Long-term vitamin D₃ supplementation is more effective than vitamin D₂ in maintaining serum 25-hydroxyvitamin D status over the winter months

Victoria F. Logan¹, Andrew R. Gray², Meredith C. Peddie¹, Michelle J. Harper¹ and Lisa A. Houghton¹*

¹Department of Human Nutrition, University of Otago, PO Box 56, Dunedin 9054, New Zealand
²Department of Preventive and Social Medicine, University of Otago, PO Box 913, Dunedin 9054, New Zealand

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Abstract

Public health recommendations do not distinguish between vitamin D₂ and vitamin D₃, yet disagreement exists on whether these two forms should be considered equivalent. The objective of the present study was to evaluate the effect of a daily physiological dose of vitamin D₂ or vitamin D₃ on 25-hydroxyvitamin D (25(OH)D) status over the winter months in healthy adults living in Dunedin, New Zealand (latitude 46°S). Participants aged 18–50 years were randomly assigned to 25 mg (1000 IU) vitamin D₃ (n = 32), 25 mg (1000 IU) vitamin D₂ (n = 31) or placebo (n = 32) daily for 25 weeks beginning at the end of summer. A per-protocol approach, which included 90% supplement compliance, was used for all analyses. Serum 25-hydroxyvitamin D₃ (25(OH)D₃), 25-hydroxyvitamin D₂ (25(OH)D₂) and parathyroid hormone (PTH) were measured at baseline and at 4, 8, 13 and 25 weeks. Geometric mean total serum 25(OH)D concentrations (sum of 25(OH)D₂ and 25(OH)D₃) at baseline was 80 nmol/l. After 25 weeks, participants randomised to D₂ and placebo had a significant reduction in serum 25(OH)D₃ concentrations over the winter months compared with vitamin D₃-supplemented participants (both \( P < 0.001 \)). Supplementation with vitamin D₂ increased serum 25(OH)D₂ but produced a 9 (95% CI 1, 17) nmol/l greater decline in the 25(OH)D₃ metabolite compared with placebo (\( P < 0.036 \)). Overall, total serum 25(OH)D concentrations were 21 (95% CI 14, 30) nmol/l lower in participants receiving vitamin D₂ compared with those receiving D₃ (\( P < 0.001 \)), among whom total serum 25(OH)D concentrations remained unchanged. No intervention-related changes in PTH were observed. Daily supplementation of vitamin D₃ was more effective than D₂; however, the functional consequence of the differing metabolic response warrants further investigation.

Key words: Vitamin D₂; Vitamin D₃; Serum 25-hydroxyvitamin D; Parathyroid hormone

During recent years, a number of studies have been performed in human subjects to investigate the relative potencies of two commonly used forms of vitamin D, ergocalciferol (vitamin D₂) and cholecalciferol (vitamin D₃). Vitamin D₃, the form produced in the skin of humans after exposure of 7-dehydrocholesterol to sunlight, is found either naturally in animal products such as fatty fish and cod-liver oil, or added as a fortificant to foods. Commercial production of vitamin D₃ is performed by UV irradiation of 7-dehydrocholesterol extracted from the lanolin of sheep wool. Vitamin D₂ is made either naturally or synthetically from the UV irradiation of ergosterol obtained from yeast, and added to foods. Structurally, vitamin D₂ differs from vitamin D₃ in that its side chain has an added methyl group on carbon 24 and an additional double bond between carbons 22 and 23. These structural differences, however, do not prevent the metabolic activation of the two forms. Before exerting their biological effects, both vitamin D₂ and vitamin D₃ must undergo 25-hydroxylation to form 25-hydroxyvitamin D₂ (25(OH)D₂) or 25-hydroxyvitamin D₃ (25(OH)D₃), respectively, followed by \( \alpha \)-hydroxylation to produce the respective biologically active metabolites 1,25-dihydroxyvitamin D (1,25(OH)₂D).

