Predominance of Clathrin Light Chain LCb Correlates with The Presence of a Regulated Secretory Pathway

Susan L. Acton and Frances M. Brodsky
Departments of Pharmacy and Pharmaceutical Chemistry, School of Pharmacy, University of California, San Francisco, California 94143

Abstract. Two forms of clathrin light chains, LCa and LCb, are expressed in all mammalian and avian tissues that have been examined, whereas only one type is found in yeast. Regions of structural dissimilarity between LCa and LCb indicate possible functional diversity. To determine how LCa and LCb might differentially influence clathrin function, light chain expression patterns and turnover were investigated. Relative expression levels of the two light chains were determined in cells and tissues with and without a regulated secretory pathway. LCa/LCb ratios ranged from 5:1 to 0.33:1. A higher proportion of LCa was observed in cells and tissues that maintain a regulated pathway of secretion, suggesting a specialized role for the LCb light chain in this process. The ratio of light chains in assembled clathrin was found to reflect the levels of total light chains expressed in the cell, indicating no preferential incorporation into triskelions or coated vesicles. The half-lives of LCa, LCb, and clathrin heavy chain were determined to be 24, 45, and 50 h, respectively. Thus, LCa is turned over independently of the other subunits. However, the half-lives of all three subunits are sufficiently long to allow triskelions to undergo many rounds of endocytosis, minimizing the possibility that turnover contributes to regulation of clathrin function. Rather, differential levels of LCa and LCb expression may influence tissue specific clathrin regulation, as suggested by the predominance of LCb in cells maintaining a regulated secretory pathway.

Clathrin is the major coat protein of coated pits and vesicles that mediate the selective internalization and transport of receptors (for review, see Brodsky, 1988). Cells use clathrin to endocytose nutrients and hormones as well as to transport lysosomal enzymes from the Golgi apparatus to a prelysosomal compartment (Griffiths et al., 1988). In cells that specialize in regulated secretion clathrin participates in two additional functions: packaging of secretory granules (Tooze and Tooze, 1986; Orci et al., 1984) and rapid retrieval of membrane after stimulated secretion (Heuser and Reese, 1984). In all these processes, clathrin polymerizes into a polyhedral protein lattice followed by membrane invagination, coated vesicle formation, and finally clathrin depolymerization.

The clathrin molecule has a triskelion (three-legged pinwheel) shape (Ungewickell and Branton, 1981). It is composed of three identical heavy chains and three light chains (for review see Pearse and Crowther, 1987). The backbone of the coat lattice is formed by the clathrin heavy chain. The contribution(s) of the light chains are not yet defined, although many of their properties suggest they play a regulatory as well as structural role in clathrin function (Schmid et al., 1984; Bar-Zvi et al., 1988). In mammalian and avian cells there are two types of light chains, LCa and LCb, while yeast has only one type (Payne and Schekman, 1985). LCa and LCb, which are encoded by different genes, are 60% identical in protein sequence and have several domains that are very different in primary structure implying that they serve functionally different roles (Jackson and Parham, 1988). Major sequence dissimilarities between LCa and LCb include the distribution of cysteines at the COOH terminus (Parham et al., 1989), a region of low homology on the NH2-terminal side of the heavy chain binding region (Jackson et al., 1987) and a phosphorylation site that is present in LCb but not LCa (Hill et al., 1988; Bar-Zvi and Branton, 1986). These differences are maintained between species (95–98% identity in nucleotide sequence) (Jackson and Parham, 1988) indicating that LCa and LCb perform distinct functions in mammalian and avian cells that are not required of clathrin light chain in yeast.

To gain insight into differential roles for the two light chains, two major differences between LCa and LCb were characterized. First, expression levels of each light chain were compared in tissues and cells with and without a regulated secretory pathway to determine if the additional clathrin functions in these cells preferentially require one light chain. LCa was found to predominate in cells and tissues maintaining a regulated secretory pathway, suggesting that LCa plays a specialized role in either secretory granule formation and/or rapid membrane retrieval after secretion. This is the first evidence for a differentiated function for LCa. A second difference between LCa and LCb was inves-
tigated to follow up earlier studies indicating the possibility of differential turnover of the two light chains (Brodsky, 1985a). A very short half-life for one of the clathrin light chains would render clathrin susceptible to regulation by the availability of that light chain. Although half-lives of LC$_a$ and LC$_b$ were found to be different, both half-lives are sufficiently long to allow participation in many rounds of endocytosis before degradation. This minimizes the possibility that turnover contributes to regulation of clathrin function. The results of these studies suggest that it is the differential levels of LC$_a$ and LC$_b$ expression that may influence clathrin function and regulation in different cell types.

