h⁻¹, consistent with previous literature. However, EC, triglyceride, and phospholipid fractions respectively contained 1.0±0.07%, 80.0±0.5%, and 18.9±0.3% of cell [3H]oleate, indicating triglycerides were much more metabolically active than EC. In addition, the mass of triglyceride in THP-1 macrophages exceeded that of EC both before and after exposure to AcLDL. Esterification of nonlipoprotein-derived cholesterol was compared in THP-1 cells and nonhuman Fu5AH, CHO, and RAW macrophage cells. Whereas the nonhuman cell lines all esterified over 30% of 2-hydroxypropyl-β-cyclodextrin (hp-β-CD)–delivered cholesterol within 6 hours, THP-1 cells esterified <8.0% of incorporated cholesterol. Kinetics of cholesterol efflux from AcLDL–loaded THP-1 cells were first investigated after loading with only FC, and interactions between efflux and EC hydrolysis were further assessed after loading cells with both EC and FC. Over 24 hours, human apolipoprotein (apo) A-I, apoHDL reconstituted with phosphatidylcholine, and HDL₃ respectively removed 46.6±3.7%, 61.3±3.4%, and 76.4±10.1% of [3H]FC from FC-enriched THP-1 cells. Cholesterol efflux to apoA-I was saturated by 24 hours and was enhanced by using apoA-I–phospholipid instead of pure apoA-I. Kinetic modeling identified that 97% of effluxed FC derived from a slow pool, with a T₁/₂ ranging from 27.7 hours for HDL to 69.3 hours for apoA-I. Although efflux enhanced net clearance of EC, hydrolysis of EC during concurrent inhibition of ACAT was unaffected by cholesterol efflux. Supplementation of THP-1 cultures with cAMP to stimulate hormone-sensitive lipase did not significantly enhance net hydrolysis of EC or cholesterol efflux. In conclusion, human THP-1 macrophages contain a large and metabolically active pool of triglyceride and a relatively inactive pool of EC. The low specific activity of EC relative to FC is contributed to by reduced esterification of FC, slow hydrolysis of EC, and accumulated lipoprotein EC. The relative inactivity of the EC pool may further contribute to otherwise impaired cholesterol efflux from these cells. Net cholesterol efflux from human macrophages is achieved by pure apoA-I and is substantially further enhanced by the presence of phospholipid in acceptor particles. (Arterioscler Thromb Vasc Biol. 1998;18:1589-1599.)

Key Words: macrophage ■ atherosclerosis ■ cholesterol ■ triglyceride ■ cyclodextrin
previously available human monocyteoid lines. THP-1 cells, like mature human primary macrophages, synthesize and secrete M-CSF and apolipoprotein (apo) E, and IL-8 secretion has been described in THP-1 cells. THP-1 cells have been particularly useful for studying the induction of ScR expression during their differentiation from monocytes to macrophages during exposure to phorbol myristate acetate (PMA).

Previous studies have confirmed both ScR expression and increased cholesterol esterification after exposure to acetylated LDL (AcLDL) in THP-1 cells, although the relative quantitative and metabolic activities of FC, EC, and triglyceride (TG) pools in THP-1 cells are as yet undefined. Given that ex vivo human foam cell macrophages and primary cultures of human monocyte-derived macrophages are described as containing significant amounts of TG, the size and metabolic activity of TG may be an important component of lipid metabolism of human macrophages in general and THP-1 cells in particular.

Previous literature has suggested that there is deficient EC hydrolysis in THP-1 cells and that this factor was limiting for cholesterol efflux. Westman et al suggested that cholesterol efflux does not occur from THP-1 cells to phospholipid-deficient apoA-I, an observation which, if confirmed, would imply that THP-1 cells differed markedly from other macrophage species (see References 19 and 20). It would also imply that apolipoprotein-mediated efflux of cholesterol may be unimportant in human macrophages. The kinetics of cholesterol efflux per se, independent of EC hydrolysis, have not been established in THP-1 cells, nor is it known if cholesterol efflux from these macrophages is derived from multiple kinetic pools.

In these studies, we have investigated the accumulation and efflux of cholesterol and the relative size and metabolic activity of the EC and TG pools in human THP-1 macrophages. THP-1 cells contained large quantities of metabolically active TG and had a low specific activity in their EC pool compared with that of the FC pool. This finding was attributable to the combination of accumulated undegraded lipoprotein EC, slow esterification of exogenous FC, and sluggish EC hydrolysis. In addition, slow efflux of FC from THP-1 cells was observed, independent of impaired EC hydrolysis. Cholesterol efflux followed a 2-pool kinetic model, with important differences between cholesterol acceptors according to their phospholipid composition; however, definite efflux to pure apoA-I was observed.

Methods

Materials

BSA (essentially fatty acid free), heat-inactivated fetal bovine serum (FBS), cholesteryl methyl ether, gentamicin, penicillin/streptomycin, cAMP, and FC were purchased from Sigma Chemical Company. Radioisotopes [2,3-3H]cholesterol (46.5 Ci/mmol), [4,14C]cholesterol (51.3 mCi/mmol), and [1,2-3H]oleate (10.0 Ci/mmol) were obtained from New England Nuclear. Organic solvents were obtained from Fisher Scientific. Tissue-culture flasks and plates were from Falcon and Corning. RPMI culture medium was obtained from ATCC (Manassas, VA). Sodium-58035 (S-58035) and Pfizer CP-113,818 (CP-113,818) were gifts from Sandoz (Dr J. Heider) and Pfizer (Dr M. Bamberger).

Radioisotopes

[1,2-3H]cholesterol (46.5 Ci/mmol) and [4,14C]cholesterol were isolated against 0.15 mol/L NaCl, and sterilized by 0.45 μm filter. LDL was acetylated with acetic anhydride. Dispersions containing FC and egg PC and preparations of pure human apoA-I were prepared as described. ApoHDL protein reconstituted with POPC (rHDL-PC) and apoA-I–PC were prepared by sonication of delipidated HDL apoprotein, or apoA-I, in 0.9% NaCl solution with POPC at 4°C under nitrogen, achieving a phospholipid-to-protein mass ratio of 2.5:1.