With the use of appropriate assay systems to detect the 25(OH)D₂ metabolite, several randomised trials using large oral dose preparations ranging from 1250 to 7500 mg (50 000–300 000 IU) have suggested that vitamin D₂ is less effective in elevating or maintaining total serum 25-hydroxyvitamin D (25(OH)D) levels in healthy adults (3,6,9,10), whereas the few studies which have directly compared daily administered low-dose preparations of vitamin D₃ and vitamin D₂ have yielded inconsistent results (1,2,5,7–9). In addition to varying dose and dosing regimens, these latter studies have been

Abbreviations: 1,25(OH)₂D, 1,25-dihydroxyvitamin D; 25(OH)D, 25-hydroxyvitamin D; PTH, parathyroid hormone.

* Corresponding author: L. A. Houghton, fax +64 3 479 7958, email lisa.houghton@otago.ac.nz
limited by short study duration (4–12 weeks), small participant numbers and have included confounding by other variables such as BMI and contribution of vitamin D from cutaneous production, fortified foods and supplemental sources.

In an attempt to address some of the limitations of previous research, we conducted a randomised, double-blind, placebo-controlled trial to evaluate the efficacy of a daily physiological dose of vitamin D2 and vitamin D3 in healthy-weight adults for a 25-week period beginning at the end of summer. We specifically investigated the time course of 25(OH)D2 and 25(OH)D3 serum levels and the concomitant variations in parathyroid hormone (PTH) concentration after a daily initiation of 25 μg (1000 IU) vitamin D2 or D3 supplementation. The study was conducted in New Zealand at a latitude of 46°S where food fortification of vitamin D is not mandated nor common.

Methods

Participants

A total of ninety-five healthy, adult women and men aged 18–50 years, inclusive, were recruited from the staff and student population at the University of Otago, Dunedin, New Zealand (latitude 46°S), and from the community through advertisements in the local newspaper. This region has a temperate climate with a summer mean temperature of 14°C and a winter mean temperature of 5°C with mean sunshine hours in the winter ranging from 98 to 122 h/month(11). The nadir in UV radiation occurs midwinter (July) after the peak 6 months earlier in summer (December). Participants were excluded if they had a BMI $\geq 25$ kg/m2, had reported granulomatous conditions, gastrointestinal disease, liver or kidney disease, or diabetes, were taking medications that might affect vitamin D metabolism (e.g. anticonvulsants, steroids in any form or barbiturates), or were planning to travel during the next 14 d. Participants were to return to the clinic at weeks 4, 8, 12 and 24 to provide non-fasting blood samples at a standard time in the day between 08.00 and 11.00 hours. The average number of days from baseline for each targeted study week was as follows: 4 weeks (28–3 d); 8 weeks (56–0 d); 12 weeks (92–3 d, equivalent to 13 weeks); 24 weeks (175 d, equivalent to 25 weeks). At each subsequent visit, participants were asked questions relating to the use of prescription medications and travel outside of the surrounding area since the last study visit. Measurements of height and weight were taken once again at the completion of the study. Compliance was assessed using cumulative pill counts at the end of the study. The blinding of the arms of the study was maintained for all researchers, including the statistician, until the final data analyses were completed. The present study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human participants were approved by the Human Ethics Committee at the University of Otago, Dunedin, New Zealand. Written informed consent was obtained from all participants. The study was registered at www.actr.org.au as ACTRN12609000273280.

Study design

The study was designed as a 24-week randomised, double-blind, placebo-controlled trial. At the baseline study visit, a non-fasting venous blood sample was collected and participants completed a brief self-administered sociodemographic and health questionnaire. They were asked to report the use of any vitamin D- and Ca-containing supplements over the past 3 months and current prescription medications (including oral contraceptives). Height was measured to the nearest 0.1 cm using a calibrated self-made stadiometer, and weight was measured to the nearest 0.1 kg using a calibrated platform digital scale (Seca). Lastly, participants were given detailed verbal and written instructions on how to collect diet records to assess dietary Ca intakes, and were asked to record all foods and beverages consumed for five weekdays and two weekend days within the next 14 d. Participants were then randomly assigned to receive one of three daily tablets labelled to contain 25 μg (1000 IU) vitamin D2, 25 μg (1000 IU) vitamin D3 or a placebo. The vitamin D and placebo supplements were manufactured as hard tablets by New Zealand Nutritional Limited, and were identical in appearance. The tablet content was independently verified on 19 August 2009 (New Zealand Laboratory Services Limited), and the actual amounts labelled to provide 25 μg (1000 IU) of vitamin D2 and vitamin D3 were 32 μg (1295 IU) (CV 6 %) and 28 μg (1110 IU) (CV 6 %), respectively. Randomisation of participants was conducted with a computer-generated block randomisation scheme stratified by sex.

