Exposure of K562 Cells to Anti-receptor Monoclonal Antibody OKT9 Results in Rapid Redistribution and Enhanced Degradation of the Transferrin Receptor

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Abstract. When the human erythroleukemia cell line K562 is treated with OKT9, a monoclonal antibody against the transferrin receptor, effects on receptor dynamics and degradation ensue. The apparent half-life of the receptor is decreased by >50% as a result of OKT9 treatment. The transferrin receptor is also rapidly redistributed in response to OKT9 such that a lower percentage of the cellular receptors are displayed on the cell surface. OKT9 treatment also leads to a decrease in the total number of receptors participating in the transferrin cycle for cellular iron uptake. The reduction in iron uptake that results from the loss of receptors from the cycle leads to enhanced biosynthesis of the receptor. Receptors with bound OKT9 continue to participate in multiple cycles of iron uptake. However, OKT9 treatment appears to result in a relatively small increase per cycle in the departure of receptors from participation in iron uptake to a pathway leading to receptor degradation. Radiolabeled OKT9 is itself degraded by K562 cells and this degradation is inhibitable by leupeptin or chloroquine. In the presence of leupeptin, OKT9 treatment results in the enhanced intracellular accumulation of transferrin. Because the time involved in the transferrin cycle is shorter (12.5 min) than the normal half-life of the receptor (8 h), a small change in recycling efficiency caused by OKT9 treatment could account for the marked decrease in receptor half-life. In this paper the implications of these findings are discussed as they relate to systems in which receptor number is regulated by ligand.

Proliferating cells require exogenous iron and acquire it via receptor-mediated endocytosis of the iron-carrier protein transferrin (Tf) for review see reference 6. Iron uptake via the Tf cycle involves binding of diferric Tf to a specific, high-affinity surface receptor followed by internalization of the receptor ligand complex. Within the cell, the complex encounters an acidic (~pH 5) environment that is instrumental in iron unloading (22, 31). Apo-Tf is then released intact from the cell, and the transferrin receptors (TfR) are reused (2, 9). The Tf cycle shares certain aspects with other systems of receptor-mediated endocytosis but also exhibits distinctive features, including the return of undegraded ligand and receptor to the cell exterior.

In the present study, we describe perturbations of the pathway traversed by the TfR that result from exposure of K562 cells to a monoclonal anti-receptor antibody (OKT9). The monoclonal antibody OKT9 recognizes the human TfR at a site distinct from the ligand binding site and has been used to examine the structural features of the receptor as well as in the chromosomal localization and cloning of the TfR gene (3, 15, 25). We have found that treatment of K562 cells with OKT9 affects receptor distribution and the rates of receptor degradation and biosynthesis. Many of the effects of OKT9 on TfR dynamics in K562 cells resemble phenomena observed in other endocytic systems including what is thought to be physiologic modulation of receptor function. Accordingly, we believe that certain implications of our experiments may be generally applicable to receptor dynamics.

Materials and Methods

Cells and Chemicals

K562, a human erythroleukemia cell line, was grown in RPMI 1640 with 25 mM Heps containing 10% fetal bovine serum, penicillin, and streptomycin (growth medium). Cells were maintained at densities of 2-6 x 10⁶/ml at 37°C in 5% CO₂ incubator.

Human Tf (Calbiochem-Behring Corp., San Diego, CA) was made diferric by published procedures (11). Anti-TfR monoclonal antibody OKT9 was prepared from ascites fluid using DEAE Affigel blue (Bio-Rad Laboratories, Richmond, CA) as previously described (1). It was further purified by high-pressure liquid chromatography by passage through a TSK G3000 SW column (LKB Instruments, Gaithersburg, MD) with elution in phosphate-buffered saline (PBS) at 0.5 ml/min. 0.25-ml fractions were collected and the IgG peak was detected by absorbance at 280 nm. Monoclonal antibody B3/25 was obtained from Boehringer-Mannheim Diagnostics (Houston, TX) and exhaustively dialyzed against PBS.

