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Title: Evidence of low vitamin D intakes in the Australian population points to a need for data-driven nutrition policy for improving population vitamin D status

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Bio

Eleanor (Ellie) Dunlop is a dietitian, research associate and final-year PhD student, focusing on food composition. She currently contributes to projects that investigate dietary vitamin D in the general Australian and Aboriginal and Torres Strait Islander populations. Ellie also works on a Hort Innovation project to update food composition data for Australian-grown fruit and vegetables, and other projects investigating the role of diet in the risk and progression of multiple sclerosis.

Key points

- We quantified usual intakes of vitamin D in the Australian population using up-to-date, comprehensive vitamin D composition data and nationally representative food consumption data
- Mean usual intakes ranged between 1.8 and 3.2 µg/day, assuming equal bioactivity of the D vitamers
- We estimated that more than 95% of the population had inadequate vitamin D intakes compared to the Estimated Average Requirement (10 µg/day) recommended by the Institute of Medicine
- This new evidence of low vitamin D intakes, together with high prevalence of vitamin D deficiency in Australia, suggests that data driven nutrition policy is required to safely increase intakes of vitamin D and improve vitamin D status at the population level.

Abstract

Background: Nearly one in four Australian adults are vitamin D deficient (serum 25-hydroxyvitamin D concentrations (25(OH)D) <50 nmol/L) and current vitamin D

intakes in the Australian population are unknown. Internationally, vitamin D intakes are commonly below recommendations, although estimates generally rely on food composition data that do not include 25(OH)D.

Objective: We aimed to estimate usual vitamin D intakes in the Australian population.

Design: Nationally-representative food consumption data were collected for Australians aged ≥2 years (*n*=12,153) as part of the cross-sectional 2011-2013 Australian Health Survey (AHS). New analytical vitamin D food composition data for vitamin D_3, 25(OH)D_3, vitamin D_2 and 25(OH)D_2 were mapped to foods and beverages that were commonly consumed by AHS participants. Usual vitamin D intakes (µg/day) by sex and age group were estimated using the National Cancer Institute method.

Results: Assuming a 25(OH)D bioactivity factor of one, mean daily intakes of vitamin D ranged between 1.84 and 3.25 µg/day. Compared to the Estimated Average Requirement (EAR) of 10 µg/day recommended by the Institute of Medicine, more than 95% of people had inadequate vitamin D intakes. We estimated that no participant exceeded the Institute of Medicine's Upper Level of Intake (63-100 µg/day, depending on age group).

Conclusions: Usual vitamin D intakes in Australia are low. This evidence, paired with the high prevalence of vitamin D deficiency in Australia, suggests that data-driven nutrition policy is required to safely increase dietary intakes of vitamin D and improve vitamin D status at the population level.

Keywords: 25-hydroxyvitamin D; Australia; food; usual intakes; vitamin D

Introduction

Vitamin D deficiency (serum 25-hydroxyvitamin D (25(OH)D) concentrations <50 nmol/L [(1)]) affects many Australians (20% of adults aged ≥25 years [(2)], 32% of young adults aged 18-24 years, and 17% adolescents aged 12-17 years [(3)]). To date, there has not been an assessment of usual vitamin D dietary intakes in the Australian population using comprehensive vitamin D food composition data and nationally-representative food consumption data. Elsewhere, vitamin D intakes fall short of recommendations. In the US [(4)], Canada [(5)] and many European countries [(6; 7; 8)], estimated mean intakes of vitamin D are ≤5 µg/day, which is considerably lower than the Estimated Average

Requirement (EAR) of 10 µg/day recommended by the Institute of Medicine [9]. Those estimates, however, do not appear to have accounted for the contribution of all D vitamers that may be present in food [10; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20], particularly 25-hydroxyvitamin D (25(OH)D) which is present in some foods, and may be more biologically active than vitamin D itself [21].

Previous estimates of Australian vitamin D intakes were low (2-3 µg/day) [22; 23], but were based on very limited vitamin D food composition data and/or used data produced using outdated analytical methods. The high prevalence of vitamin D deficiency reported recently [1; 2; 3] suggests that intakes are too low to compensate for inadequate safe sun exposure. This is because naturally rich food sources of vitamin D are uncommon and few food products are fortified with vitamin D in Australia. Fortification has been suggested as a potential solution to low vitamin D status [6; 7; 24; 25]. In the Finnish population, vitamin D intakes from food alone were approximately doubled following addition of vitamin D to fluid milk products and fat spreads, and the prevalence of people with serum 25(OH)D concentrations <50 nmol/L decreased from 56% in 2000 to 9% in 2011 [26]. However, dietary strategies to improve vitamin D status in the Australian population cannot be modelled without an accurate estimate of usual baseline intakes.

