ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Original Article

Modeling thiamine fortification: a case study from Kuria atoll, Republic of Kiribati

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In 2014, there was an outbreak of beriberi on Kuria, a remote atoll in Kiribati, a small Pacific Island nation. A thiamine-poor diet consisting mainly of rice, sugar, and small amounts of fortified flour was likely to blame. We aimed to design a food fortification strategy to improve thiamine intakes in Kuria. We surveyed all 104 households on Kuria with a pregnant woman or a child 0–59 months. Repeat 24-h dietary recalls were collected from 90 men, 17 pregnant, 44 lactating, and 41 other women of reproductive age. The prevalence of inadequate thiamine intakes was >30% in all groups. Dietary modeling predicted that rice or sugar fortified at a rate of 0.3 and 1.4 mg per 100 g, respectively, would reduce the prevalence of inadequate thiamine intakes to <2.5% in all groups. Fortification is challenging because Kiribati imports food from several countries, depending on price and availability. One exception is flour, which is imported from Fiji. Although resulting in less coverage than rice or sugar, fortifying wheat flour with an additional 3.7 mg per 100 g would reduce the prevalence of inadequacy to under 10%. Kiribati is small and has limited resources; thus, a regional approach to thiamine fortification is needed.

Keywords: thiamine intake; thiamine deficiency; beriberi; food fortification; Kiribati

Background

In late 2014, health workers began reporting an unusual and often fatal illness on several remote atolls in the Republic of Kiribati. Nilles and colleagues visited Kuria, the most affected atoll, and identified beriberi, a disease of thiamine deficiency, as the most likely cause.[1] Young and middle-aged men were mainly affected, but there were also suspected cases among pregnant women, lactating women, and breastfed infants.[1] Beriberi was likely caused by a thiamine-poor diet that consisted mainly of white rice and sugar.[2] However, the consumption of thiamine antagonists, such as thiaminases found in raw fish, as well as reduced thiamine intake and absorption due to excessive alcohol consumption, may also have contributed.[3] Previous beriberi outbreaks among adult men have been attributed to thiamine-poor and carbohydrate-rich diets in conjunction with heavy physical labor, both of which increase thiamine requirements.[4] Thiamine requirements also increase during pregnancy and lactation.[5] Inadequate maternal thiamine intakes during lactation lead to low breastmilk thiamine levels,[6] and this may have precipitated beriberi in the infants. Infantile beriberi can be fatal, but even when thiamine deficiency is not severe enough to cause beriberi, it can lead to irreversible cognitive impairments.[7] Since the initial outbreak of beriberi in 2014, additional cases have been reported on Kuria and other atolls.

Thiamine supplementation is one strategy to prevent and treat beriberi, but it requires behavior change, compliance is often low, and supplementation programs are challenging to sustain over the long term.[8] Therefore, other strategies are needed to combat thiamine deficiency on these remote atolls. Fortification of food is a sustainable and low-cost strategy used to prevent micronutrient deficiencies.[8] For example, salt iodization has eliminated iodine deficiency disorders where it has been appropriately implemented and maintained.[9] Kiribati imports thiamine-fortified wheat flour (6.0 mg/kg) from Fiji.[10] However, flour is not consumed in large quantities on the remote atolls, but is common on the main island, South Tarawa, where beriberi has not been reported.[10] Other fortification options need to be explored to improve thiamine intakes in these remote regions.

As described in a review in this special issue,[11] to design a fortification strategy, the usual thiamine intake distribution of the target population is needed, as well as the deficit between the current intake of thiamine and the desired intake. The next step is to identify potential fortification vehicles and quantify their usual intake consumption. Finally, the optimal amount of thiamine to be added to the vehicle should be determined through modeling.[11] We aimed to model various fortification scenarios using common foods consumed by adults on Kuria to reduce inadequate thiamine intakes in Kiribati and ultimately, the wider region.

Methods

Location
The Republic of Kiribati is a remote and low-lying nation in the Pacific Ocean consisting of 32 atolls and one raised coral island that are spread out across an area the size of the continental United States. The population is around 120,000 people, with over half living on South Tarawa, the capital and administrative center of Kiribati.[12] Kuria atoll is part of the Central Gilbert Administrative Region. It consists of two islets with a total area of 16 km^2 and a population (Census 2015) of 1046 people living in 215 households.

