Interlaboratory Trial for Measurement of Vitamin D and 25-Hydroxyvitamin D [25(OH)D] in Foods and a Dietary Supplement Using Liquid Chromatography—Mass Spectrometry

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ABSTRACT: Assessment of total vitamin D intake from foods and dietary supplements (DSs) may be incomplete if 25-hydroxyvitamin D [25(OH)D] intake is not included. However, 25(OH)D data for such intake assessments are lacking, no food or DS reference materials (RMs) are available, and comparison of laboratory performance has been needed. The primary goal of this study was to evaluate whether vitamin D3 and 25(OH)D3 concentrations in food and DS materials could be measured with acceptable reproducibility. Five experienced laboratories from the United States and other countries participated, all using liquid chromatography tandem—mass spectrometry but no common analytical protocol; however, various methods were used for determining vitamin D3 in the DS. Five animal-based materials (including three commercially available RMs) and one DS were analyzed. Reproducibility results for the materials were acceptable. Thus, it is possible to obtain consistent results among experienced laboratories for vitamin D3 and 25(OH)D3 in foods and a DS.

KEYWORDS: reference material, food, dietary supplement, vitamin D3 (cholecalciferol), 25-hydroxyvitamin D3 (25-hydroxycholecalciferol)

INTRODUCTION

Vitamin D deficiency is a worldwide concern because of its major health consequences, including rickets and the postulated increased risk of other diseases.1–3 Numerous epidemiological evaluations of vitamin D intake and vitamin D status have been reported, as have studies on the relationship of these factors with occurrence of various diseases.4–9 Humans and animals obtain vitamin D3 (cholecalciferol) from dietary sources and from synthesis when 7-dehydrocholesterol in the skin is exposed to UV light.10 Vitamin D3 is the primary form in the diet, although vitamin D2 (ergocalciferol) can be present in some foods and supplements.5–7,10–13 These “parent” compounds of vitamin D are metabolized by humans and animals to 25(OH)D and other metabolites before they are used by the body. Therefore, animal tissue—and, in turn, animal-derived human foods—contain 25-hydroxyvitamin D [25(OH)D] as well as the parent vitamin D, and the 25(OH)D can contribute to the overall vitamin D value of the food. In fact, evidence suggests that the content of 25(OH)D may be 2–5 times more potent than the content of parent vitamin D.10–12 Therefore,
accurate estimates of dietary vitamin D intake require the inclusion of the 25(OH)D content of foods.\textsuperscript{13}

Current estimates of vitamin D intake suggest that many people in the United States consume considerably less than the established dietary requirement.\textsuperscript{14} The serum 25(OH)D concentrations of the U.S. population, an indicator of vitamin D status, are higher than expected on the basis of estimated vitamin D intakes alone.\textsuperscript{15,16} Although sun exposure is often cited as a major factor in this discrepancy, another possibility is the failure to account for intakes of 25(OH)D in foods. This potentially important omission could result in a significant underestimation of vitamin D intake because the reliability of calculated vitamin D intake rests heavily on the trueness and availability of food composition data,\textsuperscript{15} which do not typically include 25(OH)D assessments. For example, information on vitamin D in the major source of food composition data in the United States, the U.S. Department of Agriculture’s (USDA’s) National Nutrient Database for Standard Reference,\textsuperscript{17} is currently being updated,\textsuperscript{18} but it does not provide 25(OH)D values. Some limited data on the 25(OH)D content of foods are available in other databases outside the United States,\textsuperscript{19,20} but the lack of data in the United States on 25(OH)D\textsubscript{3} in foods and the extent to which dietary 25(OH)D\textsubscript{3} contributes to vitamin D status merit further exploration.