Tf and IgG were iodinated by Enzymobeads (Bio-Rad Laboratories) according to the supplier’s instructions. After from 30 min to 1 h of iodination at room temperature the reaction mixture was passed through a Sephadex G-25
saturated ammonium sulfate (adjusted to pH 7.6 with "Iris base) was added, and washed three times with 1 ml lysis buffer lacking serum albumin. The resin linked with Acrylaide and bonded to Gel Bond (FMC Corp., Chicago, IL) using both cases, the resins were tumbled for 90 min at 4°C before being centrifuged

scanning densitometer (Hoefer Scientific Instruments, San Francisco, CA) and sample was quantitated from the resultant autoradiograph using a Hoefer

methionine incorporation into total cellular protein as judged by 10% trichloroacetic acid precipitation. 

The rate of biosynthesis of the TfR was also assessed by immunoprecipitation, gel electrophoresis, and autoradiography. In these biosynthetic experiments, K562 cells (1 x 10^6/ml) were incubated for 30 min in RPMI 1640 medium containing one-tenth the normal amount of methionine, 10% fetal bovine serum, and 0.2 M sodium salicylate. Nonspecific binding was assessed by inclusion of 250 μg of unlabeled human diferric Tf in the solubilization mixture. The presence of OKT9 did not affect the values obtained using this soluble receptor assay (data not shown).

Binding and Uptake Studies

Binding studies with either 125I-Tf or 125I-OKT9 were carried out in RPMI 1640 with 25 mM Hepes, pH 7.4 containing 0.1% BSA (assay medium). Binding experiments were performed at 125I-Tf concentrations of ~10 μg/ml. Under these conditions no effect of the presence of OKT9 on the amount of 125I-Tf bound was seen. Nonspecific binding was determined by the addition of a 100-fold excess of the unlabeled material of interest. Cell-associated radioactivity was separated from unbound material by layering of 200 μl of either 1 M sucrose in PBS, pH 7.2-7.4, or 150 μl dibutyl phthalate (Aldrich Chemical Co., Milwaukee, WI) in 400-μl microfuge tubes (Bio-Rad Laboratories). The cells were pelleted by centrifugation in a Beckman microfuge (Beckman Instruments Inc., Palo Alto, CA) for 1 min. The tips containing cell pellets were cut and their content of 125I was determined in a Packard Auto Gamma 5060 gamma-counter (Packard Instrument Co., Inc., Downers Grove, IL). In untreated cells, the nonspecific binding/uptake always represented <15% of total cell-associated radioactivity and was usually ~5%. The absolute levels of nonspecific binding/uptake were not significantly changed by any of the treatments employed.

Results

Effect of Anti-receptor Antibody on the Degradation of the TfR

Treatment of K562 cells with mouse monoclonal IgG (OKT9) against the TfR resulted in a decrease in the apparent half-life of the TfR from ~8 to ~4 h. This effect of OKT9 on receptor degradation was assessed by pulse-chase experiments using cells labeled metabolically with [35S]methionine (Fig. 1) or in chase experiments after surface radioiodination (data not shown). The apparent half-life of total cellular proteins in K562 cells as judged by the loss of 10% trichloroacetic acid-precipitable radioactivity was found to be ~19 h. The presence of saturating levels of human Tf did not affect the degradation rate of the TfR (18), nor did added human Tf alter the enhanced degradation rate seen in OKT9-treated cells. Another monoclonal antibody against the human TfR (B3/25) prevented the effect of OKT9.

Figure 1. Effect of OKT9 treatment on the degradation of the TfR. K562 cells were metabolically labeled with [35S]methionine for 2 h at 37°C as described in Materials and Methods. After being washed free of unincorporated [35S]methionine and incubated for an additional 45-min at 37°C, the cell suspension was divided, and OKT9 (5 μg/ml) was added to half of the cells. At the indicated times thereafter, samples were removed and their content of radiolabeled receptor was determined by immunoprecipitation, gel electrophoresis, autoradiography, and densitometry as described in Materials and Methods. Values are expressed as percentages of the value obtained at the time of antibody addition. Shown are the first-order decay curves for untreated (○) and OKT9 treated (●) cells.
had effects analogous to those of OKT9 on receptor degradation whereas an unrelated monoclonal antibody (OKT3) did not. To determine whether receptor shedding might account for the OKT9 effect, we solubilized and immunoprecipitated K562 cells together with their incubation medium rather than the washed cells alone. Here, a similar OKT9-mediated decrease in receptor half-life was observed, arguing against a shedding of TfR in response to OKT9 treatment as an explanation of the OKT9 effect. When the OKT9 IgG was itself radioiodinated and incubated with K562 cells at 37°C, the 125I-IgG became associated with the cells at a level approximately twofold higher than the binding capacity of the cell surface (Fig. 2). Between 2 and 3 h of incubation the level of cell-associated 125I-IgG began to decline. All of the loss of cell-associated radioactivity could be accounted for in 10% trichloroacetic acid-soluble radioactivity, suggesting that proteolysis occurred. The loss of radioactivity from the cells and appearance of acid soluble radioactivity were prevented by inclusion of the protease inhibitor leupeptin. In other experiments, we found that chloroquine also inhibited 125I-OKT9 degradation (data not shown).

