

Radioligand Receptor Assay for 25-Hydroxyvitamin D₂/D₃ and 1 α ,25-Dihydroxyvitamin D₂/D₃

APPLICATION TO HYPERVITAMINOSIS D

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ABSTRACT A competitive protein binding assay for measurement of the plasma concentration of 1 α ,25-dihydroxyvitamin D₃ [1 α ,25-(OH)₂D₃] has been extended to include the immediate precursor of this hormone, 25-hydroxyvitamin D₃ (25-OHD₃). In addition, the assay system is capable of measuring the two metabolic products of ergocalciferol, namely, 25-hydroxyvitamin D₂ (25-OHD₂) and 1 α ,25-dihydroxyvitamin D₂ [1 α ,25-(OH)₂D₂]. The target tissue assay system consists of a high affinity cytosol receptor protein that binds the vitamin D metabolites and a limited number of acceptor sites on the nuclear chromatin. By utilizing a series of chromatographic purification steps, a single plasma sample can be assayed for any of the four vitamin D metabolites either individually or combined. Therefore, the assay procedure allows for both the quantitative and qualitative assessment of the total active vitamin D level in a given plasma sample.

To show that the binding assay was capable of measuring 1 α ,25-(OH)₂D₂ as well as 1 α ,25-(OH)₂D₃, two groups of rats were raised. One group, supplemented with vitamin D₃, produced assayable material that represented 1 α ,25-(OH)₂D₃. The other group, fed only vitamin D₃ in the diet, yielded plasma containing only 1 α ,25-(OH)₂D₃ as the hormonal form of the vitamin. The circulating concentrations of the two active sterols were nearly identical (15 ng/100 ml) in both groups, indicating that the competitive binding assay can be used to measure both hormonal forms in plasma.

In a separate experiment, 1 α ,25-(OH)₂D₂ was generated in an *in vitro* kidney homogenate system using

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25-OHD₂ as substrate. Comparison of this sterol with 1 α ,25-(OH)₂D₃ in the assay system showed very similar binding curves; the D₂ form was slightly less efficient (77%). Comparison of the respective 25-hydroxy forms (25-OHD₂ vs. 25-OHD₃) at concentrations 500-fold that of 1 α ,25-(OH)₂D₃, again suggested that the binding of the D₂ metabolite was slightly less efficient (71%).

Finally, the assay was employed to measure the total active vitamin D metabolite pools in the plasma of normal subjects and patients with varying degrees of hypervitaminosis D. The normal plasma levels of 25-OHD and 1 α ,25-(OH)₂D measured in Tucson adults were 25–40 ng/ml and 2.1–4.5 ng/100 ml, respectively. Both sterols were predominately (> 90%) in the form of vitamin D₃ metabolites in this environment. Typical cases of hypervitaminosis D exhibited approximately a 15-fold increase in the plasma 25-OHD concentration, and a dramatic changeover to virtually all metabolites existing in the form of D₂ vitamins. In contrast, the circulating concentration of 1 α ,25-(OH)₂D was not substantially enhanced in vitamin D-intoxicated patients. We therefore conclude that hypervitaminosis D is not a result of abnormal plasma levels of 1 α ,25-(OH)₂D but may be caused by an excessive circulating concentration of 25-OHD.

INTRODUCTION

It is now well established that 25-hydroxyvitamin D₃ (25-OHD₃)¹ and 1 α ,25-dihydroxyvitamin D₃ [1 α ,25-

¹ *Abbreviations used in this paper:* 25-OHD₂, 25-hydroxyvitamin D₂ or 25-hydroxyergocalciferol; 25-OHD₃, 25-hydroxyvitamin D₃ or 25-hydroxycholecalciferol; 1 α ,25-(OH)₂D₂, 1 α ,25-dihydroxyvitamin D₂; 1 α ,25-(OH)₂D₃, 1 α ,25-dihydroxyvitamin D₃. When no subscript is present after the D, both D₂ and D₃ are implied.

(OH)₂D₃] are two metabolites of the native vitamin involved in regulating calcium and phosphorus metabolism (1). Formation of 25-OHD₂ occurs in the liver, intestine, and kidney (2), and subsequent activation of the sterol to 1 α ,25-(OH)₂D₃ occurs exclusively in the kidney (3), producing what is considered to be the hormonal form of the vitamin. 1 α ,25-(OH)₂D₃ has been shown to be the most active metabolite of vitamin D in stimulating intestinal calcium transport (4) and bone calcium mobilization (5). Although the exact sequence of events that mediate the effect of 1 α ,25-(OH)₂D₃ on its target tissue is not yet completely understood, an early step has been shown to be the interaction between the hormone and a specific macromolecular component in the target tissue cytoplasm (6). The hormone-receptor complex subsequently translocates to the nuclear compartment where it attaches to specific acceptor sites (6-8). Our laboratory has utilized this series of events to develop a sensitive competitive binding assay for the hormonal form of vitamin D (9). The method utilizes a saturable, reconstituted receptor system consisting of intestinal mucosa cytosol and nuclear chromatin. An isotope-dilution curve is obtained by incubating reconstituted cytosol-chromatin and [³H] 1 α ,25-(OH)₂D₃ with increasing amounts of nonradioactive 1 α ,25-(OH)₂D₃ and then separating the free and bound sterol by trapping the sterol-receptor-chromatin supercomplex on glass fiber filters. This technique has been shown to be a reliable and valid method for quantitation of hormone concentrations as low as 1.0 ng/100 ml plasma (10).

The present study was undertaken for the following reasons: (a) to determine if the presently available chromatography methods could separate vitamin D₃ from vitamin D₂ metabolites, (b) to ascertain if the discrimination against ergocalciferol metabolites by the chick is at the level of the sterol's target tissue receptor, (c) to extend the 1 α ,25-(OH)₂D₃ assay (9, 10) to incorporate 25-hydroxyvitamin D₂ (25-OHD₂), 25-OHD₃, and 1 α ,25-dihydroxyvitamin D₂ [1 α ,25-(OH)₂D₂], thus developing a single method for the qualitative and quantitative assessment of these biologically active forms of vitamin D and, (d) to measure these metabolites in hypervitaminosis D patients, possibly allowing a more complete delineation of the disorder.

METHODS

Animals. Chicks used were White Leghorn cockerels (donated by Demler Farms, Anaheim, Calif.) that were raised on a vitamin D-deficient diet (11) for 3-4 wk. Male weanling Holtzman rats were used in the experiment generating 1 α ,25-(OH)₂D₃ and 1 α ,25-(OH)₂D₂ *in vivo*.