All the participants began the study between 6 March and 13 March 2009 (early autumn) and completed the study between 27 August and 14 September 2009 (late winter).

Biochemical analyses

Serum 25(OH)D2 and 25(OH)D3 concentrations were determined by isotope dilution liquid chromatography–tandem MS on a API 3200 instrument (Applied Biosystems) according to the method of Maunsell et al.(12). The limit of quantification for the assay was <5 nmol/l for both metabolites. Values for serum 25(OH)D reported as less than 5 nmol/l were considered to be zero. To assess accuracy and inter-assay variability, we prepared an internal quality control by adding 25(OH)D2 and 25(OH)D3 to a pooled serum sample and ran an external quality control serum material (UTAK Laboratories) with a verified 25(OH)D2 value of 24.2 nmol/l (mean 23.3 (SD 1.2) nmol/l; CV 5.2 %) and a 25(OH)D3 value of 27.5 nmol/l (mean 25.9 (SD 2.4) nmol/l; CV 9.3 %). For the internal quality control, the inter-assay CV for 25(OH)D2 and 25(OH)D3 were 3.8% at 69.8 nmol/l and 4.5% at 83.6 nmol/l, respectively. Intact PTH was measured by an automated electromulunescence immunoassay (Elecys 1010® Roche Diagnostics). Manufacturer-provided controls (Elecys Preci-Control Bone 1, 2 and 3) were analysed with each reagent kit. The means and CV (%) for the three controls were 45.2
(SD ±2.8) pg/ml and 6.1%, 155.7 (SD ±10.3) pg/ml and 6.6%, and 650.7 (SD ±33.5) pg/ml and 5.2%, respectively, and were within the range of the results provided by the manufacturer. Serum samples from each subject (for all clinic visits) were analysed together in the same batch.

Statistical analysis

A per-protocol approach, which included all participants ≥90% compliant with the study supplement, was used for all analyses. Additionally, an intent-to-treat analysis that included all randomly assigned subjects irrespective of compliance was performed. The intent-to-treat results were only slightly different from the per-protocol results and the differences were not clinically significant (see Table S1, available online). Therefore, only the per-protocol results are presented, unless noted otherwise.

The original study design included a sample size calculation based on a planned intention-to-treat analysis before the decision to examine the efficacy aspects of supplementation in the primary analysis reported herein. As such, there is no power analysis reported for the per-protocol study, and the power to detect practically important effect sizes is reflected in the widths of the CI included in the results.

The outcome variables were total serum 25(OH)D, 25(OH)D3, and PTH concentration. Mixed-effects linear regression models were used to evaluate the fixed effect of the intervention on total serum 25(OH)D, serum 25(OH)D3 and PTH including a random subject effect to account for the repeated measures within subjects and controlled for baseline levels. Models with PTH as an outcome variable also included dietary Ca. Natural log transformations were used where this improved residual normality and/or homoscedasticity. The difference in changes between the groups was assessed using combinations of treatment group effects and group × time interactions. Stata (version 11.0; Stata Corporation) was used for all analyses and a two-sided $P<0.05$ was considered statistically significant in all cases.

