Simulation Model Accurately Estimates Total Dietary Iodine Intake¹,²

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Abstract

One problem with estimating iodine intake is the lack of detailed data about the discretionary use of iodized kitchen salt and iodization of industrially processed foods. To be able to take into account these uncertainties in estimating iodine intake, a simulation model combining deterministic and probabilistic techniques was developed. Data from the Dutch National Food Consumption Survey (1997–1998) and an update of the Food Composition database were used to simulate 3 different scenarios: Dutch iodine legislation until July 2008, Dutch iodine legislation after July 2008, and a potential future situation. Results from studies measuring iodine excretion during the former legislation are comparable with the iodine intakes estimated with our model. For both former and current legislation, iodine intake was adequate for a large part of the Dutch population, but some young children (<5%) were at risk of intakes that were too low. In the scenario of a potential future situation using lower salt iodine levels, the percentage of the Dutch population with intakes that were too low increased (almost 10% of young children). To keep iodine intakes adequate, salt iodine levels should not be decreased, unless many more foods will contain iodized salt. Our model should be useful in predicting the effects of food reformulation or fortification on habitual nutrient intakes. J. Nutr. 139: 1419–1425, 2009.

Introduction

Iodine is required for good functioning of the thyroid and the production of thyroid hormones. Inadequate iodine intake results in iodine deficiency disorders. One of the best known clinical symptoms of iodine deficiency disorders is goiter. In addition, inadequate iodine intake in pregnancy and early childhood results in impaired brain development and, as a consequence, reduced mental function. In many countries, including The Netherlands, the levels of iodine naturally present in foods are not adequate (1). To overcome this, The Netherlands has a long history of using iodized salt, beginning in 1928. Besides iodine deficiency, excessive iodine intakes cause elevated thyroxin and decreased thyroid stimulating hormone concentrations. It remains uncertain whether chronic exposure to these biochemical changes will result in clinical health effects (2,3).

The best way to gain insight into population iodine status is to measure urinary iodine excretion (4). However, such data are scarce. In addition, the potential effects of proposed changes in iodine policy on iodine intake cannot be measured in advance. For this purpose, the estimation of population habitual iodine intake distributions using food consumption and food composition data are required. In The Netherlands, no data have been collected about the discretionary use of (iodized) salt in food consumption surveys, and detailed information about the addition of iodine (iodized salt) in industrially processed foods is lacking in food composition databases. Estimations of market shares of industrially processed foods with added iodine can be used. However, it is uncertain which people will consume those foods. With a probabilistic approach, these uncertainties and other variability can be taken into account. In a probabilistic model, ranges of values for variables in the form of probability distributions are randomly sampled, which is done repeatedly. This is in contrast to a deterministic model in which outcomes are precisely determined through known relationships without any room for random variation.

To estimate habitual total iodine intake, we therefore developed a new simulation model in which the advantages of both the deterministic and probabilistic approaches are combined. In this article, we describe this combined simulation model. The model was applied to estimate habitual total iodine intake in the Dutch population for 3 different scenarios: 1) the former iodine policy (until July 2008); 2) the new iodine policy of 2008; and 3) a potential future change in iodine policy.

Scenarios and Methods

Scenarios

A simulation model combining deterministic and probabilistic approaches was developed to estimate habitual iodine intake in the Dutch population for 3 scenarios (Table 1). The first scenario represented the iodine policy in The Netherlands until July 2008 (transition period until July 2009). Iodized salt could voluntarily

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Iodine can be added to bread and bread-replacing products (70–85 mg I/kg salt), kitchen salt (30–40 mg I/kg salt), and meat products (20–30 mg iodate/kg nitrate grid salt). In the new Dutch iodine policy (scenario 2), the number of foods that may contain iodized salt was extended and the concentration of iodine in salt was decreased. Iodized salt with a maximum level of 65 mg I/kg salt may be applied to bread, bread-replacing products, and other bakery products, and salt with a maximum level of 25 mg I/kg salt may be applied in all other industrially processed foods (excluding drinks containing >1.2 volume% alcohol). In the third scenario, foods to which iodized salt may be added were the same as in the second scenario, but only one single type of iodized salt containing 25 mg I/kg salt was applied. This iodine level is relatively low compared with the historical and current Dutch situation; however, it is comparable to levels used in other European countries (3) and may therefore be considered as an option for future harmonization of iodine levels in salt in Europe.

