Retinoids Are Important Cofactors in T Cell Activation
By Annette Garbe, Jochen Buck, and Ulrich Hämmerling

From the Immunology Program, Memorial Sloan-Kettering Cancer Center, New York 10021

Summary
Murine thymic T cells depleted of antigen-presenting cells proliferate poorly in response to crosslinking anti-CD3 monoclonal antibodies or concanavalin A when cultured in conventional fetal calf serum-containing serum. However, in a serum-free medium formulated to contain, in addition to basic ingredients, insulin, transferrin, albumin, linoleic acid (ITLB), and retinol, proliferation is vigorous. The presence of retinol is critical, because when omitted, cells do not become activated. The subsets of T cells proliferating with the assistance of retinol cofactor are both CD4+ and CD8+ thymic T cells, and CD4+ peripheral T cells. Mature CD8+ T cells of lymph nodes can also be activated in ITLB medium plus retinol, provided that interleukin 2 (IL-2) is added. Retinol needs to be present at the time when T cell receptor triggering is initiated, suggesting that early activation events (G0 to G1 transition) are dependent on retinol. It is currently less clear whether or not subsequent events associated with G1 to S phase transition also require the presence of retinol. 14-hydroxy-retroretinol (14HRR) is a metabolic product of retinol in lymphocytes, and this retinoid effectively supports T cell activation in conjunction with a mitogen in lieu of retinol. Thus, while retinol and its intracellular product, 14HRR, are unable to activate T cells on their own, they are important cofactors. The requirement for retinol in CD3-mediated T cell activation cannot be satisfied by retinoic acid or ILs-1, 2, 4, and 6, and tumor necrosis factor-α whereas interferon γ can substitute for retinol. Our experiments are compatible with the idea that retinol, in the course of cellular activation, is converted to 14HRR, which is needed as intracellular messenger. If substantiated by molecular studies now underway, our data should lead to the description of a new signal pathway distinct from the retinoic acid signal pathway observed in nonlymphoid cells, but perhaps functioning by a similar mechanism, i.e., ligand-assisted transcriptional regulation.

The activation of resting T cells is initiated by interaction of the TCR with antigen peptide bound to MHC on APCs. Pairs of ligand receptor structures on the interacting cells contribute secondary signals (for review see references 1 and 2). Although these molecular interactions have been described in considerable detail, the intracellular events ensuing are still poorly understood. However, the emerging overall picture presents multiple, interactive signal cascades that converge on the nucleus to effect transcriptional activation. As a general rule, these events are mediated by two different chemical classes of molecules, proteins and small lipophilic molecules, that shuttle to the nucleus to regulate transcription. For example, the protein products of the rel gene family (e.g., NF-kB) translocate upon activation from the cytoplasm to the nucleus and regulate transcription (3). Small lipophilic molecules including the steroids, vitamin D, thyroid hormone, and several forms of retinoic acids, bind to and activate their specific receptors belonging to the superfamily of steroid receptors for transcriptional activation (3–5).

To study the requirements of T cell activation, cellular immunologists customarily use culture media supplemented with FCS. Because FCS contains a number of growth factors and hormones, including steroids, vitamin D and retinoids, it is desirable to reduce this complexity. Several serum components appear to be indispensable while others may be inhibitory, as documented recently for platelet-derived growth factor (6). The essential ones include albumin, thought to play a role in the stabilization and transport of fatty acids and possibly other lipids, transferrin for regulation of iron metabolism, and insulin, ostensibly for control of carbohydrate metabolism (7, 8). Our laboratory has recently described retinol as a further serum constituent necessary for the growth of B lymphocytes (9). Both human and murine-activated B cells perish rapidly in culture when deprived of retinol, and this may be related to earlier findings that vitamin A-deficient...
mammals exhibit severe defects in lymphopoiesis and immune function (10-12). The essential role of retinol for the immune system has recently been highlighted in epidemiological studies where even mild vitamin A deficiency was associated with immune dysfunction (13).

