Clinical Research Article

Vitamin D₃ Dose Requirement That Raises 25-Hydroxyvitamin D to Desirable Level in Overweight and Obese Elderly

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Abbreviations: 25(OH)D, 25-hydroxyvitamin D; AUBMC, American University of Beirut Medical Center; BMI, body mass index; IOM, Institute of Medicine; LCMS, liquid chromatography mass spectroscopy; MENA, Middle East and North Africa; RCT, randomized controlled trial; RDA, recommended daily allowance.

Received: 14 January 2021; Editorial Decision: 27 April 2021; First Published Online: 5 May 2021; Corrected and Typeset: 14 June 2021.

Abstract

Context: Guidelines for the dosage of vitamin D supplementation vary widely globally.

Objective: To investigate the impact of 2 vitamin D doses, bracketed between the IOM recommended dietary allowance (RDA) and the upper tolerable limit, on vitamin D nutritional status in elderly individuals.

Methods: This post hoc analysis of data collected from a 12-month, double-blind, randomized control trial included 221 ambulatory participants (≥ 65 years) with a mean BMI of 30.2 kg/m² and a mean baseline serum 25-hydroxyvitamin D [25(OH)D] level of 20.4 ± 7.4 ng/mL, who were recruited from 3 outpatient centers in Lebanon. All participants received 1000 mg of elemental calcium daily from calcium citrate plus the daily equivalent of either 600 IU or 3750 IU of vitamin D₃.

Results: Mean 25(OH)D level at 12 months was 26.0 ng/mL with low dose and 36.0 ng/mL with high dose vitamin D₃. The proportion of participants reaching a value ≥ 20 ng/mL was 86% in the low dose, and 99% in the high dose arms, with no gender differences.
The increment of 25(OH)D per 100 IU/day was 1 ng/mL with the low dose, and 0.41 ng/mL with the high dose. Serum 25(OH)D levels at 1 year were highly variable in both treatment arms. Baseline 25(OH)D level and vitamin D dose—but not age, BMI, gender, or season—were significant predictors of serum 25(OH)D level post-intervention.

**Conclusion:** The IOM Recommended Dietary Allowance (RDA) of 600 IU/day does not bring 97.5% of ambulatory elderly individuals above the desirable threshold of 20 ng/mL. Country-specific RDAs are best derived taking into account the observed variability and predictors of achieved 25(OH)D levels.

**Key Words:** vitamin D, elderly, RDA, desirable level, IOM, guidelines

Vitamin D is a steroid hormone known for its critical role in bone metabolism and musculoskeletal health (1, 2). Ample evidence also demonstrates its extraskeletal physiologic actions (1). Vitamin D deficiency is a worldwide health problem that affects all populations (3, 4). It is particularly common in the Middle East, despite the region’s abundant sunlight (5, 6). Vitamin D supplementation is a universally accepted therapeutic approach; but guidelines vary widely globally (7). The Institute of Medicine (IOM) recommends that a daily vitamin D3 dose of 600 IU is adequate to bring 97.5% of the population to a prespecified desirable 25-hydroxyvitamin D [25(OH)D] level of 20 ng/mL (8). The 2011 Endocrine Society clinical practice guideline proposes that the daily dietary intake should be 1000 to 2000 IU to reach a target level above 30 ng/mL (9). Some reasons behind this lack of consensus include scarcity of clinical trials-based evidence, different target populations, varied desirable 25(OH)D levels, and discordant approaches to the vitamin D dose-response relationship (10, 11).

Randomized controlled trials (RCTs) clearly demonstrate substantial variability in reported levels achieved for comparable doses, within, and between ethnic groups (12-14). This raises questions regarding the applicability of the IOM recommended daily allowance (RDA) to non-US populations. Furthermore, there has been a rising trend for hypervitaminosis D due to over supplementation in both developing and developed countries (15, 16).

In this study, we capitalize on data available from a completed vitamin D trial, to investigate the impact of 2 doses of vitamin D, bracketed between the IOM RDA and the upper tolerable limit, on vitamin D nutritional status, in elderly ambulatory individuals.

**Methods**

**Objective and Aims**

We aim to:

1. Test the hypothesis whether the RDA recommended by the IOM brings 97.5% of our study population above the desirable cutoff value of 20 ng/mL.
2. Compare the proportion of subjects in each treatment arm who reach the desirable 25(OH)D cutoff levels, as recommended by the 2010 IOM report (20 ng/mL), and the 2011 Endocrine Society guidelines (30 ng/mL).
3. Evaluate the interindividual variability in serum 25(OH)D levels achieved, within and between treatment arms.
4. Investigate predictors of serum 25(OH)D levels achieved in response to vitamin D supplementation.