Simulation model

The model was developed to fit the data of the most recent population-wide National Food Consumption Survey in The Netherlands (1997–1998). Respondents (n = 6250, aged 1–97 y) were selected from a representative consumer panel of households. For each household member, food intake was recorded on 2 consecutive days (children <13 y assisted by caretakers) (6). Quantities of foods were estimated by the subject in household units or natural units. The interviewer measured the volumes of common household measures and weighted regularly consumed foods like slices of bread.

The simulation model is based on the framework for intake simulation of functional ingredients of Kloosterman et al. (7) and consists of 6 steps (Fig. 1). Briefly, in steps 1–4, the iodine intake from 4 different potential dietary sources were estimated separately: 1) iodine found naturally in foods; 2) iodine added to industrially processed foods by adding iodized salt; 3) discretionarily added iodized salt; and 4) iodine containing dietary supplements. In the step 5, observed total iodine intake was calculated for each subject on each observation day and each iteration. Population habitual iodine intake distribution was estimated for each iteration separately in step 6. Unless otherwise stated, we used SAS software (SAS 9.1.3, SAS Institute) for modeling. Population habitual total iodine distributions were compared to the estimated average requirements (EAR) (3) and tolerable upper intake levels (UL) (2) for iodine to estimate the proportion of the population at risk of inadequate or potentially excessive iodine intakes using a cut-point method (8). Below, each of the modeling steps is described in more detail.

**Step 1: iodine intake from natural sources.** Daily iodine intake from natural sources only was calculated in a deterministic way by multiplying the consumed amount of a food by a point estimate of the natural iodine level in that food. The iodine content of foods for special dietary use, such as infant foods and clinical foods, was taken into account in the calculation of natural iodine. Because these foods for special dietary use have separate legislation, we assumed that no additional iodine could be added as iodized salt. Subsequently, the natural iodine intake was summed over all foods per participant per day.

Because the most recent population-wide food consumption data are from 1997–1998, we combined these data with the most recent food composition data to get more accurate estimates of current iodine intake. From 2007 onwards iodine levels were added to the Dutch food composition database (9). For this study, missing iodine levels were completed and available iodine levels were, if required, updated using the manufacturer's

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### Table 1: Overview of the different scenarios of use of iodized salt both in industrially processed foods and in discretionary use

<table>
<thead>
<tr>
<th>Food group</th>
<th>Scenario 1</th>
<th>Scenario 2a</th>
<th>Scenario 2b</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Market share</td>
<td>Iodine</td>
<td>Market share</td>
<td>Iodine</td>
</tr>
<tr>
<td>Bread</td>
<td>%</td>
<td>mg/kg salt</td>
<td>%</td>
<td>mg/kg salt</td>
</tr>
<tr>
<td>Bread-replacing products</td>
<td>90</td>
<td>77.5</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>Brand-specific, bread-replacing products known to contain iodized salt</td>
<td>5</td>
<td>77.5</td>
<td>5</td>
<td>65</td>
</tr>
<tr>
<td>Other bakery products</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Meat products</td>
<td>5</td>
<td>25</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Other industrially processed foods</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Discretionarily used kitchen salt</td>
<td>81</td>
<td>35</td>
<td>81</td>
<td>25</td>
</tr>
</tbody>
</table>

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**Figure 1** Schematic overview of the different steps in the simulation model to estimate population habitual total iodine intake.
Step 2: iodine intake from industrially added iodized salt. We estimated iodine intake from industrially added iodized salt using a probabilistic approach. Market shares of the use of iodized salt in 35 groups of industrially processed foods were used to estimate iodine intake from industrially added iodized salt.