Culture and Loading of Cells

THP-1 monocytes (American Type Culture Tissue Culture Collection, Cambden, NJ) were grown in suspension at 37°C in 5% CO₂ in bicarbonate-buffered RPMI containing 10% FBS (vol/vol), 50 μmol/L β-mercaptoethanol, and 50 μg/mL gentamicin, at a cell density of 0.2 to 1.0×10⁶/mL. Cells were plated at a density of 1.2×10⁶/cm² dish or 2.4×10⁶/cm² dish in RPMI with 10% FBS, 50 μmol/L β-mercaptoethanol, 50 μg/mL gentamicin, and 50 ng/mL PMA for 3 to 4 days to become fully differentiated macrophages before use in experiments. Cells were used between passages 5 and 20.

Differentiated THP-1 macrophages were washed extensively with serum-free RPMI before exposure to RPMI containing AcLDL (150 μg protein per milliliter), 1% FBS, 50 ng/mL PMA, [3H]cholesterol (2 μCi/mL), and mercaptoethanol and gentamicin as above, for 24 to 96 hours. In the majority of experiments, cells were enriched with cholesterol by exposing them to AcLDL-containing medium for 24 hours. In some experiments, maximizing the size of the EC pool was desirable, which was achieved by increasing the duration of cholesterol enrichment to 48 or even 96 hours. In initial experiments, there were only minor differences in lipid metabolism and some of these comparative data are presented in “Results.” In general, there were only minor differences in lipid metabolism between groups with and without ongoing PMA, and PMA was routinely continued throughout experiments to maximize cell viability.

Resident mouse peritoneal macrophages were isolated by lavage from unstimulated Q5 mice and plated in 35-mm diameter tissue-culture wells (Costar) at 5×10⁶ cells per well as described. Cultures were incubated at 37°C for 1 to 2 hours to establish adherence, then washed 3 times with prewarmed PBS before incubation with Dulbecco’s modified Eagle’s medium containing lipoprotein-deficient serum (10% vol/vol, equivalent to final protein...
concentration of 2.5 mg/mL), penicillin G, and streptomycin, plus AcLDL as previously described. To selectively load cells with \( [3 \text{H}] \) cholesterol, passage through Sepharose PD10 columns (columns supplied by Pharmacia; data not shown). To selectively load cells with \( [3 \text{H}] \) cholesterol, passage through Sepharose PD10 columns (columns supplied by Pharmacia; data not shown). To selectively load cells with \( [3 \text{H}] \) cholesterol, passage through Sepharose PD10 columns (columns supplied by Pharmacia; data not shown).

**Metabolic Labeling**

THP-1 macrophages exposed to AcLDL for 22 hours were pulsed with \( [\text{H}] \) oleate complexed with BSA (molar ratio oleic acid to BSA, 5:1; specific activity of oleic acid, 5.8 \times 10^7 \text{cpm/\mu g}) for 2 hours. To quantify lipid fractions isolated by thin-layer chromatography (TLC), \( [\text{H}] \) cholesterol was used as an internal standard and was added to culture dishes at the time of addition of isopropanol.

To label cells with \( [\text{H}] \) cholesterol during cholesterol enrichment, AcLDL and \( [\text{H}] \) cholesterol in ethanol were coincubated with FBS and 10% of the calculated final volume of RPMI overnight at 37°C, then diluted to final concentrations of 150 \( \mu \)g protein per milliliter for AcLDL, 1% FBS (vol/vol), and 2 \( \mu \)g/mL \( [\text{H}] \) cholesterol in RPMI, as previously described. The final concentration of ethanol in RPMI was 0.2% (vol/vol). After enrichment with \( [\text{H}] \) cholesterol, TLC of AcLDL in FBS-RPMI revealed that in excess of 98% of \( [\text{H}] \) cholesterol was unesterified and that the specific activity of \( [\text{H}] \) cholesterol was unchanged by 0.45 \( \text{mM/L} \) filtration or by passage through Sepharose PD10 columns (columns supplied by Pharmacia; data not shown). To selectively load cells with \( [\text{H}] \) FCS, THP-1 macrophages were loaded in the presence of 1 to 10 \( \mu \)g/mL ACAT inhibitor (5-8035 or CP-113 818; stock solutions in DMSO with final volume \( \leq 0.1\% \), vol/vol culture medium). In preliminary experiments, almost complete (\( >95\% \)) maximal inhibition of cholesterol esterification in THP-1 cells was demonstrated by both ACAT inhibitors over this concentration range. To investigate cAMP-mediated stimulation of neutral cholesteryl ester hydrolase (nCEH) activity, solutions of nCEH, frozen, and aliquots thawed immediately before use. A final concentration of 100 \( \mu \)g/mL cAMP (DMSO \( \leq 0.1\% \), vol/vol culture medium) was added to cholesterol-enriched cells after overnight equilibration, as previously described.

To label cells with nonlipoprotein-derived cholesterol, a cyclodextrin solution saturated with respect to cholesterol was prepared in RPMI containing 25 \( \mu \)g/mL HP-β-CD (lot No. E8309), 0.625 \( \mu \)g/mL cholesterol, and 4.0 \( \mu \)g/mL \( [\text{H}] \) cholesterol (specific activity of cholesterol–HP-β-CD solution of 17 224 \text{cpm/\mu g cholesterol}). As described in detail previously, \( [\text{H}] \) cholesterol and unlabeled cholesterol were mixed in chloroform, evaporated under nitrogen, and dissolved in toluene from which an aliquot was removed for scintillation counting. The tolune solution was re-evaporated and the film of dry cholesterol(\( [\text{H}] \) cholesterol was incubated in RPMI containing HP-β-CD overnight at 37°C before filter sterilization (0.45 \( \mu \)mol/L) and incubation with THP-1 cells. Cholesterol–HP-β-CD solution thus prepared was added without addition of PMA or serum to culture medium for up to 8 hours, after which cell cultures were extracted in isopropanol and analyzed as described below. In preliminary experiments, coincubation of PMA with cholesterol–HP-β-CD solution had no effect on cholesterol accumulation or cell viability over short 6- to 8-hour incubations. To investigate the possibility that exposure to 10% FBS during differentiation subsequently modified the cellular response to nonlipoprotein-derived cholesterol, differentiated THP-1 cells were washed and preincubated for 24 hours with RPMI or RPMI containing 10% FBS (vol/vol) before incubation with cholesterol–HP-β-CD solution in each experiment.