Sterols. Crystalline 25-OHD₂ and 25-OHD₃ were a generous gift from Dr. Jack Hinman and Dr. John Babcock of the Upjohn Company, Kalamazoo, Mich. [26,27-*methyl*-³H]-25-OHD₃ (6.5 Ci/mmol) was obtained from Amersham/Searle Corp., Arlington Heights, Ill. [26,27-*methyl*-³H]1 α ,

25-(OH)₂D₃ (6.5 Ci/mmol) was produced *in vitro*, by a modification (12) of the method of Lawson et al. (13) and purified by column chromatography as previously described (7, 14). Nonradioactive 1 α ,25-(OH)₂D₃ was either prepared and purified via similar procedures (12) or obtained as the crystalline, synthetic compound from Dr. M. Uskokovic of Hoffman-LaRoche Inc., Nutley, N. J. Biologically generated and synthetic nonradioactive 1 α ,25-(OH)₂D₃ yielded identical quantitative competition in the binding assay, verifying the equivalency of sterol from these two sources. Nonradioactive 1 α ,25-(OH)₂D₂ was generated *in vitro* in a similar fashion (12). Sterols were quantitated by ultraviolet absorption spectrophotometry and stored in distilled ethanol at -20°C.

Chromatography. After addition of 2,000 cpm each of tritiated 25-OHD₃ and 1 α ,25-(OH)₂D₃ (6.5 Ci/mmol) to the plasma and extraction of sterols as described elsewhere (10), chromatographic procedures were carried out as follows. (See Fig. 1 for schematic diagram.) Sephadex LH-20 (Pharmacia Fine Chemicals Inc., Piscataway, N. J.) column chromatography was performed as described previously (10). One 1 × 15-cm (5 g) column resulted in the separation of 25-OHD from 1 α ,25-(OH)₂D; 25-OHD emerged between 0 and 40 ml elution volume, whereas 1 α ,25-(OH)₂D eluted between 40 and 95 ml. Throughout the remainder of the purification scheme the sterols were treated separately. 25-OHD was purified on silicic acid (Bio-Rad Laboratories, Richmond, Calif., minus 325 mesh; activated by heating at 120°C for 24 h in a vacuum oven) by eluting first with 20 ml hexane-diethyl ether (1:1) and then with 20 ml diethyl ether; 25-OHD emerged in the second fraction with the ether. 1 α ,25-(OH)₂D was purified similarly on silicic acid by elution with diethyl ether (10 ml) and then acetone (8 ml); the hormone emerged in the second fraction with the acetone. The entire procedure was miniaturized to 0.8 × 6.4-cm columns to provide a very rapid and simple means of removing contaminating lipid. Final purification of the sterols was accomplished by Celite (Johns-Manville, New York) liquid-liquid partition chromatography (14). The solvent system (System I) used for 25-OHD was 100% hexane (mobile) and 15% water in methanol (stationary); the solvent system (System II) for the purification of 1 α ,25-(OH)₂D was 10% ethyl acetate in hexane (mobile) and 45% water in ethanol (stationary). Celite chromatography was miniaturized to a "micro" scale (0.8 × 8.0 cm), when rapid purification without separating D₃ and D₂ forms was desired (Fig. 1B, D). 10-ml glass pipettes, fitted with glass wool plugs, serve as columns. Elution was carried out with mobile phase, and each sterol emerged between 7 and 22 ml on its respective column. When 12 samples were processed simultaneously, the total time from the initial drawing of the blood to a purified assayable sample is approximately 2 h/sample per technician using the micro-silicic acid and micro-Celite chromatography method (Fig. 1B, D). If it is necessary to separate 25-OHD₂ from 25-OHD₃ and 1 α ,25-(OH)₂D₂ from 1 α ,25-(OH)₂D₃, a longer (1 × 35-cm) column (with 5-ml fractions) was required (Fig. 1A, C). A slow flow rate (15 min/fraction) produced defined peaks with minimal overlap. When sample purification on a successive series of Sephadex LH-20, silicic acid, and Celite chromatography was utilized, any possibility of cross-contamination between the mono- and dihydroxy-metabolites was avoided (14). All samples for sterol assay were evaporated under nitrogen and solubilized in 400 μ l ethanol. After determination of yield by counting an aliquot of each sample for tritium (yields range from 40 to 80%), radioreceptor assays were performed on 100- μ l portions. Triplicate assays

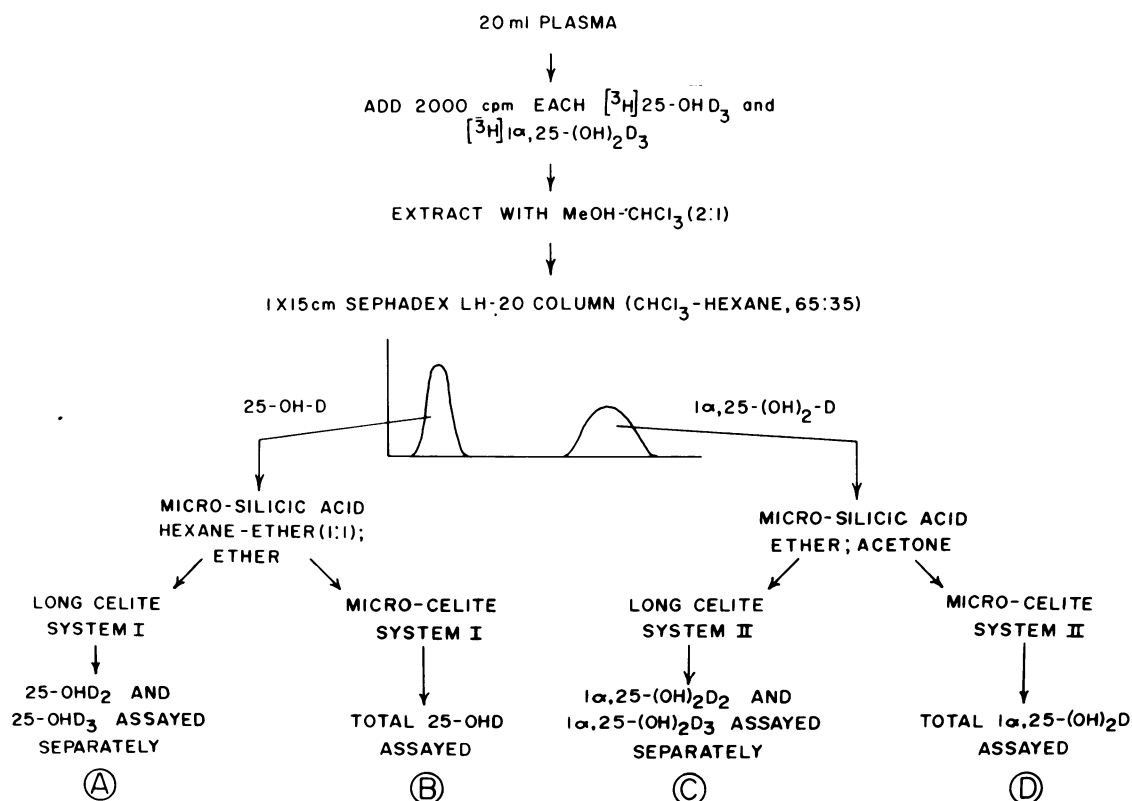


FIGURE 1 Purification scheme for 25-OHD₂ and(or) 25-OHD₃ (A, B), and 1α,25-(OH)₂D₂ and(or) 1α,25-(OH)₂D₃ (C, D). For a complete vitamin D metabolite profile of the plasma, pathways A and C are used. When distinctions between D₂ and D₃ metabolites are not required, the micro-Celite is employed as a final purification step (pathways B and D) and results are expressed as the "total" D-metabolite concentration. All assays are run in triplicate. Extraction of plasma is carried out as described elsewhere (10). Celite solvent systems I and II and other details are described under **Methods**.

were carried out on all samples in the present study, and interassay variation was 10–15%. All solvent used in chromatographic procedures and sterol storage were reagent grade and glass distilled before use.