In addition to limited 25(OH)D measurements in food composition data, the lack of reliable food composition data on vitamin D is also due to uncertainty about the accuracy (trueness and precision) of the methods used to generate such data. Furthermore, obtaining reliable estimates of average concentrations in foods and sources of variability in the food supply, as well as in dietary supplements (DSs), requires representative sampling, validated analytical methods, expert analysts, and accredited, documented quality-control measures. In the 1990s and early 2000s, the methodology for quantification of vitamin D\textsubscript{3} and 25(OH)D\textsubscript{3} used high-performance liquid chromatography (HPLC) with UV detection, which necessitated time-consuming cleanup steps to obtain accurate results.\textsuperscript{21,22} Recent progress has been made in the development of methodology for the quantitation of vitamin D in foods using liquid chromatography–tandem mass spectrometry (LC-MS/MS) for measurements of vitamin D\textsubscript{3} and 25(OH)D\textsubscript{3}.\textsuperscript{23–27}

When published values from different studies are compared, variability due to real differences in food composition versus those due to differences in analytical methodology and skill in assay performance cannot be discerned in the absence of common control or reference samples. In a 2008 study\textsuperscript{28} that quantified vitamin D\textsubscript{3} in the same five food matrices at six experienced laboratories, each using their standard in-house methodology, the results showed various degrees of difference among the foods and laboratories. Whether this variability was due to differences in the methods used and/or individual skills in laboratory procedures is an open question. Differences in matrix and analyte levels can affect assay performance even when the same basic methodology is used. Therefore, control and reference materials representing different food matrices are needed to ensure the trueness and precision of quantitative results across a wide spectrum of foods.

The first specific aim of this study was to determine whether vitamin D\textsubscript{3} and 25(OH)D\textsubscript{3} concentrations in a range of animal-based food matrix materials and a DS could be measured with acceptable reproducibility by laboratories that are experienced in vitamin D analysis, without a common analytical protocol. The secondary aim was to assess the potential for the use of the materials as control or reference materials in future research.

\section*{MATERIALS AND METHODS}

\subsection*{Overview.} Through an interagency agreement between the Nutrient Data Laboratory (NDL; Beltsville, MD, USA) of the USDA’s Agricultural Research Service and the Office of Dietary Supplements of the National Institutes of Health (Bethesda, MD, USA), NDL designed and conducted a pilot study that measured vitamin D and 25(OH)D levels in foods and a DS. A “roundtable” group of five experts identified and critically evaluated scientific issues related to sample selection, preparation, distribution, and tracking as well as laboratory participation and evaluation of results. The roundtable members were representatives from Health Canada (Longueuil, Quebec, Canada), U.S. Food and Drug Administration (College Park, MD, USA), National Institute of Standards and Technology (NIST; Gaithersburg, MD, USA), and USDA’s Food Composition and Method Development Laboratory (Beltsville, MD, USA). In addition, scientists from the Office of Dietary Supplements participated in the roundtable discussions. Five animal-based foods and one DS were selected by NDL in consultation with the roundtable group. Samples were prepared at a central location and distributed to each laboratory on two occasions for analysis of vitamin D and 25(OH)D contents.

\subsection*{Identification of Participating Laboratories.} NDL identified analytical laboratories with expertise in measuring vitamin D and 25(OH)D in various matrices. These laboratories had either published their vitamin D methodology or had previously provided NDL with vitamin D data that met data quality evaluation standards.\textsuperscript{29} The participating laboratories were Covance Laboratories (Madison, WI, USA), Health Canada (Longueuil, Quebec, Canada), Heartland Laboratories (Ames, IA, USA), NIST (Gaithersburg, MD, USA), and the Technical University of Denmark (Seborg, Denmark). All of the laboratories were using LC-MS/MS for separation, detection, and quantitation but varied analytical protocols to analyze vitamin D and 25(OH)D contents. Two of the laboratories also had experience analyzing DSs for vitamin D content. The five laboratories are identified in this report using randomly assigned letters A–E.

\subsection*{Selection of Food Samples.} Standard animal-based food reference materials from NIST that could contain 25(OH)D\textsubscript{3} were initially considered for the study, including NIST Standard Reference Material (SRM) 1577c Bovine Liver, NIST SRM 1546a Meat Homogenate, and NIST SRM 1845a Whole Egg Powder.