**Cellular Lipid Analysis**

Monolayers were washed with PBS, allowed to dry, then incubated in 2 mL of isopropanol and cholesteryl methyl ether internal standard overnight. Isopropanol extracts were recovered and dried under nitrogen, and FC and total cholesterol mass were respectively determined before and after saponification by gas-liquid chromatography (GC), and mass of cholesterol in EC was derived by difference. Dried isopropanol extracts were redissolved in toluene, and total \( [\text{H}] \) cholesterol was determined from aliquots analyzed by scintillation counting. Residual toluene extracts were dried and redissolved in chloroform/methanol (1:1, vol/vol), and the proportion of label in \( [\text{H}] \) FC (\( R \)0.24) and \( [\text{H}] \) EC (\( R \)0.97) fractions was determined after separation by instant TLC (petroleum ether/ethanol/acidic acetate, 85:15:1, vol/vol/vol) using standards of FC and EC identified by iodine vapor. To separate EC from TG fractions, a mobile phase of petroleum ether/ethanol/acidic acetate (100:10:1, vol/vol) was used on silica gel TLC plates (\( R \) values 0.28, 0.67, 0.93 for FC, triolein, and cholesteryl oleate standards, respectively). TG mass (equivalent to micrograms of triolein) was determined on isopropanol cell lipid extracts using a modification of a commercially available colorimetric enzymatic assay (glycerol phosphate oxidase, Catalog No. 339–20, Sigma), after confirmation of linearity of glycerol and triolein standards under conditions used in these experiments.

Lipoprotein phospholipids were determined by the method of Sokoloff and Rothblat41 after Bligh and Dyer extraction39 to remove aqueous phosphate. Cell and lipoprotein protein values were determined by a modification of the Lowry assay as previously described.

**Cholesterol Efflux**

After equilibration, cells were washed and incubated in RPMI (containing β-mercaptoethanol and gentamicin as above) with or without pure apoA-I (25 \( \mu \)g protein per milliliter), HDL1 (200 \( \mu \)g phospholipid per milliliter), rHDL-PC (200 \( \mu \)g phospholipid per milliliter or 25 \( \mu \)g protein per milliliter, the latter equivalent to 62.5 \( \mu \)g phospholipid per milliliter), or apoA-I–PC (25 \( \mu \)g protein per milliliter). These concentrations of apoA-I, HDL1, and rHDL-PC have previously been found to be optimal for maximal cholesterol efflux from macrophages. Efflux incubations were performed for up to 24 hours in 22-mm (4.0-cm²) dishes, each containing 2 mL of medium. Aliquots (120 \( \mu \)L) were removed at various times, filtered through 0.45-μmol/L multiscreen filtration plates (Millipore), and 100-μL aliquots were analyzed by scintillation counter to quantify efflux of \( [\text{H}] \) cholesterol from cells. In other experiments, 1-mL aliquots of media were removed and spun at 14 000 rpm in an Eppendorf microfuge for 15 minutes to pellet any floating cells, and the supernatant was removed and counted. Media samples analyzed using both methods demonstrated identical efflux data were obtained with the filtration plate or the Eppendorf microfuge methods (data not shown).

**Data Analysis**

Percent cholesterol efflux was calculated by dividing total \( [\text{H}] \)cholesterol in the medium after efflux by that present in cells before efflux (\( t_0 \)) for kinetic studies with multiple time points or by dividing cholesterol in the medium by the sum of cholesterol in medium and in cells at the end of 24 hours’ efflux when both cells and media were extracted. Efflux values derived by either method gave almost identical results. In addition, depletion of cellular cholesterol or EC during efflux is presented as a percentage of that in cells at \( t_0 \). In figures and tables, all data points represent the mean±SD of 3 cell cultures from a single representative experiment. Computer modeling of cholesterol efflux kinetic data was analyzed by Cell Chol molecular modeling program to generate the data described in the Table and Figure 8. Data were analyzed to fit either a single kinetic pool or a 2-kinetic pool model and compared for minimization of error as described in detail previously.
Results
Accumulation of EC Mass and \(^{3}H\)EC in THP-1 Cells
Before exposure to AcLDL, THP-1 cells differentiated for 3 days in 10% FBS with PMA typically contained 10 to 30 \(\mu g\) FC per milligram cell protein and undetectable or very small quantities of EC. After 24 hours’ incubation with AcLDL, the cell FC mass doubled and EC mass increased severalfold, but after 24 hours’ loading, cell EC mass was always less than that of FC. Continued exposure of cells to PMA during loading with AcLDL appeared to increase FC content of THP-1 cells in some experiments, but any such effects were modest and varied between experiments (Figure 1A).

During 24-hour incubations with AcLDL and \(^{3}H\)FC, cells accumulated \(^{3}H\)EC, and this accumulation was largely unaffected by the continued presence or withdrawal of PMA during incubation with AcLDL (Figure 1B). The relative sizes of the cellular \(^{3}H\)FC and \(^{3}H\)EC pools were consistently even more discrepant than were the respective masses of FC and EC, as indicated by the specific activity (cpm/\(\mu g\) cholesterol; Figure 1C). The low specific activity of EC compared with FC indicated these 2 pools had not reached equilibrium by the end of 24 hours’ loading (without additional equilibration).

Even more prolonged cholesterol loading (48 hours), followed by a prolonged equilibration incubation (24 hours) did not achieve equal specific activities in \(^{3}H\)FC and \(^{3}H\)EC pools (Figure 2A through 2C). In comparison with cells loaded for 24 hours, cells loaded for 48 hours contained more EC mass than FC; however, the specific activity of FC and EC pools remained unequal even after attempted equilibration.