A random sample proportional to the market share of iodized salt application (Table 1) was drawn among consumers of foods from a specific food group. The selected participants were assumed to use the iodized salt-containing variants of all the foods consumed from this food group. Participant selection was independently performed for each observed day. The sampling was repeated for 100 iterations to take into account this uncertainty. For each iteration, the daily intake of iodine from industrially added iodized salt was calculated per subject by multiplying the consumed amount of a food by the amount of added sodium chloride (salt) and a point estimate of the iodine concentration in salt. The total iodine intake from industrially added iodized salt was calculated by summing the iodine intake over all food groups per participant per day per iteration.

Because iodine is only added to industrially processed foods as iodized salt, sodium levels available in the Dutch Food Composition Database were updated using similar procedure as described above for iodine. The proportion of total sodium industrially added as sodium chloride was crudely estimated based on recipe information. For most industrially processed foods, the proportion of added sodium chloride was set at 100%, except for dried and salted shrimp (30%), liquorice (50%), salted fries (70%), all cheese excluding cheese spread (75%), canned vegetables and canned fish (80%), cheese spread, chips, smoked fish (85%), sesame paste, and meat products (90%). The amount of salt in industrially processed foods was estimated as 2.5 times the added sodium concentration, because the molecular weight of sodium chloride (58.5) is 2.5 times the molecular weight of sodium (23).

Because the exact salt iodine levels and market shares of application of iodized salt are unknown, we had to make several assumptions in the 3 different scenarios (Table 1). In the first scenario (former iodine policy), the salt iodine concentration was assumed to be the mean of the legal range. The market shares of use of iodized salt in the different food groups were based on crude information of the Dutch Food and Consumer Product Safety Authority (Erik Konings, Dutch Food and Consumer Product Safety Authority, The Netherlands, personal communication). The proportion of participants using discretionary iodized kitchen salt was therefore calculated to be 81% (i.e. 95% × 85%). The salt iodine levels varied between the 3 scenarios. In the first scenario (former iodine policy), a salt iodine concentration of 35 mg/1kg salt was assumed, and in scenarios 2 (new iodine policy) and 3, (potential future situation) the concentration was 25 mg/kg.

Step 4: Iodine intake from dietary supplements. For the estimation of iodine intake from dietary supplements, a probabilistic approach was also used. Within the most recent population-wide Dutch National Food Consumption Survey (1997–1998), no detailed information was available on use of iodine-containing dietary supplements. Based on the results from 2 Dutch food consumption surveys conducted among young adults and young children, it was estimated that 15% of children aged ≤12 y and 15% of adults used iodine-containing dietary supplements (10–12). Because most of the iodine-containing dietary supplements were multivitamin/mineral supplements, the percentage of multivitamin users in the 1997–1998 survey was used to estimate that 7% of adolescents (13–17 y) used iodine-containing dietary supplements (12).

To select these participants using iodine-containing dietary supplements, the amount of iodine was drawn from a uniform distribution of possible amounts. This distribution was based on the 25th to 75th percentile range of observed daily doses in the 2 Dutch food consumption surveys among young adults and young children (10,11). We applied the range of young children (15–50 μg iodine) to children aged 1–12 y and the range for young adults (50–150 μg iodine) was applied to both adolescents (13–17 y).
and adults. It was assumed that for subjects using iodine-containing dietary supplements on both observed days, the amount of iodine was equal on each day.

**Step 5 and 6: total observed iodine intake and habitual iodine intake.** In step 5, the observed total iodine intake was calculated by adding the iodine intake from the 4 different sources for each subject, on each observation day, for each iteration separately. This resulted in 100 total iodine intakes per participant per day.

In the food consumption survey database, data on 2 d of dietary intake were available. This was a poor estimator of habitual intake (i.e. average intake over a longer period of time) because of the within-person variability in dietary intake. In step 6, we used statistical modeling to estimate the within- and between-person variability. For each iteration, the distribution of habitual intake (the long-run average) was estimated based on only the between-person variability using the ISU-method (developed at Iowa State University) (SIDE/IML version 1.11, 2001). This was done at the level of population subgroups, so no individuals could be identified that had an extremely high or low intake, but the proportion of the subgroup with a habitual intake below a specific cut-off level can be estimated.

