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J Clin Invest. 1979;63(3):507-515. <https://doi.org/10.1172/JCI109329>.

Research Article

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Stimulation by Triiodothyronine of the In Vitro Uptake of Sugars by Rat Thymocytes

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ABSTRACT Studies were conducted to ascertain the in vitro effect of 3,5,3'-triiodothyronine (T_3) on the accumulation of the glucose analogue, 2-deoxyglucose (2-DG), by thymocytes freshly isolated from weanling rats. At a concentration of $1 \mu\text{M}$, T_3 stimulated the 15-min uptake of ^3H -2-DG after cells had been exposed to T_3 for only 30 min. Significant stimulation of 2-DG accumulation was produced by 1 nM T_3 , with increasing stimulation at doses ranging up to $10 \mu\text{M}$. T_3 did not alter the fraction of accumulated 2-DG that was phosphorylated, and kinetic studies indicated that its effect was associated with a significant increase in the apparent V_{max} of 2-DG accumulation, but not the apparent K_m . T_3 also enhanced the accumulation by thymocytes of the nonmetabolized glucose analogue, 3-O-methylglucose (3-O-MG), an effect that was evidently the result of an increase in 3-O-MG transport into the cell, because it was seen in cells incubated with ^3H -3-O-MG for only 30 s. The proportionate increase in 2-DG accumulation produced by T_3 was not altered by preincubating cells with concentrations of puromycin or cycloheximide sufficient to reduce [^3H]leucine incorporation by 95%, and T_3 over a period of $>2 \text{ h}$ had no effect on [^3H]leucine incorporation itself.

These results indicate that T_3 stimulates the uptake of sugars in rat thymocytes in vitro by an effect on their inward transport. The promptness of the effect and its failure to be inhibited during profound inhibition of protein synthesis further indicate that this effect of T_3 is not mediated through a nuclear-dependent mechanism. Rather, the properties of this response, and of the increases in amino acid and 2-DG accumulation produced by T_3 in other tissue preparations, strongly suggest that these effects of T_3 are mediated at the level of cell membrane.

Received for publication 4 August 1978 and in revised form 15 November 1978.

INTRODUCTION

Recent years have seen a great growth of interest in the primary mechanism of action of the thyroid hormones. The voluminous data that have resulted strongly suggest that the thyroid hormones exert a primary effect at the level of the cell nucleus (1-5), and perhaps the mitochondrion as well (6-8). In addition, evidence has grown that the thyroid hormones may also exert a direct effect at the level of the cell membrane. 3,5,3'-Triiodothyronine (T_3)¹ and other thyroactive materials have, for example, been shown to stimulate the in vitro accumulation of certain amino acids by chick embryo cartilage and rat thymocytes (9-11), and, in the case of the rat thymocyte, this effect has been found after in vivo administration of T_3 (12). In addition, in cultured chick embryo myocardial cells, T_3 enhances cellular uptake of the glucose analogue, 2-deoxy-D-glucose (2-DG) (13, 14). All of these effects on substrate accumulation occur promptly and are independent of ongoing protein synthesis. In the present studies we demonstrate that the effect of T_3 on cellular 2-DG uptake is not limited to the chick myocardium, but appears to be more general, because it occurs as well in the rat thymocyte, where it is also prompt and independent of new protein synthesis, and results from enhancement of the transport of 2-DG into the cell, rather than in increase in its phosphorylation.

METHODS

Thymocyte suspensions. Rats of the CD strain, ranging in age between 25 and 27 d, were purchased from Charles River Breeding Laboratories (Wilmington, Mass.) and were maintained for a maximum of 6 d before study on a diet of Purina laboratory chow (Ralston Purina Co., St. Louis, Mo.).

¹Abbreviations used in this paper: 2-DG, 2-deoxy-D-glucose; 3-O-MG, 3-O-methyl-D-glucose; T_3 , 3,5,3'-triiodothyronine.

Thymocytes were then harvested according to the method described by Goldfine and co-workers (11). Briefly, animals were killed by cervical dislocation, thymus glands were quickly removed and washed in ice-cold Krebs-Ringer 25 mM Tris buffer, pH 7.5. Tissues were then gently teased, and the thymocytes thereby liberated were filtered through nylon mesh and centrifuged at 800 g for 5 min. The supernate was decanted and the cell pellet was resuspended in buffer. Thymocytes were counted in a hemocytometer and additional buffer was added to yield a final thymocyte concentration of 45×10^6 cells/ml. 3 ml of the cold suspension was pipetted into siliconized Erlenmeyer flasks, and these were incubated during a 30-min equilibration period at 37°C in room air. Thereafter, preincubation or incubation periods, as indicated below, were initiated.