**Materials and Methods**

**Materials**

EBTr and MDBK cells were obtained from the American Type Culture Collection (Rockville, MD). LB, an Epstein Barr virus-transformed human B cell line, was from V. Engelhard (University of Virginia, Charlottesville). Supe T (a human T cell line) was from G. Davis (University of California, San Francisco). PC12 cells were from L. Reichardt (University of California, San Francisco), and AtT20 cells were from H.-P. Moore (University of California, Berkeley). All cells were grown at 37°C in 5% CO$_2$. EBTr, MDBK, and Supe T cells were grown in RPMI 1640 with 10% horse serum. PC12 and AtT20 cells were grown in DME (high glucose) with 7% horse serum and 7% FCS. LB cells were grown in RPMI 1640 with 10% FCS. The anticalcirionic monoclonal antibodies LCB1, X16, X22, X32, and X43 have been previously described (Brodsky et al., 1987; Blank and Brodsky, 1986; Brodsky, 1985a). A very short half-life for one of the clathrin light chains was found during the chase incubation and washed twice in cold serum-free medium.

**Pulse Chase Labeling**

LB cells were pulse labeled for 10 min with 1 mCi [35]methionine (NEG-009T, New England Nuclear, Boston, MA) per 2 × 10$^5$ cells at 4 × 10$^6$ cells/ml in medium with excess unlabelled methionine, washed, and then cultured at 8 × 10$^6$ cells/ml in medium with 10× unlabelled methionine (chase medium) (Brodsky, 1985a). Ascorbic acid (0.2 mM) and Na$_2$SeO$_3$ (1 mM) were added to the labeling and chase medium to increase the scavenging of free radicals produced by the radioactive label to maintain the viability of the cells for up to 60 h. Aliquots of 2 × 10$^6$ cells were taken immediately after addition of chase medium and at various time points during the chase incubation and washed twice in cold serum-free medium. Cell aliquots were then solubilized in 150 µl of cell lysis buffer (10 mM Tris, pH 8.0, 200 mM NaCl, 1 mM EDTA, 0.5% NP-40, 0.02% NaN$_3$, and once in buffer E + 0.5 M NaCl, then resuspended in 100 µl of reducing sample buffer (Laemmli, 1970), and boiled 10 min. The samples were analyzed by PAGE (Laemmli, 1970). Gels were incubated with Enlightening (New England Nuclear) before drying and exposure to film. Clathrin heavy chain and associated light chains were immunoprecipitated with X32 or X22 (both anticalcirionic heavy chain) immune complexes. X32 was used for qualitative immunoprecipitation in pulse chase studies. For immunoprecipitation of total cellular light chains, cell lysates were first boiled for 10 min and spun at 10,000 g. Light chains were quantitatively immunoprecipitated from the supernatant with a combination of X43 (anti-LC$_b$) and X16 (anti-LC$_a$) immune complexes. Before gel analysis of light chains, X16/X43 and X22 immunoprecipitates were boiled for 10 min in 50 µl of buffer E, spun at 10,000 g, and the supernatant (containing the light chains) recovered. All pulse chase experiments included a second round of specific immunoprecipitation to ensure that the immunoprecipitation was quantitative.