Participants
This cross-sectional survey was conducted between August and September 2017. Any households on Kuria atoll with a pregnant woman or mother to

a child aged 0–59 months were eligible to participate. If present, the biological father was asked to participate. If not, a male closest in age to the woman was invited to participate. As Kiribati had no ethical review board, approval was obtained from the University of Otago Human Ethics Committee (H17/093). Informed written consent was obtained from all participants. Community leaders were consulted before commencing the survey, and their advice and recommendations were integrated into the survey design.

Questionnaire and anthropometric assessment
Trained youth volunteers administered a pretested, structured questionnaire to participants in their homes. Information on age, marital status, education, occupation, and sugar, salt, and alcohol consumption was self-reported. Anthropometric measurements (weight and height) were conducted by trained personnel using standardized methods.[13]

Dietary intake assessment
A single-day dietary intake was determined by 24-h recall for all adult participants. A second nonconsecutive day's intake for nearly all participants (>95%) was determined to account for intrasubject variation. The interactive, multiple-pass 24-h recall method, developed and validated by Gibson and Ferguson, was used.[14] This method includes four passes: (1) a list of all food and beverages consumed in a 24-h period; (2) food preparation methods; (3) portion size and recipe information; and (4) a final review, to recall any forgotten foods and to correct errors. Portion sizes were recorded using graduated sizes of various household measures (bowls, spoons, and cups), modeling clay, locally baked bread, salted cooked rice, and pictures of commonly available foods on the atoll. The weight in grams or volume in milliliters (for beverages) was used when known.

Dietary intakes were estimated from foods and beverages consumed using food composition data primarily from the Pacific Islands Food Composition Tables.[15] Food and beverage products not in these tables were obtained from the New Zealand Food Composition Table[16] and then the U.S. Department of Agriculture database,[17] or from food manufacturers when available.

Consumption of potential food vehicles (wheat flour, sugar, rice, and plant-based oil) for

Table 1. Characteristics of the survey population by the participant group

	WRA (n = 42)	Pregnant women (n = 17)	Lactating women (n = 45)	Men (n = 93)
Age, mean (SD)	32.4 (8.9)	27 (6.8)	28.9 (9.5)	36.0 (12.0)
BMI (kg/m^2), mean (SD)	35.7 (7.2)	–	30.9 (4.1)	30.8 (6.7)
Marital status				
Cohabitating	10 (24)	6 (35)	15 (33)	27 (29)
Never married	3 (7)	3 (18)	5 (11)	9 (10)
Currently married	27 (64)	6 (35)	23 (51)	56 (60)
Other	2 (5)	2 (11)	2 (4)	1 (1)
Education				
Senior secondary completed	19 (45)	6 (35)	24 (53)	34 (37)
Junior secondary completed	21 (50)	10 (59)	19 (42)	47 (51)
Primary school completed	2 (3)	1 (6)	1 (2)	10 (11)
Less than primary/no school	0 (0)	0 (0)	0 (0)	2 (2)
Occupation				
Unemployed	10 (24)	4 (24)	9 (20)	24 (26)
Government employee	6 (14)	1 (6)	6 (12)	
Nongovernment	6 (14)	3 (18)	4 (9)	16 (17)
Homemaker	16 (38)	7 (41)	19 (42)	19 (20)
Other	4 (10)	1 (6)	7 (16)	18 (19)
Salt added to food before eating				
Always	18 (27)	3 (18)	15 (33)	14 (16)
Often	9 (14)	1 (6)	6 (13)	17 (20)
Sometimes	21 (31)	7 (41)	13 (29)	17 (20)
Rarely	11 (16)	6 (35)	4 (9)	31 (36)
Never	8 (12)	0 (0)	7 (16)	7 (8)
Salt added to food when cooking				
Always	21 (50)	8 (47)	23 (51)	15 (16)
Often	7 (17)	2 (12)	6 (13)	18 (19)
Sometimes	8 (19)	2 (12)	11 (24)	7 (8)
Rarely	6 (14)	3 (18)	4 (9)	32 (34)
Never	0 (0)	0 (0)	0 (0)	7 (8)
Do not know	0 (0)	2 (13)	1 (2)	0 (0)
Alcohol				
Consume ever	16 (38)	9 (47)	19 (42)	69 (74)
If yes, in the past 30 days	1 (2)	0 (0)	2 (4)	14 (15)