³H-2-DG uptake. Either at the beginning of incubation or, more commonly, after preincubation of cell suspensions with various agents, ³H-2-DG (8.26 Ci/mmol sp act)² was added to the medium to a final concentration of 3 μCi/ml (0.36 μM). After specified periods, 200-μl aliquots were removed, pipetted into microtubes, and centrifuged in a Beckman microfuge (Beckman Instruments, Inc., Spinco Div., Palo Alto, Calif.) at 10,000 rpm for 20 s. The supernate was quickly removed by aspiration and the pellet was suspended in 100 μl of ice-cold 5% trichloroacetic acid (TCA). The entire suspension was quantitatively transferred to counting vials with the aid of Toluene-Triton X-100 (Rohm and Haas Co., Philadelphia, Pa.) scintillation counting fluid. Samples were counted in a beta-scintillation counter with automatic quench correction.

In preliminary experiments, uptake of ³H-2-DG was shown to be linear during at least the 1st h of incubation. Therefore, a 15-min period of incubation with ³H-2-DG was employed in all subsequent experiments.

[3-³H]Methylglucose uptake. In experiments to assess the effect of T₃ on the uptake of the nonmetabolized sugar, 3-O-methyl-D-glucose (3-O-MG), cells were prepared as above and were equilibrated and preincubated with or without T₃ as in experiments with ³H-2-DG. At the end of preincubation periods, ³H-3-O-MG (3 μCi/ml; 80.8 Ci/mmol sp act) was added, and the incubation continued. At specified intervals thereafter, aliquots were removed and processed for measurement of the ³H content of the thymocytes as described above.

Corrections for occluded extracellular fluid. Because the final cell pellets inevitably contained occluded extracellular fluid, preliminary experiments were conducted to assess the efficacy of using D-[³H]mannitol as an extracellular fluid marker. Cell suspensions were incubated with D-[³H]mannitol (3 μCi/ml; 24 Ci/mmol sp act) for varying periods and the content of ³H in cell pellets was measured. No change in ³H content of pellets obtained between 1 and 60 min of incubation was observed, and values were the same whether the incubation temperature was 4° or 37°C. Pellet contents of D-[³H]mannitol were consistently in the order of 0.45–0.60% of the total ³H present in the 200 μl of cell suspension from which the pellets were derived, and were unaffected by the presence of T₃. The findings indicated that in this system [³H]mannitol is confined to the extra-cellular space.

² L-[2-deoxy-³H]glucose, D-[³H]mannitol, [3-³H]methylglucose, D-[glucose-6-¹⁴C]phosphate, and [³H]leucine were purchased from New England Nuclear (Boston, Mass.). D-Glucose-6-phosphate, 2-deoxyglucose-6-phosphate, puromycin, cycloheximide, L-3,5,3'-triiodothyronine, L-thyroxine, 3,5-diiodothyronine, and L-thyronine were purchased from Sigma Chemical Co. (St. Louis, Mo.). 3,3',5-Triiodothyronine was kindly provided by Baxter-travenol Laboratories (Morton Grove, Ill.).

Consequently, in each experiment, parallel cell suspensions containing [³H]mannitol, rather than ³H-2-DG or ³H-3-O-MG, were incubated so that corrections for occluded extracellular fluid in the cell pellets could be made.

Phosphorylation of 2-DG. In experiments to determine the percentage of accumulated ³H-2-DG that had undergone phosphorylation within the thymocytes, cell suspensions were prepared, equilibrated, and preincubated with or without T₃ according to the techniques described above. Media were then enriched with ³H-2-DG in concentrations ranging between 0.36 μM and 8 mM. 15 min later, triplicate aliquots of 200 μl of suspension were removed for measurement of total ³H-2-DG uptake and duplicate 500-μl aliquots were removed at the same time for fractionation of ³H-2-DG into phosphorylated and nonphosphorylated moieties. The latter suspensions were centrifuged, the cell pellets were dispersed into 5% cold TCA and were resedimented. Supernates were enriched with 2 mM 2-DG-6-phosphate carrier and were then brought to pH 7.0 with concentrated NaOH. Somogyi reagent (15) was added, and the mixture was centrifuged. Aliquots of the supernate were taken for measurement of nonphosphorylated ³H-2-DG, and the quantity of ³H-2-DG-6-phosphate calculated as the difference between total ³H in the cell pellet and ³H in the Somogyi supernate.

Control experiments in which a 5% solution of TCA was first enriched with [³H]glucose-6-phosphate and the foregoing procedure was then carried out revealed that 98% of the ³H was contained in the final precipitate.

Kinetics of 2-DG accumulation. In the experiments to assess the phosphorylation of ³H-2-DG described above, triplicate 200-μl aliquots of cell suspension were removed 10 min after varying concentrations of ³H-2-DG had been added. Total ³H uptake was measured, and the data obtained were subjected to analysis.

