Neutral Triglyceride Lipase in Macrophages

John C. Khoo, Jean E. Vance, Eileen M. Mahoney, Dennis Jensen, Edward Wancewicz, and Daniel Steinberg

High levels of neutral triglyceride lipase activity have been demonstrated in several types of macrophages (J774 cells, human monocyte/macrophages, rabbit alveolar macrophages, and resident mouse peritoneal macrophages). The pH optima ranged from 6.5 to 7.4 depending upon the buffer and the conditions of incubation. The addition of bovine serum albumin stimulated activity at low concentrations, as expected for a fatty acid-releasing reaction, but strongly inhibited at higher concentrations; maximal activity was observed in the presence of 0.625 mg/ml of bovine serum albumin. The enzyme was remarkably thermostable, showing no apparent loss of activity at 50°C for as long as 6 hours. The lipase was inhibited 80% by 0.1 M NaCl. Assayed under optimal conditions, the specific activity of the neutral triglyceride lipase from J774 cells was more than 100-fold greater than the activity of lipoprotein lipase or neutral cholesterol esterase from those cells; this activity was 10-fold greater than the levels of hormone-sensitive lipase from 3T3-L1 adipocytes. This neutral triglyceride lipase may play an important role in the degradation and mobilization of cytosolic triglyceride in macrophage-derived foam cells.

(Teratogenesis, Carcinogenesis and Development 4:34-40, January/February 1984)
stratified the presence of a neutral triglyceride lipase in resident mouse peritoneal macrophages, rabbit alveolar macrophages, and human monocyte/macrophages.

**Methods**

**Cell Preparations**

Suspensions of J774 cells (clone G8), an established line derived from mouse ascites tumor, were maintained in alpha-minimal essential medium containing 5% heat-inactivated newborn calf serum. After 2 to 3 days the cells reached a density of about 5 x 10^6 cells per ml and were harvested by centrifugation (250 x g for 5 minutes); the packed cells were then stored at -70°C. The frozen cells were thawed and then homogenized in 4 volumes of a buffer containing 0.25 M sucrose, 1 mM EDTA and 25 mM Tris-HCl (pH 7.4). The homogenate was centrifuged successively at 1,000 x g for 10 minutes, 40,000 x g for 1 hour, and 120,000 x g for 1 hour at 4°C; the supernatant fraction and pellet were assayed for lipase activity at each step. The 40,000 x g supernatant fraction was designated S_40 and the 120,000 x g supernatant fraction, S_120.

Resident mouse peritoneal macrophages were harvested from animals that had received intraperitoneal injections of mineral oil 3 days previously.

Alveolar macrophages were harvested from rabbits by lavage with phosphate-buffered saline, pH 7.4 (PBS).

Human monocytes were prepared from blood of normal healthy donors as previously described with some minor modifications. Blood was collected in 50-ml syringes containing 0.2 volumes of an anticoagulant (0.8% citric acid/2.2% trisodium citrate/2.45% glucose) and then diluted 1:1 with PBS. The supernatant plasma (including many platelets) was centrifuged for 1 hour, and 120,000 x g for 1 hour at 4°C; the supernatant fraction was designated S_40 and the 120,000 x g supernatant fraction, S_120.

Lipid Peroxidation and Macrophages

The 3T3-1 adipocytes were cultured as previously described by Kawamura et al.

**Enzyme Assays**

The triglyceride lipase of macrophages was assayed as described by Khoo et al. with modifications. For 10 assays, 0.1 ml of stock solution of tri[14C]-oleoylglycerol in absolute ethanol was rapidly injected into 3.9 ml H_2O in a 50 ml plastic centrifuge tube, followed by vortexing and the addition of 2 ml 0.2 M Hepes buffer (pH 6.6). To initiate the reaction, 0.6 ml of this substrate mixture was added to a 13 x 100 mm disposable test tube containing 0.2 ml of enzyme protein source and bovine serum albumin (BSA). The final volume of 0.8 ml incubation mixture contained 0.125 mM tri[14C]-oleoylglycerol (0.16 µCi), 50 mM Hepes (pH 6.6), 0.625 mg/ml BSA, and enzyme preparation (generally 20–40 µg). Assays were carried out at 30°C for 5 or 10 minutes. The activities of diglyceride lipase and monoglyceride lipase were assayed in the same manner using di[14C]-oleoylglycerol and mono[14C]-oleoylglycerol.