We have hypothesized that retinol serves in lymphocytes as a precursor for one or more intracellular retinoid derivatives that might mediate the retinol effects, possibly through participation in signal transduction. The analogy supporting this hypothesis is retinoic acid. This molecule is derived from retinol, passes into the nucleus of target cells, and binds to specific retinoic acid receptors, leading to increased transcription of selected genes. Although this mechanism is well documented for a variety of tissues and cell types, it does not apply to B lymphocytes. B cells neither produce detectable levels of retinoic acid, nor respond to it (14). We therefore performed a biochemical analysis of the intracellular retinoids of B cells and found several known retinoids (e.g., retinol and retinyl esters) and at least two hitherto undescribed retinoids. Because one of these, 14-hydroxy-retro-retinol (14HRR), was capable of supporting the proliferation of B cells in the absence of an external supply of retinol, we have speculated that this compound might serve as an intracellular mediator of retinol effects by a pathway distinct from that of retinoic acid (15). T lymphocytes also synthesize 14HRR (as indeed many other cell types studied by us), and we were therefore led to study whether T cell activation is critically dependent on 14HRR or its precursor molecule, retinol. The results reported here support this assumption.

Materials and Methods

Reagents and Culture Medium. The following antibodies were purified by protein A-Sepharose chromatography: Anti-CD3e, clone 1452C11 (16), anti-I-A^d, clone MKD6 (17); anti-IE^d, clone 13/18 (19); anti-Lyt2.2, cone 19/178 (20); anti-IL-4, clone 11B11 (18). Fluorochrome-labeled antibodies were from commercial sources: anti-CD4 PE (Becton Dickinson & Co., San Jose, CA); anti-CD8 FITC (Boehringer Mannheim, Indianapolis, IN); and normal rat IgG FITC and normal rat IgG PE for controls (Southern Biotechnology, Birmingham, AL).

Retinoids. All-trans retinol, all-trans retinal, and all-trans retinoic acid were purchased from Sigma Chemical Co. (St. Louis, MO). The retinoids were dissolved at a concentration of $3 \times 10^{-2}$ M in methanol or DMSO with $10^{-4}$ M butylated hydroxytoluene (Sigma Chemical Co.) added and stored in the dark at $-20$°C in a nitrogen atmosphere. Immediately before use, the stock solutions were diluted in serum-free medium. 14HRR was isolated from the pellets of HeLa cells fed with retinol by using a series of reversed phased HPLC columns as described (15). 14HRR was pure according to the retention time on an analytical C$_18$ reversed phase column and the typical UV absorption spectrum.

Interleukins and Growth Factors. Human rIL-1α was a gift from Hoffmann LaRoche Co. (Nutley, NJ); hrIL-2 and hrIL-6 were purchased from Boehringer Mannheim; murine rIL-4 was purchased from R&D Systems, Inc. (Minneapolis, MN); rTNF-α was donated by Genentech, Inc. (San Francisco, CA); mouse rIFN-γ was purchased from Genzyme Corp. (Cambridge, MA). Bovine insulin and human transferrin were purchased from Collaborative Research (Bedford, MA). Delipidated bovine albumin, all-trans retinol, linoleic acid, and Con A were bought from Sigma Chemical Co.

Mice. BALB/c mice of either sex were bred and housed in the Sloan-Kettering Laboratory Animal Facility. Our institution complies with regulations promulgated by the Animal Welfare Act.

Preparation of Cells. Thymuses of 3-6-wk-old BALB/c mice were teased in serum-free RPMI medium supplemented with 1% BSA, $10^{-5}$ M linoleic acid, and antibiotics. Depletion of accessory cells was achieved by two cycles of complement-dependent lysis with a mixture of anti-I-A^d (5 μg/ml) and anti-IE^d (1:500 diluted ascites fluid). Briefly, cells were incubated on ice for 30 min with Ig antibodies, spun down, resuspended in 1:40 diluted rabbit complement, and incubated at 37°C for 45 min. Incubations and two subsequent washes were carried out with RPMI medium containing 1% BSA. Cell viability was evaluated by trypan blue dye exclusion. To determine the extent of depletion of accessory cells, samples were stained with FITC-conjugated anti-Fc receptor antibody and analyzed by flow cytometry on a FACSscan instrument (Becton Dickinson & Co.). No FcR-bearing cells were detected by this procedure.

Mature T cells were obtained from pooled intestinal, axillary, inguinal, and submandibular lymph nodes of 4-10-week-old BALB/c mice. To fractionate cells into CD4 and CD8 subsets and at the same time remove APC, a combination of adherence and complement lysis was used as follows: The cell suspension in a 2 ml-vial was applied to a nylon wool column (22) (0.6 g of washed nylon fibers in the barrel of a 10-ml syringe) and incubated at 37°C for 40 min. The nonadherent cells were recovered by washing with warm serum-free medium at a flow rate of 1 ml/min. The cells were then spun down and treated as described for thymocytes with two cycles of complement lysis, using either a mixture of MKD6, 13/18, and 19/178 (to obtain CD4-enriched T cells), or MKD6, 13/18, and GK1.5 (to obtain CD8-enriched T cells). The success of the enrichment procedures was monitored cytfluorimetrically using FITC-conjugated anti-CD8 and PE-conjugated anti-CD4. In either case, the T cell subsets were over 95% homogeneous. Analysis with FITC-conjugated anti-mouse IgG(k) revealed <2% contamination by B cells.