**Results**

In general, habitual iodine intake increased with age and was higher among men than women (Table 2). In scenario 1, representing the iodine policy until July 2008 in The Netherlands, the mean habitual iodine intake ranged from 121 μg/d for young children (1–3 y) to 305 μg/d for adult men. The habitual iodine intake in scenario 2a (new Dutch iodine legislation; similar market shares to scenario 1, but extended number of foods containing iodized salt and lower salt iodine concentration) was similar to the habitual intake distribution of scenario 1. The mean habitual iodine intake ranged from 118 μg/d for young children (1–3 y) to 303 μg/d for adolescent boys (15–17 y). When market shares of industrially processed foods containing iodized salt increased from 5 to 50% in combination with the new iodine legislation (scenario 2b), the mean habitual iodine intake increased −15%, ranging from 137 μg/d for young children (1–3 y) to 348 μg/d for adult men. If only one type of iodized salt is allowed, with a relatively low iodine concentration (25 mg I/kg salt), as in scenario 3, then the mean habitual iodine intake decreased 10–15% to a range of 103 μg/d for young children (1–3 y) to 260 μg/d for adult men.

The differences in habitual iodine intake distributions among scenarios 1, 2b, and 3 are illustrated for children aged 1–3 y (Supplemental Fig. 1). Using scenario 1 as a reference, the increased market share of foods containing iodized salt, although with smaller salt iodine concentrations (scenario 2b), resulted in a shift toward higher intakes. In scenario 3 (one single low salt iodine concentration), the distribution not only shifted upward toward lower iodine intake levels, but the distribution was also steeper compared with the other 2 scenarios.

The percentage of subjects with a habitual iodine intake below the EAR was in general highest for young children and slightly higher in women than in men (data not shown). In the scenarios of the former legislation (scenario 1) and the new legislation with low market shares (scenario 2a), the percentage of young children (1–3 y) with iodine intakes that were too low (below EAR) was comparable, 4.7 and 5.8%, respectively (Fig. 2). Increasing the market share in scenario 2b resulted in a decrease to 1.8% of young children with inadequate intakes.

Reduction of the salt iodine concentration in scenario 3 resulted in an increase to 9.3% in the percentage of young children with inadequate iodine intakes. In all scenarios, the percentage of the remaining age categories (≥4 y) with an iodine intake that was too low was ≤1% (data not shown).

In general, the percentage of participants with a habitual iodine intake above the UL was little higher for men than women and was highest for children (1–10 y). In scenario 1, the percentage of children (1–10 y) with excessive intakes ranged from 1.5–3.6% (Fig. 3, children aged 1–3 y). In all other age categories, the percentage of participants with a habitual iodine intake above the UL was <1%; somewhat lower percentages of 0.8–2.5% of the children (1–10 y) were found for scenario 2a. Increasing the market share in scenario 2b resulted in an increase in the percentage of participants with potentially excessive iodine intakes; 2.0–8.0% of the children aged 1–10 y and the boys aged 11–17 y had a habitual iodine intake above the UL. In the other age categories, this percentage was <1%. Reducing the salt iodine concentration to 25 mg I/kg salt (scenario 3) resulted in a decrease in the percentage of participants with excessive intakes. In all age categories, the percentage with a habitual iodine intake above UL was <1%.