Foods included in the initial screening were cooked chicken liver, cooked beef liver, rotsisserie chicken with skin, a cooked pork and egg yolk composite, and cooked ground beef. The materials chosen for screening represented a variety of food matrices with potential for measurable levels of 25(OH)D.

NDL collaborated with scientific partners at Virginia Tech (Blacksburg, VA, USA) to screen these materials and samples of other foods for vitamin D\textsubscript{3} and 25(OH)D\textsubscript{3} contents. A homogeneous composite of locally procured (Blacksburg, VA, USA) retail samples of chicken liver, beef liver, and rotsisserie chicken was prepared for each of these three foods using validated protocols.\textsuperscript{30,31} The ground beef and the pork and egg yolk samples had been previously prepared using the same protocols for use as control materials in the USDA National Food and Nutrient Analysis Program.\textsuperscript{30} Subsamples of all composites were maintained in glass jars, sealed under nitrogen at ~60 °C and protected from light. The frozen samples were shipped on dry ice via express overnight delivery to Covance Laboratories, where they were analyzed for vitamin D\textsubscript{3} and 25(OH)D\textsubscript{3} contents.

The screening results were evaluated by the roundtable experts who selected the following materials to represent a range of expected vitamin D\textsubscript{3} and 25(OH)D\textsubscript{3} concentrations and diverse matrices in this study: NIST SRM 1577c Bovine Liver; NIST SRM 1546a Meat Homogenate; NIST SRM 1845a Whole Egg Powder; cooked chicken liver; and cooked ground beef. The roundtable experts selected these materials because they were sufficiently diverse to represent variability in method performance based on specific matrix characteristics that...
Table 1a. Methodology Used by Participating Laboratories To Analyze Vitamin D Content in Foods and 25(OH)D Content in Foods and a Dietary Supplement