Leucine incorporation. To assess the effect of T₃ in vitro on leucine incorporation into thymocyte protein, cell suspensions were prepared and equilibrated in the standard manner, and were then preincubated with or without T₃ for varying periods. Thereafter, [³H]leucine (84 Ci/mmol sp act) was added in a concentration of 1 μCi/ml, and incubations were continued for 30 min. The entire suspension was transferred to centrifuge tubes, cells were sedimented, resuspended in 3 ml of 5% cold TCA, resedimented, and washed twice again with 5% cold TCA. After a final centrifugation, the sediment was taken up in Toluene-Triton X-100 counting fluid and its content of ³H measured.

Statistical analyses. As appropriate to the experimental design, statistical analyses were performed with Student's *t* test, the paired *t* test, or by Dunnett's test (16).

RESULTS

Latency of T₃ effect. Initial experiments were conducted to determine whether T₃ would influence the uptake of 2-DG by thymocytes, and, if so, how long a period of exposure of cells to T₃ would be required. For these experiments, cells were incubated with T₃ at a concentration of 1 μM, because this had been shown to enhance the accumulation of cycloleucine by thymocytes under similar in vitro conditions (11). Control and T₃-enriched thymocyte suspensions were preincubated for varying periods, after which ³H-2-DG was added and its uptake by the cells measured 15 min later.

As compared with values in corresponding controls,

uptake of ^3H -2-DG in specimens preincubated with T_3 for 30, 60, and 120 min was significantly increased in each of five individual experiments (Fig. 1). In specimens preincubated with T_3 for 15 min, a significant increase in ^3H -2-DG uptake was not seen in any of the five experiments; however, when mean values for control and T_3 -treated specimens of the five experiments were compared by the paired *t* test, a significant increase ($P < 0.05$) was demonstrable. Hence, at a concentration of $1 \mu\text{M}$, a significant stimulatory effect of T_3 on 2-DG accumulation by thymocytes was seen after cells have been exposed to the hormone for a total of only 30 min.

In control specimens, the uptake of 2-DG remained constant after preincubation periods of from 15 to 30 min, increased slightly in cells preincubated for 1 h, and was substantially increased in cells preincubated for 2 h. Consequently, the percentage stimulation of 2-DG uptake produced by T_3 was greatest in cells preincubated for 1 h, and this period of preincubation with T_3 was selected for most subsequent studies of the T_3 effect.

Dose-response relationship. As determined in five experiments in which cells were preincubated with or without T_3 for 1 h, uptake of 2-DG by thymocytes displayed a linear log dose-response relationship at T_3 concentrations up to $10 \mu\text{M}$ (Fig. 2). The lowest concentration of T_3 that produced significant stimulation of 2-DG uptake ($P < 0.05$) was 1 nM , and this was true

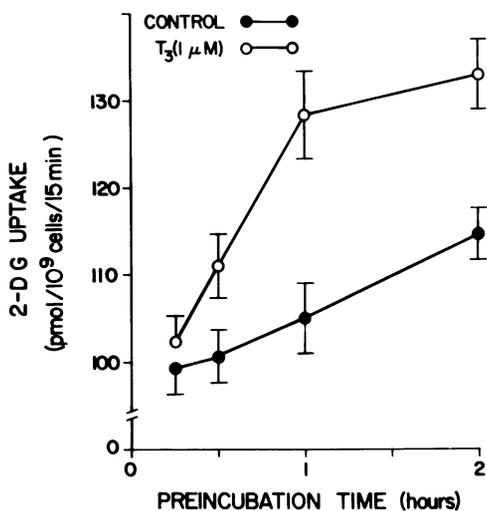


FIGURE 1 Time-course of the T_3 effect on the accumulation of ^3H -2-DG by rat thymocytes in vitro. Cells were preincubated with T_3 ($1 \mu\text{M}$) for the periods indicated. ^3H -2-DG was then added and its accumulation in the cells measured 15 min later. Values shown are mean \pm SE of those obtained in five experiments in which quadruplicate vessels were incubated for each experimental point. Statistically significant enhancement of 2-DG accumulation ($P < 0.05$) was present in cells preincubated for 15 min.

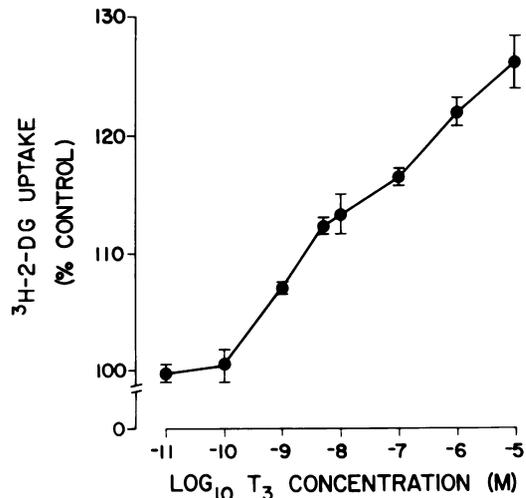


FIGURE 2 Dose-response curves for the T_3 effect on ^3H -2-DG accumulation by rat thymocytes. Cells were preincubated with the indicated concentrations of T_3 for 1 h, and the 15-min accumulation of ^3H -2-DG was then measured. Values are expressed as a percent of those found in T_3 -free controls and represent the mean \pm SE of those obtained in five experiments in which quadruplicate vessels in each group were studied.

both for individual experiments and when data from the five experiments were pooled and analyzed on the basis of either absolute values or percentage increases from control.