Proliferation Assays. Cells were cultured in serum-free medium, referred to as ITLB, containing RPMI 1640 supplemented with $8 \times 10^{-7}$ M insulin (5 μg/ml), $7 \times 10^{-8}$ M transferrin (5 μg/ml), $2 \times 10^{-6}$ M linoleic acid, $2 \times 10^{-6}$ M delipidated BSA (0.12 mg/ml), 2 mM l-glutamine, 1 mM sodium pyruvate, and antibiotics. They were seeded into 96-well flat-bottomed plates at varying concentrations for stimulation of T cells was determined for each batch of anti-CD3 mAb and Con A. The optimal range of Con A was particularly narrow in serum-free medium (0.5-0.2 μg/ml) and...
Retinoids are required cofactors for proliferation of anti-CD3ε activated thymocytes at low cellular density. (A) Purified BALB/c thymocytes were activated with immobilized anti-CD3ε antibody and cultivated varied with the cell density used. To assess the costimulatory activities of retinoids with other lymphokines, various concentrations of IL-1, -2, -4, -6, IFN-γ and TNF-α were added to cultures. Cultures were carried out in duplicate. Plates were incubated at 37°C in a humidified 5% CO₂ atmosphere. Cellular proliferation was determined by [³H]thymidine uptake (0.5 μCi/well; New England Nuclear, Boston, MA) after the incubation times indicated for each experiment with a 4-h labeling pulse. Cells were harvested onto glass filters and [³H]Tdr incorporation was determined by liquid scintillation counting. The data presented are the means of duplicate or six replicate cultures. The restriction to duplicate measurements was necessary to conserve scarce 14HRR. They were within 20% of each other. Each experiment was repeated at least twice.

Flow Cytometry. To determine the phenotype of blast cells generated in the thymocyte cultures stimulated with immobilized anti-CD3 antibody and retinoids, as well as the purity of CD4 and CD8 subsets isolated from pooled mouse lymph nodes, cells (10⁶-10⁷ cells/sample), stained with FITC-conjugated anti-CD4 antibody and PE-conjugated anti-CD8 antibody, were analyzed by two-color flow cytometry with a FACScan® (Becton Dickinson & Co.). Dead cells were eliminated by forward low-angle scatter. Isotype controls were included in all experiments. To determine the phenotypes of activated thymocytes, only blast cells were gated for collection and analysis.

Results

Stimulation of Thymocytes with Anti-CD3ε in Serum-free Medium is Dependent on the Presence of Retinoids. Thymocytes depleted of APC did not proliferate appreciably in response to crosslinking anti-CD3 mAb as the sole induction stimulus when cultured in FCS-containing medium (Fig. 1 A). They also failed to proliferate in serum-free medium ITLB in the absence of retinoids, unless very high doses of anti-CD3 antibody (in excess of 2 μg/ml) were employed (Fig. 1 B). However, in the presence of retinol at 3 × 10⁻⁶ M concentration or 14HRR at 6 × 10⁻⁷ M concentration, vigorous responses were elicited. These responses were positively correlated with cell density, but were independent over a wide dose range of the anti-CD3 concentration used to coat the plastic culture trays. Addition of 3% human serum also supported anti-CD3-initiated thymocyte proliferation, but these responses faded rapidly with decreased cell density. Growth curves of thymocyte cultures established by differential counts of cells in the presence of trypan blue showed a selective and