| Method reference | Laboratory A | Laboratory B | Laboratory C | Laboratory D | Laboratory E |
|------------------|--------------|--------------|--------------|--------------|--------------|
| Sample size      | 3 g to 10 g depending on moisture content | 0.8 g to 3 g depending on moisture content | 0.6 g to 2 g | 1 g | Not available |
| Internal standard | (2H)itamin D$_3$ and (2H)$_2$25(OH)D$_3$ (IsoSciences, King of Prussia, PA) | (2H)$_2$vitamin D$_3$ and (2H)$_2$25(OH)D$_2$ (Chromaphor, Ottawa, Canada) | (2H)$_2$vitamin D$_3$ and (2H)$_2$25(OH)D$_2$ (Chromaphor, Ottawa, Canada) | (2H)$_2$vitamin D$_3$ and (2H)$_2$25(OH)D$_2$ (Chromaphor, Ottawa, Canada) | Not available |
| Initial treatment | reagent-grade alcohol with 2 % pyroglycolic acid, 50 % KOH added | methanoic KOH | sodium ascorbate, KOH, and ethanol | lipase and ethanol | enzymatic digestion for 2 hours at 37°C |
| Lipid treatment  | saponification under N$_2$ overnight | saponification under N$_2$ at room temperature overnight | saponification under N$_2$ at room temperature for 16-18 hours | 2X hexane extracted, pooled, with addition of ~1g MgSO$_4$, to remove extra water; centrifuged; and dried |
| Extraction step   | solution of 30 ml 20 % ether and 80 % hexane | 3x hexane/ethyl acetate (65/15) | ethyl acetate/n-heptane (20/80) | | |
| Clean-up step     | dried and redissolved in 1 mL 70 % acetonitrile-H$_2$O [not done for 25(OH)D] | dried and redissolved in 1 mL hexane/methylene chloride | loaded into an SPE cartridge, eluted with methylene chloride/isopropanol, two cleanings through HPLC columns, final solution methylene chloride and isopropanol | | |
| Additional clean-up | | purified using HPLC normal phase (silica column) and fractions collection | | | |
| Derivatization    | evaporated to dryness and 2 mg/mL PTAD in 100 % ACN added. | fractions evaporated to dryness, PTAD reagent in ethyl acetate added, evaporated to dryness, reconstituted in 0.2 mL of methanol | | | |
| HPLC column       | Thermo, UHPLC column, Hypersil GOLD aq (1.9mm) 100 mm x 2.1 mm | Phenomenex LUNA-C18 (3.0 µm) 150 mm x 2.1 mm | SupelcoSil LC-18 ODS column (5µm) 3.3 cm x 4.6 mm | Ascentis Express C18 (2.1 mm x 10 cm, 2.7 µm particles) column and C18 (2.1 x 5 mm, 2.7 µm particles) guard column | YMC-Pack Pro C18 RS (5µm,80mm) 150 mm x 4.8 mm |
| HPLC separation   | mobile phase: (1) 0.1 % formic acid, 20 % MeOH in ultrapure water; (2) 0.1 % formic acid in methanol | mobile phase: (1) ACN/55 % H$_2$O; (2) methanol, both with 2 mM ammonium acetate and 0.04 % formic acid | mobile phase: (1) Milli-Q water, methanolamine (5 mM), and formic acid (0.1 %); (2) methanol, methylamine (5 mM), and formic acid 0.1 % | mobile phase: (1) water, (2) methanol | |
| Quantification    | 4000 LC-MSMS System (Sciex): triple quadrupole tandem mass spectrometer | LC-Agilent 1100 with binary pump coupled to an Agilent 6460 triple quadrupole LC/MS/MS system operated in positive MRM mode | LC-Agilent 1200 UHPLC system coupled to an Agilent 6460 triple quadrupole LC/MS/MS system operated in positive MRM mode | Agilent 6410B MS/MS system, APCl, positive ionization mode | |
| Ion Masses$^a$   | $D_4$: 560 (383, 298, 280) 25(OH)D$_3$: 558 (298, 280, 247) 25(OH)D$_2$: 572 (298, 250) N/A | D$_2$: 256 (298, 280) 25(OH)D$_3$: 256 (298, 280) 25(OH)D$_2$: 256 (298, 280) | D$_2$: 256 (298, 280) 25(OH)D$_3$: 256 (298, 280) 25(OH)D$_2$: 256 (298, 280) | D$_2$: 256 (298, 250) 25(OH)D$_3$: 256 (298, 280) 25(OH)D$_2$: 256 (298, 280) | D$_2$: 256 (298, 250) 25(OH)D$_3$: 256 (298, 280) 25(OH)D$_2$: 256 (298, 280) | |
| Limit of quantification | Vitamin $D_3/D_2$: 0.05/0.20 µg/100g; 25(OH)D$_3$: 0.012 µg/100g | high moisture: 0.08 ng/g, low moisture: 0.2 ng/g | 0.5 ng/g | <0.1 ng/g | 0.20/0.7 ng/g |

$^a$Masses in parentheses are the product ions.

$^b$Abbreviations: HPLC, high-performance liquid chromatography; SPE, solid-phase extraction; PTAD, 4-phenyl-1,2,4-triazole-3,5-dione; ACN, acetonitrile; UHPLC, ultrahigh-performance liquid chromatography; MS/MS, tandem mass spectrometry; ESI, electrospray ionization; MRM, multiple reaction monitoring.
might affect extraction and quantitation [e.g., fat content, concentration of vitamin D₃ and 25(OH)D₃] and animal tissue type (e.g., muscle, liver, or egg)].