The 2011-12 National Nutrition and Physical Activity Survey (NNPAS) provides the most comprehensive and nationally-representative food and dietary supplement consumption data in Australia to date. These food consumption data and the serum 25(OH)D concentrations used to estimate the prevalence of vitamin D deficiency were collected during the same period; therefore, it is relevant to consider them together. However, vitamin D intakes were not estimated due to a lack of locally-relevant vitamin D food composition data [27]. Recently, Australia's first comprehensive analytical vitamin D food composition database was produced [28] using liquid chromatography with triple quadrupole mass spectrometry, a highly sensitive and specific method for measurement of D vitamers. Hence, we aimed to provide the first estimates of usual vitamin D intakes in a nationally-representative sample of the Australian population, and to identify the major food sources of vitamin D, based on new comprehensive vitamin D food composition data.

Methods

We used nationally-representative food (including beverages) and dietary supplement consumption data and new analytical vitamin D food composition data to estimate

vitamin D intakes in the Australian population using either the National Cancer Institute (NCI) method (for usual intakes of food; Figure 1) or a determinisitic method (including dietary supplements).

Study population

The Australian Health Survey 2011-2013 (AHS) provided the most recent nationally representative health-related data for the Australian population [29]. Usual residents of metropolitan and rural private dwellings were eligible. An area-based sampling approach was adopted to ensure geographically representative sampling. Approximately 35,000 households were selected with the aim of achieving ~26,000 fully-responding households, allowing for non-response and sample attrition (Supplementary Figure 1). Core demographic, household and other general information (published previously [30]) were collected for one adult or one adult plus one child from 25,080 households. Participants were then allocated to either the National Health Survey (*n*=20,426), which focused on health status and conditions, or the NNPAS (*n*=12,153), which included a food consumption component.

Food consumption data

Food and dietary supplement consumption data were collected for Australians aged ≥2 years by trained Australian Bureau of Statistics (ABS) interviewers. Food consumption collection methods have been described in detail by the ABS [29]. In summary, the USDA Dietary Intake Data System [31] was used to collect and code food consumption data. This digital system comprises the Automated Multiple-Pass Method [32] for 24-hour dietary recall, the Post Interview Processing System (PIPS) and Survey Net. The Automated Multiple-Pass Method was modified by the ABS in collaboration with Food Standards Australia New Zealand (FSANZ) to represent foods consumed in Australia. Participants were invited to complete two 24-hour dietary recalls: the first was conducted during an in-person interview (*n*=12,153) and the second by telephone call (completed by 64% of participants, *n*=7,735). Where possible, the second interview was scheduled at least eight days after the first and on a different day of the week. These interviews were conducted under the *Census and Statistics Act 1905*. A responsible adult responded for all children aged <15 years and also for children aged 15-17 years where permission for self-response was denied by a parent or guardian. All data were recorded electronically during interviews. As respondents identified foods and dietary supplements that were consumed, questions specific to the type of these were prompted by the adapted Automated Multiple-Pass

Method program in order to determine details about the food and its preparation. The AHS Food Model Booklet [33] aided estimation of the amounts of foods consumed. Interview data were prepared and partially coded in PIPS. Final coding and calculation of the gram weight of consumed items were carried out in Survey Net, which incorporated a food measures database compiled by FSANZ for the AHS [27]. The coded data were imported into Harvest, FSANZ's custom-built dietary modelling software [34].

Vitamin D food composition data

Analytical vitamin D composition data were obtained as previously described [28]. In brief, a sampling plan was developed to include food products that were reported in the NNPAS as being commonly consumed (as per past nutrition surveys and knowledge of current market availability) or that were expected to contain vitamin D. Between August 2018 and June 2019, 896 primary food samples of 98 different food products were purchased in three cities representing both sides of the continent and where approximately half of Australia's population resides: Sydney (August 2018, 186 samples), Melbourne (October-December 2018, 516 samples) and Perth (April-June 2019, 194 samples). Products were purchased in one, two or three cities depending on the likelihood of high vitamin D concentration in the product, frequency of consumption and whether they are produced and used regionally or distributed nationally from one source. Primary samples were composited into 149 analytical samples each comprising six primary samples per food type per city, with the exception of dark chocolate, for which eight primary samples were combined. Vitamin D_3, 25(OH)D_3, vitamin D_2 and 25(OH)D_2 were analysed in duplicate using a liquid chromatography with triple quadrupole mass spectrometry method at the National Measurement Institute of Australia, a National Association of Testing Authorities-accredited laboratory for measurement of vitamin D in food. A detailed description of the analytical method has been published previously [28].

Calculating vitamin D equivalents from analytical food composition data

Vitamin D equivalents (VDE) were calculated by summing concentrations of the four D vitamers measured, assuming equal bioactivity. Currently, there is no consensus on a bioactivity factor for 25(OH)D [21]. Where it is included in national food composition databases, a bioactivity factor of either one or five is used. Hence, we estimated intakes using both bioactivity factors in order to allow comparison with other studies. Trace values, where the concentration of a nutrient is detected below the

limit of reporting (LOR) and cannot be quantitated with certainty, present a risk of under-estimation (if trace values are assigned a zero value) or over-estimation (if trace values are assigned the LOR value) of nutrient intakes. Trace values were, therefore, assigned a value of LOR/2 (LOR = 0.1 μg/100 g for all foods except those with a high fat content, for which the LOR was 0.25 μg/100 g).

