Does fortification of staple foods improve vitamin D intakes and status of groups at risk of deficiency? A United Kingdom modeling study^{1,2}

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ABSTRACT

Background: More than one-fifth of the United Kingdom population has poor vitamin D status (serum 25-hydroxyvitamin D [25(OH)D] concentration <25 nmol/L), particularly individuals with low sun exposure or poor dietary intake. The highest mortality rates seen in individuals with serum 25(OH)D concentrations <30 nmol/L. To prevent deficiency and achieve dietary intakes in line with United Kingdom Reference Nutrient Intakes (RNIs; defined as daily intakes required to meet the needs of 97.5% of each population group), at-risk groups are advised to consume supplementary vitamin D. Young children, older adults, pregnant and breastfeeding women, and some ethnic minority groups are considered at risk of vitamin D deficiency for reasons such as their increased vitamin D requirement, poor dietary vitamin D intake, or reduced vitamin D synthesis in the skin. Other individuals with poor dietary vitamin D intake or poor sun exposure are also considered at risk (5, 6). Fortified foods can provide a valuable source of supplementary vitamin D (8), particularly for population groups with little sunlight exposure and low vitamin D intakes from natural sources or supplements. A number of countries have introduced the fortification of staple foods with vitamin D to improve status and, therefore, prevent micronutrient deficiencies. Canada, Finland, and the United States voluntarily fortify milk with vitamin D (9, 10), and in the United States, mandatory fortification of cereal grains with vitamin D has also been proposed (11). In the United Kingdom, margarine, infant formulae, and dieting foods are statutorily fortified with vitamin D (12–14); e.g., margarine must be fortified with 7.05–8.82 μg vitamin D/100 g as well as being fortified with vitamin A (12). Some United Kingdom manufacturers are likely to safely increase population vitamin D intakes and vitamin D status.

Objective: We identified the fortification vehicle and concentration most likely to safely increase population vitamin D intakes and vitamin D status.

Design: Wheat flour and milk were identified as primary fortification vehicles for their universal consumption in population groups most at risk of vitamin D deficiency including children aged 18–36 mo, females aged 15–49 y, and adults aged ≥65 y. With the use of data from the first 2 y (2008–2010) of the National Diet and Nutrition Survey Rolling Program, we simulated the effect of fortifying wheat flour and milk with vitamin D on United Kingdom food consumption. Empirically derived equations for the relation between vitamin D intake and the serum 25(OH)D concentration were used to estimate the population serum 25(OH)D concentration for each fortification scenario.

Results: At a simulated fortification of 10 μg vitamin D/100 g wheat flour, the proportion of at-risk groups estimated to have vitamin D intakes below United Kingdom Reference Nutrient Intakes was reduced from 93% to 50%, with no individual exceeding the United Kingdom Tolerable Upper Intake Level; the 2.5th percentile of the population winter serum 25(OH)D concentration rose from 20 to 27 nmol/L after fortification. The simulation of the fortification of wheat flour at this concentration was more effective than that of the fortification of milk and milk flour at this concentration was more effective than that of the fortification of wheat flour. The proportion of at-risk groups estimated to have vitamin D deficiency was reduced from 93% to 50%, with no individual exceeding the United Kingdom Tolerable Upper Intake Level; the 2.5th percentile of the population winter serum 25(OH)D concentration rose from 20 to 27 nmol/L after fortification. The simulation of the fortification of wheat flour and milk with vitamin D on United Kingdom food consumption. Empirically derived equations for the relation between vitamin D intake and the serum 25(OH)D concentration were used to estimate the population serum 25(OH)D concentration for each fortification scenario.

Conclusion: To our knowledge, this study provides new evidence that vitamin D fortification of wheat flour could be a viable option for safely improving vitamin D intakes and the status of United Kingdom population groups at risk of deficiency without increasing risk of exceeding current reference thresholds. Am J Clin Nutr 2015;102:338–44.