Isolation of subcellular fractions. Intestinal mucosa (6 g) from two rachitic chicks was homogenized in 25 ml of 0.25 M sucrose in 0.05 M Tris-HCl (pH 7.4), 0.025 M KCl, and 0.005 M MgCl₂. Cytosol fraction was obtained by centrifugation at 100,000 g for 1 h. Chromatin was prepared from crude nuclei (isolated from original homogenate by centrifugation at 1,000 g for 10 min) by homogenizing successively in one 25-ml portion of 0.8 mM EDTA, 25 mM NaCl, pH 8; one 25-ml portion of 1% Triton X-100 (Rohm & Haas Co., Philadelphia, Pa.), 0.01 M Tris-HCl, pH 7.5; and one 25-ml portion of 0.01 M Tris-HCl, pH 7.5. The chromatin was harvested by sedimentation at 30,000 g for 10 min after each wash. The entire chromatin pellet from 6 g of mucosa was reconstituted with the cytosol fraction by homogenization to create a cytosol-chromatin receptor system for the competitive binding assay. The reconstituted mixture was prepared fresh daily and immediately before use. All operations were performed at 0–4°C.

Binding assay. To each assay tube containing [³H]1α,25-(OH)₂D₃ and unlabeled sterol (dried together with a stream of nitrogen) were added 20 μl of distilled ethanol and 200

μl of reconstituted cytosol-chromatin system. The ethanol that was added just before the receptor system aids in solubilizing the sterols to achieve a higher binding efficiency and reduces nonspecific binding; this represents a modification of our earlier procedures (9, 10). The final concentration of [³H]1α,25-(OH)₂D₃ was 4.3 nM. After incubation, for 20 min at 25°C, the quantity of labeled sterol bound to chromatin was determined by filtration (Millipore Corp., Bedford, Mass., 30-place manifold). 1 ml of cold 1% Triton X-100 in 0.01 M Tris (pH 7.5) was added to each assay tube, and the entire mixture was applied to a Type A or A/E glass fiber filter (Gelman Instrument Co., Ann Arbor, Mich.) at very low vacuum. After 2–4 min the vacuum was increased to achieve uniform flow rates of approximately 1 ml/min, and each of the filters was washed with 2 ml of 1% Triton X-100, 0.01 M Tris, pH 7.5. After filtration, the filters were placed in liquid scintillation vials with 5 ml of methanol-chloroform (2:1, vol/vol). After 20 min the methanol-chloroform was evaporated on a hot plate under a stream of air. Without removal of the glass filter, sterols were solubilized in 5 ml of toluene counting solution consisting of 4 g of PPO and 50 mg of POPOP per liter of toluene. Samples were counted in a refrigerated Beckman LS-233 liquid scintillation spectrometer (Beckman Instruments, Inc., Scientific Instruments Div., Irvine,

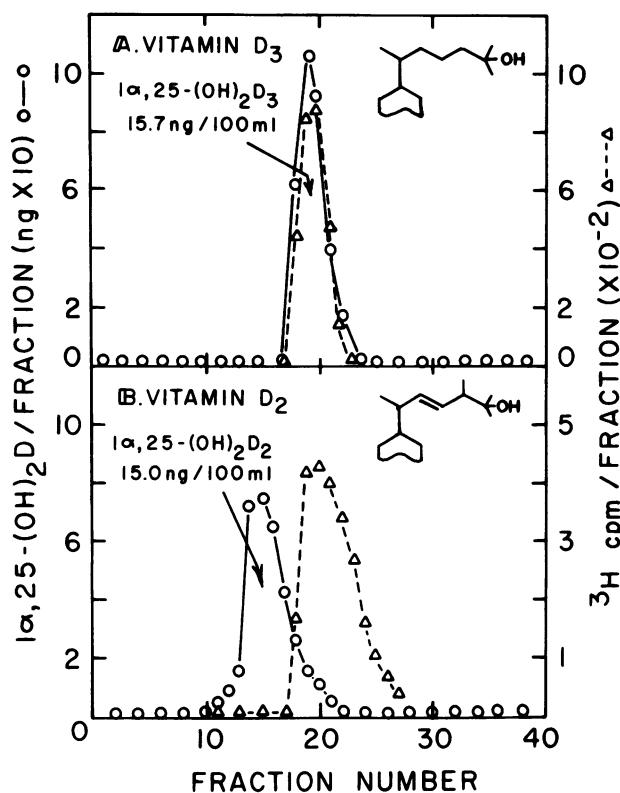


FIGURE 2 Celite chromatography (1 × 35 cm; System II) of purified plasma from rats fed. (A) Vitamin D₃ or (B) vitamin D₂. [3H]1 $\alpha,25-(OH)_2D_3$ (4,200 cpm; 6.5 Ci/mmol) was added to each pooled plasma sample from 12–15 rats (32 ml) and purified for 1 $\alpha,25-(OH)_2D_3$ and 1 $\alpha,25-(OH)_2D_2$ as outlined under Methods and in Fig. 1, pathway C. Recovery of tritium after extraction and chromatography was 63% for D₃-fed animals and 68% for D₂-fed animals. The radioreceptor assay was used to quantitate 1 $\alpha,25-(OH)_2D$ in each 5-ml fraction the final Celite column (○). Migration of [3H]1 $\alpha,25-(OH)_2D_3$ marker (Δ) was determined by counting an aliquot of each fraction.

Calif). Efficiency for tritium was 48% and was identical for all counted samples. Routinely, 2,000–3,000 cpm of the approximately 6,000 cpm of [3H]1 $\alpha,25-(OH)_2D_3$ present in the incubation are recovered in the chromatin in the absence of competing nonradioactive sterol (33–50% binding efficiency). Other aspects of the validity, sensitivity, specificity, and accuracy of this assay are described elsewhere (10, 15).