It was concluded that mass data and radioactivity could not be simply correlated when using THP-1 macrophages, and data for each was always calculated independently by GC and scintillation counting, respectively, in all experiments.

We hypothesized that cellular accumulation of undegraded, lipoprotein-derived (hence unlabeled) EC contributed to the low EC specific activity. To test this, THP-1 cells were loaded with AcLDL and \(^{3}H\)cholesterol for 24 hours or 48 hours in the presence or absence of ACAT inhibitor (CP-113 818), and FC and EC mass and radioactivity were measured (Figure 3). ACAT inhibition during cholesterol enrichment decreased cell \(^{3}H\)EC to <5% of that present without ACAT inhibition, whereas EC mass was decreased to 35% of that present without ACAT inhibition. Even though EC mass in THP-1 cells was clearly greater after 48-hour than after 24-hour loading, the proportion of cell EC that persisted in the presence of ACAT inhibitor was approximately 30% in the 2 conditions. The discrepancy between substantial residual EC mass and trivial residual \(^{3}H\)EC implied that immediately after loading, approximately 30% of EC mass in THP-1 cells was derived from undegraded AcLDL-derived EC and may contribute to the relatively low specific activity of \(^{3}H\)EC.

Metabolic Labeling of THP-1 Cells With \(^{3}H\)Oleate, and Quantification of TG Accumulation
To establish that cholesterol esterification by THP-1 cells in our laboratory was consistent with that of previous literature, THP-1 cells were loaded with unlabeled AcLDL for 22 hours, then pulsed with \(^{3}H\)oleate complexed to BSA. Inhibition
of ACAT effectively inhibited the formation of cholesteryl \([3H]\)oleate in THP-1 cells. THP-1 cells esterified approximately 2.0 nmol of \([3H]\)oleate to \([3H]\)EC per milligram of cell protein per hour, and did so regardless of the presence or absence of PMA during exposure to AcLDL (Figure 4A). This rate of esterification is consistent with previous THP-1 literature ranging between 1.0 and 5.0 nmol mg\(^{-1}\) h\(^{-1}\),\(^{11,12}\) but is substantially less than rates of approximately 12 nmol mg\(^{-1}\) h\(^{-1}\) achieved with mouse peritoneal macrophages exposed to AcLDL.\(^{31}\)

Despite similar rates of \([3H]\)oleate esterification as in previous THP-1 literature, we found that esterification of oleate to EC represented a minute proportion of the total cell oleate separated by TLC (Figure 4B). Nineteen percent of cellular \([3H]\)oleate was within the phospholipid fraction, 80% was in the TG pool, and only 1% was present in the EC pool, indicating that differentiated THP-1 cells have a previously uncharacterized metabolically active TG pool and a relatively inactive EC pool.

To further investigate the quantitative importance of the TG pool in these cells, TG mass was measured and related to cholesterol mass in the same cell cultures (Figure 5A). As indicated above, THP-1 cells loaded for 24 hours with AcLDL accumulated both FC and EC. However, the mass of TG in THP-1 cells was greater than that of total cell cholesterol both before exposure to AcLDL and after 24 hours. Figure 5A shows the mass of TG and total cell cholesterol in THP-1 cells before and after exposure to AcLDL with or without PMA.

**Figure 1.** Accumulation of FC (solid bars) and EC (open bars) in THP-1 macrophages after loading with AcLDL. THP-1 macrophages differentiated in 10% FBS and 50 ng/mL PMA for 72 hours were washed and incubated for 24 hours with 150 μg/mL AcLDL, 2 μCi/mL \([3H]\)cholesterol, and 1% FBS, as indicated in “Methods,” with or without 50 ng/mL PMA during the loading incubation. Isopropanol extracts were analyzed for cholesterol mass by GC (A); free or esterified \([3H]\)cholesterol was separated by TLC (B); and the specific activity of the \([3H]\)cholesterol in each fraction in the cell extracts was determined (C). In this and subsequent figures, data points represent mean ± SD of 3 dishes; where error bars are not visible, they are obscured by the top of the bar or by the symbol.

**Figure 2.** Unequal specific activity of \([3H]\)FC and \([3H]\)EC pools despite prolonged loading and equilibration. Differentiated THP-1 macrophages were incubated with AcLDL and \([3H]\)cholesterol for 48 hours and washed and equilibrated for 24 hours before lipids were extracted and analyzed for FC and EC mass and radioactivity. In all 3 panels, FC mass or radioactivity is indicated by the shaded bars and EC mass or radioactivity by the solid bars. A, FC or EC mass (μg/mg cell protein); B, FC or EC radioactivity (cpm/mg cell protein); and C, specific activity (cpm FC or EC per microgram FC or EC cholesterol, respectively). The corresponding data for specific activity in cells loaded for 48 hours but before the 24-hour equilibration were 20 513 cpm/μg for \([3H]\)FC and 5348 cpm/μg for \([3H]\)EC.

**Figure 3.** Effect of ACAT inhibition on EC mass and \([3H]\)EC in THP-1 macrophages. In separate experiments, differentiated THP-1 macrophages were enriched with FC and EC by incubating with AcLDL and \([3H]\)cholesterol for 24 hours or 48 hours. In each experiment, incubations were performed with or without 1 μg/mL ACAT inhibitor CP-113 818. Lipids were extracted immediately at the end of loading and analyzed for EC mass and \([3H]\)EC (EC label) content. The percent residual EC mass (solid bar) or percent residual \([3H]\)EC (open bar) represents that present in cells loaded in the presence of CP-113 818 divided by that present in cells loaded in the absence of CP-113 818. At 24 hours, EC mass decreased from 31.2 ± 3.7 to 10.6 ± 2.4 μg/mg with CP-113 818, whereas \([3H]\)EC decreased from 3934.7 ± 324 to 209.4 ± 16.7 cpm/mg cell protein. In a separate experiment, at 48 hours, EC mass decreased from 79.9 ± 5.2 to 31.9 ± 14.0 μg/mg with CP-113 818, whereas \([3H]\)EC decreased from 3.2 ± 0.3 × 10^5 cpm/mg to 0.16 ± 0.02 × 10^5 cpm/mg cell protein. Thus, even though ACAT-mediated cholesterol esterification was effectively inhibited, significant EC mass was accumulated.
hours’ incubation with AcLDL. Although incubation with AcLDL achieved a greater increment in EC than TG mass, TG mass was 3-fold greater than EC mass in THP-1 cells after loading with AcLDL. Systematic manipulations of culture conditions during the 24-hour loading phase, such as omission of FBS, varying the concentration of FBS from 1% to 10%, or incubating cells with BSA (to bind free fatty acids) did not significantly alter the mass of the TG pool in these cells (data not shown).