for 4 d in ITLB medium with or without retinol (3 × 10⁻⁶ M), 14HRR (6 × 10⁻⁷ M) (fresh 14HRR was added every 12 h), human serum (3%) or FCS (10%) at the cellular densities shown. Proliferation was assayed by tritiated thymidine incorporation into cellular DNA. The SDs were <20%. (B) BALB/c thymocytes (10⁶/ml) were added to microtiter plates coated with titrated amounts of anti-CD3ε antibody with 3 × 10⁻⁶ M retinol or without, as indicated. Proliferation was measured in hexaduplicate wells on day 3 by [³H]thymidine incorporation assay. (C) BALB/c thymocytes (3 × 10⁶/ml) were activated with anti-CD3ε mAb as in A. The total number of viable cells was determined by counting trypan blue excluding cells, and those of blast cells by counting viable large cells in six replicate wells. Because of the relatively low cell density required in the culture (see A), the numbers reported for blast cells are best estimates.
The proliferative responses of thymocytes were clearly dependent on the presence of all-trans retinol added at initiation of culture. Under these conditions, the optimal retinol concentration was between 3 and $1 \times 10^{-6}$ M (Fig. 2 A). Because retinol decays in serum-free tissue culture medium with an estimated half-life of 24 h (14), we have replenished retinol twice daily and have found that with repeated feeding, five- to tenfold lower retinol concentrations were sufficient to sustain cell proliferation over the 3-d culture period (Fig. 1 A). We have described that retinol is metabolized by lymphocytes to 14HRR, and have hypothesized that this molecule serves as an intracellular mediator (15). To test this assumption in T cells, 14HRR was added instead of retinol and dose responses were recorded. A single addition of 14HRR given at the start was ineffective, probably because of the brief half-life of 14HRR of 4 h (data not shown). However, when provided at 12-h intervals, 14HRR was as potent as retinol in supporting T cell proliferation with a dose optimum of $5 \times 10^{-7}$ M (Fig. 2 A). Among other retinoids tested, 13-cis-retinol (data not shown) and all-trans retinal were equally effective as all-trans retinol. However, all-trans retinoic acid was completely inactive over a wide dose range tested irrespectively of how often the cultures were fed.

The growth kinetics of anti-CD3-activated thymocytes in serum-free medium revealed exponential growth over a 4-d period (Fig. 3) that was totally dependent on the presence of either retinol ($3 \times 10^{-6}$ M) or 14HRR ($6 \times 10^{-7}$ M). Human serum (3%) was also capable of supporting exponential growth, although in the experiment with $10^5$ cells per well shown in Fig. 3 the proliferative indices were only half of those obtained with retinoids. Human serum contains retinol at $2 \times 10^{-6}$ M. Attempts to remove retinol from serum by delipidation and subsequently replenish it were unsuccessful.
Table 1. Growth-stimulating Effect of Retinol on Thymocytes in the Presence of Different Interleukins

| Stimulating agent | Dose | No retinol $^{cpm}$ | $^{10^{-6}}$ M retinol $^{cpm}$ |
|-------------------|------|---------------------|-------------------------------|
| IL-1              | 10   | 959 ± 30            | 118,924 ± 3,051               |
| IL-2              | 2    | 458 ± 156           | 77,343 ± 11,739               |
| IL-4              | 5    | 991 ± 105           | 115,849 ± 20,630              |
| IL-6              | 5    | 1,005 ± 815         | 130,590 ± 23,803              |
| IFN-γ             | 40   | 81,876 ± 11,868     | 220,359 ± 27,726              |
| TNF-α             | 12   | 464 ± 95            | 122,905 ± 11,577              |
| IL-2 + IL-4       | 2/5  | 1,081 ± 103         | 103,025 ± 5,280               |
| none              | -    | 585 ± 207           | 79,247 ± 17,567               |

Proliferation of activated thymocytes in response to interleukins in presence and absence of retinol. Purified thymocytes ($5 \times 10^5$ cells/well) were activated with immobilized anti-CD3 antibody in serum-free medium in the presence or absence of interleukins and retinol ($3 \times 10^{-6}$ M). Proliferation was assayed after 3 d by tritiated thymidine incorporation.

Garbe et al. 113
To test whether or not activation through the TCR is unique or whether other modes of stimulation lead to proliferation sustained by retinol, we have used Con A at the optimal concentration of 0.5 μg/ml in serum-free ITLB medium. Thymocyte proliferation was entirely retinol dependent, the cultures with 3 × 10^-6 M retinol growing exponentially, and those without retinol perishing rapidly (Fig. 2 B).

Stimulation of Peripheral Lymphocyte Subsets Is Also Retinol Dependent. Because the phenotype analysis had implicated mature T cells among the thymocytes responsive to anti-CD3 activation in the presence of retinoid, we tested whether this finding also held true for peripheral T cells. Fig. 4 indicates that stimulation of lymph node T cells was dependent on the presence of retinol although at high cell density (2 × 10^6/ml) the dependence was less pronounced than at low density (5 × 10^5/ml or below) (Fig. 4 A). The dose-response curves for lymph node T cells were very similar to those for thymocytes (compare Figs. 2 and 4 B). Furthermore, 14HRR is effective over the same dose range as observed for thymocytes, whereas retinoic acid is nearly inert, except for a very modest stimulatory activity elicited at 10^-5 M concentration.