Mapping analytical data to consumed foods

Australia's nutrition survey food composition database, AUSNUT [27], is used to estimate usual nutrient intakes based on food consumption data from the NNPAS. As vitamin D was not included in AUSNUT 2011-2013, we mapped our new analytical vitamin D data to AUSNUT food entries.

The process of mapping analytical concentrations to consumed foods was conducted using the same method as for Australian total diet studies [35; 36]. Mapping can consist of direct mapping of concentrations to foods, direct mapping with factors applied, or assigning a recipe. The 5,740 food entries in AUSNUT can be divided into two types: non-recipe foods (individual, staple-type foods, such as rice) and recipe foods (foods that contain more than one non-recipe food, such as fried rice). We manually assigned analytical D vitamer concentrations to all non-recipe foods, with the exception of oral nutritional supplements and meal-replacement products designed for weight loss (*n*=21), for which label data were used. Methods of data derivation were recorded together with details, such as label data source, where appropriate. The direct mapping with factors method allows the mapping of a food's analytical concentration to other relevant foods with an additional adjustment factor applied to account for food manufacturing or preparation practices such as dehydration or cooking in water [35]. For example, a conversion factor would be applied to the analytical value for powdered infant formula to derive a value for ready-to-drink infant formula [35]. Similarly, a conversion factor would be applied to the analytical value for apple to derive a value for apple juice [35].

Concentration values were derived for recipe foods using Harvest [34]. Harvest allows for multiple levels of nested recipes, i.e. a recipe within a recipe within a recipe. For example, a recipe for 'filled pasta with cheese sauce' contains 'filled pasta' and 'cheese sauce' as separate ingredients. These ingredients are in turn made from recipes. Harvest determines a nutrient concentration for the mixed food based on the nutrient concentrations for ingredient foods and the proportion of an ingredient within a recipe.

Estimating vitamin D concentrations for raw versions of analysed cooked foods

In order to sample as diverse a range of foods as possible with the available funds, we prioritised analysis of foods in the form that they are consumed, i.e. cooked meats, fish and seafood rather than raw; however, some recipe foods include raw versions of these foods as ingredients and, therefore, values for the raw food were estimated. Conversion factors, as explained in the previous section, were applied to cooked meat and seafood concentrations to derive values for raw versions to use in these recipes; however, this did not include retention factors as retention factors were not listed for vitamin D in the AUSNUT 2011-2013 data files [(27)]. Retention factors for different foods and cooking methods were published in 2002 [(37)]; however, there is limited up-to-date data on the retention of vitamin D in foods. A recent study examined retention factors for vitamin D in farmed Danish rainbow trout using eight different cooking methods and temperatures, finding that true retention of vitamin D ranged between 85 ± 6% and 114 ± 13% [(38)]. Hence, it is possible that the use of retention factors may introduce error rather than reduce it. In our study, omitting retention factors should have no major effect on intake estimates as the vitamin D concentration values used were derived from levels of vitamin D in foods as consumed.

Estimating intakes

Usual intakes of vitamin D were estimated using the NCI Method [(39)]. Implementation of the method was consistent with the approach taken by the ABS and FSANZ in estimating usual nutrient intakes for the NNPAS. Further information about this approach is available elsewhere [(29)].

In order to apply the NCI method, at least two dietary intakes for a subset of survey respondents are required. Using the NNPAS 24-hour dietary recall data and our new vitamin D food composition data, vitamin D intakes for each respondent for either day one only, or for the two survey days (64% of respondents), were calculated using Harvest, which is the custom-built dietary modelling program used by FSANZ [(34)]. These Harvest-generated intake data were then used as the input for the NCI method. Rather than using NCI macros for SAS® software, the NCI model was run in the statistical programming software R (version 3.0.3) [(40)]. FSANZ previously translated the SAS® macros into R code. At the time of translation, FSANZ undertook testing to validate the R code. Outputs from R were compared and found to be consistent with those from SAS software (unpublished report).

A summary of the specific NCI model set-up is as follows. The amount-only model type was used to estimate usual intakes, as nearly all respondents had a non-zero intake for vitamin D on day one of the NNPAS. The covariates used in the model were sex, age, weekend vs weekday and sequence effect (which considers the potential reporting differences between day one and day two of the nutrition survey). The default of 100 simulations for each respondent was used in the Monte Carlo simulation component of the model. The model was run separately for three population groups: children ≤8 years, males ≥9 years and females 9 years and over. This ensured that the model fitting was done more specifically using respondents with similar food consumption patterns. Usual vitamin D intakes were then extracted and reported in µg/day by the age/sex groups used in the Nutrient Reference Values (NRVs) for Australia and New Zealand [41].