**Study Design**

This is a post hoc analysis on data collected from a double-blind RCT (NCT01315366) conducted at the American University of Beirut Medical Center (AUBMC), Hotel Dieu de France, and Rafic Hariri Governmental University Hospital, to investigate the impact of vitamin D on 2 primary outcomes: indices of insulin resistance (17); and indices of bone and mineral metabolism (18). Recruitment, prescreening, and screening procedures were performed at all centers between January 2011 and July 2013; enrollment and protocol implementation were exclusively conducted at AUBMC and ended in July 2014.

**Study Population**

The study group consisted of 221 ambulatory elderly (≥ 65 years) Lebanese, who were overweight or obese (body mass index [BMI] > 25 kg/m²) and had a baseline serum 25(OH)D level in the range from 10 to 30 ng/mL. Study subjects were recruited from outpatient clinics or through advertisements posted at AUBMC, Hotel Dieu de France, Rafic Hariri Governmental University Hospital, and health dispensaries of the Ministry of Social Affairs, all from the greater Beirut Area.

Exclusion criteria included patients with prediabetes on oral hypoglycemic medications, diabetes (fasting plasma glucose ≥ 126 mg/dL or glycated hemoglobin [HbA1C] ≥ 6.5%), chronic heart failure (stage III or IV), liver failure or cirrhosis, chronic kidney disease (estimated glomerular filtration rate [eGFR] < 30 mL/min), cancer, or autoimmune diseases. Participants were also excluded...
if they had conditions or were on medications known to affect bone metabolism, such as osteomalacia, history of kidney stones, fragility fractures, or a 10-year fracture risk (FRAX) exceeding 10% for major osteoporotic fractures using the Lebanon Fracture Risk Assessment Tool (FRAX) version 3.08 (https://www.shef.ac.uk/FRAX/tool.jsp).

Study Drug
All subjects received 4 tablets of calcium citrate daily (Citracal D: 250 mg elemental calcium and 125 IU vitamin D3/tablet) amounting to a total of 1000 mg of elemental calcium and 500 IU of vitamin D3 daily. Additionally, each subject received 2 pills identical in shape, size, color, smell, and taste, taken once weekly, consisting of placebo in the low dose arm and vitamin D3 (Euro D: 10 000 IU/pill) in the high dose arm. All the pills were provided by Europharm, Canada. Based on the certificate of analysis provided by Europharm to the Canadian regulatory agencies for all trial lots, the actual vitamin D3 content was 150 IU and 11 000 IU in the Citracal D and Euro D tablets, respectively. Therefore, participants received a total daily vitamin D3 equivalent of 600 IU in the low dose arm and 3750 IU in the high dose arm. Daily calcium intake was assessed through a detailed food-frequency questionnaire about the consumption of several dairy products.

All the study drugs were stored and dispensed in identical boxes at the central pharmacy in AUBMC, where the senior pharmacist implemented randomization and allocation concealment with stratification by gender and center (17). Allocation was concealed based on a simple randomization approach, and all the participants and study team members were blinded to the drug assignment until the completion of the trial and data entry.

The protocol was approved by the Institutional Review Board at each center, and all participants provided written informed consent. An external Data Safety Monitoring Board (see “Acknowledgments”) reviewed the final protocol and monitored the trial safety.

Study Visits and Measurements
Participants presented for follow-up every 3 months, where weight, height, and vital signs were measured, questionnaires were administered, study bottles were returned, and refill bottles were provided. At each visit (3, 6, and 12 months), study subjects were asked about adverse events, medication intake, and pill counts. Each participant was also contacted by phone every 2 weeks to encourage compliance, which was calculated as the percentage of full possible dose ([total number of study drug pills taken/total number of pills provided] x100).

Serum 25(OH)D levels were assayed at 0, 3, 6, and 12 months. Blood samples were allowed to clot for 30 minutes, centrifuged for 20 minutes, and immediately processed, or stored at −80 °C, depending on the assay. Serum 25(OH) D was run using liquid chromatography mass spectroscopy (LCMS) at the Mayo Clinic Clinical Laboratories, (Mayo Clinic, Rochester, Minnesota). That laboratory participates in the vitamin D quality assurance program, DEQAS. The LCMS methodology in that laboratory is directly traceable to NIST, Mayo Lab = 0.9599 × NIST − 1.3716, R² = 0.9922. Vitamin D assays were run in batches at study completion, and samples drawn at serial time points for each hormone were included within the same assay for each study subject. Intra-assay coefficients of variation are 3.8%, 2.4%, and 4.7% at 25, 54, and 140 ng/mL, respectively. Inter-assay coefficients of variation are 6.4%, 6.8%, and 5.0% at 24, 52, and 140 ng/mL, respectively.

Sample Size Calculation
The trial’s sample size was calculated based on a post hoc analysis from a vitamin D and calcium trial previously conducted in overweight elderly Caucasian participants (19). Based on an anticipated between-arms mean ± SD difference in insulin resistance index (HOMA-IR) of 0.9 ± 2, a power of 80%, and a significance level of 0.025 (taking into account the 2 primary outcomes), the total sample size needed was calculated to be 222. Allowing for a possible dropout rate of 30%, 257 subjects were enrolled in the study.