**Effect of Anti-receptor Antibody on the Cellular Content and Biosynthesis of the TfR**

The antibody-mediated increase in TfR degradation would be expected to result in a corresponding decrease in the steady state content of cellular TfR. However, when TfR binding sites were measured in detergent-solubilized cells after lengthy treatment with OKT9, the level of TfR was found to be decreased by <30% (Fig. 3) despite a >50% decrease in receptor survival time. The relatively smaller drop in total receptor number led us to assess directly the biosynthetic rate of the receptor in OKT9-treated cells. The results shown in Fig. 4 demonstrate that treatment with OKT9 resulted in a greater than twofold increase in the rate of TfR biosynthesis.

In contrast, cells treated with saturating levels of human Tf exhibited a rate of biosynthesis that is decreased to <50% of the control value. This human Tf effect has been previously documented by our laboratory and appears to be due to decreased levels of TfR mRNA resulting from transcriptional modulation (18, 20, 21). A decrease in receptor biosynthesis was also seen when cells were treated with other iron-supply-

![Figure 2. Uptake and degradation of 125I-OKT9. K562 cells were washed into ice-cold assay medium. To the suspension of cells (1 × 10^6 cells/ml), 1 µg/ml 125I-OKT9 was added and the cell suspension was incubated at 4°C for 30 min before rewarming. Leupeptin (0.1 mg/ml) was added to these incubations where indicated ( ■, ■). Cells were warmed to 37°C in a 5% CO_2 incubator for the indicated times when samples were removed and cell-associated 125I-OKT9 (■, ■) was determined as described in Materials and Methods. To determine the extent of degradation of 125I-OKT9 samples of the cell suspension were added to an equal volume of ice-cold 20% trichloroacetic acid, 4% phosphotungstic acid. After 30 min on ice, this material was centrifuged and the amount of acid-soluble radioactivity was determined ( ■, ■). For the cultures not receiving leupeptin, cell-associated and acid-soluble radioactivity have been summed ( △) to demonstrate that all radioactivity lost from the cells can be accounted for as degraded 125I-OKT9. To account for acid-soluble radioactivity that was not due to cellular uptake, flasks containing the appropriate media and 125I-OKT9 were incubated without K562 cells, and corresponding values were subtracted.

![Figure 3. Effect of OKT9 treatment on cellular content of transferrin receptors. OKT9 (2 µg/ml) was added to K562 growth cultures such that the indicated treatment times were attained. The cells (2 × 10^6) were centrifuged, lysed in detergent, and the 125I-Tf binding capacity of the solubilized cells was determined as described in Materials and Methods. Values are expressed as percentages of the value obtained with cells having never been incubated at 37°C with OKT9.

![Figure 4. Effect of various treatments on rate of biosynthesis of the TfR. K562 cells were incubated for 6 h at 37°C with no additions (lane A), 5 µg/ml OKT9 (lane B), 5 µg/ml B3/25 (lane C), 40 µg/ml human diferric Tf (lane D), or 5 µg/ml OKT9 plus 40 µg/ml human diferric Tf (lane E). Cells (1 × 10^6) from each incubation were centrifuged, and the rate of receptor biosynthesis was determined by pulse-labeling with 35S-methionine, immunoprecipitation, electrophoresis, and autoradiography as described in Materials and Methods. The upper portion of the figure displays the results of quantitative densitometry of the autoradiograph. These data are expressed as percentages of the value obtained for control cells (lane A).
ing substances such as ferric ammonium citrate (21) or hemin (24). Simultaneous treatment with human d ferric Tf and OKT9 (Fig. 4) has the effect of preventing the enhanced biosynthesis of TfR seen in cells treated with OKT9 alone. To evaluate whether the biosynthetic effect of OKT9 might be related to iron deprivation, hemin was employed as an iron source. We have recently shown that hemin can serve as a very efficient source of chelatable iron that can depress TfR biosynthesis. In the presence of hemin, OKT9-mediated reduction of total cellular TfR is considerably more pronounced (Table I), owing to lower rates of receptor biosynthesis under these conditions. These results suggest that the OKT9 effect on TfR biosynthesis is probably a secondary effect resulting from a decrease in iron within the regulatory iron pool.