**Quantitation of Light Chains**

Light chain levels were determined by quantitative immunoblotting. Tissues and cells were homogenized in buffer D (10 mM Hepes, 150 mM NaCl, 1 mM EDTA, 0.5 mM MgCl$_2$, 0.02% NaN$_3$, pH 7.2) and then centrifuged at 1,000 g, 30 min. The resulting supernatants were boiled for 10 min, and then centrifuged at 10,000 g for 10 min, leaving the clathrin light chains in solution while the heavy chains precipitate along with most of the other cellular proteins (Brodsky et al., 1983). Preliminary studies were conducted to ensure that both light chains were equally boiling resistant. Boiled tissue homogenates were reduced and run on a 2.5% polyacrylamide gels. Dilutions of either purified adrenal LC$_a$ or LC$_b$ were also run on each gel (starting at 100 ng) to generate a standard curve. Proteins were transferred to nitrocellulose (14 V, 20 min) and blots incubated overnight with 1% nonfat milk in TBS (10 mM Tris; 150 mM NaCl), pH 7.4. Membranes were blocked by primary antibody for 1 h at room temperature. mAbs X16 (anti-LC$_a$) and LCB1 (anti-LC$_b$) were used for LC$_a$ and LC$_b$ quantitation, respectively. Antibody binding was detected following a 2-h incubation with 125I-rabbit anti-mouse IgG (0.5 × 10$^4$ cpm/ml in TBS) and autoradiography (Brodsky, 1985a). Standard curves were plotted as band density versus nanograms of light chain standard yielding linear plots. Only those standard curves of four points or more with an r$^2$ value >0.95 were used to calculate quantities in tissue and cell samples. In addition, only numbers that fell within the standard curve were accepted since there was no guarantee of linearity upon extrapolation. The relative quantities of light chains obtained for unknown samples are reported in Table 1 as a ratio of LC$_a$ to LC$_b$ (ng LC$_a$/ng LC$_b$).

**Assembled and Unassembled Clathrin**

Tissues or cells were homogenized in buffer D with 0.05% PMSF. Control experiments similar to those of Goud et al. (1985) were performed to ensure that clathrin did not assemble or disassemble in this buffer during this procedure. The homogenate was spun at 10,000 g and a known volume of the resulting supernatant was then spun at 100,000 g in an ultracentrifuge (TL100; Beckman Instruments, Inc., Palo Alto, CA). The 100,000 g supernatant was measured and adjusted to the original volume. The pellet was

** Autoradiography and Densitometry**

Dried gels and nitrocellulose blots were exposed to film at −80°C for varying periods. Film exposure was tested for linearity with radioactivity by running a standard curve or was made linear by preflushing the film (Hames and Rickwood, 1981). Autoradiographs were scanned using a DU-64 spectrophotometer (Beckman Instruments, Inc., Palo Alto, CA) with gel scanning accessories and software to integrate the peak areas. Data from pulse chase experiments were plotted as natural log of the peak area versus time. This yielded linear plots with slope equal to the degradation rate constant given by the first order equation: ln[P$_t$/P$_0$] = −kt (Geldberg and Dice, 1974). The half-life is calculated as: $t_{1/2} = \ln 2/k_t$. Half-life studies were repeated to ensure reproducibility of results.
Method for quantitation of clathrin light chain ratios. Purified adrenal LCa or LCb was run on SDS polyacrylamide gels (10%) alongside homogenates of kidney cortex and medulla. Proteins were transferred to nitrocellulose and reacted with X16 (anti-LCa) or LCB.1 (anti-LCb). Bound antibody was detected with 125I-rabbit anti-mouse Ig. The autoradiographs of the nitrocellulose blots are shown. Den- 
sitometry of the autoradiographs produced a linear standard curve (from four of the six quantities loaded) for each light chain. (A) X16 binding to LCa. Lanes a-f are purified adrenal LCa. (a) 100 ng; (b) 75 ng; (c) 50 ng; (d) 25 ng; (e) 12.5 ng; and (f) 6.3 ng. Lanes 
g-i are kidney cortex samples prepared from three separate kidneys. Lanes j-l are kidney medulla samples from three separate kidneys. (B) 
Standard curve from densitometry of purified LCa. y = -0.4665 + 57.388x with a correlation coefficient of 0.999. (C) LCB.1 binding 
to LCb. Lanes a-f contain purified adrenal LCb. (a) 100 ng; (b) 75 ng; (c) 50 ng; (d) 25 ng; (e) 12.5 ng; and (f) 6.3 ng. Lanes 
g-i as in A. (D) Standard curve from densitometry of purified LCb. y = -0.1365 + 75.332x with a correlation coefficient of 0.993. The stan-
dard curves were used to calculate the quantity of light chain in the unknown samples. Only points that could be interpolated on the curve 
were used. The light chain ratios are determined as LCa/LCb (ng/ng).