Phosphorylation of 2-DG. Two experiments were performed in which thymocytes were preincubated for 1 h with or without $1 \mu\text{M}$ T_3 , and the total accumulation and percentage phosphorylation of ^3H -2-DG were measured 15 min after exposure of cells to varying concentrations of 2-DG. At all concentrations of 2-DG tested, total accumulation of ^3H -2-DG was greater in cells preincubated with T_3 than in those not preincubated ($P < 0.02$). Percentage phosphorylation of accumulated 2-DG was $\approx 98\%$ in specimens incubated at the lowest concentration of 2-DG ($0.36 \mu\text{M}$), remained almost constant over a 347-fold increase in 2-DG concentration to 0.125 mM , and then declined progressively to $\approx 80\%$ in specimens incubated with the highest concentrations of 2-DG tested (8 mM) (Fig. 3). Values for the percentage phosphorylation of accumulated 2-DG were not detectably influenced by preincubation with $1 \mu\text{M}$ T_3 .

Kinetics of 2-DG accumulation. In the two experiments described immediately above, the effect of T_3 on the kinetics of 2-DG accumulation was evaluated from data obtained 10 min after addition of varying concentrations of ^3H -2-DG. As in specimens incubated for 15 min, total accumulation of 2-DG was higher in T_3 -treated than in control specimens at all concentrations of 2-DG employed ($P < 0.02$) (Fig. 4). Despite the

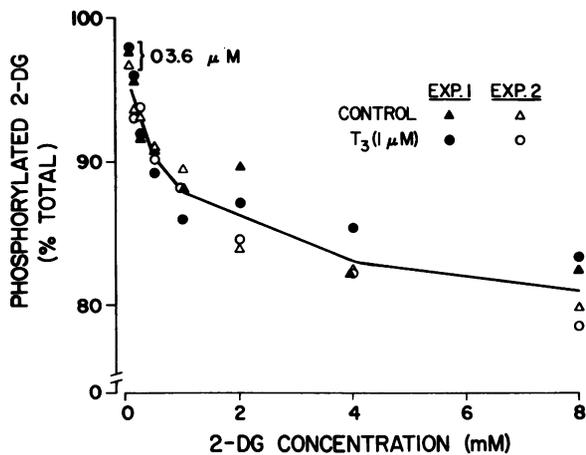


FIGURE 3 Phosphorylation of accumulated 2-DG by rat thymocytes in the presence and absence of T_3 . Shown are the results of two experiments in which quadruplicate vessels were studied for each experimental point. Cells were preincubated with or without T_3 ($1 \mu\text{M}$) for 1 h, after which ^3H -2-DG and unlabeled 2-DG were added for 15 min at the concentrations indicated. Cells were then harvested and the accumulated 2-DG was fractionated into phosphorylated and nonphosphorylated moieties as described in the text.

complex nature of 2-DG accumulation, which involves both transport into the cell and phosphorylation, we attempted to apply conventional kinetic analysis to the foregoing data, as others have done with respect to the accumulation of 2-DG in other tissues (17–20). With computer assistance, least square fits to hyperbolic

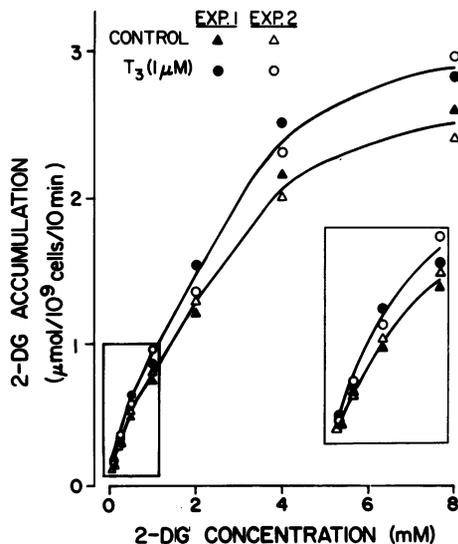


FIGURE 4 Saturation studies of the effect of T_3 on the accumulation of 2-DG by rat thymocytes in vitro. Incubation conditions were the same as those for Fig. 3, except that samples for measurement of total 2-DG accumulation were withdrawn at 10 min.

functions were calculated from the pooled data for control and T_3 -treated groups, respectively, from the two experiments. These analyses revealed no significant difference in values of the apparent K_m in the T_3 -treated ($2.77 \pm 0.25 \text{ mM}$; mean \pm SD) and the control ($3.00 \pm 0.35 \text{ mM}$) groups, values in both groups being well within the range of the K_m for 2-DG accumulation reported in other tissues (17–20). Values for apparent V_{max} were significantly higher ($P < 0.02$), however, in T_3 -treated ($3.91 \pm 0.25 \mu\text{mol}/10^9$ cells per 10 min) than in control ($3.45 \pm 0.28 \mu\text{mol}/10^9$ cells per 10 min) groups.