Patients. For routine assays, blood was drawn from healthy volunteers (ages 20–50 yr) in Tucson, Ariz. In addition, blood was obtained from three patients receiving high doses of vitamin D₂. The first patient (A) was a 59-yr-old man with osteomalacia due to unexplained vitamin D resistance. He had been receiving as much as 500,000 IU vitamin D₂/day, but at the time of this study he was receiving 250,000 IU D₂/day. The serum calcium was 14.0 mg/100 ml (N = 9.5–10.5 mg/100 ml), serum phosphorus was 4.6 mg/100 ml (N = 3.0–4.5 mg/100 ml), alkaline phosphatase was 165 U (N = 5–13 U), and serum magnesium was normal. Bone biopsy revealed osteomalacia (unknown etiology) with increased osteoid seams. The second

patient (B) was a 47-yr-old woman with postsurgical hypoparathyroidism receiving 150,000 IU D₂/day. Her serum calcium was 11.1 mg/100 ml and phosphorus was 3.2 mg/100 ml. The third patient (C) was a 60-yr-old man with postsurgical hypoparathyroidism. This subject was receiving 100,000 IU D₂/day but did not exhibit vitamin D intoxication since his serum calcium was 9.6 mg/100 ml and serum phosphorus was 3.2 mg/100 ml. All patients receiving vitamin D₂ had normal creatinine clearance within 1 mo of blood drawing.

RESULTS

Rat in vivo generation of 1 $\alpha,25-(OH)_2D$. To determine if the 1 $\alpha,25-(OH)_2D_3$ assay of Brumbaugh et al. (10) also measures 1 $\alpha,25-(OH)_2D_2$, both sterols were generated in weanling rats in vivo. Rats were chosen for the study because it is thought that these animals do not discriminate between cholecalciferol and ergocalciferol as does the chick (16). Two groups of animals were raised for 3 wk on a normal calcium (0.6%) and phosphorus (0.6%) diet. Both groups were treated identically except that the diet of one group was supplemented with vitamin D₃ (2 IU/g diet), whereas, the second group received only vitamin D₂ (2 IU/g) in the diet. Blood was obtained by cardiac puncture, pooled within each group, and subjected to chromatographic purification. Tracer [3H] 1 $\alpha,25-(OH)_2D_3$ (4,200 cpm) was added to the samples to quantitate losses and serve as a column marker for authentic hormone. After lipid extraction with methanol-chloroform (2:1) and Sephadex LH-20 chromatography (see Methods), the extracts were further purified on a 35-cm Celite column, and individual fractions were assayed for 1 $\alpha,25-(OH)_2D$ binding activity (Fig. 2). As shown in Fig. 2A, the binding activity of the plasma extract from vitamin D₃-fed animals migrated exactly with the added [3H] 1 $\alpha,25-(OH)_2D_3$ tracer. The total assayable 1 $\alpha,25-(OH)_2D_3$ in the plasma sample corresponds to 15.7 ng/100 ml of plasma (0.4 nM), and this value correlates well with previously reported (17) concentrations of the hormone in normal rat plasma. Fig. 2B depicts the Celite profile of the pooled plasma sample from vitamin D₂-fed rats. The assayable material does not migrate with authentic 1 $\alpha,25-(OH)_2D_3$, and the value of 15.0 ng/100 ml correlates well with 15.7 ng/100 ml obtained in Fig. 2A. Taken in combination with the fact that vitamin D₃ and vitamin D₂ are believed to be metabolized equally in the rat, the data suggest that the assayable metabolite (Fig. 2B) is 1 $\alpha,25-(OH)_2D_2$. This preliminary identification will be supported (below) by the fact that the elution position of this metabolite corresponds with the elution position of 1 $\alpha,25-(OH)_2D_2$ that was generated in vitro from authentic, crystalline 25-OHD₃. In addition, the data of Fig. 2 which illustrate the near equivalency of levels of the two generated sterols as assayed by the chick intestinal receptor system, indicate that the binding pro-

tein does not discriminate between them but rather binds $1\alpha,25-(OH)_2D_3$ and $1\alpha,25-(OH)_2D_2$ with approximately the same affinity.

In vitro generation of $1\alpha,25-(OH)_2D_3$. In the next experiment, a more direct approach was undertaken to generate $1\alpha,25-(OH)_2D_3$. Since the kidney is the sole location of the 1α -hydroxylase enzyme that produces the hormonal form of the vitamin, renal tissue from 4-wk-old, severely rachitic chicks (12 animals, plasma $Ca^{++} \leq 5.5$ mg%) was removed. Kidney homogenates were incubated in a phosphate buffer and NADPH generating system as previously described (2, 12). The reaction was initiated with 4,500 IU (292.5 nmol) crystalline $25-OHD_2$ and was allowed to proceed under air at $37^\circ C$ for 2 h; the generated dihydroxy-sterol was purified on silicic acid, Sephadex LH-20, and Celite and finally quantitated by ultraviolet absorption spectrophotometry. These identical conditions are routinely employed for the production of $1\alpha,25-(OH)_2D_3$ from $25-OHD_2$; it is reasonable that the substrate $25-OHD_2$ will produce $1\alpha,25-(OH)_2D_3$ in this system. Moreover, the sterol displayed a uv spectrum with a minimum at 228 nm and a maximum at 265 nm which is characteristic of $1\alpha,25-(OH)_2D$. In addition, the dihydroxy-metabolite migrated on Celite to the same position (fraction 14) as the in vivo-produced sterol of the previous experiment.

Competitive binding of $1\alpha,25-(OH)_2D_3$ and $25-OHD_2$. To verify that the target tissue receptor system efficiently binds $1\alpha,25-(OH)_2D_3$, the in vitro-generated sterol was added to the reconstituted cytosol-chromatin system and allowed to compete with [3H] $1\alpha,25-(OH)_2D_3$ for the receptor. Fig. 3A illustrates the competitive binding curves obtained when either $1\alpha,25-(OH)_2D_3$ or $1\alpha,25-(OH)_2D_2$ is the competing sterol. Results indicate that $1\alpha,25-(OH)_2D_3$ is approximately 1.3 times more efficient than the dihydroxyergocalciferol metabolite. Nevertheless, the assay receptor system can bind and therefore detect both the D_2 and D_3 forms of the hormone.