Note: n (%), unless specified otherwise.
BMI, body mass index; WRA, nonpregnant nonlactating women of reproductive age.

fortification was calculated in grams after disaggregating mixed dishes. Although a common fortification vehicle for iodine, salt was not assessed because salt intakes cannot be accurately assessed via 24-h recalls. Foods contributing to flour intakes were wheat flour, buns, and doughnuts. Donuts and buns were calculated as 45% and 57% flour, respectively. As rice was calculated in its cooked form, the amount of raw rice estimated for the use as a food vehicle was calculated using the standard conversion factor, dividing by three.[10]

Data analysis
The survey group was disaggregated into women of reproductive age (WRA; nonpregnant and nonlactating women who had a child under 59 months), pregnant women, lactating women, and men. The Goldberg method was used to predict any low energy reporters (excluding pregnant women) using the ratio <0.96 of usual energy intake by estimated basal metabolic rate.[18] Two participants were considered low energy reporters; however, they were not excluded due to the limitations of using these cutoffs[18] and issues of food insecurity in Kiribati.

Table 2. Median (5th and 95th percentiles) usual daily intake of energy and thiamine as well as the prevalence of inadequacy (%) of thiamine by population group[a]

Usual daily nutrient intake	WRA (n = 41)	Pregnant women[b] (n = 17)	Lactating women (n = 44)	Men (n = 90)
Energy (kcal)	2435 (1476, 3549)	1825 (1499, 2282)	2710 (1889, 3751)	2864 (1995, 3962)
Thiamine (mg)	1.0 (0.6, 2.0)	1.0 (0.5, 1.5)	1.4 (1.3, 2.1)	1.2 (0.6, 2.2)
Prevalence of inadequacy of thiamine	43	70	38	32

[a] Usual intakes and prevalence of inadequacy estimated using IMAPP.
[b] Unreliable due to a small number of women.
WRA, nonpregnant nonlactating women of reproductive age.

Details of thiamine fortification modeling are described in another article in this special issue.[11] Briefly, the Intake Modeling, Assessment and Planning Program (IMAPP) (Iowa State University, Ames, IA) was used to determine usual thiamine intake distributions and thiamine inadequacy among each group. This method uses the estimated average requirement (EAR) cut-point method[19] and the U.S. National Academy of Medicine Dietary Reference Intakes for thiamine.[5] The EAR for thiamine for WRA, pregnant women, lactating women, and men is 0.9, 1.2, 1.2, and 1.0 mg/day, respectively.[5] Food staples considered as vehicles for fortification modeling were: flour, rice, sugar, and plant-based oils, as they were thought to be consumed regularly by the residents of Kuria. The intake distribution of these vehicles was estimated using the Multiple Source Method.[20]

IMAPP was used to estimate the amount of thiamine that needed to be added to a food vehicle to reach the desired prevalence of nutrient adequacy (2.5%, 5%, or 10%). In doing so, IMAPP simulated different fortification scenarios to compare the fortification food vehicles and predict intakes of thiamine for the population groups used. This modeling aimed to find the lowest dose of fortificant (thiamine) that could be added to a food vehicle that would allow the majority of the population to achieve their EAR for thiamine without having some in the population having excessive intakes. Although there is no upper limit for thiamine, we aimed to have no population group with a 95th percentile of intake exceeding 10 milligrams.

Results

Participant characteristics

One-hundred and four households met the eligibility criteria, and all agreed to participate. Within these households, 42 WRA, 17 pregnant women, 45 lactating women, and 93 men participated in the survey. Two men refused to participate, and nine households did not have an eligible male present. One man died and four people left the atoll between the initial interview and the 24-h recall. Sociodemographic and select health characteristics are presented in Table 1. The mean body mass index fell within the obese category for all population subgroups. Self-reported consumption of alcohol was highest among men, but low overall.