Statistical Analyses
The analyses were performed on all randomized subjects who completed the 1-year trial. For almost all variables, data was normally distributed, based on an inspection of histograms and stem leaf plots. Variables were appropriately summarized as mean ± SD or N (%). Serum 25(OH) D levels were compared between groups using the independent t test and within the same group using paired t test. Categorical variables (proportions) were compared using Pearson chi-squared test or Fisher’s exact test, as applicable. Analysis of variance (ANOVA) was used for comparison between different seasons. Scatter plots tracing each individual’s response to therapy were created by GraphPad Prism version 9.0 (GraphPad Software, San Diego, CA). Dynamically fit sigmoidal curves illustrating the percentage of patients reaching a spectrum of desirable 25(OH)D levels, in both arms, were generated using SigmaPlot version 15.0 (Systat Software Inc., San-Jose, CA). Bland-Altman plots showing the overlap in delta 25(OH)D between the low and high dose arms were also...
generated using SigmaPlot. Multivariate linear and logistic regression analyses were performed to explore possible predictors of mean serum 25(OH)D levels at 1 year, and the likelihood of reaching a level above the preset threshold values of 20 and 30 ng/mL. Predictors assessed were age, gender, baseline BMI, season, having a baseline serum 25(OH)D >20 ng/mL, and the vitamin D dose. We calculated the mean delta 25(OH)D per 100 IU at 1 year in each of the low dose and high dose arms, unadjusted and after adjustment for significant predictors. Given that the relationship between vitamin D dose and serum 25(OH)D level is linear at doses between 400 and 1600 IU/day (14, 20), we calculated the dose that would bring 97.5% of our cohort to a serum 25(OH)D level ≥ 20 ng/mL. A P value of ≤ 0.05 was considered statistically significant and was not adjusted for multiplicity of testing. Data analyses were performed using IBM SPSS version 26.0 (IBM Corporation, Armonk, NY).

Results

Baseline Characteristics

Originally, 129 and 128 elderly participants were randomly assigned to receive the high and low dose of vitamin D₃, respectively. Of them, 35 subjects (14%) did not complete the study, and 1 participant refused to share samples with collaborators (for LCMS assay). There was no statistical difference in the dropout rate between the 2 treatment arms. Participants’ baseline characteristics and comorbidities did not differ in the remaining 221 participants from the originally randomized group of 257 subjects (data not shown). The volume of blood sample from 1 subject in the low dose arm and 5 subjects in the high dose arm was not sufficient at follow-up; hence, no outcome data is available for these subjects.

The remaining overall study group consisted of 122 women and 99 men with a mean age of 71.1 ± 4.7 years, a BMI of 30.2 ± 4.5 kg/m², and a mean baseline serum 25(OH)D level of 20.4 ± 7.4 ng/mL. A total of 111 participants received the low dose, and 110 received the high dose (Table 1). Age, gender, baseline BMI, dietary calcium intake, baseline mean serum 25(OH)D levels, and season of recruitment did not differ across treatment arms.

Response to Vitamin D₃ Supplementation

The mean 25(OH)D levels reached after 12 months were 26.0 ± 6.9 ng/mL in the low dose arm and 36.0 ± 9.7 ng/mL in the high dose arm (P < 0.001), both of which did not differ significantly between genders (Supplement 1) (21). The wide-ranging spread of participants’ serum 25(OH)D levels at baseline and after 1 year of supplementation, with each dose, is shown in Fig. 1.

Proportion of Subjects Above Desirable 25(OH)D Cutoff Levels at Entry and 1 Year

At randomization, overall, 50% of the participants had a 25(OH)D level ≥ 20 ng/mL, and only 10% had a level ≥ 30 ng/mL (Supplement 1) (21). The proportions of participants above the prespecified cutoff levels did not differ significantly between treatment arms, with the exception of significantly higher proportion of women above 20 ng/mL in the low dose arm (63%) compared with the high dose arm (44%) (P = 0.043, Supplement 1) (21). A higher proportion of women (63%) were above 20 ng/mL, as compared with men (44%), in the low dose arm only (P = 0.051, Supplement 1) (21).

At 1 year, there was a significant increase in the proportion of subjects above specific cutoffs, with both doses (P < 0.001, Fig. 2). The proportion of participants reaching the cutoff value of 20 ng/mL was 86% in the low dose arm and 99% in the high dose arm (P < 0.001, Fig. 2), with no differences across genders (Supplement 1) (21). The proportion of subjects reaching a level ≥30 ng/mL remained low at 26% in the low-dose arm but increased to 73% in the high-dose arm (P < 0.001, Fig. 2), with no gender differences in either treatment arm (Supplement 1) (21). Figure 3 illustrates the proportion of subjects reaching a spectrum of desirable serum 25(OH)D levels at 1 year. There was a clear shift of the baseline sigmoidal curve to the right after supplementation, both with the low dose, and more substantially with the high dose.