In the next experiment $25-OHD$ binding to the receptor was explored. Nonradioactive $25-OHD_3$ is approximately 500 times less effective than nonradioactive $1\alpha,25-(OH)_2D_3$ in the ability to displace [3H] $1\alpha,25-(OH)_2D_3$ from its intestinal receptor (18). Therefore, if cytosol-chromatin is incubated with the standard amount (360 pg) of [3H] $1\alpha,25-(OH)_2D_3$, a 500-fold excess (180 ng) of $25-OHD_3$ will result in 50% competition at the receptor (Fig. 3B). Since the dihydroxy- D_2 metabolite was capable of binding (Fig. 3A), the monohydroxy- D_2 metabolite ($25-OHD_2$) was also tested for its competitive ability. Fig. 3B illustrates that nanogram quantities of both $25-OHD_3$ and $25-OHD_2$ are capable of competing with picogram amounts of [3H] $1\alpha,25-(OH)_2D_3$ but that $25-OHD_3$ is approximately 1.4 times more efficient. This is consistent with the results of Fig. 3A, indicating that

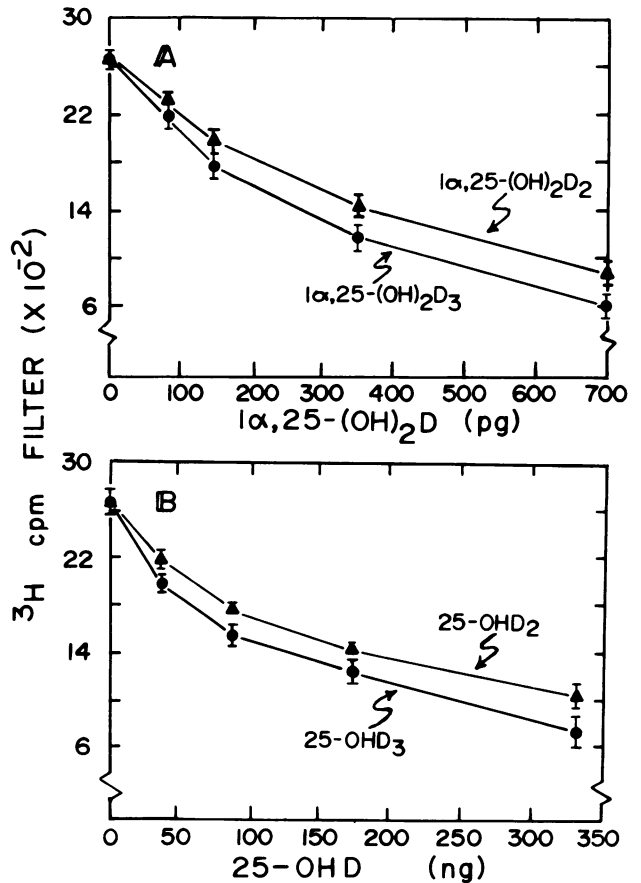


FIGURE 3 Competitive binding standard curves for $1\alpha,25-(OH)_2D_3$ or $1\alpha,25-(OH)_2D_2$ (A), and $25-OHD_3$ or $25-OHD_2$ (B). A sample of [3H] $1\alpha,25-(OH)_2D_3$ (360 pg; 6.5 Ci/mmol) was incubated with increasing amounts of non-radioactive sterol in the reconstituted cytosol-receptor system. The amount of bound tritiated compound (as determined by filtration) is plotted as a function of the amount of nonradioactive sterol in the incubation mixture. Each point represents the average of quadruplicate assays \pm SEM.

cholecalciferol metabolites bind slightly better than ergocalciferol metabolites. Therefore, standard competitive binding curves can be obtained for all four of the sterols of interest, and this allows for the measurement of these metabolites in plasma.

Isolation and measurement of plasma vitamin D metabolites. Before the circulating concentration of these metabolites can be measured by the competitive binding method, the plasma sample must first be purified to separate the sterols of interest and remove contaminating lipid. Fig. 1 is a schematic diagram depicting the purification process and the chromatographic options that are employed in the isolation of these biologically active vitamin D sterols from plasma. A single 20-ml plasma sample (with added radioactive tracers to quantitate purification yields) is processed in such a way that the

25-hydroxymetabolites are separated from the $1\alpha,25$ -dihydroxy metabolites on Sephadex LH-20 (Fig. 1). Each of the two groups are then purified on micro silicic acid columns using elution systems appropriate for the particular metabolite (see Methods). Final resolution of 25-OHD_3 from 25-OHD_2 and $1\alpha,25\text{-(OH)}_2\text{D}_3$ from $1\alpha,25\text{-(OH)}_2\text{D}_2$ is achieved by Celite liquid-liquid partition chromatography on $1 \times 35\text{-cm}$ columns (Fig. 1, pathways A and C). Subsequent radioreceptor assay of the separated sterols results in a complete metabolite profile of the four most biologically active forms of vitamin D in the circulation.

In many instances (see Discussion) it is not necessary to distinguish between the D_2 and D_3 metabolite concen-

trations. Consequently, a simplified version of the purification scheme has been developed that utilizes a "micro" ($0.8 \times 8.0\text{-cm}$) Celite column that does not resolve D_2 from D_3 metabolites (Fig. 1, pathways B and D). To demonstrate the inability of the micro-Celite system to separate the two hormonal sterols, rats, which apparently metabolize D_2 and D_3 equivalently, were raised on either vitamin D_2 or D_3 in a similar manner to the experiment illustrated in Fig. 2. After purification (as outlined in Fig. 1D) the average $1\alpha,25\text{-(OH)}_2\text{D}$ in the D_2 - and D_3 -raised rats was $18.8 \pm 2.0 \text{ ng}/100 \text{ ml}$ (SD) ($n = 3$; 30 total rats) and $17.1 \pm 3.0 \text{ ng}/100 \text{ ml}$ (SD) ($n = 6$; 60 total rats), respectively. Thus, the micro-Celite chromatography system is necessary to remove contaminating