Because a proportion of lymph node T cells proliferated upon activation by anti-CD3 independently of retinol, we tested whether these cells might belong to a particular subset. However, when CD4+ and CD8+ subsets were purified by negative immunoselection, and tested for proliferation in the presence or absence of retinol, they behaved no differently from unseparated cells, i.e., each subset responded to the activating signal (anti-CD3 for CD4+ cells; anti-CD3 plus IL-2 for CD8+ cells) only if retinol or 14HRR were present (Fig. 4, C and D).

Retinol Is Required at Onset of Culture. We have determined the kinetics of requirement of retinol by thymocytes and have found that the highest responses were elicited when retinol was supplied together with the activation signal. When delayed by 12 h, retinol still produced a growth supporting effect but this trailed behind by a margin of 4:1. A delay of 24 h caused complete failure of activation (Fig. 5). It is unclear from present experiments whether once activated, continued proliferation of normal T cells is also critically dependent on retinol in the culture medium. This issue is under investigation. 13-cis-retinol and retinal but not all-trans retinoic acid can substitute for retinol. A new retinoid, 14HRR recently discovered by us (15) was also capable of supporting activation and sustaining proliferation of T cells, provided that it was replenished twice daily to compensate for its rapid decay. Our experiments do not distinguish between defined stages in the activation process of resting T cells beyond a broad requirement during early and late events. The impact on early events is implied by the observation that a 12-h delay in retinol addition leads to stagnation, whereas the requirement for late events follows from the observation that a single addition of 14HRR does not enable sustained proliferation. Although retinol appears to be an important cofactor, its presence may not be absolutely required in situations where potent alternate second signals are given. For instance, interferon-γ proved quite...
efficient in anti-CD3-mediated activation in the absence of retinol (Table 1).

Retinol, an essential vitamin, circulates in blood as a stable complex with retinol-binding protein (RBP) and transthyretin (TTR) (23). Its concentration in plasma is closely regulated at 1-2 \times 10^{-6} \text{ M}, whereas intracellular concentrations vary between tissues and appear to depend on the extent concentration of cellular retinol-binding protein (CRBP) (24). Because the tissue distribution of CRBP is nearly universal (25), it is inferred that retinol is present ubiquitously as well (26). A general physiological purpose of retinol itself has not been discerned, but there is agreement that retinol is used as a metabolic precursor of other retinoids, including 11-cis-retinal functioning as the photoreceptor in vision (27), all-trans retinoic acid which has been implicated in differentiation (28) and morphogenesis (29), and 9-cis retinoic acid that has been found to activate the RXR receptor (30, 31).

Pursuing the hypothesis that retinol serves as a precursor of intracellular retinoid mediators, we have analyzed the metabolic products of retinol in B lymphocytes in previous studies (14, 15). B lymphocytes did not produce retinoic acids, but they synthesized a new class of retinoids, the retro-retinoids, hitherto seen in nature only in the form of all-trans-retinol (32). Retro-retinoids are characterized by a completely planar ring-to-tail configuration, rigidly enforced by the rearrangement of the carbon double bond system so as to fix the six-membered ring by a double bond to the polyene tail. 14-hydroxy-retinoic acid is the first naturally occurring retro-retinoid to be discovered in mammalian cells, and is 20-40 times more potent on a concentration basis in preventing necrotic cell death in B lymphocytes than its parent molecule, retinol.

Our results in this study show that retinol is an essential component in serum-free medium, without which T cells can be activated only superficially and T cell proliferation does not proceed. Serum is a customary supplement of culture media used for in vitro experimentation in cellular immunology, and the retinol herein might be part of the secret of why it is such an effective ingredient in growth medium. As implied by our results, however, components of serum other than retinol, albumin (as a transport protein of fatty acids), transferrin (to regulate iron metabolism), and insulin may not be needed for lymphocyte cultures. Indeed, the advantage of avoiding unknown influences by hormones and growth factors (notably PDGF) forms a compelling reason for experimentation in defined serum-free medium as discussed in detail by Daynes et al. (6).