To evaluate the relative size of the TG pool in other commonly used macrophages, primary cultures of murine and human macrophages were incubated with AcLDL (THP-1) macrophages were incubated with AcLDL for 22 hours (with or without CP-113,818 [Pfizer] and with or without PMA), then washed and pulsed with BSA-[3H]oleate for 2 hours, and lipids extracted. (PMA was omitted from all conditions for the pulse phase.) Isopropanol extracts of cell cultures were analyzed for total [3H]oleate by scintillation counting and lipid subfractions separated by TLC with petroleum ether/ethyl ether/acetic acid (100:10:1, vol/vol/vol) using [14C]cholesterol as internal standard (as described in “Methods”). A, Esterification of [3H]oleate, calculated from the specific activity of [3H]oleate-BSA used during pulse; B, Percent of total [3H]oleate in cell distributed in phospholipid (PL, solid bars), TG (open bars), and EC (striped bars) fractions. Total cell [3H]oleate for which percent values in B are described were 59,580±1335 cpm/mg cell protein (+PMA) and 55,699±6707 cpm/mg cell protein (−PMA).

Figure 4. Esterification of [3H]oleate in THP-1 macrophages loaded with AcLDL. THP-1 macrophages were incubated with AcLDL for 22 hours (with or without CP-113,818 [Pfizer] and with or without PMA), then washed and pulsed with BSA-[3H]oleate for 2 hours, and lipids extracted. (PMA was omitted from all conditions for the pulse phase.) Isopropanol extracts of cell cultures were analyzed for total [3H]oleate by scintillation counting and lipid subfractions separated by TLC with petroleum ether/ethyl ether/acetic acid (100:10:1, vol/vol/vol) using [14C]cholesterol as internal standard (as described in “Methods”). A, Esterification of [3H]oleate, calculated from the specific activity of [3H]oleate-BSA used during pulse; B, Percent of total [3H]oleate in cell distributed in phospholipid (PL, solid bars), TG (open bars), and EC (striped bars) fractions. Total cell [3H]oleate for which percent values in B are described were 59,580±1335 cpm/mg cell protein (+PMA) and 55,699±6707 cpm/mg cell protein (−PMA).

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To evaluate the relative size of the TG pool in other commonly used macrophages, primary cultures of murine and human macrophages were incubated with AcLDL and analyzed (Figure 5B). Murine macrophages accumulated more EC than did human macrophages (or THP-1 cells) in response to incubation with AcLDL for 24 hours, but the mass of accumulated TG in murine cells was clearly less than the total cell cholesterol. Human macrophages accumulated less EC than THP-1 cells after exposure to AcLDL, as previously described, and, even more markedly than in THP-1 cells, TG mass in primary human macrophages exceeded total cell cholesterol even after exposure to AcLDL. Interestingly, all 3 types of macrophage accumulated some intracellular TG during incubation with AcLDL. The presence of an intracellular pool of TG that was large relative to the mass of accumulated EC was thus confirmed to be a property shared by both primary and THP-1 human macrophages, but not primary murine macrophages.

Esterification of [3H]Cholesterol Delivered to Cells Through the Plasma Membrane via hp-β-CD

From the above data, it appeared likely that THP-1 cells esterified cholesterol relatively sluggishly compared with other cell types. To address the issue of cholesterol esterification independently of lipoprotein binding and degradation, we investigated accumulation and esterification of nonlipoprotein-derived cholesterol delivered by hp-β-CD. Cyclodextrins have been used to stabilize sterols in solution and to enrich cells with cholesterol, and cellular loading and esterification of cholesterol stabilized in solution by cyclodextrins have recently been characterized in this laboratory in detail. Delivery of cholesterol to cells by cyclodextrins avoids potential cholesterol crystal formation in aqueous solution, while allowing direct assessment of cholesterol incorporation and esterification.

THP-1 cells were differentiated as described in “Methods,” incubated for 24 hours in RPMI/10% FBS (10%, vol/vol) or RPMI alone (preincubation), then incubated with cholesterol-
Efflux of Cholesterol From THP-1 Macrophages

Efflux of Unesterified Cholesterol

To assess cholesterol efflux independent of the rate of hydrolysis of EC, cholesterol efflux was evaluated after loading and equilibrating THP-1 macrophages in the presence of ACAT inhibitor (CP-113 818). More than 98% of cholesterol label (TLC) and mass (GC) in THP-1 cells so loaded were confirmed to be unesterified (data not shown). Because previous investigations indicated that pure apoA-I did not cause cholesterol efflux from THP-1 macrophages18 and to evaluate the relative contribution of selected structural components of HDL in causing cholesterol efflux, we compared several cholesterol acceptors. Lipid-free apoA-I (25 μg protein per milliliter), reconstituted HDL-PC (rHDL-PC) and HDL3 (both at 200 μg phospholipid per milliliter), and rHDL-PC (25 μg protein per milliliter, equivalent to 62.5 μg phospholipid per milliliter) were compared with RPMI (control medium) for their capacity to induce efflux of [3H]cholesterol. (As identical kinetics were observed with or without PMA in the efflux medium, only data with PMA are presented.)