Predictors of Response to Vitamin D₃ at 1 Year

Unadjusted analyses

Baseline serum 25(OH)D level, vitamin D₃ dose received, and having a baseline 25(OH)D level ≥ 20 ng/mL—but not age, gender, season, or BMI—predicted both the serum 25(OH)D level at 1 year and the likelihood of achieving a serum 25(OH)D level of ≥ 20 ng/mL; however, having a baseline level of ≥ 20 ng/mL did not significantly predict the likelihood of achieving a level of ≥ 30 ng/mL (Supplement 3) (21). The most powerful predictor was vitamin D treatment dose with a model R² of 7% to 28% (Supplement 3) (21).

Multivariate adjusted analyses

Baseline 25(OH)D levels (P < 0.001) and treatment arm (P < 0.001) remained the only significant predictors of serum 25(OH)D levels after 1 year of supplementation,
after adjusting for other covariates, including age, gender, season, and baseline BMI, with an R² of 36.2% (Table 2). Similarly, treatment with high vitamin D dose and baseline serum 25(OH)D level were the only significant predictors for achieving a 25(OH)D level ≥ 20 ng/mL and ≥ 30 ng/mL at 1 year, after adjusting for the same covariates (Table 2). Highest odds ratio estimates were noted in the high dose treatment arm, where subjects were 29 times more likely to achieve a level ≥ 20 ng/mL, and 9 times more likely to achieve a level ≥ 30 ng/mL, as compared with those receiving the lower dose (Table 2).

### Table 1. Baseline characteristics of the study group overall, by dose, and by gender

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Low dose (600 IU/day)</th>
<th>High dose (3750 IU/day)</th>
<th>P value&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects n = 221</td>
<td></td>
<td>n = 111</td>
<td>n = 110</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>71.1 ± 4.7</td>
<td>70.9 ± 4.6</td>
<td>71.2 ± 4.8</td>
<td>0.712</td>
</tr>
<tr>
<td>Gender (F/M)</td>
<td>122/99</td>
<td>59/52</td>
<td>63/47</td>
<td>0.538</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>30.2 ± 4.5</td>
<td>29.9 ± 4.6</td>
<td>30.6 ± 4.3</td>
<td>0.286</td>
</tr>
<tr>
<td>Calcium dietary intake (mg/day)</td>
<td>419.7 ± 282.2</td>
<td>442.2 ± 304.7</td>
<td>396.9 ± 257.0</td>
<td>0.234</td>
</tr>
<tr>
<td>Serum 25(OH)D (ng/mL)</td>
<td>20.4 ± 7.4</td>
<td>20.1 ± 6.9</td>
<td>20.6 ± 7.9</td>
<td>0.555</td>
</tr>
<tr>
<td>Season</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan-March</td>
<td>72 (32.6)</td>
<td>34 (30.6)</td>
<td>38 (34.5)</td>
<td></td>
</tr>
<tr>
<td>Oct-Dec</td>
<td>27 (12.2)</td>
<td>13 (11.7)</td>
<td>14 (12.7)</td>
<td></td>
</tr>
<tr>
<td>Apr-Jun</td>
<td>66 (29.9)</td>
<td>35 (31.5)</td>
<td>31 (38.2)</td>
<td></td>
</tr>
<tr>
<td>Jul-Sep</td>
<td>56 (25.3)</td>
<td>29 (26.1)</td>
<td>27 (24.5)</td>
<td></td>
</tr>
<tr>
<td>Men:</td>
<td>n = 99</td>
<td>n = 52</td>
<td>n = 47</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>72.4 ± 5.5</td>
<td>72.1 ± 5.2</td>
<td>72.8 ± 5.8</td>
<td>0.535</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>28.7 ± 3.3</td>
<td>28.6 ± 3.2</td>
<td>28.9 ± 3.4</td>
<td>0.624</td>
</tr>
<tr>
<td>Calcium dietary intake (mg/day)</td>
<td>412.6 ± 266.9</td>
<td>410.7 ± 256.2</td>
<td>414.6 ± 281.2</td>
<td>0.943</td>
</tr>
<tr>
<td>Serum 25(OH)D (ng/mL)</td>
<td>19.5 ± 6.3</td>
<td>18.6 ± 6.0</td>
<td>20.4 ± 6.6</td>
<td>0.174</td>
</tr>
<tr>
<td>Women:</td>
<td>n = 122</td>
<td>n = 59</td>
<td>n = 63</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>69.9 ± 3.7</td>
<td>69.9 ± 3.8</td>
<td>70.0 ± 3.6</td>
<td>0.937</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>31.5 ± 4.9</td>
<td>31.1 ± 5.3</td>
<td>31.8 ± 4.6</td>
<td>0.436</td>
</tr>
<tr>
<td>Calcium dietary intake (mg/day)</td>
<td>425.4 ± 295</td>
<td>469.9 ± 341.6</td>
<td>383.7 ± 238.9</td>
<td>0.107</td>
</tr>
<tr>
<td>Serum 25(OH)D (ng/mL)</td>
<td>21.1 ± 8.2</td>
<td>21.3 ± 7.5</td>
<td>20.9 ± 8.8</td>
<td>0.762</td>
</tr>
</tbody>
</table>

<sup>a</sup>P value: independent t-test comparing means between low dose and high dose of vitamin D supplementation.