In the serum-free medium composition used here, retinol is not protected by its physiological serum carrier proteins, RBP and TTR, is therefore labile, and decays with a half-life of <24 h in cell culture (14). The optimally effective dose of retinol is 2 \times 10^{-6} \text{ M}, when given once in a 3-d culture, or 2 \times 10^{-7} \text{ M} when provided at 12-h intervals. This dose range corresponds to the concentration of retinol in normal sera, i.e., 1-2 \times 10^{-6} \text{ M}.

The question of whether retinol mediates its effect on T cells through its metabolic product, 14HRR, cannot be answered definitely by the experiments shown in this study, but the arguments that follow support this mechanisms. First, 14HRR is capable of supporting T cell activation and proliferation in the absence of any extraneous source of retinol. Second, the dose-response curves for retinol and 14HRR in T cells are very similar, a finding of some concern, because a putative downstream mediator (i.e., 14HRR) might have been expected to be active at lower concentrations than its precursor. However, 14HRR is intrinsically a much more labile molecule than retinol. Previous analyses with B lymphocytes have demonstrated activity for 14HRR at 5 \times 10^{-9} \text{ M} concentration compared with 2 \times 10^{-7} \text{ M} for retinol, a 40-fold difference (15). Why T cells require higher concentrations of 14HRR is unclear. Third, 14HRR is a metabolic product of retinol on the basis of isotope-labeling experiments and because of the fact that 14HRR is an optically active compound, and therefore enzymatically derived (15). Fourth, 14HRR (in contrast to retinal) does not revert to retinol (our unpublished observations). Fifth, it is noteworthy that T lymphocytes neither respond to externally provided retinoic acid nor synthesize appreciable amounts of it (J. Buck and U. Hämmerling, unpublished results). Thus, 14HRR does not appear to be an intermediary compound in retinoic acid synthesis, an unlikely possibility on structural considerations, anyway.

Although these considerations leave unanswered the question whether 14HRR might be the intracellular mediator itself, they strongly suggest a regulatory retinol pathway distinct from that of retinoic acid observed in nonlymphoid cells. Retinoic acid has frequently been referred to as the active mediator of retinol effects, but our findings suggest alternative mediators and pathways. Having dismissed retinoic acid as an actual mediator of retinol effects, but our findings suggest alternative mediators and pathways. Having dismissed retinoic acid as an actual mediator of retinol effects, but our findings suggest alternative mediators and pathways. Having dismissed retinoic acid as an actual mediator of retinol effects, but our findings suggest alternative mediators and pathways. Having dismissed retinoic acid as an actual mediator of retinol effects, but our findings suggest alternative mediators and pathways.
published elsewhere, we have observed that 14HRR facilitates the expression of immediate early genes in fibroblasts. If substantiated for T cells, this finding would handsomely explain the requirement for retinoids in T cell activation.

Throughout our work we have been concerned that our results might violate the precept of dual signaling in T cell published elsewhere, we have observed that 14HRR facilitates the expression of immediate early genes in fibroblasts. If substantiated for T cells, this finding would handsomely explain the requirement for retinoids in T cell activation. We have attempted to determine whether retinol is required during the activation phase, G0 to G1, during the progression through S phase, or during both phases. Our results support the notion that retinol is needed for initial activation, because a delay in addition of retinol after the TCR signal was given caused a marked decrease in proliferation. The answer to the second question is less clear as retinol, once given to cells, cannot easily be removed by washing because of its lipid nature. However, a single dose of 14HRR given at initiation of culture, and decaying with a half-life of ~4 h, was insufficient to drive T cell proliferation, speaking for a continuous requirement of retinol also for transition to S phase. Supporting this notion is also our published record concerning continuously growing lymphoid tissue culture lines that are dependent on retinol (9).

To complement the study of activation requirements in serum-free medium we have inquired into the role of exogenous lympho- and cytokines. The salient points of these experiments are that none of the interleukins tested (IL-1, -2, -4, and -6) nor TNF-α are substitutes for retinol. They are in agreement with the assumption that retinol needs to be physically present as a source for further metabolic modifications. However, this argument is partly negated by the observation that IFN-γ can circumvent the retinol requirement and initiate durable proliferation in the absence of retinol or 14HRR, whereas strong additive effects were seen when retinoids were present simultaneously with IFN-γ.

We thank B. Forbes for preparation of the manuscript.

This work was supported in part by a fellowship to A. Garbe from the Deutsche Krebshilfe, and grants CA-38351 and CA-49933 from the National Institutes of Health.

Address correspondence to Dr. Ulrich Hämmerling, Immunology Program, Memorial Sloan-Kettering Cancer Center, 1275 York Avenue, New York, NY 10021.