It was found that this macrophage triglyceride lipase behaves differently from other triglyceride lipases in that the BSA must be added to the substrate along with the enzyme as the last addition in order to obtain optimal activity; when substrate and BSA were allowed to interact prior to the addition of the enzyme, much lower activities were observed. The choice of buffer was also critical, especially in the case of J774 cells. Assays carried out in Hepes buffer were essentially linear for 15 minutes (Figure 1); assays carried out in piperazine-N,N’-bis(2-ethanesulfonic acid, Pipes) buffer were decidedly nonlinear, especially when higher concentrations of enzyme protein were added in the assay. A comparison of assays in two different buffers is shown in Figure 1.

Cholesterol esterase was assayed in an 0.8 ml incubation mixture containing 0.125 mM cholesteryl 1,12-14C-oleate, 5 mg/ml BSA, 0.15 M NaCl, 10% glycerol, 2 mM EDTA, 50 mM Tris-HCl (pH 7.0) and homogenate prepared from J774 cells.

Lipoprotein lipase was assayed in an incubation mixture of 0.8 ml containing 0.125 mM tri [14C]-oleoylglycerol, 0.15 M NaCl, 5 mg/ml BSA, 50 mM Tris-HCl (pH 8.2), 3 µg/ml of apoprotein (apo) C-II and homogenate prepared from J774 cells. The assays were carried out at 30°C for 1 hour. Lipoprotein lipase activity was expressed as the activity assayed in the presence of apo C-II minus the activity in its absence.

Hormone-sensitive lipase was assayed in an incubation mixture of 0.8 ml containing 0.125 mM tri [14C]-oleoylglycerol, 50 mM sodium phosphate (pH 7.0), 5 mg/ml BSA and homogenate prepared from 3T3-L1 adipocytes. The assay was carried out at 30°C for 30 min.

Acid triglyceride lipase was assayed in an incubation mixture containing 0.125 mM tri [14C]-oleoylglycerol, 50 mM sodium acetate (pH 4.6), 0.625 mg/ml...
Table 1. Subcellular Distribution of Triglyceride Lipase in the J774 Macrophage-Like Cell

<table>
<thead>
<tr>
<th>Subcellular fraction</th>
<th>Total activity* (μmol/hr)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogenate</td>
<td>1996</td>
<td>100</td>
</tr>
<tr>
<td>1000 × g supernatant</td>
<td>1683</td>
<td>82</td>
</tr>
<tr>
<td>1000 × g pellet</td>
<td>550</td>
<td>28</td>
</tr>
<tr>
<td>40,000 × g supernatant</td>
<td>1769</td>
<td>89</td>
</tr>
<tr>
<td>40,000 × g pellet</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>120,000 × g supernatant</td>
<td>1437</td>
<td>72</td>
</tr>
<tr>
<td>120,000 × g pellet</td>
<td>79</td>
<td>4</td>
</tr>
</tbody>
</table>

The assays were carried out at 30°C for 10 minutes, as described under Experimental Procedures, using 50 mM Hepes (pH 6.6).

*Total activity in 30 ml of homogenate prepared from 7.5 ml of frozen packed cells in a buffer containing 0.25 M sucrose, 1 mM EDTA, and 25 mM Tris-HCl, pH 7.4.

BSA and homogenate prepared from J774 cells. The assays were carried out at 30°C for 30 min.

All assays were terminated by the addition of 3 ml of chloroform/methanol/benzene (1:2.4:2, v/v). 14C-oleic acid was extracted by the addition of 0.1 ml of 1M NaOH and quantified as described.14

Results

The J774 macrophage-like cell line was found to contain a very active neutral triglyceride lipase, most of it recovered in the high speed supernatant fractions. As shown in Table 1, about 89% of the total homogenate activity was recovered in the 1000 g fraction, and about 72% in the 40,000 g fraction. These results suggest a cytoplasmic location for the lipase activity, but since frozen cells were used in all these studies, that conclusion remains tentative.