Results

Of the ninety-five participants recruited and enrolled in the study, eighty-five completed the intervention trial (vitamin D3, thirty out of the thirty-two enrolled; vitamin D2, twenty-five out of thirty-one; placebo, thirty out of thirty-two). Reasons for discontinuing the intervention were as follows: lack of time (n = 3); personal reason (n = 1); unspecified health reasons (n = 4); exacerbation of eczema (n = 2). An additional twenty-four participants were excluded from the per-protocol analysis for compliance <90% (vitamin D3, n = 6; vitamin D2, n = 12; placebo, n = 5) and compliance unknown (did not return pill bottle) (vitamin D3, n = 1), resulting in a total of sixty-one participants who completed the study with known supplement compliance ≥90%: 25 μg (1000 IU) vitamin D3/d, n = 24, 25 μg (1000 IU) vitamin D2/d, n = 13; placebo, n = 25. At baseline, the mean age of participants included in the analysis was 29 years (range 18–50 years) and the majority of the participants were New Zealand Europeans (84%), well educated with at least some tertiary education (89%), and female (79%). All of the participants were classified as normal weight (BMI 18–24.9 kg/m2) with a mean BMI of 22.7 (SD ±2.3) kg/m2. Median dietary Ca intake (fifty-three out of sixty-one participants who completed baseline diet records) was 869 (25th and 75th percentile 696, 1029) mg/d. There were eight (14%) participants who regularly took a Ca-containing supplement. There was no evidence of a significant difference in dietary Ca among the three groups ($P=0.98$). Total serum 25(OH)D concentrations (i.e. the sum of 25(OH)D2 and 25(OH)D3) at baseline ranged from 40 to 136 nmol/l with the geometric mean serum total 25(OH)D of

![Fig. 1](https://www.cambridge.org/core) Mean serum 25-hydroxyvitamin D2 (25(OH)D2, —-) and 25-hydroxyvitamin D3 (25(OH)D3, ——) concentrations over time in healthy adult participants treated with (a) 25 μg/d vitamin D2, (b) 25 μg/d vitamin D3 or (c) placebo over a 6-month intervention (n = 61). Values are means, with 95% CI represented by vertical bars.
Table 1. Per-protocol analysis of total serum 25-hydroxyvitamin D (25(OH)D) and parathyroid hormone concentrations at baseline and over the 25-week intervention period (Geometric means and 95 % confidence intervals)

<table>
<thead>
<tr>
<th>Measurement and treatment groups</th>
<th>Total serum 25(OH)D (nmol/l)</th>
<th>Parathyroid hormone (pg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>80 (SD 18)</td>
<td>54.7 ± 0.4</td>
</tr>
<tr>
<td>Week 4</td>
<td>78 (SD 17)</td>
<td>53.1 ± 0.8</td>
</tr>
<tr>
<td>Week 8</td>
<td>76 (SD 16)</td>
<td>51.2 ± 0.7</td>
</tr>
<tr>
<td>Week 13</td>
<td>74 (SD 15)</td>
<td>50.3 ± 0.6</td>
</tr>
<tr>
<td>Week 25</td>
<td>72 (SD 14)</td>
<td>49.4 ± 0.5</td>
</tr>
</tbody>
</table>

Estimated change after 25 treatment groups

- Total serum 25(OH)D (nmol/l) adjusted for baseline concentration:
  - 25(OH)D3: 51 (SD 14, 36) nmol/l
  - 25(OH)D2: 44 (SD 13, 36) nmol/l

- Parathyroid hormone (pg/ml) adjusted for baseline concentration:
  - 25(OH)D3: 37.5 (SD 14, 29) pg/ml
  - 25(OH)D2: 21 (SD 14, 29) pg/ml

Discussion

The present results show that a daily intake of 25 μg (1000 IU) vitamin D₃ is more effective than 25 μg (1000 IU) vitamin D₂ in maintaining serum 25(OH)D concentration during the autumn and winter months. In New Zealand (latitude ranging from 35°S to 47°S), very few foods are fortified with vitamin D, and the relative contribution of dermal production of vitamin D₃ is markedly diminished during the winter months. Of the unsupplemented (placebo) participants, 84 % had low vitamin D status (< 50 nmol/l). To our knowledge, this is the first study comparing vitamin D₃ and D₂ by mapping the time course of serum 25(OH)D from the summertime peak through to the autumn and winter months.
wintertime nadir. As expected, total serum 25(OH)D concentrations decreased substantially among the present study participants assigned to the placebo group over the course of the study, whereas a daily intake of 25 μg (1000 IU) vitamin D3 was efficacious in maintaining summertime serum 25(OH)D levels. In contrast, while participants assigned to the vitamin D2 group exhibited significantly higher total serum 25(OH)D levels than the placebo group, concentrations were 21 nmol/l lower (equivalent to 28% of the baseline mean) at the end of the study relative to the vitamin D3 group. Furthermore, the greater fall in 25(OH)D3 levels observed in the D2-supplemented participants compared with placebo suggests a more rapid metabolism or clearance of circulating 25(OH)D4 following D2 supplementation, which may partly explain the inability of this form to maintain the total serum 25(OH)D levels.