All acceptors caused clear time-dependent efflux of [3H]cholesterol (Figure 7A), and extraction of cells at 60 (onset of efflux incubation) and at 24 hours confirmed significant depletion of both cell [3H]cholesterol and cell cholesterol mass during efflux incubations (Figure 7B). The kinetic profiles of efflux of [3H]cholesterol into the medium (Figure 7A) indicated that lipid-free apoA-I was the only acceptor to clearly become saturated by 24 hours. These kinetic data suggested that phospholipids were important in maintaining the net gradient for cholesterol efflux to occur from human THP-1 cells. To exclude the possibility that apolipoprotein composition alone explained the difference between rHDL-PC (25 μg protein per milliliter) and apoA-I (25 μg protein per milliliter), THP-1 cells were incubated with apoA-I, apoA-I–phospholipid particles, and HDL3 (Figure 7C). These data confirmed that like macrophages from other species, lipid-free apoA-I can cause significant cholesterol efflux from these cells, but phospholipid itself enhanced apoA-I–mediated efflux.

In view of the complex kinetics observed, the experimental data derived from cells enriched exclusively with FC were subjected to detailed modeling using the Cell Chol model46 (Table). Data were first modeled to fit a fast and slow pool of cholesterol (2 pools) of cellular [3H]cholesterol. rHDL-PC was the most effective of the acceptors not containing cholesterol (unlike HDL3), and thus, interpretation of efflux to this acceptor is not complicated by 2-way flux of lipoprotein-derived cholesterol and cell-derived cholesterol. The t1/2 for efflux to rHDL-PC at 200 μg phospholipid per milliliter was 18.2 hours when estimated using a single-pool model.

Modeling data to a fast and slow pool of cholesterol (2 pools) of unspecified cellular location, both of which were accessible for efflux and which could exchange cholesterol with each other, revealed a far superior fit of the data (Table). Error decreased 5-fold to 10-fold using a 2-pool model. During efflux to maximally effective concentrations of acceptors, approximately 97% of cholesterol derived from the

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**Figure 6.** Time-dependent accumulation of cyclodextrin-solubilized [3H]cholesterol in THP-1 macrophages. THP-1 cells were differentiated in 10% FBS–RPMI as described in "Methods," then were washed and incubated in RPMI (circles) or 10% FBS–RPMI (squares) for 24 hours (preincubation). All cells were then washed and incubated in hp–β-CD–cholesterol solution (100% saturated with respect to cholesterol, 25 mmol/L hp–β-CD, and 6.25 mmol/L cholesterol) not containing FBS or PMA for up to 8 hours. At each time point, cell cultures were removed and lipids extracted. Unesterified ([3H]FC, open symbols, A) and esterified ([3H]EC, solid symbols, A) cholesterol pools were separated by instant TLC. The activity per milligram of cell protein (cpm/mg, A) was calculated, and the distribution of [3H]cholesterol between unesterified and esterified pools in A expressed as the percent in the [3H]EC pool (%[3H]EC, B).

ol–hp–β-CD solution in RPMI. THP-1 cells demonstrated time-dependent accumulation of [3H]FC and [3H]EC (Figure 6A). The accumulation of [3H]FC was most rapid over the initial 2 hours, whereas [3H]EC accumulation was approximately linear over 6 hours, consistent with esterification subsequent to cellular accumulation of [3H]FC. Although preincubation with FBS did increase the proportion of [3H]cholesterol esterified, only between 3.5% and 8.0% (range of 4 independent experiments) of total cell [3H]cholesterol was esterified by 6 to 8 hours (Figure 6B). As the percent of [3H]cholesterol esterified had plateaued within 6 hours, incubations of 6 to 8 hours’ duration were used to compare cholesterol esterification between different cell types.

Maximal esterification of 8.0±0.8% of [3H]cholesterol in THP-1 cells compared with esterification of 35.0±1.5% (Fu5AH rat hepatoma cells), 30.0±2.1% (Chinese hamster ovary cells), and 37.0±3.3% (RAW 2.1 transformed mouse macrophages) of [3H]cholesterol incubated under identical conditions (Reference 49 and A. Christian, personal communication, 1997). Thus both macrophage and nonmacrophage cell lines of other species all esterified a greater proportion of nonlipoprotein-derived cholesterol than did THP-1 macrophages.
slow pool. Efflux from the slow pool best discriminated between the different acceptors, as all were similarly effective at removing cholesterol from the fast pool. The concentration of phospholipid-containing particles clearly affected the rate of efflux from the slow pool. For example, t\textsubscript{1/2} increased from 33.0 hours to 63.0 hours as the total concentration of rHDL-PC phospholipid decreased from 200 μg to 62.5 μg phospholipid per milliliter. Phospholipid-containing particles also demonstrated less apparent influx of cholesterol back to the cells, which is discussed in detail in the Discussion section.

Hydrolysis of Cell Esterified Cholesterol and Cholesterol Efflux

The rate of hydrolysis of cytosolic (ACAT-generated) [3H]EC was measured in THP-1 cells loaded with widely differing EC masses (range 19.9 ± 2.0 to 128.7 ± 8.5 μg/mg) by incubating THP-1 cells with AcLDL and [3H]cholesterol for between 24 and 96 hours. Cells were then incubated during the efflux phase with or without ACAT inhibitor S-58035 (58035, 1 μmol/L) or both S-58035 and cAMP (100 μmol/L). A, Residual [3H]FC or [3H]EC (cpm/mg cell protein) after 24 hours' incubation in specified media. B, Percent efflux of [3H]cholesterol into medium after 24 hours' incubation with respective media. Each point represents the mean ± SD of 3 dishes, and efflux data in B are derived from the same cell cultures generating data in A.