Keywords fortification, model, vitamin D, National Diet and Nutrition Survey, 25-hydroxyvitamin D

INTRODUCTION

More than one-fifth of the United Kingdom population has poor vitamin D status (1) defined by a serum 25-hydroxyvitamin D [25(OH)D] concentration <25 nmol/L (2). Vitamin D deficiency leads to poor bone health and may play a role in risk of developing non–bone-related chronic diseases (3) with the highest mortality rates seen in individuals with serum 25(OH)D concentrations <30 nmol/L (4). To prevent deficiency and achieve dietary intakes in line with United Kingdom Reference Nutrient Intakes (RNIs; defined as daily intakes required to meet the needs of 97.5% of each population group), at-risk groups are advised to consume supplementary vitamin D. Young children, older adults, pregnant and breastfeeding women, and some ethnic minority groups are considered at risk of vitamin D deficiency for reasons such as their increased vitamin D requirement, poor dietary vitamin D intake, or reduced vitamin D synthesis in the skin. Other individuals with poor dietary vitamin D intake or poor sun exposure are also considered at risk (5, 6). Excessive consumption of vitamin D (>250 μg/d) can be toxic (3) and may lead to the demineralization of bone and renal and cardiovascular damage as a result of excess calcium absorption (7).

Fortified foods can provide a valuable source of supplementary vitamin D (8), particularly for population groups with little sunlight exposure and low vitamin D intakes from natural sources or supplements. A number of countries have introduced the fortification of staple foods with vitamin D to improve status and, therefore, prevent micronutrient deficiencies. Canada, Finland, and the United States voluntarily fortify milk with vitamin D (9, 10), and in the United States, mandatory fortification of cereal grains with vitamin D has also been proposed (11). In the United Kingdom, margarine, infant formulae, and dieting foods are statutorily fortified with vitamin D (12–14); e.g., margarine must be fortified with 7.05–8.82 μg vitamin D/100 g as well as being fortified with vitamin A (12). Some United Kingdom manufacturers...
voluntarily fortify certain other foods with vitamin D (e.g.,
breakfast cereals, fat spreads, drinks, cheeses, and dried milks).
The universal micronutrient-fortification schemes, in general,
were seen to be effective at improving nutritional status (15),
and the consumption of foods and drinks fortified with vitamin
D was shown to improve vitamin D status (16).

We hypothesized that a universal vitamin D–fortification
scheme would improve population vitamin D dietary intakes and
serum 25(OH)D status in the United Kingdom provided that the
foods chosen as the vehicle for fortification were consumed by
groups of the population most at risk for deficiency. With the use
of high-quality nationally representative and current dietary in-
take data from the United Kingdom, the primary aim of this
study was to identify the fortification vehicle and fortification
concentration most likely to increase population vitamin D in-
takes and status above United Kingdom minimum reference
thresholds for intake and status without exceeding maximum reference thresholds.

METHODS

Nationally representative data on food-consumption habits in
the United Kingdom (17, 18) were reviewed to determine foods
and drinks likely to be suitable vehicles for fortification (i.e.,
consumed in substantial quantities by a substantial proportion of
at-risk groups). Wheat flour and milk were identified as the most
widely consumed foods within the population and were, there-
fore, selected for testing in this assessment, both of which were
also shown to improve vitamin D status in fortification-efficacy
studies (19–23).

Subjects

Individual dietary intake data from the nationally represen-
tative United Kingdom National Diet and Nutrition Survey
(NDNS) Rolling Program (2008–2010) (24) were used to sim-
ulate the effect of vitamin D fortification on population vitamin
D intakes. The NDNS survey estimates individual dietary intake
across the general United Kingdom population by using a 4-d
diet-diary method. Data from the first 2 y of the Rolling Program
(2008–2010) are the most up-to-date and high-quality data
available for the United Kingdom population. Earlier NDNS
surveys (from 1990 onward) are also available but do not ac-
curately reflect current consumption patterns in the United
Kingdom.

The impact of fortification on vitamin D intake was assessed
for the whole population as well as specifically for groups
considered most at risk of vitamin D deficiency. For the purposes
of this study, at-risk groups were defined as young children (aged
18 mo to 3 y), women of childbearing age (aged 15–49 y, rep-
resenting pregnant and breastfeeding women), and older people
(adults aged ≥65 y) as defined by the RNI (5). Study and
subgroup sample sizes are provided (Table 1). Ethnic minority
groups known to be at an increased risk of vitamin D deficiency
in the United Kingdom (2) were not separately assessed as there
was insufficient nationally representative consumption data.