Estimating adequacy of intakes

Nutrient Reference Values for Australia and New Zealand consist of a recommended Adequate Intake (AI) and Upper Level of Intake (UL) for vitamin D [41]. As the AI is unsuitable for assessment of adequacy of intakes in the population [42], intakes were compared to the US/Canadian EAR of 10 µg/day recommended by the Institute of Medicine [9]. The Australian UL is 80 µg/day for all people aged ≥1 years [41], while the Institute of Medicine recommends a UL of 63, 75 and 100 µg/day for those aged 1-3, 4-8 and ≥9 years, respectively [9].

Determining percentage contribution of foods to vitamin D intakes

Percentage contributions of foods to vitamin D intakes were derived using Harvest [34] and day one food consumption data. In AUSNUT, foods are organised under food group codes that become more specific as code digits increase. For example, the 2-digit code '13' represents the broad group of cereal based products and dishes. The 3-digit level of this broad group includes subgroups such as code 131: cakes, muffins, scones, cake-type desserts, which in turn expands to a 5-digit level (e.g. code 13301: cakes and cake mixes, chocolate). Percentage contributions of 2- 3- and 5-digit code level food groups were estimated for both 25(OH)D bioactivity factor scenarios and by NRV age/sex groups [41] as follows: (total vitamin D intake from a food group for all participants/total vitamin D intake from all foods) x 100 [43; 44].

Rounding

The dietary intakes and food contributor estimates are intended to represent habitual vitamin D intakes, which may vary with food and ingredient choice [45]. Preliminary

rounding would have rendered some small values to zero, which may not reflect actual intakes over time. For example, some recipes (e.g. a mixed dish such as curry) include an 'undefined fat' ingredient. This 'undefined fat' value is an average of concentrations assigned to the various fats that may be used, e.g. oil, butter, ghee or margarine. As a minor ingredient in a mixed dish, the 'undefined fat' concentration may be close to zero, but cannot be assumed as always zero. Therefore, all values remained unrounded until all data generation steps were complete in order that small concentrations, which may cumulatively contribute to intakes, were accounted for.

Exploring the contribution of dietary supplements to vitamin D intakes

The intake of vitamin D from dietary supplements was not included in our estimates of usual intakes as a limitation of the NCI method is that it cannot make estimations from multimodal distributions [29; 46]. However, we used the NNPAS day one food and vitamin D-containing supplement consumption data to estimate absolute intakes of vitamin D from food and dietary supplements on a single survey day. This was done deterministically using the individual respondent data from the survey unit record file data, via Stata Statistical Software version 15 [47] rather than FSANZ's Harvest program. As previously described [48], the vitamin D composition of dietary supplements reported as consumed was determined using the Australian Register of Therapeutic Goods [49] where possible; otherwise, composition data were obtained directly from manufacturers via website, telephone or email. The vitamin D contents of all dietary supplements reported as consumed were added to absolute daily intakes from food. Dietary supplements that contained vitamin D included single vitamin D supplements, vitamin D-containing multi-nutrient preparations, fish liver oils with naturally-occurring and/or added vitamin D, and fish oils with added vitamin D. These absolute intakes estimates were not compared to an EAR or UL as estimates of intake from a single day are not suitable for assessment of nutrient adequacy at the population level [42], and may result in overestimation of the prevalence of intakes below the EAR and above the UL [15].

2. Results

Usual intakes of vitamin D

In the population aged 2 years and above, the mean daily usual intake of vitamin D ranged between 1.84 and 3.25 µg/day across the age/sex groups when assuming a 25(OH)D bioactivity factor of one (Table 1). This increased to between 3.48 and 6.09 µg/day when assuming a 25(OH)D bioactivity factor of five. Children aged 2-3 years

had the lowest usual vitamin D intakes and mean intakes were lower in females than males across the age groups assessed. We estimated that, across all sex and age groups, more than 90% of people had vitamin D intakes that were below their respective Australian AI (5-15 µg/day, depending on age group) when using a bioactivity factor of 1, and over 30% were under their respective AIs when using a bioactivity factor or 5. More than 95% of the Australian population had inadequate intakes compared to the Institute of Medicine's EAR of 10 µg/day [(9)] for both scenarios. It was estimated that none of the population had usual intakes above the Australian Upper Level of Intake of 80 µg/day [(41)] or the Institute of Medicine's UL of 63-100 µg/day [(9)] for people aged ≥1 years for either scenario.

Major contributors to vitamin D dietary intakes

Including all participants aged ≥2 years and assuming a 25(OH)D bioactivity factor of one, the greatest contributors to vitamin D intakes were 'Fish and seafood products and dishes' (18.3% (range, 4.6 – 29.4%)). Of these foods, 'Packed fin fish' was the main contributor (7.3% (range, <1 – 14.6%)). 'Packed fin fish' largely represents canned products and includes popular products such as canned tuna as well as canned salmon, which had the highest analysed concentration of vitamin D [(28)]. 'Margarine and table spreads' also contributed more than 10% of intake (11.5% (range, 6.3 – 19.7%)) (Table 2). When a 25(OH)D bioactivity of five was used, the greatest contributors in the same respective order of code levels were 'Meat, poultry and game products and dishes' (26.3% (17.8 – 30.6%)), 'Eggs' (8.4% (4.4 – 11.2%)) and 'Chicken eggs' (8.3% (4.4 – 11.2%)). Greatest contributors varied by sex and age group, and according to the bioactivity factor assigned to 25(OH)D (Table 3). When assuming equal bioactivity of vitamers, fortified foods (dry beverage flavourings, breakfast cereal and margarine) were major contributors to vitamin D intakes in Australian children aged 2-18 years. When a 25(OH)D bioactivity factor of five was applied, non-fortified foods were the major contributors across the all sex and age groups.