Figure 1. Change in each participant’s 25(OH)D level (ng/mL) from baseline to follow-up after 12 months of supplementation with low and high doses of vitamin D₃. Median 25(OH)D levels in the low dose arm were 20 ng/mL and 25 ng/mL at baseline and after 12 months, respectively. Median 25(OH)D levels in the high dose arm were 18.5 ng/mL and 35 ng/mL at baseline and after 12 months, respectively.

Interindividual Variability in Serum 25(OH)D Levels Achieved at 1 Year

Scrutiny of the individual serum 25(OH)D values at 1 year, and the difference in 25(OH)D levels between 12 months and baseline, reveal high variability in the magnitude and direction of response to both doses (Fig. 1). To evaluate the impact of baseline serum 25(OH)D levels and dose on the response to therapy, we performed regression analyses of the change (delta) in serum 25(OH)D level with changing baseline 25(OH)D levels, for each dose. As the baseline 25(OH)D levels increased, the change in serum 25(OH)D levels at 1 year decreased, with both doses (Fig. 4A). However, for any baseline serum 25(OH)D level, there could be substantial variance and overlap in the delta vitamin D achieved, within and between treatment groups (Fig. 4A). The mean increment with the low dose was 6 ng/mL, with a wide range from −13 to 26 ng/mL (Fig. 4B), and 15 ng/mL with the high dose, ranging between −13 and 41 ng/mL (Fig. 4C).
The 25(OH)D delta/100 IU was 1.00 ± 1.26 ng/mL in the low dose, and less than half, with a mean of 0.41 ± 0.27 in the high dose, \((P < 0.001)\) in unadjusted analyses. This variable did not significantly differ by gender or BMI cutoff categories (above vs below 30kg/m²) (Supplement 2) (21).

The 25(OH)D delta/100 IU was 0.99 ± 0.70 ng/mL in the low dose arm after adjusting for baseline 25(OH)D level.

Projected RDA in Our Cohort

Considering our observed increment of 1 ng/mL per 100 IU/day at low doses, we calculated that if participants in the low dose arm received 1100 IU/day instead of 600 IU/day, their achieved 25(OH)D level would increase by 5 ng/mL, allowing 97.5% of individuals to reach a desirable level of 20 ng/mL.

Discussion

This 1-year double-blind controlled vitamin D trial reveals that in elderly subjects with an overall baseline serum 25(OH)D level of 20.4 ng/mL, the achieved 25(OH)D level after 1 year of supplementation was 26.0 ng/mL and 36.0 ng/mL, with low and high doses, of vitamin D₃ respectively. Importantly, it demonstrates that the recommended IOM daily dose of 600 IU only brings 86% of elderly overweight or obese ambulatory Lebanese individuals to a serum 25(OH)D level at, or above, the desirable cutoff of 20 ng/mL. However, a higher dose of 3750 IU/day, which is below the upper tolerable limit of 4000 IU/day, brings more than 99% of the study population to such a target. Baseline 25(OH)D level and vitamin D dose were the only significant predictors of 25(OH)D level post-intervention. The increments per 100 IU vitamin D₃/day were 1.00 ng/mL/100 IU with the low dose, and 0.41 ng/mL/100 IU with the high dose.

Although hypovitaminosis is a global problem, there is still lack of consensus over the recommended intake that prevents patients from developing musculoskeletal health outcomes, such as bone loss or hip fractures (8). Several international agencies, such as the Institute of Medicine (IOM) (8), Nordic Council of Ministers (NORDEN) (22), the German Nutrition Society (23), and the European Food Safety Authority (EFSA) (24), established their
recommendations based on a common target 25(OH)D level of 20 ng/mL. Yet, their recommendations for desirable dose still varied widely, reflecting the uncertainty of the evidence regarding dose response. The IOM’s and NORDEN’s RDAs, which should meet the needs of “nearly all” healthy individuals (ie, 97.5%), aged 50 to 70 years, were 600 IU/day and 400 IU/day, respectively. The German

Table 2. Multivariate analysis of predictors for response to vitamin D₃ supplementation at 1 year