Received for publication 23 January 1992 and in revised form 24 March 1992.

References

1. Allison, J.R., and L.L. Laurie. 1987. Structure, function and serology of the T cell antigen receptor complex. Annu. Rev. Immunol. 5:503.

2. Reinherz, E.L., O. Acuto, M. Fabbi, A. Bensussan, C. Milanese, H.-D. Royer, S.C. Meuer, and S.F. Schlossman. 1984. Clonotypic surface structure on human T lymphocytes: functional and biochemical analysis of the antigen receptor complex. Immunol. Rev. 81:95.

3. Lewin, B. 1991. Oncogenic conversion by regulatory changes in transcription factors. Cell. 64:303.

4. Evans, R.M. 1988. The steroid and thyroid hormone receptor superfamily. Science (Wash. DC). 240:889.

5. Green, S., and P. Chambon. 1988. Nuclear receptors enhance our understanding of transcription regulation. Trends Genet. 4:309.

6. Daynes, R.A., T. Dowell, and B.A. Araneo. Platelet-derived growth factor is a potent biologic response modifier of T cells. J. Exp. Med. 174:1323.

7. Iscove, N.N., and F. Melchers. 1978. Complete replacement of serum by albumin, transferrin, iron and soybean lipid in cultures of lipopolysaccharide-activated B lymphocytes. J. Exp. Med. 147.