Fortification vehicles and concentrations assessed

A range of fortification concentrations were selected based
on the additional daily intake of vitamin D required to reach
recommendations (RNIs) for each at-risk group and taking into
account crude estimates of the average daily consumption of flour
and milk from the main contributing food groups by these
population subgroups (5, 17). Fortification concentrations ranged
from an extreme low concentration to an extreme high con-
centration with the aim of identifying a concentration at which
RNIs would be achieved, thereby minimizing risk of excess
consumption. Fortification was simulated for: all wheat flour
[including flour for domestic use as well as wheat flour in bread,
 pastries, pizzas, and other foods containing white, brown, and
wholemeal wheat flour. Noodles and pasta were excluded as in
a previous analysis because the majority of these products are
imported (25)] at concentrations that range between 5 and 30 μg
vitamin D/100 g flour; milk and milk-containing foods (in-
cluding milk as a drink, on cereal, as an ingredient, and in drinks
such as milk shakes and hot chocolate with the exclusion of
cream, cheese, and yogurt) at concentrations that range between
0.5 and 7 μg vitamin D/100 L milk; and wheat flour and milk
simultaneously at one-half the concentrations assessed for the
separate wheat flour– and milk-fortification scenarios. Although
fortified cream, cheese, and yogurt are being produced by using
milk that has been fortified in a process called bio-addition (10),
this model excluded these products because manual fortification
of these foods typically takes place at different processing stages
that result in higher potential costs to the industry (C Vaughan,
Department of Health, personal communication, 2011). There-
fore, it is unlikely that these products would be fortified in
practice as seen in countries where milk has been fortified (3, 9,
26). Wheat flour and milk contents of composite foods reported
to have been consumed (e.g., breads, pizzas, and desserts) were
estimated from NDNS recipes and literature sources (27). Be-
fore simulating fortification, we updated the estimated vitamin
D content of fortified foods and supplements reported to have
been consumed in the NDNS and applied a suitable overage as
appropriate to ensure baseline vitamin D intakes from foods and
supplements reflected current vitamin D contents (28).

Assessing the impact of fortification on vitamin D intakes

Vitamin D contents of wheat flour– and milk-containing foods
in the NDNS dataset were manipulated to simulate fortification
at the concentrations specified, and vitamin D intakes were es-

timated for the entire population and for relevant population

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>National Diet and Nutrition Survey sample (2008–2010)1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample sizes,2 n</td>
<td>Female</td>
</tr>
<tr>
<td>Age, y</td>
<td></td>
</tr>
<tr>
<td>1.5–3</td>
<td>79</td>
</tr>
<tr>
<td>4–8</td>
<td>141</td>
</tr>
<tr>
<td>9–14</td>
<td>183</td>
</tr>
<tr>
<td>15–18</td>
<td>131</td>
</tr>
<tr>
<td>19–49</td>
<td>285</td>
</tr>
<tr>
<td>50–64</td>
<td>123</td>
</tr>
<tr>
<td>≥65</td>
<td>122</td>
</tr>
<tr>
<td>Total</td>
<td>1064</td>
</tr>
</tbody>
</table>

1From reference 24.

2Weighted to illustrate proportions used in the analysis.
Vitamin D intakes, including intakes from supplements, were calculated at baseline and at each fortification scenario. The proportion of the population with intakes below the RNI and above the Tolerable Upper Intake Level (UL) (29) was calculated.