<table>
<thead>
<tr>
<th>Predictors of serum 25(OH)D levels</th>
<th>Predictors for 25(OH)D level ≥ 20 ng/mL</th>
<th>Predictors for 25(OH)D level ≥ 30 ng/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted β (95% CI)</td>
<td>P-value</td>
<td>R² (%)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>−0.02 (−0.26, 0.21)</td>
<td>NS</td>
</tr>
<tr>
<td>Female</td>
<td>0.37 (−1.97, 2.62)</td>
<td>NS</td>
</tr>
<tr>
<td>Baseline BMI (kg/m²)</td>
<td>−0.07 (−0.33, 0.19)</td>
<td>NS</td>
</tr>
<tr>
<td>Season (vs Jan-Mar)</td>
<td>−0.16 (−1.08, 0.75)</td>
<td>NS</td>
</tr>
<tr>
<td>Apr-Jun</td>
<td>1.61 (0.16, 16.8)</td>
<td>NS</td>
</tr>
<tr>
<td>Oct-Dec</td>
<td>0.31 (0.08, 1.20)</td>
<td>NS</td>
</tr>
<tr>
<td>Jul-Sep</td>
<td>1.89 (0.28, 12.56)</td>
<td>NS</td>
</tr>
<tr>
<td>Baseline Serum 25(OH)D level (ng/mL)</td>
<td>0.41 (0.26, 0.56)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Treatment arm (high dose)</td>
<td>9.77 (7.63, 11.91)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Overall Model</td>
<td>&lt;0.001</td>
<td>36.2</td>
</tr>
</tbody>
</table>

Abbreviations: 25(OH)D, 25-hydroxyvitamin D; BMI, body mass index; NS, not significant.

Figure 4. A, Bland-Altman plot illustrating the overlap in delta 25(OH)D between the high dose and low dose arms. B, Corresponding Bland-Altman plot of the low dose arm showing regression analysis of the delta 25(OH)D ng/mL with changing baseline 25(OH)D levels (y = −0.60x + 18.0 [R² = 30%]). C, Corresponding Bland-Altman plot of the high dose arm showing regression analysis of the delta 25(OH)D ng/mL with changing baseline 25(OH)D levels (y = −0.58x + 27.3 [R² = 19%]).
Nutrition Society and the ESFA proposed “Adequate Intake (AI)” values of 800 IU/day and 600 IU/day, respectively.

Multiple randomized control trials tried to establish the optimal vitamin D dose that achieves a target desirable level. Our findings are consistent with those reported in a recent small 6-month trial by Shirvani et al, who investigated the effect of 3 different vitamin D doses (600, 4000, and 10 000 IU/day) in 30 healthy young adults with a mean BMI < 30 kg/m² and mean baseline level of 17.1 ± 5.9 ng/mL. A vitamin D dose of 600 IU/day corrected 25(OH)D level to ≥ 20 ng/mL in 71% of the participants but brought only 14% of participants to ≥ 30 ng/mL. However, higher doses of 4000 and 10 000 IU/day allowed all participants to reach a serum 25(OH)D level ≥ 30 ng/mL (25). Another trial on 225 free-living Caucasian adults >64 years demonstrated that 600 IU/day was adequate for 99% of the participants to achieve a 25(OH)D level of ≥ 20 ng/mL (26). Heaney et al investigated several vitamin D doses (0, 1000, 5000, and 10 000 IU/day) in 67 healthy men (mean age, 38.7 ± 11.2 years) in Nebraska in order to identify the steady state cholecalciferol input during winter that sustains the baseline autumn 25(OH)D level of 20.8 ng/mL. He concluded that in addition to the daily contribution from food and tissue stores, healthy men would need around 500 IU/day to sustain their starting 25(OH)D level (27).

Gallagher et al investigated a wide range of vitamin D doses (400-4800 IU/day) in 163 healthy postmenopausal women in Nebraska, (mean age, 67 years), and found that 800 IU/day is needed to achieve a level ≥ 20 ng/mL. The dose-response relationship was curvilinear, plateauing at a level of around 44.9 ng/mL in subjects receiving doses greater than 3200 IU/day (14). Smith et al combined the analysis from the VitaDAS and ViDOS studies and showed in a best fitting model that, in Caucasians, 800 IU/day and 2400 IU/day are required to reach serum 25(OH)D levels of 20 ng/mL and 30 ng/mL, respectively (12). A trial of 126 Chinese adults > 60 years of age showed that 2000 IU/day is required to allow > 86% of individuals to achieve the Endocrine Society recommended level of 30 ng/mL (28). In another trial of 92 healthy postmenopausal Indian women (mean age, 54.8 years), only 16% and 66.67% of participants achieved a level ≥ 20 ng/mL with 500 IU and 1000 IU per day, respectively (29). An RCT of 328 healthy African American women (43-59 years of age) showed that 1640 IU/day was required to achieve 20 ng/mL in 97.5% of the participants (30), possibly reflecting the need for a higher dose in subjects with lower baseline levels.