Results

Differential Light Chain Expression

To investigate whether LCa and LCb contribute differentially to the role of clathrin in the regulated secretory pathway, levels of the light chains in two tissues specializing in regulated secretion, brain cortex, and adrenal medulla were compared to levels in five other tissues (Fig. 1). Bovine tissue homogenates were run on SDS polyacrylamide gels alongside dilutions of known quantities of purified bovine adrenal LCa or LCb. Proteins were transferred to nitrocellulose that was then probed with anti-LCa or anti-LCb mAb plus iodinated rabbit anti-mouse IgG and exposed to film. Densitometry revealed a standard curve for the purified light chains and allowed determination of the quantities of light chain in unknown samples. Most of the tissues contained an LCa/LCb ratio of approximately 1:1 (Table I). However, both brain
cortex and adrenal medulla were found to have more LCb than LCa, suggesting a correlation between regulated secretion and LCb expression. Because tissues are generally a mixture of different cell types, it is possible that each tissue examined included cells with different light chain ratios. Since the ratios of light chains determined for these tissues represent the total LCa divided by total LCb, cellular variation in ratios is obscured in these numbers.

To examine the light chain ratios in individual cell types, cell lines with and without a regulated secretory pathway were analyzed by one of two methods. Light chains in bovine and human cells were quantitated by the immunoblotting method described above (Table I). For rat and mouse cell lines, light chain ratios were estimated by immunoprecipitation of clathrin from [35S]cysteine-labeled cells (Fig. 2). This second approach was implemented because the anti-LCb antibody (LCB.1) used for immunoblotting analysis does not react with rat or mouse LCb. LCB.1 recognizes residues 1-19 at the amino terminus of LCb (S. Acton, unpublished results) that are identical in human and bovine LCa and differ by one amino acid in rat LCb (Jackson and Parham, 1988). Absolute light chain ratios cannot be determined from immunoprecipitated clathrin because the light chains are turned over at different rates, albeit slowly (see below). However, a comparison of the light chain ratios de-
Table 1. Clathrin Light Chain Ratios in Tissues and Cell Lines

<table>
<thead>
<tr>
<th>Sample</th>
<th>LCa/LCb (ng/ng)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tissue</td>
<td></td>
</tr>
<tr>
<td>Adrenal cortex</td>
<td>1.01 ± 0.06 (3)</td>
</tr>
<tr>
<td>Adrenal medulla</td>
<td>0.72 ± 0.08 (3)</td>
</tr>
<tr>
<td>Kidney cortex</td>
<td>1.00 ± 0.07 (3)</td>
</tr>
<tr>
<td>Kidney medulla</td>
<td>0.97 ± 0.10 (3)</td>
</tr>
<tr>
<td>Spleen</td>
<td>1.24 ± 0.28 (3)</td>
</tr>
<tr>
<td>Primary lymphocytes</td>
<td>1.00 ± 0.11 (2)</td>
</tr>
<tr>
<td>Brain cortex</td>
<td>0.33 ± 0.01 (3)</td>
</tr>
<tr>
<td>Cell line</td>
<td></td>
</tr>
<tr>
<td>EBTr</td>
<td>2.02 ± 0.69 (2)</td>
</tr>
<tr>
<td>MDBK</td>
<td>5.22 ± 0.36 (3)</td>
</tr>
<tr>
<td>LB</td>
<td>4.97 ± 0.91 (7)</td>
</tr>
<tr>
<td>Supe T</td>
<td>0.83 ± 0.20 (4)</td>
</tr>
</tbody>
</table>

* The sample standard deviation of the ratios is given along with the number of samples tested (in parentheses).

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Cell lines with a regulated secretory pathway were found to have a higher proportion of LCa than other lines (Table I; Fig. 2). Supe T, PC12, and AtT20 are lines that maintain a regulated secretory pathway, while MDBK, LB, and EBTr are lines that do not. The light chain ratio of Supe T, a human lymphocyte cell line, can be compared to that of LB cells, a human B lymphocyte line. T lymphocytes secrete lymphokines or cytolyzins in a regulated manner in response to T cell receptor interactions with a target cell (Kupfer and Singer, 1989), while B lymphocytes secrete antibodies in a constitutive manner. LB cells have predominantly LCa (\(\sim 5:1\) LCa/LCb ratio) while the Supe T cells have more LCa than LCb (0.83:1 LCa/LCb ratio). The intensely predominant labeling of LCa in AtT20 and PC12 cells also indicates increased LCa expression in cells capable of regulated secretion. AtT20 cells are mouse pituitary tumor cells that secrete ACTH in response to 8-bromo-cAMP (Moore et al., 1983). PC12 cells are rat adrenal pheochromocytoma cells that secrete norepinephrine in response to various secretagogues (Greene and Rein, 1977). In the cell lines that do not maintain a regulated secretory pathway (MDBK, LB, and EBTr) LCa expression predominates. Considering the light chain ratios determined for 13 tissues and cell lines, the five samples with predominant expression of LCa were those capable of regulated secretion.