Absolute intake of vitamin D from food and dietary supplements

Of 12,153 respondents with day one food consumption data, 2,039 reported taking a supplement that contained vitamin D. The mean (95% confidence interval) absolute intake of vitamin D from food on day one was 2.95 (2.86, 3.04) µg, increasing to 5.27 (5.05, 5.48) µg with vitamin D from dietary supplements added (Supplemental Table 1). The lowest mean absolute intake of vitamin D from food and dietary supplements

combined was seen in females aged 2-3 years (2.19 [1.83, 2.55] µg/day), and was greatest for females aged ≥71 years (9.50 [8.26, 10.74] µg/day). With dietary supplements included, mean absolute intakes remained below 5 µg/day for all age groups ≤18 years, and for males aged 19-70 years and remained below 10 µg/day for all sex and age groups assessed (Supplemental Table 1). Among supplement users only, the mean absolute intake from food and dietary supplements was 17.72 (16.72, 18.72) µg/day, ranging from 4.82 (3.75, 5.91) µg/day in females aged 2-3 y to 24.00 (21.37, 26.64) µg/day in females aged ≥71 y (Supplemental Table 2).

4. Discussion

Usual mean intakes of vitamin D from food were low in the Australian population, at <3.5 µg/day across all sex and age groups, assuming a bioactivity factor of one for the D vitamers (vitamin D_3, 25(OH)D_3, vitamin D_2 and 25(OH)D_2). Usual vitamin D intakes were lowest in younger age groups and lower in females than males. The overall amount of food consumed may play a role in these differences; however, the EAR of 10 µg/day [(9)] remains the same for all people aged ≥1 years and the mean usual vitamin D intake is estimated as substantially below this recommendation across the age and sex distribution in the Australian population. Our research to date shows that those particularly at risk of vitamin D deficiency in Australia include young adults [(3)], Aboriginal and Torres Strait Islander people living in remote areas [(50)] and people born outside Australia or the main English-speaking countries [(2)]. It is not possible to determine whether the population groups with the lowest usual vitamin D intakes correspond with those with lower vitamin D status, as there has not been a national survey of circulating 25(OH)D concentrations in Australian children aged <12 years.

Our estimate of usual vitamin D intakes in the Australian population remained relatively low even when a 25(OH)D bioactivity factor of five was applied. The 25(OH)D bioactivity factor of five was used in our secondary model as it is used in a small number of national food composition databases. It is generally accepted that 25(OH)D is more bioactive than vitamin D; however, the extent to which it is has not yet been confirmed, and it has been suggested that the vitamers should be considered equal until definitive data are available [(21)]. Here, we have shown that vitamin D intakes from food in Australia remain low even under the likely best case scenario of 25(OH)D being up to five times more bioactive that vitamin D.

Dietary supplements also contribute to intakes of vitamin D and are important to consider when estimating baseline intakes. Our earlier study showed that ~17% of Australians aged ≥2 years had consumed a vitamin D-containing supplement in the 24 hours preceding the first 24-hour dietary recall interview [48]. Only 4% of participants had taken a single vitamin D supplement (typical daily dose = 25 µg). Approximately 3% of participants had taken a vitamin D-containing calcium supplement, 11% had taken a vitamin D-containing multivitamin-multimineral supplement and 1% had taken a vitamin D-containing fish oil preparation. The median (range) doses for these preparations, in the same respective order, were 5 (0.1-25), 5 (1-25) and 5 (0.1-25) µg/day. Less than 0.5% of participants had taken fish liver oil with a median (range) dose of 2 (0.2-6) µg/day [48]. We found that, for the majority of the sex and age groups assessed, mean intakes of vitamin D from food and dietary supplements were not substantially greater than intakes from food only. The greatest difference between absolute intakes from food only and with dietary supplements was seen in females aged >50 years (increase of 5-6 µg/day), who have greater risk of osteoporosis with increasing age. Among supplement users only, there was a greater difference between absolute intakes from food only and from food and dietary supplements. These nationally-representative data suggest that, in 2011-2012, the majority of Australians either did not use vitamin D-containing dietary supplements, did not report it on the day surveyed due to it being infrequently consumed, or did not take a daily dose sufficient to increase their dietary intake to recommended levels.