Table 3. Usual median (5th and 95th percentiles) daily intakes of potential fortification vehicles by population group[a]

Daily intake	WRA (n = 41)	Pregnant women[b] (n = 17)	Lactating women (n = 44)	Men (n = 90)
Rice (g/day)	208 (148, 338)	219 (145, 276)	268 (204, 352)	320 (153, 489)
Sugar (g/day)	76 (44, 114)	96 (24, 151)	90 (44, 160)	82 (40, 138)
Wheat flour (g/day)	55 (5, 147)	46 (16,87)	68 (19, 129)	59 (19, 146)
Plant-based oil (g/day)	1.1 (0.5, 10.0)	2.6 (1.1, 3.4)	5.3 (2.9, 8.3)	4.5 (1.6, 9.7)

[a] Usual intakes calculated using the Multiple Source Method.
[b] Unreliable due to a small number of women.
WRA, nonpregnant nonlactating women of reproductive age.

Table 4. Modeling of thiamine fortification of wheat flour, rice, sugar, and oil and prevalence of dietary thiamine inadequacy among men and lactating women

Food vehicle for fortification	Desired prevalence of inadequacy[a] (%)	Amount of fortificant needed[b] (mg/100 g)	WRA (*n* = 41)		Lactating women (*n* = 44)		Men (*n* = 90)	
			Prevalence of inadequacy (%)[c]	Thiamine intake (mg/day) median (5th and 95th)[d]	Prevalence of inadequacy (%)	Thiamine intake (mg/day) median (5th and 95th)	Prevalence of inadequacy (%)	Thiamine intake (mg/day) median (5th and 95th)
Rice (raw)								
	2.5	0.3	2	1.8 (0.9, 3.2)	1	2.1 (1.4, 3.2)	0	2.3 (1.4, 3.3)
	5	0.3	2	1.8 (0.9, 3.2)	1	2.1 (1.4, 3.2)	0	2.3 (1.4, 3.3)
	10	0.2	6	1.5 (0.9, 2.6)	4	1.9 (1.2, 2.8)	1	1.9 (1.2, 2.8)
Sugar								
	2.5	1.4	2	2.1 (1.1, 3.9)	0	2.8 (1.9, 3.9)	0	2.5 (1.6, 3.9)
	5	1.0	4	1.8 (0.9, 3.4)	0	2.4 (1.6, 3.3)	0	2.1 (1.4, 3.4)
	10	0.3	22	1.3 (0.6, 2.4)	12	1.6 (1.1, 2.3)	9	1.6 (1.1, 2.3)
Wheat flour								
	2.5	24.3	3	12.0 (2.0, 64.4)	1	12.8 (2.5, 38.0)	0	15.6 (2.0, 45.2)
	5	6.9	5	3.7 (0.9, 19.3)	5	4.6 (1.2, 12.5)	1	5.5 (1.8, 16.7)
	10	3.7	10	2.4 (0.7, 10.9)	9	3.1 (1.0, 9.7)	3	3.5 (1.2, 9.7)
Plant-based oil								
	2.5	92.4	3	4.4 (1.1, 18.7)	1	5.9 (2.0, 13.7)	0	5.3 (2.4, 10.5)
	5	33.0	5	2.3 (0.9, 5.8)	4	3.0 (1.2, 6.5)	0	2.7 (1.4, 4.9)
	10	15.1	10	1.6 (0.8, 3.4)	13	2.1 (0.9, 4.2)	4	1.9 (1.1, 3.3)

[a] The prevalence of inadequacy we hope to achieve with our fortification scenario.
[b] The amount of thiamine that needs to be added.
[c] The prevalence of inadequacy under this fortification scenario.
[d] Thiamine intake achieved under this scenario. In the absence of an upper limit having no population group with a 95th percentile of intake exceeding 10 mg was considered desirable.
WRA, nonpregnant nonlactating women of reproductive age.

Thiamine intakes and prevalence of inadequacy

Median (5th and 95th percentiles) usual daily intakes of thiamine were 1.0 (0.5, 2.0), 1.0 (0.5, 1.5), 1.4 (0.3, 2.1), and 1.2 (0.6, 2.2) mg/day for WRA, pregnant women, lactating women, and men, respectively (Table 2). The prevalence of inadequate thiamine intake was highest for pregnant women and lowest for men, but all groups were above 30%.