3-O-MG accumulation. In each of two experiments, quadruplicate samples of thymocytes were preincubated with T_3 (1 nM or $1 \mu\text{M}$) for 1 h, after which ^3H -3-O-MG was added and its cellular accumulation measured at intervals varying between 30 s and 30 min later. Three additional experiments were conducted in which the effect of T_3 only on accumulation of ^3H -3-O-MG during 30 s was assessed. Analysis of the data revealed that $1 \mu\text{M}$ T_3 increased ^3H -3-O-MG accumulation at all of the time intervals studied, and that 1 nM T_3 did so at all except that 30-min interval. This was true whether data from individual experiments were analyzed or whether the results of replicate studies were pooled and analyzed together. As seen in Fig. 5, the proportionate effect of both $1 \mu\text{M}$ and 1 nM decreased over the time that the cells were exposed to 3-O-MG.

[^3H]Leucine incorporation. In four experiments, thymocytes were preincubated for 1 or 2 h in media either lacking T_3 or containing T_3 at concentrations of

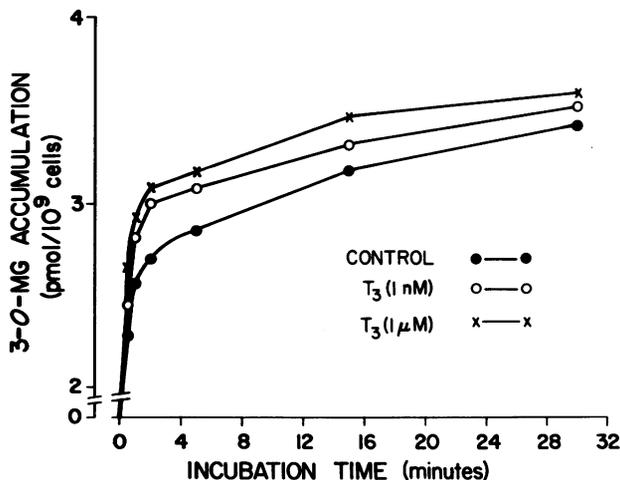


FIGURE 5 The effect of T_3 on the accumulation of 3-O-MG by rat thymocytes in vitro. Results represent the pooled data from two experiments in which quadruplicate samples were incubated for each experimental point. Cells were preincubated with T_3 (1 nM or $1 \mu\text{M}$) for 1 h, after which ^3H -3-O-MG was added, and its accumulation by cells measured at the indicated intervals thereafter.

1 nM or 1 μ M. The incorporation of [³H]leucine over the subsequent 30 min was then measured in quadruplicate aliquots from each experimental group.

[³H]Leucine incorporation was significantly lower in cells preincubated for 2 h than in those preincubated for 1 h, regardless of whether or not T₃ was present. However, for each period of incubation, values of [³H]-leucine accumulation were not changed by T₃ at either concentration studied (Table I).

Inhibition of protein synthesis. Experiments were conducted to determine the conditions under which puromycin and cycloheximide each would produce profound inhibition of amino acid incorporation by thymocytes. When thymocytes were preincubated with puromycin (100 μ g/ml) for 10 min, incorporation of [³H]leucine into TCA-precipitable moieties during the ensuing 30 min was only 5% of that in control specimens. A similar preincubation exposure to cycloheximide (100 μ g/ml) decreased [³H]leucine incorporation by 96%. This effect was not accompanied by a change in cell viability, because 95% of the thymocytes retained their ability to exclude nigrosin during incubation periods of 150 min, regardless of whether or not cycloheximide or puromycin was present.

12 experiments were then performed in which thymocytes were variously preincubated for 10 min in the absence or presence of puromycin (100 μ g/ml), and for an additional 1 h in the absence or presence of T₃ (1 nM or 1 μ M), and in which the uptake of ³H-2-DG was then assessed. Puromycin alone produced a significant ($P < 0.01$), $\approx 20\%$, inhibition of 2-DG uptake (Table II). Both concentrations of T₃ significantly increased 2-DG uptake whether or not puromycin was present, and the percentage stimulation of

TABLE I
The Effect of Preincubation with T₃ on the In Vitro Incorporation of [³H]Leucine into Protein by Rat Thymocytes*

	T ₃ concentration	[³ H]Leucine incorporation
60-min preincubation with T ₃	0	1.90 \pm 0.03
	1 nM	1.81 \pm 0.02
	1 μ M	1.82 \pm 0.04
120-min preincubation with T ₃	0	1.24 \pm 0.05‡
	1 nM	1.35 \pm 0.02‡
	1 μ M	1.25 \pm 0.05‡

* Cells were preincubated with T₃ at the indicated concentrations for the periods of time shown. [³H]Leucine was then added, and its incorporation (expressed in picomoles per 10⁹ cells) into protein was measured 30 min later. Values shown are mean \pm SE of those obtained in four experiments in which quadruplicate vessels in each experimental group were studied.