Figure 7. Efflux of cholesterol from THP-1 macrophages to apoA-I and phospholipid-containing acceptors. A and B, THP-1 macrophages were differentiated and incubated for 24 hours with AcLDL-[3H]cholesterol in the presence of CP-113 818, equilibrated in RPMI without AcLDL but with CP-113 818 (t\textsubscript{0} after equilibration), and then incubated with efflux media (all in RPMI with CP-113 818) for 24 hours. At t\textsubscript{0}, total cell cholesterol was 39.2 ± 5.5 μg/mg cell protein and total [3H]cholesterol was 287 ± 1532 cpm/mg cell protein. Analysis of THP-1 extracts at t\textsubscript{0} by TLC ([3H]cholesterol) and GC (cholesterol mass) confirmed selective loading with unesterified cholesterol. Efflux media were RPMI, apoA-I (25 μg protein per milliliter), reconstituted apodHDL-PC (rHDL-PC 200 μg phospholipid per milliliter), HDL3 (200 μg phospholipid per milliliter), and reconstituted apoHDL-PC 25 (25 μg protein per milliliter, equivalent to 62.5 μg phospholipid per milliliter). Results were identical with and without PMA during efflux; thus, only +PMA results are included. A, Aliquots of media were removed as described in "Methods" at specified intervals, filtered, and counted by scintillation. Cumulative efflux was calculated separately at each time point for each dish and percent efflux by dividing total counts in the medium per dish by counts in control cell extracts removed at t\textsubscript{0}. B, Cell cultures from A were washed after 24 hours' efflux, lipids extracted and analyzed for [3H]cholesterol (cpm/mg cell protein) and total cholesterol mass (μg/mg cell protein), and values calculated as percent of that in cultures removed at t\textsubscript{0}. C, THP-1 macrophages were differentiated and incubated for 24 hours with AcLDL-[3H]cholesterol with ACAT inhibitor, equilibrated in RPMI, and then incubated with efflux media (without ACAT inhibitor) containing either apoA-I or apoA-I-PC (each added at 25 μg apolipoprotein per milliliter) and HDL3 (193 μg phospholipid/mg protein) for up to 24 hours. Data are expressed as cumulative cpm of [3H]cholesterol released into the medium per culture dish.
with the hydrolysis observed during ACAT inhibition alone. Stimulation of efflux did not enhance hydrolysis of EC beyond that observed during ACAT inhibition, indicating that cholesterol efflux facilitated clearance of EC by preventing FC from participating further in ACAT-dependent reesterification. Identical results with regard to hydrolysis of EC were obtained with HDL3 and apoA-I–mediated efflux (data not shown).

cAMP supplementation has been previously found to enhance EC hydrolysis and cholesterol efflux in murine macrophages, via stimulation of nCEH (generally considered synonymous with hormone-sensitive lipase [HSL]). More recently, cAMP appeared to cause net accumulation of EC in human monocyte-derived macrophages rather than to promote hydrolysis, and this may be related to the absence of HSL in human macrophages. We tested cAMP-mediated stimulation of EC hydrolysis and cholesterol efflux by adding it to THP-1 cells in which EC synthesis was inhibited by coincubation with ACAT inhibitor (Figure 8). Because PMA stimulates protein kinase C and cAMP can enhance nCEH activity via a cAMP-dependent protein kinase, PMA was omitted after AcLDL loading for this experiment. At 24 hours, there was no significant enhancement of EC hydrolysis or cholesterol efflux by cAMP. This may indicate similarity between THP-1 cells and human monocytes, although persisting stimulation of nCEH activity initiated by PMA during differentiation and loading of THP-1 cells cannot be excluded.

To ensure that the apparent net decrease in [3H]EC caused by efflux reflected changes occurring in cell EC mass and not the native HDL3 and reconstituted rHDL-PC caused similar mass depletion of EC, EC mass was measured before and after efflux. THP-1 cells were loaded with AcLDL for 48 hours to maximize EC accumulation, then incubated with RPMI (control) or HDL3 or rHDL-PC, both at 200 μg/mL phospholipid for 24 hours. FC and EC content (μg/mg cell protein) of cell cultures after incubation with each of the media were respectively RPMI (36.4±2.0 FC, 96.7±11.1 EC), rHDL-PC (27.9±5.3 FC, 65.8±2.5 EC), and HDL3 (37.6±2.8 FC, 64.8±0.13 EC). Thus, rHDL-PC and HDL3 respectively caused a 29.6±8.0% and 30.7±0.2% depletion in EC mass compared with control RPMI medium, consistent with the reduction in [3H]EC described above.

Physical State of Lipid Droplets
Previous literature indicates that the physical state of lipid droplets markedly affects the rate of hydrolysis of EC, with isotropic droplets being hydrolyzed more rapidly than anisotropic droplets. We hypothesized that the physical state of lipid droplets in THP-1 cells may be anisotropic and that this may contribute to impaired EC hydrolysis. Cultures of THP-1 cells were loaded with AcLDL for 48 hours and inspected under oil immersion by polarized microscopy as previously described after 2, 24, and 48 hours’ equilibration. Ubiquitous large lipid droplets were evident in loaded THP-1 cells under light microscopy, but almost all of these were isotropic, demonstrating no phase polarization. Rare clusters of small anisotropic droplets detected at 2 hours were undetectable at later time points. The isotropic nature of the lipid droplets is consistent with the presence of cellular TG but argues against the physical nature of the droplets as being a sufficient explanation for slow cytosolic [3H]EC hydrolysis in THP-1 cells.

Discussion
Foam cell macrophages are characterized by the presence of cytoplasmic lipid droplets. EC and TGs can both contribute to cytoplasmic droplets and cannot be distinguished by oil red O staining. Foam cell macrophages from human plaque contain large quantities of EC and phospholipid and lesser but significant quantities of TG. The interaction between TG and EC accumulation in human macrophages is poorly understood. It is clear from our studies that TGs are a major lipid component in human THP-1 macrophages and primary human monocyte-derived macrophages, both immediately after maturation and after loading with AcLDL, and generally exceed EC accumulation. Given that intracellular TG can affect the hydrolysis of EC droplets, the reasons for such TG accumulation in human macrophages require further investigation.

We have identified that THP-1 foam cell macrophages differ in their metabolism of cholesterol compared with other cell types. THP-1 cells are more resistant to the accumulation of EC than murine macrophages; after exposure to AcLDL for 24 hours, the mass of EC accumulated and the esterification of oleate in THP-1 cells are less than are achieved with murine macrophages. They also demonstrate slow hydrolysis of cytosolic EC, ie, 37% hydrolysis of EC over 24 hours in THP-1 cells compared with 60% in 24 hours in murine macrophages. Even though cholesterol efflux caused net clearance of EC in THP-1 macrophages, the rate of EC hydrolysis, assessed during ACAT inhibition, was minimally affected by concurrent cholesterol efflux. Thus, apolipoprotein-mediated stimulation of EC hydrolysis described for various cell types does not appear to be quantitatively important in human THP-1 macrophages.