**Selection of the DS.** The DS product for this study was selected with the aim of developing a DS in-house control material. Scientists on the Dietary Supplement Ingredient Database team at NDL studied current vitamin D₃ supplements on the market, evaluating claimed composition and manufacturing information for both animal- and non-animal-based vitamin D₃ supplements (Supplemental Table 1). Their goal was to purchase supplements that represented a diversity of vitamin D source materials, production methods, matrices, and supplement strength (vitamin D₃ labeled content) and test them for 25(OH)D₃ content. On the basis of these criteria, six products sold as DS products sold with vitamin D₃ content claims were indicated that all six DS products sold with vitamin D₃ content claims contained 25(OH)D₃ at levels similar to those in the foods tested for inclusion in the study. However, their 25(OH)D₃ levels were minute compared to the amount of vitamin D₃ in the products. The label of the product ultimately chosen for the study claimed that it contained 25(OH)D₃ at levels similar to those in the foods tested for 25(OH)D₃ content. On the basis of these criteria, six products sold as DS products with vitamin D₃ content claims were chosen for preliminary analyses. These products had a wide range of labeled vitamin D content per serving (from 0 to 12,500 IU). Subsamples of 90 units of each product were placed in amber plastic bottles with desiccant packs, sealed under ambient conditions, and shipped by overnight delivery to Covance Laboratories for screening analysis of vitamin D₃ and 25(OH)D₃ content.

The screening results (presented in Supplemental Table 2) also indicated that all six DS products sold with vitamin D₃ content claims contained 25(OH)D₃ at levels similar to those in the foods tested for inclusion in the study. However, their 25(OH)D₃ levels were minute compared to the amount of vitamin D₃ in the products. The label of the product ultimately chosen for the study claimed that it contained 2000 IU vitamin D₃/serving, a level commonly taken by the U.S. population. This product also contained a measurable amount of 25(OH)D₃. It was a private-brand softgel capsule sold in warehouse stores and was produced using a common manufacturing process of lanolin recrystallization. Thus, purchasing this product by the case might a...
Statistical Methods. Results for each material included the replicate values for both trials from all laboratories. Data analysis was performed using PROLAB Plus software (QuiData Quality & Statistics, Dresden, Germany). Analyses included calculations of reproducibility relative standard deviations (RSDs) and repeatability RSDs for each material according to ISO 5725-2. The reproducibility RSD expresses the precision of the average of the results from different laboratories and was calculated using the SD between the averages of replicate measurements by each laboratory in each trial. On the basis of the probability of detection (POD) model, predicted reproducibility RSD is calculated as \( 2 \times C^{-0.15} \), where \( C \) is a mass fraction of analyte, and estimated RSD is expressed as percent. Predicted repeatability RSD is considered to be half of this value. As the concentration decreases, the POD decreases and predicted RSD increases, as illustrated by the Horwitz curve.

The repeatability RSD for each material expresses the variability between independent test results obtained within each laboratory. In this study, the repeatability RSD was calculated using the SD between the replicate measurements of each laboratory within each trial (the square root of the sum of the squares of the within-laboratory SD divided by 2, followed by multiplication by the number of laboratory/trials) as an estimate of overall within-laboratory variability for each analyte in each sample.

The Horwitz ratio (HorRat) was used to evaluate the reproducibility RSDs from data provided by the different laboratories for the materials. The HorRat indicates the acceptability of the reproducibility of interlaboratory measurements, taking into consideration the analyte concentration. This ratio is the RSD of the mean divided by a predicted reproducibility RSD based on the concentration of the analyte. An acceptable HorRat is \( \leq 2.0 \).

Outliers were identified using the Cochran test (analysis of variance) and Grubbs test (analysis of mean value deviations) according to ISO 5725-2. Because the purpose of this study was to evaluate both inter- and intralaboratory variability for each material, the outliers identified from these tests were not excluded from calculation of overall mean and SD. One exception, however, was a value identified as an outlier by the Grubbs test that had already been manually excluded as a result of the analyst’s data evaluation (laboratory D’s vitamin D3 measurement of the meat homogenate in trial 1). This outlier is explained under Results.

RESULTS

Analytical Methods Used for Foods. After receipt of trial 1 data, it was evident that results from laboratory E differed markedly from those of the other laboratories. Laboratory E was not given details on the results from the other laboratories. However, because this laboratory had experience primarily in determining vitamin D and 25(OH)D levels in serum, the laboratory optimized its method to measure these analytes in food matrices before analyzing additional study samples. A new set of samples was then sent to laboratory E, which reported values for the meat homogenate, ground beef, and liver samples. Laboratories A, B, C, and E analyzed each food material in triplicate (three subsamples from the same mixture on the same day), and laboratory D submitted duplicate data.