**Effect of Anti-receptor Antibody on the Tf Cycle**

The effect of antibody on a single Tf cycle was examined. After 125I-Tf was prebound to the cell surface at 4°C and unbound 125I-Tf was removed, cells were warmed to 37°C (Fig. 5). There was no detectable effect of OKT9 treatment on TfR biosynthesis is probably a secondary effect resulting from a decrease in iron within the regulatory iron pool.

**Table I. Effect of OKT9 and/or Hemin on the Number of Cellular TfR**

| Treatment             | 125I-Tf Bound | % of control |
|-----------------------|---------------|--------------|
| None                  | 37,400        | 100          |
| OKT9                  | 26,462        | 70.7         |
| Hemin                 | 35,676        | 95.7         |
| OKT9 + Hemin          | 18,588        | 49.7         |

K562 cells were treated as indicated with OKT9 (2 μg/ml), hemin (50 μM), or OKT9 plus hemin. After 6 h at 37°C in a 5% CO2 incubator, 1.4 x 106 cells were subjected to the soluble TfR assay described in Materials and Methods. Values shown represent the average of duplicate determinations.

**Figure 5.** Effect of OKT9 treatment on efflux of cellular transferrin. K562 cells were cooled to 4°C, centrifuged, and resuspended at 3.5 x 106/ml in assay medium. After the addition of 1.25 μg/ml OKT9 (●) or no addition (○), the cell suspensions were warmed to 37°C for 45 min. After cooling to 4°C, 5 μg/ml of 125I-Tf was added, and the cell suspension was incubated at 4°C for 15 min. The cells were washed twice at 4°C to remove unbound ligand and resuspended in assay medium containing 5 μg/ml unlabeled human d ferric Tf to prevent rebinding of radiolabeled. OKT9 (1.25 μg/ml) was restored to those cell suspensions that had been pretreated with the antibody. The suspensions were warmed to 37°C, and, at the indicated times, samples (0.2 ml) were removed and cell-associated radioactivity was assessed as described in Materials and Methods. Values are expressed as percentages of the initial value, and standard errors are shown. The inset provides a semilogarithmic plot of data showing that single exponential functions define the loss of cell-associated 125I-Tf in both control (○) and OKT9 treated (●) cells.

**Figure 6.** The influence of OKT9 and leupeptin on the retention of cellular 125I-Tf. K562 cells were cooled to 4°C, centrifuged, and resuspended at 4°C for 45 min at 5 x 106/ml in in assay medium in the presence of leupeptin (0.1 mg/ml). Suspensions then were made 20 μg/ml in 125I-Tf and warmed to 37°C. After 15 min of warming, either OKT9 (1 μg/ml) (●) or an equivalent volume of PBS (○) was added. The cell suspensions were kept at 37°C for an additional 75 min. Cells were then cooled to 4°C and washed twice in ice-cold assay medium before being resuspended at 5 x 106/ml in assay medium containing 80 μg/ml unlabeled human d ferric Tf and 0.1 mg/ml leupeptin. OKT9 was included in the washes and resuspension medium as indicated above. The cell suspensions were then once again warmed to 37°C for the indicated times when samples (0.2 ml) were removed and cell-associated radioactivity was assessed as described in Materials and Methods. All measurements were performed in quadruplicate, and the values obtained varied from the mean no more than ±5%.

on the lag time (~4 min), rate (t½ = 5 min), or extent (~98%) of the exponential loss of cell-associated ligand.