Light Chain Ratios in Assembled and Unassembled Clathrin

The ratios of light chains in assembled and unassembled clathrin were measured to determine whether the total cellular light chain ratio is reflected in assembled clathrin. Cells with high and low LCa/LCb ratios were chosen for analysis. Clathrin from a postnuclear supernatant of tissue or cell homogenate was separated into assembled and unassembled fractions by centrifugation at 100,000 g. The pellet (assembled clathrin) and supernatant (triskelions) were diluted to equal volumes and light chains were quantitated as above. Bovine brain cortex was used as a source of cells with a low LCa/LCb ratio. In this tissue, the same light chain ratio was found in the total, assembled and unassembled clathrin fractions (Table II) indicating no preferential incorporation of light chains into assembled structures. The percentage of assembled LCa and LCb was determined to be 88 and 87%, respectively. This is in agreement with the previous analysis of rat brain (Goud et al., 1985) showing that 86% of clathrin was assembled.

Table II. Ratios of Light Chains in Assembled and Unassembled Clathrin*

<table>
<thead>
<tr>
<th>Sample</th>
<th>LCa/LCb (ng/ng)</th>
<th>%LCa assembled**</th>
<th>%LCb assembled**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain cortex</td>
<td>0.33 ± 0.01 (3)</td>
<td>88% ± 1% (3)</td>
<td>87% ± 1% (5)</td>
</tr>
<tr>
<td>LB</td>
<td>4.97 ± 0.91 (7)</td>
<td>70% ± 6% (4)</td>
<td>79% ± 4% (4)</td>
</tr>
</tbody>
</table>

* The sample standard deviation of the ratios is given along with the number of samples tested (in parentheses).

** Percentage of each light chain assembled was determined as % assembled = assembled/(assembled + unassembled) where all values are in nanograms.
Figure 3. Half-life determination for clathrin light chains. (A) Autoradiogram of light chains labeled with [35S]methionine for 10 min and chased with cold methionine for the indicated time periods. Light chains were quantitatively immunoprecipitated with a mixture of anti-LC_a and anti-LC_b antibodies (X16/X43); (B) Natural log of the light chain band density versus chase time. The densities of the bands in A were determined and plotted according to the first order rate equation \( \ln [P]/[P]_0 = -kt \) where \([P]\) is band density at time \(t\) and \(k\) is the rate constant of degradation. The half-life is calculated as \( t_{1/2} = \ln 2/k \). (●) LC_a degradation where the line can be defined as \( y = 1.402 - 0.025x \) with a correlation coefficient of 0.99. This line showed a half-life of 27 h for LC_a. (○) LC_b degradation where the line can be defined as \( y = 0.574 - 0.016x \) with a correlation coefficient of 0.99. This line showed a half-life of 44 h for LC_b. Additional experiments demonstrated an average half-life of 24 h for LC_a and 45 h for LC_b.

Figure 4. Half-life determination for clathrin heavy chain. (A) Autoradiogram of the clathrin heavy chain labeled with [35S]methionine for 10 min and chased with cold methionine for the indicated time periods. Heavy chains were quantitatively immunoprecipitated with X32 mAb. (B) Natural log of the heavy chain band density versus chase time. The half-life was calculated as described in Fig. 3. The obtained line can be defined as \( y = 1.1344 - 0.0137x \) with a correlation coefficient of 0.986. This line showed a half-life of 50 h for the heavy chain. The zero time point falls well below the line and was not used to determine the half-life (see text).
clathrin subunits have half-lives on the order of 1-2 d, clathrin activity is most likely regulated by other means.