Assessing the impact of fortification on vitamin D status

Although the serum 25(OH)D concentration has been established as a reliable biomarker of total vitamin D exposure from both sunlight and the diet, the relation between dietary vitamin D intake and serum 25(OH)D concentrations is difficult to define because of vitamin D conversion in the skin from sun exposure. A number of studies have set out specifically to determine a dose-response relation between vitamin D intake and the serum 25(OH)D concentration in the absence of sunlight (3, 30–33). We identified that the empirically derived equations for the relation between population vitamin D intake and the winter serum 25(OH)D concentration in adults aged 20–40 y (32) and ≥65 y (33) (Cashman KD, University College Cork, personal communication, 2011) (Table 3) were the most suitable for determining the theoretical impact of increased vitamin D intake via fortification on vitamin D status in a United Kingdom setting. In the absence of an alternative, the relation for adults aged 20–40 y was used for children and for all adults aged <65 y. These equations were derived from 2 randomized, double-blind, placebo controlled trials conducted in Ireland and Northern Ireland to establish the dose of vitamin D supplement required to maintain serum 25(OH)D concentrations above specific thresholds in young (32) and older (33) adults. Cashman (personal communication, 2011) used variance terms from the regression equation and SDs to determine equations for the mean (Table 3) and 95% CIs and 2.5th and 97.5th percentiles of vitamin D intake at a given serum 25(OH)D concentration. Therefore, serum 25(OH)D concentrations could not be calculated for individuals by using these equations, and it was not possible to estimate the proportion of the population who failed to achieve specific reference serum 25(OH)D concentrations. Thus, the shift in the population mean and 2.5th and 97.5th percentile serum 25(OH)D concentration was determined by using the population mean and 2.5th and 97.5th percentiles of vitamin D intake. The 2.5th percentile of the population winter serum 25(OH)D concentration was compared with the minimum reference threshold of 25 nmol/L.

Impact of fortification by socioeconomic group

To understand whether the impact of fortification on vitamin D intake varied by socioeconomic group (National Statistics Socioeconomic Classification) (34), a 1-factor ANOVA was performed on the difference between the normalized vitamin D intake (square-root transformation) before and after fortification by socioeconomic group.

Analysis

All analyses were performed with SPSS software (PASW Statistics 18, SPSS Inc.) at the Department of Health. Approval from the London School of Hygiene and Tropical Medicine
Adults aged 20–40 y (n = 221)

\[ 25\text{(OH)D} = \exp \left[ \frac{3.538545 + (0.0365897 \times \text{total vitamin D intake})}{2} \right] \]

Men aged ≥65 y (n = 86)

\[ 25\text{(OH)D} = [5.813712 + (0.1594576 \times \text{total vitamin D intake})] \]

Women aged ≥65 y (n = 130)

\[ 25\text{(OH)D} = [5.813712 + (0.1594576 \times \text{total vitamin D intake})] \]

\[ 1\text{RCTs were carried out by Cashman et al. (32, 33; KD Cashman, University College Cork, personal communication, 2011).} \]

\[ \text{Exp}, \text{exponential function; RCT, randomized controlled trial; 25(OH)D, 25-hydroxyvitamin D.} \]

### RESULTS

Food-consumption data were available for 2127 individuals aged ≥18 mo (Table 1). Baseline mean vitamin D intakes were low and ranged from 2.5 μg/d for children aged from 18 mo to 3 y to ≥5 μg/d for adults aged ≥65 y (Table 4). Ninety-three percent of the population had vitamin D intakes below the RNI with no individuals exceeding the UL (Table 4). Fortification of wheat flour and milk at increasing concentrations of vitamin D progressively reduced the proportion of the population with intakes below the RNI and, at certain concentrations, also increased intakes above the UL (Table 4, Table 5, Supplemental Table S1).

The optimum fortification concentration is the concentration at which the lowest proportion of at-risk groups had intakes below the RNI without anyone exceeding the UL. Scenarios of flour and milk fortification, including simultaneous fortification, increased mean intakes and reduced the proportion with intakes below the RNI with increasing amounts of fortification. However, the proportion of the population who exceeded the UL also increased for many scenarios. At a population level, wheat flour fortification at 10 μg vitamin D/100 g wheat flour was the most effective at reducing the proportion of at-risk groups with intakes below the RNI with no individual exceeding the UL (Table 5); daily mean vitamin D intakes increased from 3.7 to 10.8 μg/d, thereby reducing the proportion with intakes below the RNI (from 93% to 50%) without any individual exceeding the UL. Fortification of wheat flour at a lower concentration resulted in a greater proportion of the population with intakes below the RNI, and fortification at higher concentrations led to individuals exceeding the UL. Fortification of milk or milk and wheat flour combined was not as effective as fortification at 10 μg/100 g wheat flour.