Neutral lipase activity was strongly dependent on BSA concentration. Maximal activity was obtained using BSA in the range of 0.313 to 0.625 mg/ml (Fig. 2). These concentrations of BSA gave a three-fold increase in activity over that observed in the absence of BSA; however, higher concentrations of BSA were markedly inhibitory. At 2.75 mg/ml, the activity obtained was even lower than that assayed in the absence of BSA. This inhibitory effect was observed with several preparations of BSA, including highly purified fractions and fractions treated to remove free fatty acids. Furthermore, several other nonspecific proteins (thyroglobulin, lysozyme and histone) inhibited at high concentrations. In contrast, in the case of hormone-sensitive triglyceride lipase of 3T3-L1 adipocyte-like cells and neutral cholesterol esterase of J774 cells, maximal activities were obtained at BSA concentrations ranging from 2.75 to 6.25 mg/ml. Maximum activity for the lipoprotein lipase of J774...
cells was obtained at 1.25 mg/ml BSA, and the activity decreased by about 30% at higher BSA concentrations (Figure 2). As shown in Figure 3A, the reaction rate was nonlinear in the absence of BSA but became linear for at least 10 minutes in the presence of 0.625 mg/ml BSA. Then at 5 mg/ml BSA there was a marked initial inhibition and some recovery at later time-points. Under optimal conditions for the assay, the activity observed was linear in relation to the enzyme concentration as shown in Figure 3B. At BSA concentrations just above or below the optimum, the slope of the enzyme-activity curve was lower but close to linearity up to 25 μg enzyme protein per assay.

The triglyceride lipase activity in the homogenates prepared from J774 cells, rabbit alveolar macrophages, human monocyte-macrophages, and resident mouse peritoneal macrophages was examined as a function of pH. Single peaks were observed with an optimum at pH 6.6 for rabbit alveolar macrophages, J774 cells, and mouse peritoneal macrophages and an optimum at pH 6.9 for human monocyte-macrophages (Figure 4). When bis-(2-hydroxyethyl)-iminotris(hydroxymethyl)methane (bis-Tris) was used as buffer for assay instead of Hepes, optimal activities were observed between pH 7.2 to pH 7.4 (data not shown).

This lipase was remarkably stable to heat treatment. As shown in Figure 5, there was virtually no loss in activity (there was actually a slight increase in activity) of neutral triglyceride lipase in the homogenates prepared from J774 cells and human monocyte-macrophages after incubation at 50°C for as long as 6 hours. In contrast, lipoprotein lipase lost about 90% of its activity after 3 hours at 50°C, neutral cholesterol esterase lost 70% of its activity after 6 hours of incubation at 50°C, and acid triglyceride lipase lost 60% of its activity after 4 hours of incubation at 50°C.

As emphasized by the comparisons shown in Table 2, the specific activity of neutral triglyceride lipase from the macrophage was extraordinarily high when assayed under optimal conditions. The specific activity in J774 cells was more than 100 times

![Figure 3](http://atvb.ahajournals.org/)  
Figure 3. The effects of incubation time and enzyme concentration on the rate of reaction of neutral triglyceride lipase from J774 cells. A. The enzyme in the S120 fraction was incubated at 30°C for 20 minutes in the absence of BSA (●), in the presence of 0.625 mg/ml BSA (●), and 5 mg/ml BSA (●). B. The assays were carried out at 30°C for 10 minutes with increasing concentrations of S120 fraction. The buffer used for the assays was 50 mM Hepes (pH 6.6).

![Figure 4](http://atvb.ahajournals.org/)  
Figure 4. The influence of pH on the activities of triglyceride lipase in homogenates prepared from J774 cells (○), rabbit alveolar macrophages (●), human monocyte-macrophages (●), and resident mouse peritoneal macrophages (●). The buffer used for the assays was 50 mM Hepes.
greater than the activities of lipoprotein lipase and neutral cholesterol esterase in this same cell line (all enzymes assayed under conditions optimal for their activity in whole homogenates). The specific activity was even greater than that of hormone-sensitive lipase in 3T3-L1 adipocytes treated to induce the expression of this fat-mobilizing enzyme.

The $S_{120}$ fraction previously heated at 50°C for 2 hours was assayed for activities towards triolein, diolein, and monoolein. As shown in Figure 6, the levels of activities toward triolein and diolein were almost the same, whereas on the same scale there was virtually no activity toward monoolein. The activity toward monoolein, plotted on a different scale, is shown in the inset to Figure 6. It was only about 3% of the activity toward triolein. These results predict that when triolein is used as substrate, the end products are probably a mixture of free oleic acid and monoolein. In fact, analysis of the hydrolytic products by thin layer chromatography revealed that about 50% of the end products were monoolein.