Table 1a summarizes the methodology used by each laboratory. All laboratories used LC-MS/MS to quantify vitamin D3 and 25(OH)D3 levels without using a common sample preparation protocol. The laboratories labeled their internal standards in varied ways as well, using, for example, deuterium, tritium, or carbon-13. All laboratories calibrated their standards before use, which is important for obtaining accurate results. They also optimized their methodologies to measure the low concentrations of 25(OH)D in the foods and DS of vitamin D in the foods. Laboratories A, B, D, and E derivatized the samples prior to LC-MS/MS analysis, but laboratory C did not. Another significant difference was that laboratory E did not saponify the samples but used an enzymatic digestion with lipase prior to LC-MS/MS analysis. Laboratory E indicated that its method had not been sufficiently validated for eggs and supplements, so it did not report results for those materials. In addition, laboratory D’s analyst indicated concern about the validity of the vitamin D3 value for the meat homogenate when reporting its trial 1 results. Therefore, laboratory D’s data were excluded from these study results.

Analytical Methods Used for the DS. The DS was analyzed by laboratories A, B, and C (Tables 1a and 1b). Laboratory A analyzed the fill contents, whereas laboratories B and C analyzed whole softgels. Laboratories A and C analyzed the DS in triplicate. Laboratory B submitted one value for trial 1 and values from duplicate analysis for trial 2. Laboratory C conducted both of its trials for 25(OH)D3 on the same day, rather than 2 months apart. Because laboratory C used a separate set of material and assay batches for each sample set, the data are reported here for two separate trials, even though...
the assays were not separated in time as was the case at the other laboratories. Because the 25(OH)D3 content of the DS was similar to that of the foods, the laboratories measured it as described in Table 1a. The DS’s vitamin D3 content was orders of magnitude higher than its 25(OH)D3 content and the vitamin D3 in foods. As a result the laboratories optimized their methodologies to measure the high levels of vitamin D3 in the DS (Table 1b). Laboratory B used LC-MS/MS to measure vitamin D3 but did not derivatize the sample (because it is not necessary for high levels), whereas laboratories A and C used high-performance liquid chromatography−UV (a less sensitive detection method).

Vitamin D3 and 25(OH)D3 Results for the Food Materials. Figure 1 and Table 2a summarize the results for vitamin D3 and 25(OH)D3 levels in the foods analyzed. The mean assayed vitamin D3 concentrations ranged from 0.043 μg/100 g (dried bovine liver) to 4.49 μg/100 g (whole egg powder). The mean vitamin D3 levels in the meat homogenate, whole egg powder, and chicken liver were higher than the corresponding 25(OH)D3 levels in these foods, and the 25(OH)D3 levels were higher than the vitamin D3 levels in the dried bovine liver and ground beef.

The mean assayed 25(OH)D3 concentrations ranged from 0.093 μg/100 g (meat homogenate) to 0.29 μg/100 g (whole egg powder). The mean vitamin D3 level of <0.05 for dried bovine liver (NIST 1577c) in trials 1 and 2, which is lower than the laboratory’s limit of quantification. Therefore, these values were omitted from mean and SD calculations. Laboratory C conducted both of its trials on the same day, not 2 months apart as the other laboratories did. Laboratory D indicated uncertainty about the quality of its data on meat homogenate (NIST 1546a). Therefore, this value was considered an outlier and excluded from the results reported here.

The reproducibility for vitamin D3 ranged from 8% (ground beef) to 58% RSD (dried bovine liver; predicted reproducibility RSD for this low analyte concentration is 51.28%). The corresponding HorRat values were all acceptable, ranging from 0.2 to 1.1. Repeatability for vitamin D3 ranged from 2.8% RSD (whole egg powder) to 38.7% RSD (dried bovine liver; predicted repeatability RSD for this low analyte concentration is 25.64%, Table 2a).