### TABLE 4

Vitamin D intakes and winter serum 25(OH)D concentrations for the United Kingdom population with the assumption of no fortification and fortification of flour at 10 μg/100 g flour by using NDNS data (2008–2010) (n = 2127)\(^1\)

<table>
<thead>
<tr>
<th>Population group, years of age, sex</th>
<th>Vitamin D intake, μg/d</th>
<th>Population with intakes below and above key thresholds, %</th>
<th>Winter serum 25(OH)D concentration, (^2) nmol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Median</td>
<td>Less than the RNI</td>
</tr>
<tr>
<td>No fortification: data from NDNS updated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5–3, all</td>
<td>2.5 ± 2.6</td>
<td>1.7</td>
<td>93</td>
</tr>
<tr>
<td>4–8, all</td>
<td>2.7 ± 1.9</td>
<td>2.1</td>
<td>—</td>
</tr>
<tr>
<td>9–49, males</td>
<td>3.1 ± 2.4</td>
<td>2.5</td>
<td>—</td>
</tr>
<tr>
<td>9–14, females</td>
<td>2.6 ± 2.2</td>
<td>2.0</td>
<td>—</td>
</tr>
<tr>
<td>15–49, females</td>
<td>3.0 ± 2.6</td>
<td>2.2</td>
<td>97</td>
</tr>
<tr>
<td>50–64, all</td>
<td>5.0 ± 3.8</td>
<td>3.9</td>
<td>90</td>
</tr>
<tr>
<td>≥65, all</td>
<td>5.0 ± 4.1</td>
<td>3.7</td>
<td>89</td>
</tr>
<tr>
<td>Total</td>
<td>3.7 ± 3.0</td>
<td>2.8</td>
<td>93(^3)</td>
</tr>
<tr>
<td>10 μg vitamin D/100 g flour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5–3, all</td>
<td>6.3 ± 3.3</td>
<td>5.6</td>
<td>65</td>
</tr>
<tr>
<td>4–8, all</td>
<td>9.1 ± 3.3</td>
<td>8.7</td>
<td>—</td>
</tr>
<tr>
<td>9–49, males</td>
<td>11.5 ± 4.8</td>
<td>11.3</td>
<td>—</td>
</tr>
<tr>
<td>9–14, females</td>
<td>9.7 ± 3.9</td>
<td>9.3</td>
<td>—</td>
</tr>
<tr>
<td>15–49, females</td>
<td>9.4 ± 4.3</td>
<td>8.8</td>
<td>62</td>
</tr>
<tr>
<td>50–64, all</td>
<td>12.0 ± 5.5</td>
<td>10.7</td>
<td>43</td>
</tr>
<tr>
<td>≥65, all</td>
<td>12.2 ± 5.3</td>
<td>10.9</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>10.8 ± 4.7</td>
<td>10.1</td>
<td>50(^3)</td>
</tr>
</tbody>
</table>

\(^1\)Winter serum 25(OH)D concentrations were rounded to the nearest integer. NDNS, National Diet and Nutrition Survey (24); RNI, Reference Nutrient Intake; UL, Tolerable Upper Intake Level (29); 25(OH)D, 25-hydroxyvitamin D.

\(^2\)Estimated by using equations of Cashman (32, 33; KD Cashman, University College Cork, personal communication, 2011).