Because the TfR participates in many cycles of iron uptake in its lifetime, a relatively small increase in the percentage of the TfR being degraded per cycle could be responsible for the enhanced receptor degradation seen in OKT9 treated cells. Since Tf does not dissociate from TfR in the Tf cycle (2, 6, 9) OKT9 might also be expected to lead to intracellular accumulation of 125I-Tf. If a small percentage of the receptor ligand complexes engaged in each Tf cycle were to leave the cycle and remain within the cell pending degradation, this would be detected only if ligand molecules that had departed the cycle were allowed to accumulate over multiple cycles. An experiment of this nature is shown in Fig. 6. In OKT9-treated cells ~15% of the radiolabeled ligand that had accumulated in a 90-min incubation with 125I-Tf was retained within the cell during the second 90-min incubation with excess unlabeled ligand in the medium. In control cells <7% of the 125I-Tf was found in this nonexchangeable pool. This experiment was performed in the presence of the protease inhibitor leupeptin to prevent proteolytic breakdown of the 125I-Tf. The levels on nonexchangeable ligand in both control and OKT9-treated cells were significantly decreased by omission of leupeptin (data not shown). These results together with those in Fig. 2 suggest that OKT9 enhances movement of the antibody receptor-ligand complex from the normal Tf cycle to an intracellular pathway that terminates in leupeptin-sensitive degradation of receptor-associated OKT9 and of receptor-associated ligand.

When K562 cells are incubated at 37°C with 125I-Tf, the
amount of cell-associated ligand soon reaches a plateau that represents the steady state between endocytosis of diferric Tf and exocytosis of apo Tf (2, 9). In the course of the normal Tf cycle, this provides an estimate of the number of TfR involved in iron delivery, i.e., this level of cell-associated $^{125}$I-Tf serves as a measure of the cycling pool of TfR. Treatment of cells with OKT9 results in a decrease in the apparent size of this cycling pool (Fig. 7). Consistent with the results in Fig. 5, the rate at which the cycling pool is filled with ligand does not appear to be markedly affected by treatment with OKT9.

The results presented above demonstrate that most cell-associated Tf is released when OKT9 is present (Figs. 5 and 6) but that, after treatment with OKT9, cells increase their accumulation of Tf during multiple cycles (Fig. 6). To confirm that continued uptake of iron via the Tf cycle is occurring in the presence of Okt9, uptake of $^{59}$Fe from $[^{59}$Fe]$^{Tf}$ was compared in control and OKT9-treated cells (Fig. 8). The uptake rate (slope) in OKT9-treated cells was decreased ~20% as compared with that seen in the control cells. These results demonstrate that the Tf cycle is operative in OKT9-treated cells and that iron uptake is decreased commensurate with the reduction shown in Fig. 7 of the number of TfR within the cycling pool. These results do not rule out the possibility that continued iron uptake in the presence of OKT9 is due to entry of new receptors into the system. The inset of Fig. 8 argues against this possibility. Here cells were incubated in the presence of $^{125}$I-OKT9 under conditions used in $^{59}$Fe uptake experiments. As receptor-bound OKT9 does not readily dissociate from K562 cell membranes at 37°C (data not shown), this inset can be interpreted to indicate that no significant number of receptors without bound OKT9 appears at the cell surface in the period (2–3 h of OKT9 treatment) during which $^{59}$Fe uptake was measured. Thus, it appears that most of the receptors with bound OKT9 continue to participate in the Tf cycle and continue to mediate iron uptake.

**Figure 8.** Effect of OKT9 treatment on iron uptake in K562 cells. K562 cells were treated where indicated (○) with 1 μg/ml OKT9 for 2 h at 37°C in a 5% CO$_2$ incubator. Cells were then cooled to 4°C, centrifuged, and resuspended at 2.8 × 10$^6$/ml in ice-cold assay medium. OKT9 (1 μg/ml) was re-added to the appropriate cell suspensions. $^{59}$Fe-Tf (9,000 cpm/μg) was then added at a concentration of 40 μg/ml, and after 20 min at 4°C the cells were warmed to 37°C. At the indicated times cell-associated $^{59}$Fe was assessed as described in Materials and Methods. A comparison was made to cells not treated with OKT9 (○). Standard errors are shown. In the inset is shown cell-associated $^{125}$I-OKT9 in a parallel experiment in which K562 cells were incubated at 37°C with 1 μg/ml $^{125}$I-OKT9. At the indicated times cells were cooled to 4°C, centrifuged, and resuspended in assay medium at 4 × 10$^6$/ml. Cell-associated radioactivity was assessed as described in Materials and Methods. The zero-time value represents the value for cell-associated $^{125}$I-OKT9 obtained with unwarmed cells.