Our results indicate that the majority of Australians consume less vitamin D from food than people in the US, Canada and some European countries. This was despite all four D vitamers being measured in all sampled foods, irrespective of animal or plant origin, and accounted for in our estimates. Conversely, food composition data used for US [4; 18; 19], Canadian [5; 20] and some European [10; 11; 12; 13; 14; 15; 16; 17; 51] intakes estimates included fewer vitamers and/or not all vitamers were measured in all foods. Caution is needed when comparing intake estimates across countries; however, the gap between intakes in these regions and intakes in Australia could be conceivably greater if the compositional datasets used were of similar scope.

This gap may be due to differing fortification practices. Vitamin D is found naturally in relatively low concentrations in a narrow range of foods [7]. As it can, therefore, be difficult for many people to meet dietary vitamin D requirements through naturally-occuring food sources [7], fortified foods are important sources of vitamin D in

countries where they are available [4; 5]. In Australia, only margarine is mandatorily fortified. Although vitamin D is permitted to be added via voluntary fortification to low fat milk, dairy alternatives and breakfast cereals, vitamin D fortification of these products is not routine. In contrast, foods such as dairy products, dairy alternatives and juice are commonly fortified with vitamin D in the US and Canada [9], while fortification practices vary across European countries [7]. In Finland, the proportion of the population with serum 25(OH)D concentrations >50 nmol/L increased from 44 to 91% following fortification of fluid milk products and fat spreads in 2003 [26]. Moreover, greater improvements in circulating 25(OH)D concentrations were seen in those with concentrations <30 nmol/L than those with concentrations ≥50 nmol/L [26]. Nutrition policy informed by modelling food and nutrient intakes could assist in determining potential fortification strategies to optimise dietary intakes and reduce the prevalence of vitamin D deficiency in Australia.

We estimated that more than 95% of Australians aged ≥2 years had vitamin D intakes below the EAR of 10 µg/day recommended by the Institute of Medicine. In light of this, population-level strategies may be needed to address the low population vitamin D intakes and concomitant low vitamin D status in Australia. However, it should be noted that the aforementioned EAR recommended for the US and Canada is based on minimal sunlight exposure [9], and most Australians have more opportunity for sun exposure than people living in North America. Despite year-round opportunity for sun exposure in many regions of the country, the high prevalence of vitamin D deficiency [2; 3] implies that most Australians do not produce sufficient vitamin D via this source. Even higher prevalence of low vitamin D status, together with low vitamin D intakes, have been reported for some Northern African and Middle-Eastern countries with ample opportunity for sun exposure [7; 52; 53]. Skin pigmentation, cultural clothing practices, sun/heat avoidance and protective measures against skin damage and skin cancer may play a role in the relatively high prevalence of vitamin D deficiency in sunny countries. In Australia, vitamin D dietary supplements may be needed on an individual basis by people with increased dietary vitamin D requirements [9; 41], such as the elderly [7], and others at high risk of vitamin D deficiency. However, relatively few Australians, particularly younger people, use dietary supplements [48], and they may not be effective as a population-wide solution to vitamin D deficiency. Increasing the dietary supply of vitamin D through fortification, on the other hand, is

an alternative strategy that could potentially safely improve mean serum 25(OH)D concentrations across the whole population.

Globally, the methods outlined here may be useful to other countries that have, like Australia, lacked comprehensive vitamin D food composition data and are building a new system for estimating usual vitamin D intakes from food. Nationally, our new data on usual vitamin D intakes in the Australian population will allow investigation of potential associations between vitamin D intakes and various health conditions, as well as how health conditions affect intakes, which may be used to inform public health nutrition campaigns. In combination with our new vitamin D food composition data, the data will also allow researchers to predict the effect of adding various concentrations of vitamin D to various foods on circulating 25(OH)D concentrations, and to develop a potential option to improve vitamin D status at the Australian population level.

Major strengths of this study were the use of nationally-representative food consumption data and comprehensive food composition data that included four D vitamers measured using a sensitive and specific LC-QQQ method. Food composition data were based on analytical values for major foods in the form that they would usually be consumed, i.e. cooked meat and seafood. These intakes estimates are, however, subject to the usual limitations of self-reported food consumption data, such as recall bias and measurement error [(54)], and of food composition data, such as sampling and measurement uncertainty [(28)]. Although we did not include vitamin D from dietary supplements in the estimation of usual intakes due to limitations of the NCI method, we produced estimations of absolute vitamin D intakes from food and dietary supplements from day one consumption data only. Our findings suggest that vitamin D supplement use in Australia did not sufficiently compensate for low vitamin D intakes from food for the majority of Australians. Due to the age of NNPAS data, food consumption and supplementation practices may have changed over time; however, there are no more recent nationally-representative data available to confirm this.

We have presented estimates of usual vitamin D intakes for the Australian population using nationally-representative food consumption data and comprehensive food composition data. Our new data show that vitamin D intakes from food in Australia are lower than recommendations and lower than in the US, Canada and many European countries. Given the prevalence of low vitamin D status in the population,

despite relatively good opportunity for sun exposure, strategies to address low vitamin D intakes from food are needed in Australia. This could include measures such as food-fortification or -biofortification to increase the dietary supply of vitamin D. Our estimate of vitamin D intakes will allow modelling of various food fortification scenarios to inform nutrition policy for improving vitamin D status in the Australian population.