Previous studies employing higher-dosage regimens ranging from 100 μg/d (4000 IU/d) to a single dose of 7500 μg (300 000 IU) have consistently reported a substantial discrimination in favour of vitamin D3 (3–5,7,9,10), while limited evidence generated from studies using lower physiological daily doses have argued that D2 and D3 are essentially equivalent (5,8). Holick et al. (5) provided the first published evidence of the effective equivalence of the two forms in human subjects in a randomised, placebo-controlled trial demonstrating that serum 25(OH)D levels increased to the same extent in participants receiving 25 μg (1000 IU) daily as vitamin D2, vitamin D3 or a combination of 12.5 μg (500 IU) vitamin D2 and 12.5 μg (500 IU) vitamin D3. These findings suggested that the pharmacokinetic parameters of vitamin D2 and vitamin D3 change with increasing dose such that low doses of D2 and D3 appear equivalent while higher doses of D2 are less effective than D3. However, Heaney et al. (10) have argued that at lower doses, the increase in serum 25(OH)D would be relatively small and thus not sufficient to allow detection of differences between the two forms due to the combined effects of analytical and biological variability of serum 25(OH)D. Participants in Holick’s study (5) were generally obese (mean BMI 30 kg/m²), which may have an effect on the outcome measure of total serum 25(OH)D, and nearly 40% (six out of sixteen) of the participants assigned to the D2 group were taking a 10 μg (400 IU) vitamin D2-containing supplement during the time period of the study. We sought to avoid the effects of potential predictors in the present study by excluding participants with a BMI greater than or equal to 25 kg/m² and prohibiting the use of vitamin D-containing supplements during the study. Although we did not measure background dietary vitamin D intakes from food sources, the absence of widespread fortification of food with vitamin D in New Zealand makes it unlikely that the present results were confounded by dietary intake from fortified food sources. Moreover, the serum 25(OH)D assay detection limit of 10 nmol/l in Holick’s study was high, and values for serum 25(OH)D less than 10 nmol/l were obtained by subtracting 25(OH)D3 from the total 25(OH)D. This method employed to quantify serum 25(OH)D2 levels may have led to an overestimation of actual concentrations. In contrast, our assay was more sensitive with a non-detectable serum 25(OH)D2 level of less than 5 nmol/l. We also conservatively assumed a value of zero for any 25(OH)D reported as <5 nmol/l.

More recently, Binkley et al. (9) evaluated daily administration of 40 μg (1600 IU) of vitamin D2 and D3 and concluded that vitamin D3 was significantly more effective than D2 on the basis of a greater absolute increase in serum 25(OH)D levels for those participants treated with vitamin D3 (23 nmol/l) compared with D2 (15 nmol/l). However, mean baseline 25(OH)D levels in the D2 participants in the present study were higher than the D3 participants, and there was no evidence of a significant difference in mean 25(OH)D levels after 12 months of intervention (97.5 nmol/l in the D3 group when compared with 95.3 nmol/l in the D2 group). The present study is therefore the first intervention, to our knowledge, to clearly demonstrate that long-term administration of a daily physiological dose of D2 produces a substantially larger effect than D3 in a healthy adult population. The more rapid metabolism of vitamin D2 than D3 could reflect the lower affinity of serum 25(OH)D2 for vitamin D-binding protein than 25(OH)D3 (i.e. shorter circulating half-life) and/or the increased affinity of 25(OH)D2 for the 24-hydroxylase enzyme (i.e. greater rate of catabolism) (13,14). Furthermore, the present findings of a greater decline in serum 25(OH)D3 levels in the D2-treated participants than in the placebo group have also been previously reported in other studies ranging from 25 μg (1000 IU)/d to 1250 μg (50 000 IU) single and weekly dose regimens (3,7,10). It has been proposed that an up-regulation in mechanisms required to metabolise vitamin D2 and its metabolites may increase the metabolic degradation of circulating 25(OH)D2 levels (3).