The reproducibility for 25(OH)D3 ranged from 8.3% RSD (chicken liver) to 23.5% RSD (ground beef). The HorRat values ranged from 0.2 (chicken liver) to 0.6 (ground beef). Repeatability for 25(OH)D3 ranged from 3.4% RSD (chicken liver) to 15.6% RSD (ground beef; Table 2a).

Vitamin D3 and 25(OH)D3 Results for the DS. The mean assayed concentration of vitamin D3 in the DS was 56,400 μg/100 g. The mean 25(OH)D3 value was 1.82 μg/100 g, which was comparable to the levels found in the foods. The mean vitamin D3 amount for the DS in this study was 14.8% above the labeled level [% difference for screened supplements ranged from 10.8 to 57.5% (see Supplemental Table 2)]. Reproducibility was 12.7% RSD for vitamin D3 and 45.1% RSD for 25(OH)D3. Repeatability was 2.9% RSD for vitamin D3 and 14.8% RSD for 25(OH)D3. For comparison, predicted reproducibility and repeatability RSDs for 25(OH)D3 were 40.93 and 20.46%, respectively. However, the three laboratories handled the DS differently. Two laboratories dissolved the capsules and provided the data in micrograms per 100 g (whole capsule). The other laboratory cut the capsules open, emptied the contents, and provided the data in micrograms per 100 g of the capsules.
fill as well as the total weights of the fill and capsule shell. The weight data were applied to the first laboratory’s results to calculate the results in micrograms per 100 g of fill for direct comparison. For the DS results reported based on fill weight, the HorRat values were 2.1 for vitamin D₃ and 1.6 for 25(OH)D₃ (see Table 2a). The HorRat values for the DS results based on the weight of the whole capsule were 1.8 and 1.3, respectively (see Supplemental Table 3).

**Vitamin D₂ and 25(OH)D₂ Results for the Foods and DS.** Only three laboratories reported results for vitamin D₂ and 25(OH)D₂ levels, and only laboratory B reported values for vitamin D₂ and 25(OH)D₂ in all materials. Therefore, results for vitamin D₂ and 25(OH)D₂ are provided for descriptive purposes only, and only values above the limit of quantitation are reported (Table 2b). The vitamin D₂ level reported by laboratory B was below the limit of quantitation in all materials except ground beef, and 25(OH)D₂ was only measurable in ground beef and dried bovine liver. The vitamin D₂ and 25(OH)D₂ levels reported by laboratory B were lower than those of vitamin D₃ and 25(OH)D₃ (<0.1 μg/100 g).

### DISCUSSION

For the foods in this study, the HorRat values for vitamin D₃ and 25(OH)D₃ (ranging from 0.2 to 1.1) demonstrated acceptable between-laboratory reproducibility at the analyte concentration present for all of the matrices (ground beef, chicken liver, whole egg powder, meat homogenate, and dried bovine liver). In our study, the low repeatability RSDs for vitamin D₃ and 25(OH)D₃ seen in all of the matrices except vitamin D₂ in bovine liver, suggest that the laboratories had consistent within-laboratory results and, thus, acceptable within-laboratory precision for all study materials. Therefore, our study shows that it is possible to obtain results with acceptable overall reproducibility among experienced laboratories using LC-MS/MS to measure levels of vitamin D₃ and 25(OH)D₃ for a variety of food matrices having naturally occurring vitamin D₃ and 25(OH)D₃.

For the DS, the three laboratories demonstrated that they were able to measure vitamin D₃ at high levels as well as very low levels of 25(OH)D₃. The HorRat values of 2.1 and 1.8 for vitamin D₃ and 1.6 and 1.3 for 25(OH)D₃ indicate acceptable or close to acceptable reproducibility relative to the analyte concentration. The elevated RSDs obtained experimentally are close to theoretically predicted RSDs at such low analyte concentrations, and this is reflected in acceptable HorRat ratios. For example, the % RSD for the very low level 25(OH)D₃ in bovine liver seems very high. However, it is an acceptable RSD because as the concentration decreases, the predicted RSD increases, as illustrated by the Horwitz curve.37