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Figure legend

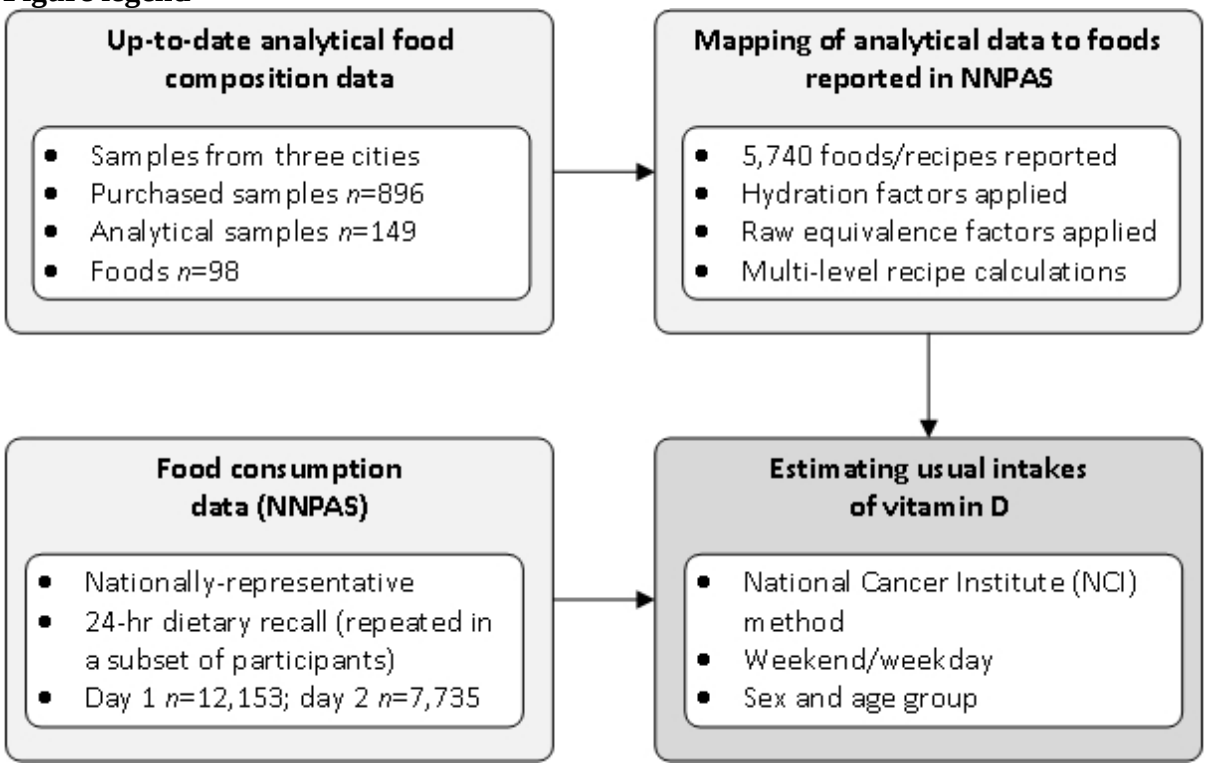

Figure 1. Methods for estimating usual vitamin D intakes in the Australian population NNPAS, 2011-2012 National Nutrition and Physical Activity Surve

Table 1. Usual vitamin D intakes in the Australian population based on food consumption data from the 2011-2012 National Nutrition and Physical Activity Survey for ages ≥2 years, stratified by sex[1]

			25(OH)D bioactivity factor = 1						25(OH)D bioactivity factor = 5					
				Percentile						Percentile				
Age group, y	Sex	*n* [2]	Mean	5th	25th	50th	75th	95th	Mean	5th	25th	50th	75th	95th
			(μg/day)											
2-3	Males	165	2.08	0.92	1.42	1.91	2.55	3.82	3.79	2.08	2.91	3.64	4.51	6.08
2-3	Females	152	1.84	0.81	1.25	1.68	2.26	3.43	3.48	1.89	2.64	3.31	4.14	5.63
4-8	Males	401	2.42	1.07	1.65	2.23	2.96	4.45	4.07	2.23	3.11	3.90	4.83	6.52
4-8	Females	374	2.18	0.94	1.48	1.99	2.68	4.01	3.77	2.03	2.88	3.60	4.50	6.06
9-13	Males	435	3.11	1.39	2.18	2.92	3.83	5.50	5.46	2.68	4.03	5.23	6.63	9.06
9-13	Females	426	2.86	1.20	1.92	2.63	3.54	5.32	4.89	2.37	3.55	4.64	5.93	8.29
14-18	Males	373	3.25	1.50	2.31	3.05	3.99	5.72	6.09	3.12	4.58	5.83	7.34	9.95
14-18	Females	367	2.44	0.99	1.63	2.24	3.03	4.57	4.35	2.05	3.14	4.12	5.30	7.44
19-30	Males	1,116	3.09	1.39	2.18	2.88	3.80	5.47	5.93	2.98	4.44	5.66	7.16	9.74