**Discussion**

We presented a simulation model to estimate habitual total dietary iodine intake in The Netherlands. A novelty of this model is that it makes use of a combination of deterministic and probabilistic techniques to take into account observed individual dietary patterns and several uncertainties in data. From our simulation study, it can be concluded that, as also stated by WHO (1), iodine deficiency was under control during the former iodine legislation in The Netherlands (until July 2008). Young children aged 1–3 y old had the largest proportion of inadequate intake (<5% had intakes below EAR). Under the current Dutch iodine legislation, compared with the former, the number of foods that may contain added iodized salt increased and the iodine level in salt decreased. When the market shares of iodized salt-containing industrially processed foods will not increase to the desired higher percentages as assumed scenario 2b, iodine deficiency is expected to be still under control. The percentage of young children with iodine intakes below EAR increased slightly to 5.8%. An increase of the market share by stimulation of the use of iodized salt in industrially processed foods from 5 to 50% logically decreases the percentage of participants with intakes below the EAR (<2%). Reducing the salt iodine level to 25 mg/kg and a market share of 50% for iodized salt-containing industrially processed foods resulted in an increased percentage of the Dutch population with intakes below EAR, especially young children (almost 10%). With the current practice, in which only ~5% of foods contain iodized salt, the percentage of the Dutch population with inadequate iodine intakes could even be higher. The observation that young children are at the highest risk of inadequate iodine intake may be caused by the fact that some of these children consume specific infant foods instead of bread. These specific infant foods generally contain less iodine than bread.

The intake estimates in this article are based on simulations using individual level data from food consumption surveys, population level estimates of market shares, and various assumptions. Some of the assumptions are inherent to predicting potential future scenarios, as others are required because of inadequate data. Our estimations of iodine intake under the former legislation (until July 2008) were comparable with the
In nutrition science, a deterministic approach is usually applied to estimate (habitual) nutrient intakes. A disadvantage of this approach is that uncertainties or variability in concentration or consumption data cannot be taken into account. A mean value or worst-case approach is often applied and the results of a recently conducted Dutch study measuring iodine excretion in 24-h urine samples. In this study, mean iodine excretion was 297 μg/d for men and 244 μg/d for women (14), which corresponds to an intake of 323 and 265 μg/d, respectively (3) (our estimation was 305 and 239 μg/d). The comparable results in-
cate that our estimates of iodine intake under the former legislation are valid.

Our study also has limitations. We used data from the last population-wide food consumption survey, which is 10 y old (1997–1998). Therefore, we combined these data with most recent food composition data (from 2007 and updated for this study) to obtain an updated picture of iodine intakes from current foods. Apart from alterations in food composition, alterations in food habits over time also occur. In the period from 1987 to 1997, bread consumption tended to have a nonsignificant decrease (15). In The Netherlands, bread is an important source of iodine because of the large-scale use of iodized bread salt; continuation of this trend after 1997 might have influenced our results. In addition, in dietary assessment and monitoring studies, energy intake is underestimated. This was also the case in some age categories in the food consumption survey (an average of 5% for men, 10% for women, no underestimation for young children), which might have resulted in a similar underestimation of total iodine intake (15).

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### TABLE 2

Mean and distribution (5th, 50th, and 95th percentile) of habitual total dietary iodine intake of the Dutch population for 3 different scenarios

<table>
<thead>
<tr>
<th>Group and age, y</th>
<th>n</th>
<th>Scenario 1</th>
<th>Scenario 2a</th>
<th>Scenario 2b</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean P5 P50 P95</td>
<td>Mean P5 P50 P95</td>
<td>Mean P5 P50 P95</td>
<td>Mean P5 P50 P95</td>
</tr>
<tr>
<td>Children 1–3</td>
<td>254</td>
<td>121 65 118 188</td>
<td>137 79 135 205</td>
<td>103 59 100 156</td>
<td>117–123 (64–69) (115–119) (181–192)</td>
</tr>
<tr>
<td>Boys 11–14</td>
<td>162</td>
<td>215 144 217 297</td>
<td>248 170 244 327</td>
<td>181 123 177 246</td>
<td>(207–223) (134–162) (205–222) (286–305)</td>
</tr>
</tbody>
</table>