\(^3\)RNI was applicable only to children aged between 18 mo and 3 y, pregnant and breastfeeding women (represented by women aged 15–49 y), and adults >50 y old (5).
The effectiveness of selected vehicles and concentrations of vitamin D fortification to increase vitamin D intakes above the RNI without exceeding the UL varied between at-risk groups. For example, fortification at 5 μg vitamin D/100 g wheat flour and 1 mg vitamin D/100 g milk was the most-effective scenario for young children and reduced the proportion with intakes below the RNI from 93% to 50% with no individual exceeding the UL. However, in women of childbearing age and older adults, this fortification scenario was not as effective as fortification at 10 μg vitamin D/100 g wheat flour. There was no difference in the impact of fortification on vitamin D intakes by socioeconomic group (F = 1.107; P = 0.4). At 10 μg vitamin D/100 g flour, the estimated theoretical population mean winter serum 25(OH)D concentrations increased from 39 nmol/L prefortification to 51 nmol/L postfortification; the 2.5th percentile increased from 20 to 27 nmol/L, which exceeded the minimum threshold of 25 nmol/L, and the 97.5th percentile increased from 74 to 95 nmol/L.

**DISCUSSION**

**Summary**

With the use of high-quality, nationally representative data, we simulated the effect of fortifying wheat flour and milk with vitamin D on population vitamin D intakes and vitamin D status. At a simulated fortification of 10 μg vitamin D/100 g wheat flour, the proportion of at-risk groups estimated to have vitamin D intakes below the RNI was reduced (from 93% to 50%) with no individual exceeding the UL; the estimated theoretical 2.5th percentile of population winter serum 25(OH)D concentration rose from 20 to 27 nmol/L postfortification, which was above the minimum reference threshold of 25 nmol/L, and vitamin D intakes were improved across all socioeconomic groups. Fortification of wheat flour at this concentration was more effective than was fortification of milk or milk and flour combined at any of the concentrations assessed and was, therefore, considered the optimal fortification concentration.

A similar modeling exercise was published by The Scientific Advisory Committee on Nutrition in assessing the potential impact of fortifying flour with folic acid on the health of the United Kingdom population (27). As with this modeling, NDNS data were used to estimate the concentration of folic acid in flour required to increase folate intakes above minimum thresholds without exceeding maximum thresholds (27). The impact of increasing vitamin D intakes through the manipulation of dietary intake data, including increasing concentrations of fortification, was assessed in Switzerland (S Beer-Borst, University of Bern, personal communication, 2012), although food-consumption data used were based on a small dietary survey of 32 adults.

**Relevance to the United Kingdom**

Poor vitamin D status is a global health problem. Most people in the United Kingdom obtain sufficient vitamin D through the conversion of 7-dehydrocholesterol to vitamin D in the skin through exposure to sunlight. However, because of the latitude of the United Kingdom, the population only benefits from the UVB radiation of a wavelength (290–310 nm) able to make this conversion during the summer months (2). The use of sunscreen and clothing to protect against sun damage further reduces this window of opportunity. The vitamin D content of staple foods is...
relatively low with only a few natural dietary sources including oily fish, egg yolk, red meat, and liver (5). A number of countries introduced schemes to improve vitamin D intakes through national fortification including voluntary milk fortification in Canada, Finland, and the United States (9, 10). In the United Kingdom, margarine, infant formulae, and dietary foods are statutorily fortified with vitamin D (12–14) as well as a number of different foods voluntarily fortified by manufacturers including breakfast cereals, drinks, fat spreads, and cheeses.

In the United Kingdom, all white and brown wheat flour (not including wholemeal) is restored with thiamine, niacin, and iron to concentrations equivalent to those in wholemeal flour and also fortified with calcium (35). Therefore, it would be relatively straightforward to fortify all brown and white wheat flour by adding vitamin D to the existing fortificant mix. However, fortification of wholemeal flour would require the addition of vitamin D before separation of the flour into white, brown, and wholemeal in the mill, and this may be less feasible in practice. The Scientific Advisory Committee on Nutrition previously modeled scenarios that included and excluded the fortification of wholemeal flour with folate and showed only a small difference in overall folate consumption (27).

Strengths and limitations

Large-scale dietary surveys such as the NDNS carry a number of limitations including a bias in dietary self-reporting and nonresponse. Experiments that used doubly labeled water previously identified underreporting of dietary intakes in the NDNS (1). Therefore, it may be that actual intakes of vitamin D–fortified wheat flour and milk in the United Kingdom may be higher than estimated in our model. In addition, 4 d of data collection may not reliably reflect longer-term vitamin D intake. With these limitations withstanding, the NDNS is recognized as a high-quality survey representative of the United Kingdom population and was the best available for use in this study.