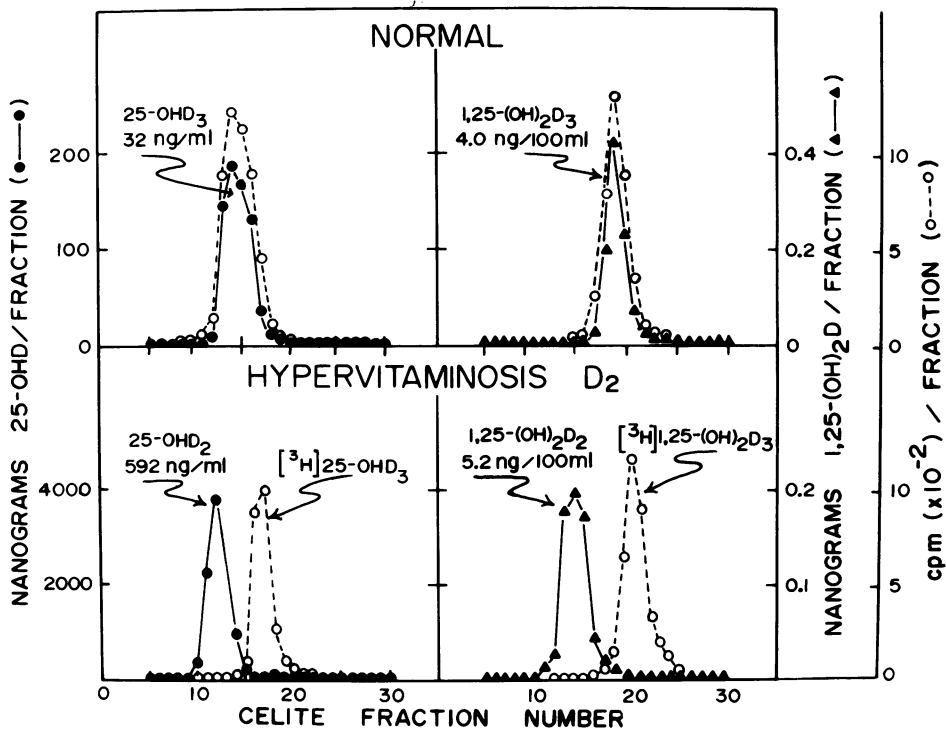


FIGURE 4 Celite resolution and radioligand receptor assay of D metabolites in normal subjects and in patient A with hypervitaminosis D. All Celite columns were $1 \times 35 \text{ cm}$ and 5-ml fractions were collected. The plasma from normals and a hypervitaminosis D patient was purified as outlined in Fig 1A and C and as described under Methods. The plasma from the normal subjects (four donors; 40 ml) yielded assayable 25-OHD_3 (●), which migrates with authentic $[^3\text{H}]25\text{-OHD}_3$ (○) in system I solvents (top left), and $1\alpha,25\text{-(OH)}_2\text{D}_3$ (▲) which migrates with $[^3\text{H}]1\alpha,25\text{-(OH)}_2\text{D}_3$ (○) in system II solvents (top right). The plasma (23 ml) from the hypervitaminosis D patient (patient A; see Methods) yielded assayable material that does not migrate with authentic $[^3\text{H}]25\text{-OHD}_3$ in system I solvents (lower left), or $[^3\text{H}]1\alpha,25\text{-(OH)}_2\text{D}_3$ in system II solvents (lower right). These assayable peaks (fractions 12 and 14, respectively) migrate to the exact positions of crystalline 25-OHD_2 and in vitro generated $1\alpha,25\text{-(OH)}_2\text{D}_2$ (see Results). Purification yields were as follows: pooled normal subjects = 49% 25-OHD_3 and 56% $1\alpha,25\text{-(OH)}_2\text{D}_3$; hypervitaminosis D_2 subject = 76% 25-OHD_2 and 60% $1\alpha,25\text{-(OH)}_2\text{D}_2$. In calculating the 25-OHD_2 and $1\alpha,25\text{-(OH)}_2\text{D}_2$ plasma concentrations the factors 1.4 and 1.3, respectively, are included since the assay standard curves are obtained using the respective D_3 metabolites (see text). Yields are assumed to be identical for D_2 and D_3 forms.

lipid from $1\alpha,25\text{-(OH)}_2\text{D}$ and permit valid radioreceptor assay (10), but the column yields a mixture of $1\alpha,25\text{-(OH)}_2\text{D}_2$ and $1\alpha,25\text{-(OH)}_2\text{D}_3$. This column greatly simplifies the final purification step before assay and allows for the routine processing of numerous samples to yield "total" 25-OHD and $1\alpha,25\text{-(OH)}_2\text{D}$ concentrations in plasma.

With the use of this technique, the biologically active metabolites of vitamin D have been measured in humans. Normal plasma $1\alpha,25\text{-(OH)}_2\text{D}$ in humans (78 subjects) is 3.3 ± 0.6 ng/100 ml (SD) or approximately 0.1 nM. Utilizing 2 SD in either direction from the average, we obtain a normal range of 2.1–4.5 ng/100 ml for 95% of all normals assayed. The concentration of 25-OHD in normal human plasma as measured by this assay is 25–40 ng/ml and this value correlates well with data obtained by other assay techniques (19–21).

Determination of D_2 vs. D_3 forms in the human and application of assay to hypervitaminosis D. The vitamin D metabolite assay, coupled with long Celite columns (Fig. 1, pathways A and C), was next used to monitor the plasma concentrations of 25-OHD₂, 25-OHD₃, $1\alpha,25\text{-(OH)}_2\text{D}_2$, and $1\alpha,25\text{-(OH)}_2\text{D}_3$ in healthy human subjects and patients with varying degrees of vitamin D intoxication (Figs. 4 and 5). All of the assayable 25-OHD in normal human plasma migrates with authentic [³H] 25-OHD₃ at a concentration of 32 ng/ml (Fig. 4, top left); 25-OHD₂ was undetectable.² When the $1\alpha,25\text{-(OH)}_2\text{D}$ concentration was examined (Fig. 4, top right) all of the assayable material migrated with [³H] $1\alpha,25\text{-(OH)}_2\text{D}_3$; $1\alpha,25\text{-(OH)}_2\text{D}_2$ was undetectable² in these normal volunteers. A circulating level of 4.0 ng/100 ml was obtained when the column peak fractions were assayed. Therefore, Celite preparative chromatography and the radioreceptor assay has allowed for the measurement of both 25-OHD and $1\alpha,25\text{-(OH)}_2\text{D}$ in human plasma and demonstrates that greater than 90%² of the circulating concentration in the normal subject is in the form of cholecalciferol metabolites.

In contrast to these normal values, the assayed plasma from a hypervitaminosis D patient (Methods, subject A) contained 592 ng/ml 25-OHD (Fig. 4, lower left), and all of the assayable material migrated on the Celite column (fractions 10–15) as 25-OHD₂. Similarly, the only measurable hormone concentration in the plasma of this hypervitaminosis D patient was also the ergocalciferol metabolite; the $1\alpha,25\text{-(OH)}_2\text{D}_2$ concentration was deter-

²The sensitivity of the dual assay is 17 pg of $1\alpha,25\text{-(OH)}_2\text{D}$ hormone (10) and 8.5 ng of precursor 25-OHD. With these values, if a 20-ml plasma sample is purified to a 50% sterol yield, it can be calculated that >90% of the circulating vitamin D metabolites in a normal (Tucson) human will be in the D_3 form. This value correlates well with the results of Haddad and Hahn (22) who measured 25-OHD in normal (St. Louis, Mo.) subjects.

mined to be 5.2 ng/100 ml of plasma and $1\alpha,25\text{-(OH)}_2\text{D}_3$ was undetectable (Fig. 4, lower right). This value is only slightly above the normal human range of 2.1–4.5 ng/100 ml, whereas the assay value for 25-OHD of 592 ng/ml represents more than a 15-fold increase over the normal human subjects. The plasma from two additional patients with postsurgical hypoparathyroidism, who were receiving large doses of vitamin D₂ (patients B and C) was also studied (Fig. 5). The circulating concentration of 25-OHD was elevated 10- to 16-fold above normal values (Fig. 5, left panels) while the $1\alpha,25\text{-(OH)}_2\text{D}$ concentration only slightly increased (Fig. 5, right panels). It is possible that the mass action effect of the elevated 25-OHD substrate on the renal 25-hydroxy- 1α -hydroxylase may account for the slight increase seen in the hormone's concentration. In any case, the results in Figs. 4 and 5 indicate that vitamin D-intoxicated patients with intact kidneys maintain near normal hormone levels in the form of $1\alpha,25\text{-(OH)}_2\text{D}_2$, but display highly elevated circulating concentrations of 25-OHD₂.