1 Results presented as P50 (P5–P95) of the 100 iterations in each simulation.
latter results in an overestimation of both tails of the intake distribution. To take into account uncertainty or variability, a probabilistic approach can be used. However, in probabilistic approaches, samples are usually drawn from intake distributions of separate food groups, assuming independence between intakes of the food groups. As a consequence, the complex interrelationships in individual dietary patterns is not taken into account as such, which then will result in an overestimation of both tails of the intake. Alternatively, a correlation between intakes of different foods is sometimes taken into account when using parametric modeling (16). Parametric modeling of whole diets can be very complex; therefore, we kept intact the individual dietary pattern as observed in the food consumption survey to take into account the correlation between the intake of foods. A simple version of the model presented in this paper was described previously by us (7); however, to our knowledge, this is the first model in nutrition science that combines both techniques for several uncertainties at the same time while keeping the observed individual dietary pattern intact and estimating habitual intake. The model is deterministic where possible and probabilistic where needed.

In these simulations, we used point estimates of salt iodine concentrations rather than distributions of possible concentrations, because data about the distribution of salt iodine concentrations are currently lacking. When such data become available, the variation in iodine concentration can easily be taken into account in our model. However, the necessity of making the model more complex by taking into account the variation in iodine concentration should be considered. In the estimation of the habitual intake, random selection of a distribution of possible concentrations results in the mean concentration of that distribution. In these cases, a point estimate of the mean concentration is probably accurate enough.

All sampling was performed with 100 iterations to take into account the uncertainty and variability. To study the precision of the model, we performed a duplicate simulation for 1 scenario. The duplicate simulation differed only in which participants were drawn in the samples of iodized salt users or consumers of food groups that contain iodized salt. Results from these duplicate simulations were comparable; e.g. the mean iodine intake for men was estimated to be 348 μg/d in both simulations, but the CI differed slightly: 346–350 compared with 345–351 μg/d. As expected, for age-gender categories with a small number of participants, we observed a larger variation in estimated mean (or percentiles in distribution) between the 100 different iterations, indicating greater uncertainty in the estimated iodine intake. Consequently, there was also a larger discrepancy between the estimations of percentage of participants with intakes above UL or below EAR in these age-gender categories between the duplicate scenarios. The difference, however, was small; e.g. the percentage of boys aged 7–10 y exceeding the UL was estimated to be 10.8% (5.3–17.0) or 11.9% (4.8–15.9).

The estimated iodine intake distributions for The Netherlands were compared with the UL for iodine set by the European Scientific Committee on Food (SCF) (2). The long-term clinical health effects associated with intakes above the UL remain unclear. The Institute of Medicine (IOM) in the US also set a UL for iodine (3) based on the same health effects as SCF did (i.e. biochemical changes). However, due to the application of a lower uncertainty factor, the UL set by IOM is higher than that set by SCF; the age-specific UL set by IOM range from 200–1100 μg/d, whereas those from SCF range from 200–600 μg/d. The choice of the UL will therefore have a considerable impact on the estimation of the percentage of the population having potentially excessive iodine intakes. More research is required to determine the long-term clinical health effect of the observed biochemical changes at high iodine intakes.

We applied our model to examples of former, current, and potential future habitual iodine intake in The Netherlands. If data become available, our model can also be used to estimate habitual iodine intakes for other countries, using country-specific assumptions. Differences among counties should also be considered in the European discussion regarding minimum and maximum levels of vitamins and minerals (including iodine) in foods (17). Currently, iodine deficiency is not under control in many European countries (1). Our simulation study showed that under the new Dutch iodine legislation, iodine intake is expected to remain adequate. To avoid the potential future risk of iodine deficiency disorders in the Dutch population, it is not advisable to reduce the salt iodine concentration to levels more common in other European countries (10–25 mg I/kg salt).

The general concept of our model may be used for nutrients other than iodine, especially for questions regarding the effects of potential future policies or expected changes in food composition, in which parts of the input data are missing or uncertain. To be able to estimate the change in habitual intake of nutrients, and to estimate the proportion of the population with inadequate or potentially excessive intakes, the approach described in our article seems promising for further development.
Acknowledgments

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Literature Cited