Accumulation of cholesterol in cells exposed to AcLDL will be expected to occur via both whole-particle uptake via the ScR and direct transfer of cholesterol from AcLDL to the plasma membrane. The low specific activity of [3H]EC compared with [3H]FC in THP-1 cells incubated with AcLDL is therefore likely due to a combination of several factors: (1) a cold pool of EC derived from undegraded lipoprotein but perhaps also contributed to by the esterification of undefined cold pools of cell cholesterol; (2) slow esterification of cholesterol, including that from the plasma membrane, compared with other cell types; (3) preferential incorporation of fatty acids into TG and phospholipid pools in preference to their esterification to cholesterol; (4) slow hydrolysis of cytosolic esterified cholesterol, necessitating longer incubations if equilibrium is to be achieved. Selective utilization of synthesized cholesterol for incorporation into EC could contribute to the low specific activity of EC in these cells. However, previous studies in differentiated THP-1 cells indicate that cholesterol synthesis, as assessed by acetate incorporation, is markedly inhibited after cholesterol accumulation after exposure to AcLDL, making this possibility less likely. From our studies, it appears that at least several...
days of equilibration would be required to achieve equivalent specific activity between FC and EC pools in THP-1 cells. Preliminary experiments in our laboratory showed that such very prolonged equilibration phases resulted in loss of cells and were not practicable. Consequently, variable specific activity must be anticipated between different cholesterol pools, and sterol metabolism must be interpreted cautiously using THP-1 cells.

Although we have not at this time fully characterized the rate of lysosomal hydrolysis of AcLDL-derived EC in THP-1 cells, it is clear that immediately at the end of loading, a substantial pool of undegraded EC is present. Previous literature does not adequately indicate how this finding differs from other cell types, because inhibition of ACAT and concurrent measurement of EC mass and [3H]EC have not been performed. Importantly, studies from Kruth et al indicate that human macrophages can sequester AcLDL and cholesterol crystals in compartments contiguous with the extracellular space. If this is also the case in human THP-1 macrophages, the hydrolysis of lipoprotein lipids in THP-1 cells would reflect not only lysosomal degradation but also delivery of lipids from the sequestered compartment to the lysosome. Studies in progress in our laboratories addressing the hydrolysis of lipoprotein-derived EC and the effect of lysosomotropic agents will help characterize more fully the accumulation of undegraded lipoprotein in these cells.

THP-1 cells demonstrated cholesterol efflux to phospholipid-free apoA-I, and in this respect THP-1 macrophages behave like murine macrophages. In addition, consistent with previous work, phospholipids played a major role in enhancing the rate of efflux of cholesterol from THP-1 cells. This was best demonstrated in the comparison of efflux mediated to 25 μg protein per milliliter apoA-I and 25 μg protein per milliliter rHDL-PC (Figure 7 and Table) and in the direct comparison of apoA-I with apoA-I–PC (Figure 7C). Kinetic modeling indicated that THP-1 cells, which had accumulated only [3H]FC, effluxed cholesterol from a large slow pool and a relatively small fast pool. Slow [3H]EC hydrolysis would be expected to further increase the size of the slow pool and further retard overall efflux.

Net clearance of cellular cholesterol represents the balance of bidirectional cholesterol movement, i.e., of cholesterol efflux from and influx to the cell. In the absence of exogenously supplied cholesterol (as with apoA-I and rHDL-PC), influx represents reuptake by the cells of [3H]FC previously removed. Kinetic modeling in the Table indicated that t1/2 for influx from apoA-I to the cellular cholesterol pool was 3 times faster than that from phospholipid-containing acceptors, consistent with the apparent early saturation of apoA-I. This observation indicates that acceptor particle phospholipid prevented saturation and influx of cholesterol back to THP-1 cells, as well as accelerating the rate of efflux. The small size and slow hydrolysis of the EC pool probably underlies the failure of ACAT inhibition during efflux to significantly enhance cholesterol efflux. That CAMP did not enhance EC hydrolysis or cholesterol efflux may be due to various factors. First, if HSL is either not responsible for nCEH activity in human macrophages or present in very low amounts, macrophages may use a different enzyme to hydrolyze cytosolic EC. Second, if the lack of effect of CAMP in THP-1 cells indicates that nCEH activity is already maximal because of prior PMA exposure, then alternative avenues for stimulating hydrolysis of EC in human cells must be established, as EC hydrolysis is clearly slow in these cells in spite of previous or ongoing PMA exposure.

In summary, these studies have established that although THP-1 cells accumulated both EC and FC in response to loading with AcLDL, they contain a relatively small and metabolically inactive pool of EC compared with the size and activity of the TG pool and demonstrate slow esterification of nonlipoprotein-derived cholesterol. In addition to slow hydrolysis of EC, efflux of FC is itself slow in THP-1 cells. Cholesterol efflux is substantially enhanced by the presence of phospholipid in acceptor particles, confirming the importance of phospholipid in establishing net efflux from human macrophages.

Acknowledgments

This study was supported in part by an International Atherosclerosis Society Travelling Fellowship from the Royal Australian College of Physicians, and program project grant HL-22633 and training grant HL-07443 (to A.C.) from the National Institutes of Health. ACAT inhibitors S-58035 and CP-113 818 were gifts from Sandoz (Dr J. Heider) and Pfizer (Dr M. Bamberger) Pharmaceuticals, respectively. A portion of the hp-β-CD was a gift from Cerestar, Hammond, Ind. Drs M. de la Llera-Moya, W. Johnston, S. Lund-Katz, G. Weibel, and P. Haynes are thanked for helpful discussions. T. Sloane is thanked for excellent technical assistance.

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Arterioscler Thromb Vasc Biol. 1998;18:1589-1599
doi: 10.1161/01.ATV.18.10.1589
Arteriosclerosis, Thrombosis, and Vascular Biology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1079-5642. Online ISSN: 1524-4636

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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