DISCUSSION

Elucidation of the chick intestinal cytoplasmic and nuclear receptor system for $1\alpha,25\text{-(OH)}_2\text{D}_3$ by Brumbaugh and Haussler (6–8) has allowed for the development of a competitive binding radioreceptor assay for this hormone (9, 10). The value obtained by this assay for the circulating concentration of $1\alpha,25\text{-(OH)}_2\text{D}$ in normal humans (0.1 nM; see reference 10) has recently been confirmed by Hill et al. (23) using a bioassay. However, several questions remained regarding the applicability of the radioreceptor assay to the measurement of active vitamin D metabolites in animals and patients. Most notable of these was the uncertainty as to whether $1\alpha,25\text{-(OH)}_2\text{D}_2$ was also detected by the radioreceptor assay. Haddad and Hahn (22) have shown that patients treated with therapeutic doses of vitamin D₂ have a significant plasma concentration of 25-OHD₂. Since many human disorders such as hypoparathyroidism, renal osteodystrophy, and vitamin D-resistant rickets are routinely treated with ergocalciferol, the measurement of $1\alpha,25\text{-(OH)}_2\text{D}_2$ is critical to the assessment of the vitamin D status in these cases. Because the binding system utilized for the radioreceptor assay is derived from the chick intestine and the chick is known to discriminate against the D_2 vitamins (16), it was essential to determine directly the effectiveness of $1\alpha,25\text{-(OH)}_2\text{D}_2$ binding to the intestinal receptor. Furthermore, in the purification scheme of Brumbaugh et al. (10) it was not known whether $1\alpha,25\text{-(OH)}_2\text{D}_2$ was resolved from $1\alpha,25\text{-(OH)}_2\text{D}_3$. Thus, $1\alpha,25\text{-(OH)}_2\text{D}_2$ could have been either excluded completely from measurement by the chromatography or quantitated in combination with the $1\alpha,25\text{-(OH)}_2\text{D}_3$.

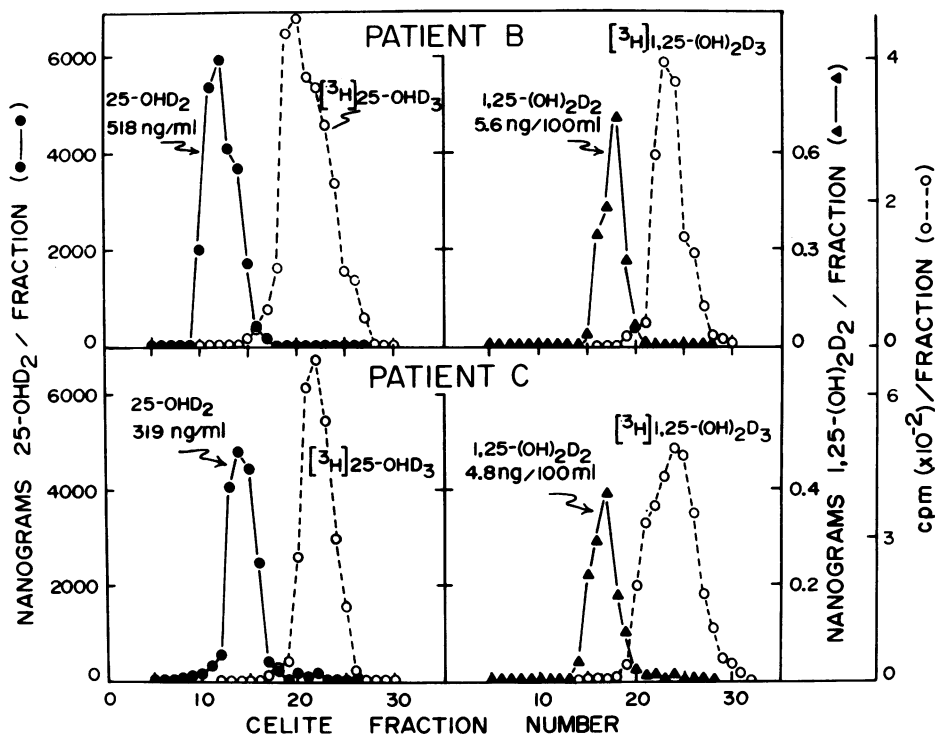


FIGURE 5 Celite resolution and radioligand receptor assay of D metabolites in two patients with postsurgical hypoparathyroidism treated with large doses of vitamin D₂. The assayable material (●) from an additional D₂-intoxicated subject (patient B) as well as the material from a patient with normal serum calcium on a high dose of vitamin D₂ (patient C; see Methods) does not migrate with authentic [³H]25-OHD₂ in system I solvents (left panels), or with [³H]1,25-(OH)₂D₃ in system II solvents (right panels). The plasma was processed according to Fig. 1 (pathways A and C) and concentrations calculated as described in the legend to Fig. 4. Celite columns were 1 × 35 cm and 5-ml fractions were collected. Plasma volume and purification yields were as follows: patient B (top panels), 22 ml, 49.5% 25-OHD₂, and 68% 1,25-(OH)₂D₃; patient C (lower panels), 22 ml, 78.5% 25-OHD₂, and 43.5% 1,25-(OH)₂D₃.

The present results (Figs. 2 and 3) clearly demonstrate that the chick receptor system binds 1,25-(OH)₂D₃ with an efficiency approximating that of 1,25-(OH)₂D₂ and sufficient to allow quantitation of this ergocalciferol metabolite in rats and man (Figs. 2, 4, and 5). Moreover, 1 × 35-cm Celite liquid-liquid partition columns are capable of separating 1,25-(OH)₂D₂ from 1,25-(OH)₂D₃. This represents the first reported chromatographic resolution of these two hormonal sterols.⁸ Therefore, to determine separately 1,25-(OH)₂D₂ and 1,25-(OH)₂D₃ in a given plasma sample, a 1 × 35-cm Celite column must be used in the final chromatographic step before the radioligand receptor assay. Since Brumbaugh et al. (10) employed micro-Celite columns similar to those used in some of the current experiments (Fig. 1B and D) and these small columns do not resolve 1,25-

(OH)₂D₂ from 1,25-(OH)₂D₃, the original radioreceptor assay for 1,25-(OH)₂D₃ actually measures total 1,25-(OH)₂D.