Despite the differential response of serum 25(OH)D to vitamin D2 and D3, there was no evidence of a difference in PTH concentrations between the treatment groups, which raises the more important question of whether the ingestion of D2 v. D3 makes any functional difference. We did not measure the active form of vitamin D, 1,25(OH)2D, and thus it is not known whether the lower level of circulating 25(OH)D observed in our D2-treated participants would result in lower production of the dihydroxylated form. The kidney is the major site of production of 1,25(OH)2D, and adequate production of this metabolite is dependent on the level of the serum 25(OH)D precursor and the 25(OH)D-1α-hydroxylase or cytochrome P450B1 (CYP27B1) enzyme, which converts 25(OH)D to 1,25(OH)2D (15,16). The expression of renal CYP27B1 is tightly regulated and plays an essential role in maintaining Ca and phosphate homeostasis. When serum 25(OH)D levels fall, there is a rise in PTH, which stimulates CYP27B1 enzyme activity (15). Given the strong interdependence of vitamin D and Ca, it is likely that the relatively high dietary Ca intakes in the present study population may have suppressed the rise in serum PTH that typically accompanies declining 25(OH)D concentrations (17–19). As a result, renal synthesis of 1,25(OH)2D may not be increased appropriately. Although knowledge of the regulation of CYP27B1 expression in extra-renal tissues such as skeletal muscle, liver and lung is limited, the tissue-specific synthesis of 1,25(OH)2D2 appears to be directly related to the availability
of the 25(OH)D precursor for CYP27B1, and thus low circulating 25(OH)D may lead to an earlier decline in local v. circulating levels of 1,25(OH)2D(16). We did not specifically address these outcomes in the present study, but further investigation in this area is warranted.

The relatively higher attrition rate and failure to sufficiently achieve 90% or greater self-reported compliance in participants assigned to the vitamin D2 group compared with those assigned to the D3 or placebo group (χ2 test, p=0.011) is a potential limitation. However, there appears to be no reasonable explanation for the significant difference in loss across the groups. The study was double-blinded (investigators and participants), allocation was concealed, all tablets were indistinguishable and there were no reports of adverse events. Given that the per-protocol analyses conveyed similar results to the intention-to-treat analyses, we assume that the potential bias from non-random dropout of participants or exclusion for poor compliance had no major impact on the results.

The Food and Nutrition Board of the Institute of Medicine has recommended 10 μg (400 IU) vitamin D daily to meet the needs of half of adults up to the age of 70 years, and 15 μg (600 IU) daily to meet the needs of 97.5% of these adults(20). In the present study, a daily intake of 25 μg (1000 IU) vitamin D3 maintained the summer 25(OH)D levels. Using data from controlled trials, a regression analysis of the relationship between the serum 25(OH)D level and the total intake of vitamin D predicts that a daily intake of 25 μg (1000 IU) would be associated with a mean serum 25(OH)D level of 68 nmol/l (γ = 9.9 ln(total vitamin D intake in IU/d))(20), where 40 IU vitamin D is equal to 1 μg vitamin D. The predicted level is noticeably less than the present study’s mean total serum 25(OH)D level of 80 nmol/l achieved after 25 weeks supplementation in the D3-treated participants; however, it should be noted that the simulated intake–response relationship has been determined under conditions of minimal sun exposure, which may not be fully met at latitudes below 49°. In contrast, the predicted value is substantially higher than the mean total serum 25(OH)D level of 56 nmol/l observed in our D2 participants at the end of the study. Neither the simulated intake–response relationship nor the newly revised Dietary Reference Intake (DRI) distinguish between vitamin D2 and vitamin D3.

In conclusion, daily supplementation of 25 μg (1000 IU) vitamin D3 over a 25-week intervention period was more effective than vitamin D2 in maintaining serum 25(OH)D levels. These findings contribute to the accumulating evidence that vitamin D3 and vitamin D2 have different pharmacokinetic profiles for serum 25(OH)D. As a result, care should be taken to distinguish the form of vitamin D used for both clinical studies and therapeutic use, particularly given that the dose employed in the present study is commonly used in over-the-counter dietary supplements. Nonetheless, conclusions about the biological significance of the different functional effects of the two forms cannot be drawn. Additional studies are needed to determine whether even lower doses would also suggest differences in pharmacokinetic parameters between vitamin D2 and vitamin D3.

Supplementary material
To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0007114512002851

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