Strengths of this model included the assessment of overage for food-composition data that supported this survey (28) to provide a realistic estimate of baseline vitamin D intakes. Foods chosen as vehicles for fortification were selected for their population-wide consumption to ensure groups most at risk for deficiency would benefit from fortification. Because of data limitations, it was not possible to consider the impact of fortification on ethnic minority groups. We also made a number of assumptions about other at-risk groups, including that women of childbearing age have the same diet as pregnant and breastfeeding women. Additional modeling may be needed to understand better the impact of the fortification on some population subgroups. Because this was a theoretical simulation, there were many limitations that would influence whether these observations would be seen in practice, including any potential changes to consumption patterns after the introduction of fortification as well as limitations of the use of empirically derived equations to estimate theoretical population average winter serum 25(OH)D concentrations. Models that predict a relation between vitamin D intake and the serum 25(OH)D concentration are limited in their application because they are specific to the characteristics of the population used to create the model. In this study, it was assumed that the NDNS sample (24) and the Irish/Northern Irish study samples (32, 33) had similar vitamin D intakes and population winter serum 25(OH)D concentrations, the latter of which may be affected by summer sun exposure, ethnicity, and age. The extent of differences between the ethnic profile of the United Kingdom and that of Ireland and Northern Ireland was not assessed in this model. However, regardless of any national variation, it was likely that the relatively small Irish/Northern Irish samples (total sample size: \( n < 450 \)) were less ethnically diverse than were the larger NDNS samples \(( n > 2000 )\). Because dark-skinned ethnic minorities tend to have lower vitamin D status, the 2.5th percentile serum 25(OH)D status may be lower for the United Kingdom sample than for Irish/Northern Irish samples. Because of variations in summer sun exposure between the United Kingdom and Ireland/Northern Ireland, this effect may not be true for the mean or 97.5th percentile. However, it does limit the suitability of the use of empirically derived equations from Ireland/Northern Ireland to estimate the likely impact of increasing vitamin D intakes on vitamin D status in the rest of United Kingdom.

Although it may be less effective at improving vitamin D status than cholecalciferol (vitamin D3) (36), the use of ergocalciferol (vitamin D2) is preferable to ensure suitability to a vegan diet, and thus, the impact of fortification on vitamin D status observed in this study (on the basis of intake of D2) may be reduced in practice. If wheat flour and milk were fortified with vitamin D in the United Kingdom, this fortification would likely have no impact on intakes of other micronutrients or macronutrients in the diet (1).

Policy relevance

In conclusion, this study provides new evidence, to our knowledge, that vitamin D fortification of a staple food such as wheat flour could be a viable option for improving vitamin D intakes and status of United Kingdom population groups at risk for deficiency. However, the requirement for additional research surrounding vitamin D is substantial. There are gaps in the knowledge in relation to the biology of vitamin D, the relation between intake and the serum 25(OH)D concentration, and the potential impact of deficiency and excess on bone health and other chronic diseases, which suggests that additional research is required before fortification is implemented in the United Kingdom. Before the introduction of universal fortification, a detailed impact assessment including consumer research on its public acceptability would be required (37). The European Food Safety Authority proposed revised ULs for vitamin D (38) that are double the values used in this analysis (29). If adopted in the United Kingdom, much higher concentrations of fortification than used in the current analysis could be possible without risks of exceeding the UL. The impact of any national fortification scheme on intakes, status, and health outcomes of individuals most at risk as well as in the general population should be closely monitored.

We thank Kevin Cashman for permitting the use of data from his studies, Corinne Vaughan for providing her expertise on the topic of milk fortification, and Sigrid Beer-Borst for providing information on her vitamin D modeling studies. The authors’ responsibilities were as follows—REA: conducted the research, analyzed data, and had primary responsibility for the final content of the manuscript; REA and ADD: wrote the manuscript; and all authors: designed the research, reviewed and made substantive contributions to the
draft of the manuscript, and read and approved the final manuscript. None of the authors reported a conflict of interest related to the study.

REFERENCES