According to a meta-analysis conducted in the Middle East and North Africa (MENA) region, which included 2 trials in the elderly (age > 65 years) and 17 in adults (18–65 years), only 89% receiving high dose (>2000 IU/day) and 71% of participants receiving intermediate (800–2000 IU/day) doses, reached a desirable threshold of 20 ng/mL (31). Another recent meta-regression analysis investigating region- and age-specific responses to vitamin D supplementation showed that adults in the MENA region require 1229 IU/day to reach ≥ 30 ng/mL, whereas European adults (65-85 years old) can achieve the same level with only 797 IU/day (32). Shab-Bidar et al also conducted a meta-regression analysis including 7150 individuals (mean age, 65.8) from several regions including the United States, Europe, Australia, and India, and reported that a dose of 800 IU/day is required to bring >97.5% of subjects to 20 ng/mL (33). To avoid the limitations inherent to meta-analysis of aggregate data, Cashman et al conducted an individual participant data (IPD) meta-regression using 7 wintertime North European RCTs to derive estimates of recommended vitamin D intakes. The ages in these trials varied widely, with only 1 trial in elderly participants (mean age, 70 years), while other trials were in children, adolescents, and younger adults. The IPD-derived estimate that brought >97.5% of the population to ≥ 20 ng/mL was 26 μg/day (1040 IU/day), after adjusting for age and baseline level, whereas a standard meta-regression analysis of aggregate data from the same RCTs (assessed by several international agencies) had estimated the vitamin D requirement to be ~14 μg/day (560 IU/day) (20). Considering that the relationship between vitamin D dose and serum 25(OH)D level is linear at doses from 400 to 1600 IU/day (14, 20) and the mean increment per 100 IU at low doses is 1 ng/mL, we project that the RDA in the overweight and obese Lebanese elderly would be 1100 IU/day. Such projection is based on mean increments in serum 25(OH)D levels and does not take into account individual variations in response to vitamin D supplementation. Importantly, our projection is consistent with that reported by the IPD meta-analysis by Cashman et al (20).

Baseline 25(OH)D level and vitamin D dose were the only significant predictors of 25(OH)D level post-intervention, accounting for 36.2% of the variance in response to therapy. In line with our results, several previous studies consistently reported that the vitamin D dose (31-37) and baseline 25(OH)D level (31-35) are significant predictors of the achieved level post-intervention. Exceptionally, 1 meta-analysis conducted by Autier et al on 6207 Caucasian participants older than 50 years receiving median vitamin D3 dose of 800 IU/day (range, 200-10 000 IU/day) revealed an inverse association between baseline 25(OH)D level and increments of serum 25(OH)D, but it did not reach statistical significance (38). Conversely, another global study of 7564 postmenopausal women from 5 continents showed that the achieved level was higher for individuals with a baseline level < 25 nmol/L (<10 ng/mL), compared with those > 50 nmol/L (> 20 ng/mL) (39). This
heterogeneity in results could be due to variations in ethnicity and age across studies. Other factors such as age (32, 33), type of vitamin D (32, 38), trial duration (33), as well as BMI and season (35), were significant predictors of achieved serum 25(OH)D level in the literature, but they did not reach statistical significance in our trial. This may be explained by the relatively narrow range for age and BMI, in an exclusively older cohort, with entry criteria stipulating a BMI ≥ 25 kg/m². The impact of ethnicity on BMI, in an exclusively older cohort, with entry criteria being the relatively narrow range for age and BMI, did not reach statistical significance in our trial. This may be explained by the relatively narrow range for age and BMI, in an exclusively older cohort, with entry criteria stipulating a BMI ≥ 25 kg/m². The impact of ethnicity on the achieved level after supplementation was explored by Mo et al., in an analysis that showed that vitamin D dose and baseline 25(OH)D level consistently and significantly predicted the achieved level in adults from different regions including Europe, North America, Asia, and the MENA region, whereas age was a significant predictor only in Europe (32). It was otherwise difficult to dissect the influence of ethnicity on achieved level, as many meta-analyses included trials from diverse regions/ethnicities and did not account for this variable.