**Discussion**

Receptor-mediated endocytosis provides the means for internalization of ligands and receptors in many systems (19, 26). The events that follow internalization and the ultimate fate of the ligand and receptor molecules are qualitatively different in various endocytic systems. In certain cases, ligands are

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Figures and text adapted from Weissman et al. (1985) *Cell. Biol.* 955 Weissman et al. Effect of Antibody OKT9 on K562 Cells.
Treatment of K562 cells with OKT9 results in two major effects related to receptor dynamics. Such treatment leads to an ~50% reduction in the apparent half-life of the TfR and the receptors engaged in iron uptake are redistributed. The enhancement of receptor degradation leads to a reduction in the steady state cellular content of TfR by ~30%. However, this reduction in TfR content is not as pronounced as would be expected based upon the magnitude of the effect on receptor half-life. This apparent discrepancy is reconciled by the finding that OKT9 treatment also leads to an approximate doubling of the rate of TfR biosynthesis. This effect of anti-receptor antibody on receptor biosynthesis is probably mediated via an intracellular regulatory pool of iron. Iron supplied by human diferric Tf through the TfR or by hemin via a pathway not involving the TfR was shown to result in suppression of the OKT9 effect on TfR biosynthesis. The mechanism by which OKT9 treatment leads to enhanced receptor degradation remains obscure. It is possible that receptor cross-linking by divalent IgG at some point in the process is involved. Receptor cross-linking has been implicated in endocytosis mediated by the IgG Fc receptor (19). However, note that ligands (e.g., insulin, epidermal growth factor) not thought to be capable of direct receptor cross-linking can nonetheless mediate receptor down regulation.

Treatment with OKT9 results in a reduction in the number of TfR that are participating in iron uptake. This loss of receptors from the cycling pool leads to a corresponding decrease in $^{59}$Fe accumulation from $[^{59}$Fe]$/$Tf. Trowbridge and Domingo (29) have reported that the antibody B3/25 (that like OKT9 does not block Tf binding to the TfR) can inhibit human tumor cell growth in nude mice. One possibility raised by these authors was that B3/25 might interfere in some way with tumor cell iron uptake. Our results with OKT9 agree with this hypothesis.

Although OKT9 leads to a decrease in the number of total cycling TfR and thus reduces iron uptake, it is equally clear that receptors with bound OKT9 continue to cycle and mediate iron uptake. The rate of iron uptake in antibody treated cells is decreased only ~20%, a reduction consistent with the measured decrease in the cycling pool of TfR. Moreover, the kinetic parameters that define the Tf cycle do not appear to be significantly altered by OKT9 treatment. Radiolabeled OKT9 was employed to show that "new" receptors (i.e., those that lack bound OKT9) were not responsible for the continued uptake of iron. The reduction in the size of the TfR cycling pool in OKT9-treated cells may reflect movement of TfR from the pathway involved in iron uptake to a pathway ultimately leading to receptor degradation. Taken collectively, our data suggest that enhanced degradation of the TfR results from a relatively small decrease in recycling efficiency.

As the TfR participates in many cycles of iron uptake in its lifetime, small decreases in recycling efficiency per cycle would have profound effects on receptor half-life, assuming these decreases in cycling efficiency result in a movement of TfR into a pathway committed to degradation (Table II). We have calculated a cycle time of 12.5 min for Tf using the measured rate of iron uptake and the measured number of TfR in the cycling pool. If 98.2% of these receptors normally returned per cycle and the remaining receptors were committed to degradation, the observed receptor half-life of 8 h would result. A decrease in per cycle efficiency from 98.2 to 96.5% would decrease the half-life by 50% to 4 h. Were the efficiency to drop to 86.6% the half-life would fall to only 1 h. The
Efficiency on Receptor Half-life
can change with time, then recycling of a subpopulation of degraded.
involved in iron uptake. In OKT9-treated cells, the population receptor, the more marked would be the effects of rather participating receptors, a cycle time of 12.5 min has been calculated. The above calculation of hypothetical receptor half-life assumes that receptors must leave the cycling pool to be degraded and that those that leave the cycling pool are degraded.
shorter the cycle time relative to the normal half-life of a receptor, the more marked would be the effects of rather subtle changes in per cycle recycling efficiency. This perspective is based on the behavior of the entire population of TfR involved in iron uptake. In OKT9-treated cells, the population of TfR molecules appears to recycle with an efficiency only slightly decreased from that seen in untreated cells. If the population of TfR is heterogeneous with regard to the nature of OKT9 binding, or if the nature of OKT9 TfR interaction can change with time, then recycling of a subpopulation of TfR may be more markedly affected. Nonetheless, this must be manifested in such a way as to result in only a small decrease in the recycling probability within the TfR population in OKT9-treated cells.