‡ $P < 0.02$ vs. corresponding 60-min incubation group.

TABLE II
Failure of Puromycin to Inhibit the In Vitro Stimulatory Effect of T₃ on the Accumulation of 2-DG by Rat Thymocytes*

T ₃ concentration	PM	³ H-2-DG accumulation	T ₃ effect
—	—	102 \pm 3	
—	+	84 \pm 4‡	
1 nM	—	111 \pm 3§	8.8 \pm 0.6
1 nM	+	91 \pm 2‡§	8.3 \pm 0.4
1 μ M	—	120 \pm 3§	17.6 \pm 0.7
1 μ M	+	101 \pm 4‡§	20.6 \pm 1.6

* Cells were preincubated with puromycin (PM; 100 μ g/ml) for 10 min and for an additional 60-min period with T₃ at the indicated concentrations. ³H-2-DG was then added and its accumulation (expressed in picomoles per 10⁹ cells) measured 15 min later. T₃ effect shown is the percent increase over values in the corresponding T₃-free group. Values shown are mean \pm SE of those obtained in 12 experiments in which quadruplicate samples in each experimental group were studied.

‡ $P < 0.01$ vs. corresponding PM-free group.

§ $P < 0.01$ vs. corresponding T₃-free group.

2-DG uptake produced by T₃ was unaffected by puromycin. In similar experiments, cycloheximide (100 μ g/ml) decreased ³H-2-DG accumulation by $\approx 10\%$, but failed to affect the proportionate increase in ³H-2-DG accumulation induced by T₃ (1 μ M) (Table III).

Dose-response curves for the effect on ³H-2-DG accumulation of several compounds related to T₃ revealed the following order of stimulatory potency: T₃ > thyroxine (T₄) > 3,3',5'-triiodothyronine (rT₃) > 3,5-diiiodothyronine (3,5-T₂) > thyronine (Fig. 6). Precise quantitative comparisons were not possible because of poor parallelism of dose-response curves.

DISCUSSION

The present studies seem clearly to have shown that, in thymocytes freshly isolated from weanling rats, T₃ in vitro stimulates the accumulation of two ³H-labeled analogues of glucose, 2-DG, and 3-O-MG. In the case of 2-DG, this effect of T₃ is demonstrable in cells exposed to T₃ for a total of only 30 min, i.e., after 15 min of preincubation with T₃ and 15 min of incubation with ³H-2-DG. Significant stimulation of 2-DG accumulation was produced by T₃ at a concentration of 1 nM, with a linear log dose response up to T₃ concentrations of 10 μ M, at which concentration accumulation of 2-DG was increased by $\approx 25\%$. Although not extensively explored, thyroxine, 3,3',5'-triiodothyronine, and 3,3'-diiiodothyronine were also capable of stimulating 2-DG uptake, and the potency of these compounds, relative to that of T₃, was similar

TABLE III
Failure of Cycloheximide to Inhibit the In Vitro Stimulatory Effect of T₃ on the Accumulation of 2-DG by Rat Thymocytes*

	T ₃	CH	³ H-2-DG accumulation	T ₃ effect
30-min preincubation with T ₃	-	-	100±1	
	+	-	112±1‡	12.0±1.1
	-	+	89±2§	
	+	+	101±1‡§	13.5±1.4
60-min preincubation with T ₃	-	-	98±2	
	+	-	116±3	18.4±1.3
	-	+	89±1§	
	+	+	103±2§	15.7±1.4

* Cells were preincubated for 10 min with cycloheximide (CH; 100 μg/ml) and then, for an additional period as indicated, with T₃ (1 μM). ³H-2-DG was then added, and its accumulation (expressed in picomoles per 10⁹ cells) measured 15 min later. T₃ effect shown is the percent increase over values in the corresponding T₃-free group. Values shown are mean±SE of those obtained in four experiments in which quadruplicate samples in each experimental group were studied.

‡ *P* < 0.05 vs. corresponding T₃-free group.

§ *P* < 0.01 vs. corresponding CH-free group.

^{||} *P* < 0.01 vs. corresponding T₃-free group.

in rank order to that seen in a variety of other thyroid hormone-responsive systems (see review, reference 21).

At concentrations of 1 nM and 1 μM, T₃ had no effect on the incorporation of [³H]leucine into the protein of thymocytes, even after cells had been preincubated with T₃ for as long as 2 h. Moreover, when thymocytes were preincubated with puromycin or cycloheximide at concentrations sufficient to reduce subsequent [³H]leucine incorporation by ≈95%, basal 2-DG accumulation did decrease, but the proportionate increase in 2-DG accumulation produced by T₃ was not altered. Thus, the data strongly indicate that the prompt effect of T₃ on 2-DG accumulation is unrelated to any effect on new protein synthesis.