The amount of 25(OH)D₃ in the vitamin D supplement was very low but was consistently present in all DSs analyzed in the screening and in the study. Vitamin D levels above label claims (averages) were seen in the DSs selected for this study and in the products screened for inclusion in this study. Manufacturers may add ingredient overages to provide the minimum content stated on the label at the end of the product shelf life.39

Vitamin D₂ and 25(OH)D₂ were found in small quantities in ground beef and bovine liver, with acceptable HorRat ratios, although our study’s focus was on measuring vitamin D₃ and 25(OH)D₃. Future studies need to identify whether different samples of beef in the food supply have variable vitamin D₂ content and identify sources of vitamin D₂ in food samples such as components of animals’ diets.

The source of 25(OH)D₃ in meat, poultry, and eggs could be due to the animal’s exposure to UV light, resulting in in vivo production of vitamin D₃ or derived from the animal’s feed containing vitamin D₃ or 25(OH)D₃. Thus, variation in animal diet and environment can affect vitamin D₃ and 25(OH)D₃ levels in animal-based foods.48 Unfortunately, data on the 25(OH)D₃ content of foods are limited and existing data can vary greatly.48

**Table 2b. Vitamin D₂ and 25(OH)D₂ in Dried Bovine Liver and Ground Beef Measured by Three Participating Laboratories**

|                  | Laboratory B | Laboratory D | Laboratory E |
|------------------|--------------|--------------|--------------|
| mean Vitamin D₂  | <0.01        | 0.08         | 0.08         |
| mean 25(OH)D₂    | 0.071        | 0.053        | 0.0435       |
| dried bovine liver (NIST 1577c) |
| mean Vitamin D₂  | <0.03        | 0.07         | 0.07         |
| mean 25(OH)D₂    | 0.078        | 0.040        | 0.044        |
| dried ground beef (NIST 1577c) |
| mean Vitamin D₂  | 0.055        | 0.063        | 0.060        |
| mean 25(OH)D₂    | 0.055        | 0.040        | 0.044        |
| dried ground beef (NIST 1577c) |
| mean Vitamin D₂  | 0.033        | 0.040        | 0.038        |
| mean 25(OH)D₂    | 0.184        | 0.063        | 0.060        |
| dried ground beef (NIST 1577c) |

Shaded cells indicate no data reported or not applicable. Values for foods in this table represent means from triplicate analyses within trials reported by laboratories B and E and duplicate analyses from laboratory D. Abbreviations: NIST, National Institute of Standards and Technology (Gaithersburg, MD, USA); < , value below laboratory’s limit of quantitation; SD, standard deviation; RSD, relative standard deviation.

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acceptable for all materials, some systematic bias between laboratories could have affected the comparison of nutrient content results for foods analyzed at different laboratories.

Continued efforts to determine amounts of vitamin D and 25(OH)D in foods and supplements using validated methodologies and well-characterized control and reference materials will help answer questions about discrepancies between circulating amounts of 25(OH)D in the body and vitamin D intakes calculated from composition data for foods and DSs. These endeavors can also help ensure that public health policy decisions about vitamin D are based on accurate estimates of intake.

■ ASSOCIATED CONTENT

1 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jafc.5b05016.

- Descriptions and analytical results of seven dietary supplements screened for vitamin D3 and 25(OH)D3 and per-capsule analytical results from three laboratories for the dietary supplement (PDF)

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Notes

Trade names are included for the reader’s information only and are not meant to imply endorsement or preferential treatment by the U.S. government. The authors declare no competing financial interest.

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■ ABBREVIATIONS USED

25(OH)D, 25-hydroxyvitamin D; DS, dietary supplement; USDA, U.S. Department of Agriculture; LC-MS/MS, liquid chromatography–tandem mass spectrometry; NDL, Nutrient Data Laboratory; NIST, National Institute of Standards and Technology; SRM, standard reference material; RSD, relative standard deviation; HorRat, Horwitz ratio

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