Discussion

Prevalence of LCb Correlates with the Regulated Secretory Pathway

Expression patterns of clathrin light chains, LCa and LCb, were investigated to determine their differential influence on clathrin function. Correlation between an increased proportion of LCb in a tissue or cell and the presence of a regulated secretory pathway was established. There are two stages in the regulated secretory pathway that might specifically require LCb. The first is in the formation of secretory granules where clathrin has been implicated in concentrating and packaging proteins (Tooze and Tooze, 1986; Orsi et al., 1984). The second is the coordinated rapid retrieval of granule membrane after exocytosis. Coated pit number with growth rapidly after adrenal medulla cells are stimulated to secrete catecholamines (Geisow and Childs, 1985), and after synaptic vesicles fuse with the presynaptic membrane in neuronal cells (Miller and Heuser, 1984).

Although regulated secretory cells have a predominance of LCa, all cells examined express both LCa and LCb and the intracellular distribution of LCa looks similar to that of LCb (Puszkin et al., 1989). LCb specific antibodies stain the Golgi complex and periphery of many different cell types (S. Acton, unpublished results). Given its ubiquitous distribution, LCb is probably not restricted to specialized functions. Rather, its presence could confer the capability of providing a specialized clathrin function when needed. A likely possibility is an involvement in coated pit upregulation, a process that is also used to a small capacity in non-secretory cells, explaining why all cells have some LCb. Rapid coated pit upregulation occurs not only after regulated secretion but also after treatment of some cells with growth factors such as epidermal growth factor and nerve growth factor (Connolly et al., 1984; Connolly et al., 1981).

A major difference between LCa and LCb is that LCb is readily phosphorylated in vitro (Usami et al., 1985) and in vivo (Bar-Zvi et al., 1988). Phosphorylation of LCb could provide a signal influencing regulation and recruitment of triskelions for coated pit formation. Indeed, there is potential for coordinate LCb phosphorylation/dephosphorylation and coated pit upregulation. Epidermal growth factor, which stimulates coated pit formation, also activates a casein kinase II (Sommecorn et al., 1987), possibly the same casein kinase II that has been shown to phosphorylate LCb (Bar-Zvi and Branton, 1986). The phosphorylation acceptor site (Hill et al., 1988) is located in the part of LCb most different from LCa and is included in the epitope recognized by monoclonal antibody LCB.1 (residues 1-19). This epitope on coated vesicles and triskelions was previously shown to be exposed to the cytoplasm and would therefore be accessible to activated kinases (Brodskey et al., 1987).

The presence of a phosphorylation site on LCb and the predominant expression of LCb in specialized secretory cells suggests that the LCb light chain may have evolved to fulfill regulatory functions different from those of LCa. Recent data demonstrating preferential stimulation of the 70-kD coated vesicle uncoating protein by LCb, as compared to LCa further indicates a divergence in function of the two light chains (DeLuca-Flaherty et al., 1990). Either the single light chain of yeast is able to perform the function of both LCa and LCb, or yeast does not have all the clathrin using functions of mammalian and avian cells. To our knowledge, no evidence for a regulated pathway of secretion in yeast exists (Kelly, 1985). Therefore, yeast may not need more than one light chain since it appears to have no need for regulated endocytosis. Selection for a second light chain may have occurred during the development of multicellular organisms when cell-cell communication (in the form of hormones and synapses) required a more complex method for clathrin regulation.

Turnover and Assembly of Clathrin Subunits

Measurement of clathrin subunit half-lives demonstrated that the two light chains have different fates after synthesis, but their turnover is too slow to regulate the availability of assembly competent clathrin. Light chain expression is most likely regulated at the level of transcription, since the relative amounts of LCa and LCb mRNA correspond approximately to ratios of light chain protein observed in both bovine brain and human B cell lines (A. Jackson, personal communication).