**Discussion**

The triglyceride-loaded foam cells that characterize eruptive xanthomas almost certainly arise from macrophages. In familial hyperchylomicronemia and other severe forms of hypertriglyceride-
mias, these lesions can appear rapidly — when plasma lipids rise — and disappear almost as rapidly when lipid levels are normalized. The uptake and storage of lipids from triglyceride-rich lipoproteins have been studied in several types of macrophage in vitro.15–19 This process occurs in part via saturable, receptor-mediated pathways, the best characterized being the pathway for the uptake of beta-VLDL or “remnants.”15, 16 In part through phagocytosis.16–18 The recent discovery by Khoo et al.,7 that macrophages synthesize and secrete lipoprotein lipase, elucidates additional mechanisms that may be relevant. As shown by Ostdlund-Lindqvist et al.16 and by Lindqvist et al.,17 the free fatty acids released from triglyceride-rich lipoproteins by lipoprotein lipase can be subsequently taken up into the macrophage. These authors also showed that the action of lipoprotein lipase increased the uptake of chylomicron and VLDL apoproteins, presumably reflecting the more rapid uptake of remnants.

The mechanisms involved in the mobilization of stored triglycerides from macrophages has received less attention. Since the stored lipids are in cytoplasmic droplets that do not appear to be membrane-limited, and since release of intact triglycerides is unlikely, either the triglycerides must be transferred to the lysosome for hydrolysis or there must be a cytoplasmic triglyceride lipase for that purpose. Our present studies describe such an enzyme that has remarkably high levels of activity. The specific activity of the neutral triglyceride lipase in the supernatant fraction of the J774 cell line was more than 100 times greater than that of the cytoplasmic cholesterol esterase, the intracellular lipoprotein lipase, or the lysosomal acid triglyceride lipase, all of which were measured under conditions optimal for their respective activities. The question of whether this enzyme might be identical to the cytoplasmic cholesterol esterase of macrophages previously described by Khoo et al.8 must be asked. In adipose tissue and in adrenal the two activities have never been fully resolved.20–22 Also, the acid acylhydrolase activities in lysosomes of histiocytes responsible for the hydrolysis of cholesterol ester and triglyceride appear attributable to the same enzyme.23, 24 The question is answered clearly by the completely different heat sensitivities of the two activities in the macrophage: the supernatant neutral triglyceride lipase lost almost no activity at 50°C for 6 hours, whereas the cholesterol esterase activity fell by 80% under the same conditions. Thus it appears that the macrophage possesses a uniquely active neutral triglyceride lipase that may govern its ability to mobilize and rid itself of accumulated triglycerides, separate but functionally closely related to the previously described cholesterol esterase in these cells.8 The studies of Lindqvist et al.,17 showing that albumin in the medium facilitated the loss of stored triglycerides from macrophages, together with recent results from this laboratory (E. von Hodenberg, J.C. Khoo, J.L. Witztum and D. Steinberg, unpublished results) directly demonstrating net release of free fatty acids from triglyceride-loaded macrophages, leave little doubt that triglyceride hydrolysis precedes mobilization. Whether or not the enzyme activity described in this paper is the only determinant of such mobilization and whether it is subject to regulation remains to be determined.

The unusual properties of the neutral triglyceride lipase, particularly in the J774 cell line, deserve comment. Its low apparent activity in some buffers and its sensitivity to the concentration of albumin and other proteins may explain why it has not been previously reported and also may be significant with regard to its functional behavior. Other lipases have not shown this kind of selectivity and so the enzyme must at least differ in the way it interacts with substrates presented in various ways. The remarkable heat stability of the enzyme suggests an unusual enzyme protein.

When we consider the possible significance of this triglyceride lipase, we should note that triglyceride accumulation in macrophages is by no means limited to hyperchylomicronemia and other severe hypertriglyceridemic states. Tuberous xanthomata may contain a great deal of triglyceride even in patients whose plasma triglycerides are only modestly elevated,4 presumably due to the uptake of beta-VLDL, which contain less triglyceride than normal VLDL but considerably more than LDL. When both cholesterol and triglycerides accumulate, are they stored intermingled in the same cytoplasmic droplets? If so, must both the neutral cholesterol esterase and the triglyceride lipase, shown here to be apparently separate enzymes, be simultaneously active? In other words, could the presence of a second lipid in the droplet mask the other, making it less accessible to its hydrolyase? An interesting possibility is that a deficiency in neutral triglyceride lipase could, on this basis, contribute to cholesterol ester accumulation and, conversely, that cholesterol esterase deficiency might contribute to triglyceride accumulation.

Acknowledgments

The authors acknowledge with thanks Lorna Joy’s help with the cell cultures and Anita Fargo’s expert secretarial assistance in manuscript preparation.

References


Index Terms: cytosolic triglyceride lipase • macrophages, J774 cells • hypertriglyceridemias, foam cells • xanthomata
Neutral triglyceride lipase in macrophages.
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*Arterioscler Thromb Vasc Biol.* 1984;4:34-40
doi: 10.1161/01.ATV.4.1.34

*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

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