Cellular uptake of 2-DG is the result of two functions, transport of 2-DG into the cell and its subsequent phosphorylation by hexokinase. Further metabolism of 2-DG does not occur, and the 2-DG-6-phosphate formed is retained within the cell (22, 23). At the very low concentration of 2-DG used in the present studies, transport, rather than phosphorylation, is generally the rate-limiting factor in 2-DG accumulation (24, 25). Hence, it would appear that T₃ must have increased 2-DG uptake by increasing its rate of entry into the cell. This conclusion was verified in two sets of ad-

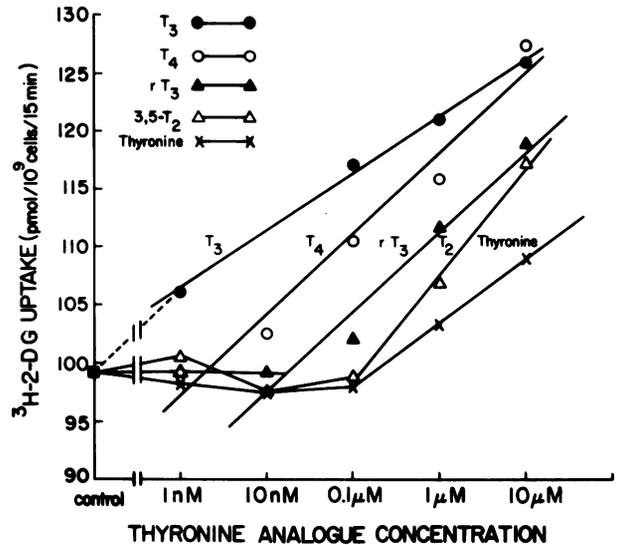


FIGURE 6 The effect of various thyroxine analogues (levorotatory isomers) on the uptake of ³H-2-DG by rat thymocytes in vitro. Results shown are the mean of values obtained in quadruplicate vessels and are typical of those obtained in two or more experiments. T₄, thyroxine; rT₃, 3,3',5'-triiodothyronine; 3,5-T₂, thyronine.

ditional experiments. First, it was shown that T₃ enhanced the accumulation of ³H-2-DG over a very wide range of extracellular 2-DG concentrations and that this increase was not accompanied by a change in the proportion of accumulated ³H-2-DG that had undergone phosphorylation. This effect is similar to that of insulin in fat, muscle, and lymphoid tissue, where insulin also increases sugar uptake without changing phosphorylation (26–31). Second, direct evidence to the point was obtained in studies with the second analogue of glucose examined, 3-O-MG. This sugar has been shown to use the same transport mechanism as glucose and 2-DG do (17–19), but does not undergo phosphorylation and remains free to diffuse out of the cell (32, 33). The effect of T₃ on 3-O-MG uptake was therefore assessed after very short periods of exposure to the ³H-labeled sugar in order to observe the process of inward transport and to minimize any effects of ³H-3-O-MG efflux on the results obtained. A stimulatory effect of T₃ was evident in cells exposed to ³H-3-O-MG for 30 s, confirming the effect of T₃ on inward transport. The proportionate effect decreased with time, as would be expected from the increasing role of ³H-3-O-MG efflux as a determinant of net accumulation. Taken together, these data provide strong evidence that T₃ acts to enhance the inward transport of sugars in this system.

Cellular accumulation of 2-DG is a complex process, which involves both transport of the sugar into the cell

and its subsequent phosphorylation, making conventional kinetic analysis difficult. Nevertheless, accumulation of 2-DG has been studied in this manner by other workers in other tissues (17–20, 34–36), and we have attempted to do the same in regard to the accumulation of 2-DG by rat thymocytes. Such analyses suggested that the stimulatory effect of T_3 was the result of an increase in the V_{\max} of 2-DG transport, rather than a change in K_m . In this respect, the effect of T_3 on sugar transport in thymocytes again resembles that of insulin in muscle and fat cells (20, 34–36); this may relate to preliminary observations we have made which indicate that the minimum concentration of T_3 necessary to stimulate 2-DG accumulation is reduced in the presence of insulin.³

A primary consideration with respect to the present findings is whether or not they reflect an action of thyroid hormone that takes place under physiological circumstances *in vivo*. We are unaware of any data concerning the effect of thyroid hormone insufficiency or excess, *per se*, on the rate of glucose uptake by tissues in the living organism. Although the rate of disappearance from plasma of administered glucose and the rate of generation of products of glucose metabolism is decreased or accelerated in hypothyroid and hyperthyroid states, respectively (37–41), it is by no means certain that these changes reflect either a change in glucose uptake by the cells or a direct action of the thyroid hormones. Indeed, a recent report indicates that hypothyroidism does not affect the transport of 3-O-MG in isolated adipocytes of the rat (42).