Perhaps the most common effect observed upon treatment of cells with various anti-receptor antibodies is a reduction in cell surface receptor number. This has been previously reported for the receptors for insulin (5, 23, 28), epidermal growth factor (4), mannose-6-phosphate (30), and Tf (7). We have observed a similar phenomenon regarding the TfR in K562 cells treated with phorbol myristic acid or upon addition of human diferric Tf (10). We have observed that neither the OKT9-mediated redistribution described here nor the phorbol myristic acid effect is additive to the human Tf-induced reduction in surface receptors. It is possible that the mechanism involved in all of these may be similar. We have also observed that incubations of cells at 37°C without a 5% CO₂ atmosphere appeared to lead to a "spontaneous" decrease in surface receptors, whereas surface receptor number on cells maintained inside an incubator remained relatively constant. The reason for this effect remains obscure but the observation demonstrates the need to carefully scrutinize even seemingly routine experimental manipulations. This phenomenon may account in part for the lack of consensus that exists regarding constitutive versus ligand-induced cycling of the TfR (10, 32).
The OKT9-mediated loss of TfR from the cycling pool was accompanied by an increase in 125I-Tf that remained cell associated during multiple cycles of endocytosis, i.e., 125I-Tf that did not exchange with extracellular unlabeled ligand in the presence of the protease inhibitor leupeptin. This suggests that it is a complex of antibody, receptor, and ligand that is removed from participation in iron uptake. In both control and OKT9-treated cells, omission of the leupeptin in this experiment resulted in less cell-associated radioactivity in this nonexchangeing pool. Degradation of cell-associated 125I-

OKT9 also exhibited sensitivity to leupeptin. Although not unambiguously shown by these experiments, lysosomal degradation of 125I-OKT9 and 125I-Tf would be consistent with the leupeptin sensitivities of both OKT9 degradation and the OKT9-mediated 125I-Tf accumulation. That chloroquine also inhibits 125I-OKT9 degradation is in accord with this hypothesis.

In the course of submission and revision of this manuscript Lesley and Schulte (17) published a paper that supports some of the results that we present here. These authors report that treatment of mouse lymphoma cells with monoclonal antibodies directed against the murine TfR reduces cell surface expression of the TfR and enhances degradation of surface radioiodinated TfR.

Ligands of the receptors for insulin and epidermal growth factor result in enhancement of receptor degradation (8, 12–14, 27). Insulin also appears to induce redistribution of its receptor (13). Although the molecular mechanism(s) involved in these phenomena remain obscure, the phenomena themselves resemble the effects reported here of OKT9 on the TfR of K562 cells. It is unclear as to whether these observations using a monoclonal antibody have a relationship to ligand mediated down-regulation. This determination will require additional insight into the molecular signaling events that distinguish the pathways traversed by the TfR from those involved in down regulation.

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Table II. Effect of Altering the Theoretical Recycling Efficiency on Receptor Half-life

| Theoretical recycling (efficiency per cycle) | Resultant receptor half-life |
|---------------------------------------------|-----------------------------|
| 100                                          | ∞                           |
| 99.1                                         | 16 h                        |
| 98.2                                         | 8 h                         |
| 96.5                                         | 4 h                         |
| 86.6                                         | 1 h                         |
| 50.0                                         | 12.5 min                    |

The above calculations are based on a first-order decay function for the TfR. From the measured rate of iron uptake and the measured number of participating receptors, a cycle time of 12.5 min has been calculated. The above calculation of hypothetical receptor half-life assumes that receptors must leave the cycling pool to be degraded and that those that leave the cycling pool are degraded.
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