19-30	Females	1,072	2.70	1.11	1.81	2.48	3.35	5.04	4.69	2.24	3.40	4.45	5.71	7.98
31-50	Males	1,757	3.22	1.46	2.27	3.02	3.94	5.67	5.91	2.97	4.40	5.66	7.13	9.69
31-50	Females	1,778	2.71	1.12	1.83	2.50	3.36	5.03	4.74	2.27	3.45	4.50	5.76	8.02
51-70	Males	1,335	3.20	1.46	2.26	3.00	3.93	5.65	5.74	2.88	4.28	5.49	6.94	9.47
51-70	Females	1,379	2.84	1.18	1.91	2.61	3.51	5.26	4.85	2.34	3.53	4.59	5.89	8.21
≥71	Males	462	3.25	1.48	2.29	3.05	3.98	5.74	5.65	2.82	4.18	5.41	6.82	9.35
≥71	Females	560	2.90	1.21	1.96	2.68	3.60	5.37	4.91	2.37	3.57	4.66	5.96	8.29

[1]Data are presented as mean values. 25(OH)D, 25-hydroxyvitamin D
[2]Weighted to the Australian population in 2011-2012

Table 2. Contribution of foods and beverage types to vitamin D intakes based on food consumption data from the 2011-12 National Nutrition and Physical Activity Survey for ages ≥2 years (*n*=12,153)[1]

25(OH)D bioactivity factor = 1		25(OH)D bioactivity factor = 5	
Food type	Contribution[2], %	Food type	Contribution[2], %
Food group			
Fish and seafood products and dishes	18.3	Meat, poultry and game products and dishes	26.3
Meat, poultry and game products and dishes	16.1	Cereal based products and dishes	14.7
Cereal based products and dishes	14.9	Egg products and dishes	13.3
Fats and oils	13.7	Milk products and dishes	11.6
Egg products and dishes	9.7	Fish and seafood products and dishes	11.1
Milk products and dishes	6.1	Fats and oils	8.1
Non-alcoholic beverages	5.8		
Cereals and cereal products	5.2		
Food sub-group			
Margarine and table spreads	11.5	Eggs	8.4
Packed (commercially sterile) fish and seafood	7.3	Mixed dishes where cereal is the major ingredient	7.7
Mixed dishes where cereal is the major ingredient	6.7	Beef, sheep and pork, unprocessed	7.4
Eggs	6.1	Dairy milk (cow, sheep and goat)	7.3
Fin fish (excluding commercially sterile)	5.5	Poultry and feathered game	7.3
Food			
Packed fin fish	7.3	Eggs, chicken	8.3
Eggs, chicken	6.0	Chicken	6.8
Monounsaturated margarine spreads, fat content ≥ 65 g/100g	5.0		

[1]Values are frequencies (%) for food and beverage types contributing ≥5% of total vitamin D intakes were included. 25(OH)D, 25-hydroxyvitamin D
[2]Calculated as (total vitamin D intake from a food group for all participants/total vitamin D intake from all foods) x 100

Table 3. Highest food and beverage contributors to vitamin D intakes for Australian age/sex groups based on food consumption data from the 2011-12 National Nutrition and Physical Activity Survey (*n*=12,153)

Age, y	25(OH)D bioactivity factor = 1	25(OH)D bioactivity factor = 5
Male		
2-3	Fortified dry beverage flavourings	Milk, cow, fluid, regular whole, full fat
4-8	Fortified dry beverage flavourings	Milk, cow, fluid, regular whole, full fat
9-13	Fortified dry beverage flavourings	Milk, cow, fluid, regular whole, full fat
14-18	Breakfast cereal, mixed grain, fortified, sugars >20 g/100 g	Eggs, chicken
19-30	Packed fin fish	Eggs, chicken
31-50	Eggs, chicken	Eggs, chicken
51-70	Eggs, chicken	Eggs, chicken
>70	Monounsaturated margarine spreads (fortified)	Eggs, chicken
Female		
2-3	Fortified dry beverage flavourings	Milk, cow, fluid, regular whole, full fat
4-8	Monounsaturated margarine spread (fortified); Packed fin fish	Milk, cow, fluid, regular whole, full fat
9-13	Breakfast cereal, mixed grain, fortified, sugars >20 g/100 g	Chicken
14-18	Breakfast cereal, mixed grain, fortified, sugars >20 g/100 g	Eggs, chicken
19-30	Fortified dry beverage flavourings	Egg dishes, savoury
31-50	Packed fin fish	Eggs, chicken
51-70	Packed fin fish	Eggs, chicken
>70	Packed fin fish	Packed fin fish

25(OH)D, 25-hydroxyvitamin D