Our 25(OH)D increments per 100 IU/day were 1 ng/mL for subjects randomized to 600 IU/day and 0.41 ng/mL for subjects randomized to 3750 IU/day. This trend is similar to what has been reported in the literature. Gallagher et al. noted increments of 1.6 ng/mL per 100 IU in postmenopausal older women randomized to 400 IU/day, and 0.6 ng/mL per 100 IU in women randomized to 4800 IU/day (14). Mo et al. also demonstrated that among the elderly, there was an inverse trend between the dose administered and the achieved level, where the increment was 3.3 nmol/L per 100 IU/day (1.3 ng/mL per 100 IU/day) with the low weighted mean dose of 606 IU, whereas it was 1.7 nmol/L per 100 IU/day (0.68 ng/mL per 100 IU/day) with higher doses of 3900 IU/day (32). He also showed that the increment per 100 IU/day is dependent on both the baseline 25(OH)D level (where it was highest in Asian adults who have a lower baseline than North Americans and Europeans), as well as age (where it was highest in adults aged >64 years compared with those aged 18-64 years receiving the same low dose) even though the weighted mean baseline 25(OH)D level in the elderly was higher than that of the adults (32). The increment per 100 IU/day also varies by body size, with smaller increments reported in individuals with higher BMI (40). Chakhtoura et al. also demonstrated that the increment per 100 IU/day was lowest (0.4-0.5 ng/mL) with high (3750 IU) and intermediate (1000 IU) doses, and highest (1 ng/mL) with low doses (600 IU) (31).

Our study has few potential limitations. It was limited geographically to the Greater Beirut area; however, study subjects were recruited from health centers that draw from 30% to 40% of the Lebanese population. The baseline 25(OH)D level (20.4 ng/mL) is representative of the general Lebanese population and is comparable to baseline levels in many other elderly cohorts worldwide (32, 33, 38). Our cohort consists of overweight and obese individuals (mean BMI, 30.2 kg/m²); therefore, our findings are not generalizable to a population of leaner elderly individuals. However, our results apply to a large proportion of males and females older than 65 years worldwide. Indeed, the overweight and obesity rates average at 40% in males and 35% in females in developing countries, and at around 65% for males and females in developed countries (41, 42). The trial lacked a placebo arm because it would be unethical to have a control group without vitamin D supplementation given that more than half of our elderly cohort had a 25(OH)D level below 20 ng/mL. Importantly, the low dose corresponds to the currently recommended RDA by the IOM for adults and elderly until age 70 years, and thus serves as an appropriate surrogate control in our cohort. Our study duration was only 1 year, but vitamin D levels plateau within few weeks of administration (14, 43). We measured serum total 25(OH)D levels, and not the free or bioavailable metabolites. However, we have recently shown in this trial cohort that free and bioavailable 25(OH)D levels are not superior to total 25(OH)D in predicting bone health outcomes (44).

We did not test the efficacy of an intermediate dose, for example, 2200 IU/day, due to lack of sufficient funding.

Our study has several important strengths, including its double-blind design, its clinical relevance from recruiting high-risk elderly individuals, having included both genders, and having recruited across all seasons. We used vitamin D₃, the most commonly used form of vitamin D, measured its actual content in the tablets administered, and used LCMS for serum 25(OH)D measurements. We also ensured high compliance of study subjects. Importantly, our choice of the doses of vitamin D also serves as a crucial strength, as the low dose (600 IU/day) is anchored at the IOM-recommended dose, and the high dose (3750 IU/day) is below the IOM upper tolerable limit.

In conclusion, in elderly overweight and obese Lebanese ambulatory subjects, with a mean 25(OH)D level of 20 ng/mL, the IOM recommended dose of 600 IU/day is not sufficient to bring 97.5% of the cohort above the desirable threshold of 20 ng/mL. The trial fills a major knowledge gap and provides evidence for care pathways and guidance for defining adequate vitamin D intake for ambulatory elderly subjects, from this region. We project that a dose of 1100 IU/day would approximate the RDA for the elderly Lebanese. A dose response curve adjusted by age and baseline 25(OH)D level would best be suited to identify the lowest dose that surely allows individuals in the Middle East to achieve the desirable level.
Acknowledgments

The authors are most grateful to study subjects for their participation, and thank the study coordinators and hospital personnel, administrators at the Lebanese Ministry of Social Affairs dispensaries, local dispensaries, for their time and dedication and making the study possible. The authors thank members of the data safety monitoring board, Heike Bischoff-Ferrari MD, DrPH (University of Zurich, Switzerland), Christopher Gallagher, MD (Creighton University, USA), and Reinhold Vieth PhD, FCACB (Mts Sinai Hospital, Montreal, Canada). The authors also thank Euro-Pharm Canada for providing the vitamin D/identical placebo tablets and calcium citrate supplements.

This trial was supported by grants from the American University of Beirut, St Joseph University, and the Lebanese Council for National Scientific Research. The serum 25(OH)D assay by LCMS/MS was made in part possible thanks to an institutional grant from the Mayo Clinic, Rochester, Minnesota, USA. Research reported in this publication was in part supported by the Fogarty International Center and Office of Dietary Supplements of the National Institutes of Health under Award Number D43 TW009118; PI Ghada El-Hajj Fuleihan. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

**Clinical Trial Information:** ClinicalTrials.gov registration number: NCT01315366.

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**Disclosures:** Authors have no conflict of interest to disclose.

**Data Availability:** Some or all data generated or analyzed during this study are included in this published article or in the data repositories listed in References.

REFERENCES