8. Herzberg, V.L., and K.A. Smith. 1987. T cell growth without serum. J. Immunol. 138:998.
9. Buck, J., G. Ritter, L. Dannecker, V. Katta, S.L. Cohen, B.T. Chait, and U. Hämmerling. 1990. Retinol is essential for growth of activated human B cells. J. Exp. Med. 171:1613.
10. Wolbach, S.B., and P.R. Howe. 1925. Tissue changes following deprivation of fat-soluble A vitamin. J. Exp. Med. 42:753.
11. David, C.Y., and J.L. Sell. 1983. Effect of retinol and retinoic acid nutrition on the immune system of chicks. J. Nutr. 113:1914.
12. Bieri, J.G., E.G. McDaniel, and W.E. Rogers. 1969. Surviving of germfree rats without vitamin A. Science (Wash. DC). 163:574.
13. Rahmathullah, L., B.A. Underwood, R.D. Thulasiraj, R.C. Milton, K. Ramaswamy, R. Rahmathullah, and G. Babu. 1990. Reduced mortality among children in southern India receiving a small weekly dose of vitamin A. N. Engl. J. Med. 323:929.
14. Buck, J., A. Myc, A. Garbe, and G. Cathomas. 1991. Differences in the action and metabolism between retinol and retinoic acid in B lymphocytes. J. Cell Biol. 115:851.
15. Buck, J., F. Derguini, E. Levi, K. Nakanishi, and U. Hämmerling. 1991. Intracellular signaling by 14-hydroxy-4', 14-retro-retinol. Science (Wash. DC). 254:1654.
16. Leo, O., M. Foo, D.H. Sachs, L.E. Samelson, and J.A. Bluestone. 1987. Identification of a monoclonal antibody specific for a murine T3 polypeptide. Proc. Natl. Acad. Sci. USA. 84:1374.
17. Kappler, J.W., B. Skidmore, J. White, and P. Marrack. 1981. Antigen-inducible, H-2-restricted, II.-2-producing T cell hybrids. J. Exp. Med. 153:1198.
18. Ohara, J., and W.E. Paul. 1985. Production of a monoclonal antibody to and molecular characterization of B-cell stimulatory factor-1. Nature (Lond.). 315:333.
19. Hämmerling, G.J., U. Hämmerling, and H. Lemke. 1979. Isolation of twelve monoclonal antibodies against Ia and H-2 antigens. Serological characterization and reactivity with B and T lymphocytes. Immunogenetics. 8:433.
20. Hämmerling, G.J., U. Hämmerling, and L. Flaherty. 1979. Qat-4 and Qat-5, new murine T-cell antigens governed by the H-2 region and identified by monoclonal antibodies. J. Exp. Med. 150:108.
21. Dialynas, D.P., D.B. Wilde, P. Marrack, A. Pierres, K.A. Wall, W. Harran, G. Otten, M.R. Locken, M. Pierres, J. Kappler, and F.W. Fitch. 1983. Characterization of the murine antigenic determinant, designated L3T4a, recognized by monoclonal antibody GKL.5: expression of L3T4a by functional T cell clones appears to correlate primarily with class II MHC antigen reactivity. Immunol. Rev. 74:29.
22. Julius, M.E., E. Simpson, and L.A. Herzenberg. 1973. A rapid method for the isolation of functional thymus-derived murine lymphocytes. Eur. J. Immunol. 3:645.
23. Goodman, D.S. 1984. Plasma retinol-binding protein. In The Retinoids. Vol. 2. M.B. Sporn, A.B. Roberts, and D.S. Goodman, editors. Academic Press, Inc., New York. 41-48.
24. Chytil, F., and D.E. Ong. Cellular retinoid-binding protein, In The Retinoids. Vol. 2. M.B. Sporn, A.B. Roberts, and D.S. Goodman, editors. Academic Press, Inc., New York. 89-123.
25. Kato, M., W.S. Blaner, J.R. Mertz, K. Das, and D.S. Goodman. 1985. Influence of retinoid nutritional status on cellular retinol and retinoid acid-binding protein concentrations in various rat tissues. J. Biol. Chem. 260:4832.
26. Noy, N., and W.S. Blaner. 1991. Interactions of retinol with binding proteins: studies with rat cellular retinol-binding protein and with rat retinol-binding protein. Biochemistry. 30:6380.
27. Wald, G. 1966. Molecular basis of visual excitation. Science (Wash. DC). 162:230.
28. Roberts, A.B., and M.B. Sporn. 1984. Cellular biology and biochemistry of the retinoids. In The Retinoids. Vol. 2. M.B. Sporn, A.B. Roberts, and D.S. Goodman, editors. Academic Press, New York. 209-286.
29. Tabin, C.J. 1991. Retinoids, homeoboxes and growth factors: toward molecular models for limb development. Cell. 66:199.
30. Levin, A.A., L.J. Sturzenbecker, S. Kazmer, T. Bosakowski, C. Huselton, G. Allenby, J. Speck, C. Kratzzeisen, M. Rosenberger, A. Lovey, and J.F. Grippo. 1992. 9-cis retinoid acid stereoisomers binds and activates the nuclear receptor RXRalpha. Nature (Lond.). 355:359.
31. Heyman, R.A., D.J. Mangelsdorf, J.A. Dyck, R.B. Stein, G. Eichele, R.M. Evans, and C. Thaller. 1992. 9-cis retinoid acid is a high affinity ligand for the retinoid X receptor. Cell. 68:397.
32. Castle, D.C., A.E. Gillam, J.M. Heiblron, and J.W. Thompson. 1934. Adsorption experiments with vitamin A concentrates. Biochem. J. 28:1702.
33. Giguere, V., S. Lyn, P. Yip, C.H. Siu, and S. Amin. 1990. Molecular cloning of cDNA encoding a second cellular retinoid acid binding protein. Proc. Natl. Acad. Sci. USA. 87:6233.
34. Giguere, V., E.S. Ong, P. Segui, and R.M. Evans. 1987. Identification of a receptor for the morphogen retinoid acid. Nature (Lond.). 330:624.
35. Krust, A., P. Kastner, M. Petkovich, A. Zelent, and P. Chambon. 1987. A third human retinoic acid receptor, hRARgamma. Proc. Natl. Acad. Sci. USA. 86:5310.
36. Brand, N., M. Petkovich, A. Krust, P. Chambon, H. de The, A. Marchio, P. Tiollais, and A. Dejean. 1988. Identification of a second human retinoic acid receptor. Nature (Lond.). 332:850.
37. Moore, D.D. 1990. Diversity and unity in the nuclear hormone receptors: a terpenoid receptor superfamily. New Biol. 2:100.
38. Mangelsdorf, D., E. Ong, J. Dyck, and R. Evans. 1990. Nuclear receptor that identifies a novel retinoid acid response pathway. Nature (Lond.). 345:224.
39. Bretscher, P., and M. Cohn. 1970. A theory of self-nonself discrimination. Science (Wash. DC). 169:1042.
40. Mueller, D.L., M.K. Jenkins, and R.H. Schwartz. 1989. Clonal expansion versus functional clonal inactivation: a costimulatory signalling pathway determines the outcome of T cell antigen receptor occupancy. Annu. Rev. Immunol. 7:445.
41. Linsley, P.S., E.A. Clark, and J.A. Ledbetter. 1990. T-cell antigen CD28 mediates adhesion with B cells by interacting with activation antigen B7/BB-1. Proc. Natl. Acad. Sci. USA. 87:5031.