The major reason to question the physiological relevance of the presently described effect of T_3 is the high concentration required to produce this effect, relative to the concentration of the T_3 presumed to be acting upon the tissues in the living animal (free T_3 concentration $\cong 5\rho\text{M}$). Although some *in vitro* effects of T_3 are demonstrable at concentrations approaching the physiological, it is often the case that *in vitro* actions of the thyroid (and other) hormones that appear to have physiological relevance require unphysiologically high concentrations for their prompt *in vitro* demonstration. For example, in the rat, the lipolytic activity of adipose tissue and the degree to which it is stimulated by epinephrine are clearly influenced by the thyroid state of the animal (see reviews, references 43–46). Nevertheless, T_3 -induced enhancement of these activities *in vitro* requires concentrations approximately six orders of magnitude greater than the concentration of free T_3 presumed to be present *in vivo*, and three orders of magnitude greater than the concentration of T_3 required to produce the effect that we

are describing (47–49). A second example is provided by studies that have demonstrated an increase in hepatic mitochondrial protein synthesis after exposure to T_3 , in which the *in vivo* sensitivity to this effect was estimated to be $\cong 10,000$ times higher than the sensitivity *in vitro* (50–52). Finally, concentrations of T_3 $\cong 100$ -fold higher than those required to enhance 2-DG uptake in thymocytes are necessary to produce inhibition of the adenylate cyclase response to exogenous thyrotropin by bovine thyroid membranes. The concentration of T_3 required for the latter effect (50 μM) is about six orders of magnitude greater than the presumed free T_3 concentration *in vivo*; nevertheless, a seemingly similar inhibition of thyroid adenylate cyclase response to exogenous thyrotropin could be produced by the administration of only 2.5 μg of T_3 to the mouse (53, 54).

In addition to the requirement that *in vitro* systems impose that any effect of T_3 be prompt, which might in itself increase the concentration required, *in vitro* systems are often impaired in the sense that they may lack other factors that act in a permissive, synergistic, or potentiating manner. With respect to the accumulation of 2-DG by rat thymocytes, we have shown that epinephrine and insulin are stimulatory when added alone, and that separately or together they enhance the response to T_3 . Thus, the minimally effective dose of T_3 is reduced by one order of magnitude, *i.e.*, to $\cong 0.1$ nM, if epinephrine is present in the medium, and is decreased still further (to $\cong 10$ pM) by the concomitant addition of insulin.³ Hence, under the appropriate conditions, the effect of T_3 that we describe can be obtained at concentrations of T_3 that are “physiological” or nearly so.

Studies carried out in our laboratories and those of our co-workers have defined a number of *in vitro* effects of T_3 that appear to have a strong commonality in respect to their major characteristics. These effects comprise the increase in 2-DG and 3-O-MG transport into rat thymocytes presently described, together with the previously demonstrated increases produced by T_3 in 2-DG accumulation by chick embryo cartilage and myocardial cells in culture (9–14). Two major characteristics of these effects are that they are very prompt in onset, being evident from 1 min or less to 30 min after addition of T_3 , and that they are not blocked by inhibitors of protein synthesis. These properties speak strongly against an action at a nuclear site. Rather, several lines of evidence lead us to suggest that they are mediated at the level of the cell membrane. First, they occur very promptly, as indicated above. Second, they appear to result from changes in functions in which the cell membrane is involved, *i.e.*, inward transport of substrates or their rate of efflux from the cell. Finally, in the rat thymo-

³ Segal, J., C. Ruegsegger, and S. H. Ingbar. Unpublished observations.

cyte, the enhancement of both amino acid⁴ and 2-DG accumulation that is produced by T₃ is further increased by coincubation with beta adrenergic agonists, which themselves are thought to act at the level of the cell membrane. The likelihood that T₃ acts directly on the cell membrane is strengthened by the recent demonstration in plasma membranes from rat hepatocytes of high affinity, low capacity binding sites for T₃, whose affinity for other iodothyronines correlates well with their respective hormonal potency (55). The presence of such sites in the nucleus (1-5) and mitochondrion (8) has been taken to suggest that these are primary sites of T₃ action. Nonetheless, it remains to be demonstrated that these sites are indeed linked to hormonal action at the membrane level, including the actions we have described.

ACKNOWLEDGMENTS

The authors are indebted to Dr. Bernard J. Ransil for advice concerning statistical analysis of the data. Data analysis was performed, in part, on the PROPHET System, a national computer resource sponsored by the Chemical/Biological Information Handling Program, National Institutes of Health.

This work was supported in part by research grant AM-18416 from the National Institute of Arthritis, Metabolism, and Digestive Diseases, and by grant RR-01032 from the General Clinical Research Centers Program of the Division of Research Resources, National Institutes of Health.

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