Supportive information concerning the possible mechanism (24) of discrimination by the chick against the D₂ vitamins is also obtained in the current study. Both 25-OHD₂ and 1,25-(OH)₂D₂ bind to the intestinal receptor with slightly lower affinity than their D₃ counterparts (Fig. 3). While this is consistent with a lower biologic potency of vitamin D₂ in the chick, the magnitude of the binding difference (1.3- to 1.4-fold) is markedly less than the 10-fold difference in biologic activities between vitamin D₂ and D₃ in the chick (16). Also, Belsey et al. (24) have observed that the chick plasma binding protein for 25-OHD₂ favors this sterol over 25-OHD₃ by approximately a factor of 10. This discrimination by the plasma binding protein can explain the relative ineffectiveness of vitamin D₂ in the chick, although other factors, such as an altered rate of vitamin D₂ metabolism, may play a part. Clearly, only a small portion of the

⁸ Since the original submission of this manuscript, G. Jones and H. F. DeLuca reported (*J. Lipid Res.* 16: 448-453, 1975) the resolution of 1,25-(OH)₂D₂ and 1,25-(OH)₂D₃ via high-speed liquid chromatography.

discrimination against D_2 can be accounted for by the slightly lower affinity of D_2 metabolites for the intestinal receptor system.

Another extension of the radioreceptor assay for $1\alpha,25-(OH)_2D_3$ which is reported here is the application of this binding system to the measurement of circulating $25-OHD_3$ and $25-OHD_2$. As reported previously (18), this receptor will bind $25-OHD_3$ but only when this sterol is present in concentrations in 500-fold excess of that required for hormone binding. Although the competitive binding system is 500-fold less sensitive for $25-OHD_3$ compared to $1\alpha,25-(OH)_2D_3$ (Fig. 3), this assay becomes possible because $25-OHD_3$ circulates in approximately 1,000-fold greater concentrations than $1\alpha,25-(OH)_2D_3$ in man. Other workers have successfully quantitated $25-OHD$ by competitive binding methods utilizing several proteins. Belsey et al. (19) have reported a sensitive, competitive binding assay for measuring both vitamin D and $25-OHD$ which uses a specific protein in rat serum. More recently, this group has developed a rapid system (without chromatography) for measuring $25-OHD$ in plasma (21). Haddad and Chyu (20) have published a sensitive competitive binding assay for $25-OHD$ using a specific protein from rat kidney cytosol. Both of the latter assays are approximately 40-fold more sensitive than the radioreceptor assay for $25-OHD$ reported here, and they require considerably less sample volume and preparation. However, the use of intestinal receptor to measure $25-OHD$ has certain distinct advantages. For instance, $25-OHD_2$ as well as $25-OHD_3$ (after chromatographic resolution) can be quantitated separately with this binding protein since both sterols bind with similar affinities (Fig. 3B). Yet the most important consideration regarding this assay lies not in its insensitivity in measuring $25-OHD$, but in its ability to quantitate the four major circulating cholecalciferol and ergocalciferol metabolites with a single competitive binding system.

The ability to monitor these biologically active metabolites in plasma may prove important in the understanding of many vitamin D-related diseases. Of particular interest in this regard is hypervitaminosis D or vitamin D intoxication. Brumbaugh and Haussler (25), based upon the fact that $25-OHD_3$ (in higher concentrations) will bind to the $1\alpha,25-(OH)_2D_3$ intestinal receptor, originally hypothesized that $25-OHD$ may be the toxic agent in hypervitaminosis D. Recently, it has been reported by Counts et al. (26) that vitamin D intoxication and hypercalcemia can occur in the anephric human; the serum concentration of $25-OHD$ in their patient was nearly 28 times larger than the normal circulating concentration of this metabolite. Since $1\alpha,25-(OH)_2D_3$ is produced exclusively in renal tissue (3), and since anephric human subjects have undetectable $1\alpha,25-(OH)_2D$ in the plasma (27), it is apparent that the hypercalcemia in

this patient was probably due to the markedly elevated $25-OHD$ concentrations in the plasma. In the present study (Figs. 4 and 5), we measured the $25-OHD$ in two hypervitaminosis D patients with intact kidneys and in one patient (normal calcium) being treated with a large dose of vitamin D_2 . Our results confirm the finding that $25-OHD$ is considerably increased in D intoxication. In addition, we found that the $1\alpha,25-(OH)_2D$ concentration is near normal in these patients (Figs. 4 and 5) when the kidneys are present. Although $1\alpha,25-(OH)_2D_3$ is the physiologic hormone regulating calcium translocation, a 100- to 500-fold greater concentration of precursor $25-OHD_3$ will mediate (in vitro) bone calcium resorption (5) and intestinal receptor binding (25). Therefore, the causative agent in hypervitaminosis D is probably the highly elevated $25-OHD$, rather than the slightly elevated $1\alpha,25-(OH)_2D$ hormone. This conjecture is supported by the findings of Shen et al. (28) that patients with idiopathic hypercalciuria have similar (slightly elevated) $1\alpha,25-(OH)_2D$ levels as we presently report for D-intoxicated patients, but are able to maintain a normal serum calcium concentration. It should be mentioned that these data do not rule out the possibility that some other vitamin D metabolite such as $1,24,25$ -trihydroxyvitamin D (29) might be involved in this disorder. Nevertheless, it seems reasonable to conclude that the hypercalcemia seen in D intoxication is not a result of abnormal plasma levels of $1\alpha,25-(OH)_2D$, but is caused by an excessive circulating concentration of $25-OHD$.

It is of interest that there are undetectable ergocalciferol metabolites in normal Tucson Caucasian adults who undoubtedly ingest vitamin D_2 in their diet. Haddad and Hahn (22), using a more sensitive assay for measuring $25-OHD$ in serum, have reported that St. Louis adults exhibit approximately 90% of their circulating $25-OHD$ as the cholecalciferol metabolite. The present report also confirms the finding (22) that $25-OHD_2$ is the predominant form when a patient is receiving large doses of ergocalciferol, and it extends this work to include the measurement of $1\alpha,25-(OH)_2D$. It is possible that preferential metabolism of the two forms of vitamin D occur under different physiological conditions, however further assessment of the metabolic disposition of natural and synthetic sources of vitamin D is required.

Vitamin D_2 and D_3 metabolites are not equivalent in this receptor system, the D_3 forms being 1.3–1.4 times more potent. Therefore, when rapid micro-Celite purification is used, equivalent displacement of radioactive $1\alpha,25-(OH)_2D_3$ by a typical sample might represent one part vitamin D_3 metabolite, 1.3–1.4 parts vitamin D_2 metabolite, or a variable combination of the two sterols. Nevertheless, meaningful clinical information has been obtained utilizing this technique for total $1\alpha,25-(OH)_2D$ measurement. Abnormal circulating levels of $1\alpha,25-$

(OH)₂D have been found in numerous human disorders including untreated hypoparathyroidism (15), pseudo-hypoparathyroidism (15), primary hyperparathyroidism (30), idiopathic hypercalciuria (28), and patients with chronic renal failure (9). Further clinical insights await refinement and simplification of the radioligand receptor assay, especially the advent of higher specific activity [³H] 1α,25-(OH)₂D₃ to allow for reduced size of plasma samples and less arduous chromatographic purification requirements.

Note added in proof. We have recently confirmed the structure of the in vitro produced 1α,25-(OH)₂D₃ used in this study (see Results) by direct-probe mass spectrometry.

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