The half-life of LCb was calculated to be 24 h. A free pool of LCb (unassociated with heavy chain) in these cells was previously shown to have a half-life of ~30 min (Brodskey, 1985b). Further studies on this free pool revealed that it is sometimes, but not always, present and indicated that it probably represents light chain made in excess of available heavy chain binding sites (not shown). The lack of a biphasic curve in Fig. 3 B indicates that the free pool was either relatively very small or was not present in this study. Thus, the half-life of 24 h is that of heavy chain-associated LCb. The half-life of LCb was determined to be ~45 h, which is close to twice that of LCa. Thus, LCb must be less susceptible to degradation within the cell. LCb also degrades more slowly than LCa in vitro after long term storage and upon incubation with proteases (not shown). An additional factor that may contribute to the longer half-life of LCb is its apparent higher affinity for the heavy chain. Clathrin extracted with thiocyanate retains LCb almost exclusively (Schmid et al., 1984). In addition, LCb competes more effectively with iodinated light chains for binding sites on heavy chain than does LCa (Brodskey et al., 1987). Binding to the heavy chain may stabilize the light chains and reduce their susceptibility to proteolysis.

Table III. Theoretical Ratios of Triskelion Types in Different Cells*

<table>
<thead>
<tr>
<th>Triskelion type**</th>
<th>Brain</th>
<th>Supe T</th>
<th>LB</th>
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<tbody>
<tr>
<td>AAA</td>
<td>2 %</td>
<td>9 %</td>
<td>58 %</td>
</tr>
<tr>
<td>AAB</td>
<td>14 %</td>
<td>34 %</td>
<td>35 %</td>
</tr>
<tr>
<td>ABB</td>
<td>42 %</td>
<td>41 %</td>
<td>7 %</td>
</tr>
<tr>
<td>BBB</td>
<td>42 %</td>
<td>16 %</td>
<td>&lt;1 %</td>
</tr>
</tbody>
</table>

* The theoretical percentage of each type of triskelion has been calculated for brain, Supe T, and LB cells using the light chain ratio from Table I. In these calculations, it is assumed that the light chains are randomly distributed on the triskelions as has been indicated by previous work (Kirchhausen et al., 1983).

** Each triskelion type is represented by three capital letters indicating the number of LCa and LCb polypeptides on that triskelion.
to proteolytic enzymes. Clathrin heavy chain was found to have a half-life of 30 h, long enough to keep the light chains bound until they are degraded. This finding correlates with previous data that showed the light chains do not alternate between a bound and free state (Brodsky, 1985b). Assuming one round of endocytosis takes 1 min (Pearse and Bretscher, 1981) half of the heavy chains will undergo at least 3,000 rounds of endocytosis before they are degraded. Our data explain earlier results that showed endocytosis continues despite protein synthesis inhibition (Goldstein et al., 1979).

The light chain ratio in assembled brain clathrin corresponds to the total light chain levels expressed in the tissue. Thus, there is no preferential incorporation of light chains into triskelions or assembled clathrin in brain. These measurements do not indicate whether coated vesicles are formed with a random distribution of light chains or with selected light chain ratios as suggested by Puzskin et al. (1989). In fact the small but consistent difference in the light chain ratios of assembled and unassembled clathrin in LB cells could be explained by the formation of different types of coated vesicles with different light chain ratios. However, the light chain ratios observed in assembled clathrin still maintain a predominance of LC<sub>C</sub> close to that measured in total clathrin in LB cells. This demonstrates that all forms of triskelions are assembly competent.

**Triskelion Distribution**

Previous work has indicated that clathrin light chains are randomly distributed on triskelions (Kirchhausen et al., 1983). Thus, all four possible types of triskelions (AAA, AAB, ABB, BBB) are produced, and their frequency can be estimated by a binomial distribution. To compare triskelions in cells and tissues, we calculated the theoretical distribution of triskelions in two cell lines and one tissue with very different light chain ratios (Table III). Cells with a light chain ratio of ∼1:1, such as Supe T cells, would produce all four types of triskelions in significant quantities and the majority would contain both LC<sub>C</sub> and LC<sub>B</sub>. In contrast, cells with very high or very low light chain ratios would have predominantly only three of the four types of triskelions. For example, <1% of the LB triskelions would be of the BBB type and only 2% of the brain triskelions would be of the AAA type. Thus, almost all of LB triskelions will have at least one LC<sub>C</sub> polypeptide and almost all of the brain triskelions will have at least one LC<sub>B</sub>. Since regulated secretory cells have a predominance of LC<sub>B</sub>, most of the triskelions in these cells could potentially be regulated by the phosphorylation/dephosphorylation of LC<sub>C</sub>.

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**References**