Thiamine food fortification modeling

Median (5th and 95th percentiles) intakes of potential food vehicles for fortification are presented in Table 3. Fortification scenarios (Table 4) could not be modeled for pregnant women due to the small sample size (*n* = 17). Thiamine fortification of rice at a rate of 0.3 mg per 100 g reduces the prevalence of inadequate intake to 2% or less for all population groups. Under this scenario, no population group is estimated to have a 95 percentile of intake that exceeds 4 milligrams. Similar results can be achieved with sugar fortification, albeit a higher amount of thiamine is required, 1.4 mg per 100 grams. Neither wheat flour nor plant-based oils

were optimal vehicles in this setting. To achieve similar results as rice or sugar, flour and oil would need to be fortified with thiamine at 24 and 92 mg thiamine per 100 g, respectively. Because the intake of these vehicles is highly variable between individuals, some would be exposed to high intakes of thiamine. For example, to achieve a 3% or less prevalence of inadequacy among WRA using flour, 2.5% of men would have thiamine intakes greater than 40 mg/day.

Discussion

The present study demonstrated a moderately high prevalence of thiamine inadequacy in all surveyed population groups on Kuria. Pregnant women were at highest risk of inadequate thiamine intakes, at 73%, but we caution that this estimate is based on only 17 women. Our modeling shows that rice is the optimal vehicle for thiamine fortification, nearly eliminating low intakes among all groups surveyed. Rice is consumed daily by all individuals in relatively consistent amounts, meaning that the amount of fortificant thiamine to be added is low and excessive intakes of thiamine can be

avoided. However, rice, unlike flour, is an intact grain resulting in several technical obstacles to its fortification that must be overcome.[11] The Solomon Islands, another small Pacific Island country, has mandated the fortification of rice with thiamine, and modeling has predicted that it will increase thiamine intakes in vulnerable populations.[21] Kiribati, however, has a population five times smaller than the Solomon Islands and is at the end of the food supply chain. In the Solomon Islands, most rice is imported from Australia, whereas in Kiribati, it is imported from many mills in several countries, which often change, depending on supply and cost.[10] It is unlikely that these mills would invest in the costly infrastructure needed to fortify rice for a small market. Similar challenges in the supply chain were seen with oils. In addition to our finding that plant-based oils would not provide optimal coverage for fortification, the large number of types and suppliers of oils make fortification impractical.

Sugar was equally as effective as rice in eliminating low intakes of thiamine and also did not lead to excessive intakes in our models. Vitamin A–fortified sugar is available, and it should be possible to fortify sugar with thiamine.[22] Most sugar in Kiribati is imported from either Australia or Fiji, which may make sugar fortification more economically feasible, as there is more consistency in the supply chain than rice.

Our findings suggest that wheat flour is not the optimal fortification vehicle on Kuria. This is because flour is not widely available on Kuria, and bread made from flour must be purchased from two local bakeries because it cannot be made at the household level, increasing cost. Nevertheless, flour sold in Kiribati is already fortified, as it is centrally milled and fortified in Fiji.[10] We predict that fortifying flour with an additional 0.3 mg per 100 g would reduce the prevalence of inadequacy to 10% in women and 3% in men, without exposing high consumers of flour to excessive thiamine intakes.

Unfortunately, we could not model salt as a fortification vehicle in this study because salt intake cannot be estimated accurately using a 24-h recall. Salt intake is best estimated using salt-specific dietary intake assessments and repeat 24-h urinary sodium excretion (see Chan *et al.*[23]). The nearly universal use of discretionary salt in Kuria may make it an ideal, low-cost vehicle. Salt iodization is

mandated in over 100 countries globally, including Kiribati. The technical expertise and equipment needed for thiamine fortification with salt is available. Because thiamine can be added to existing iodine premix for spray fortification, a minimal investment would be required to fortify salt with iodine and thiamine in Kiribati.[3]

A problem inherent with the proposed vehicles, especially sugar and salt, is that they are classified as "unhealthy" foods. Sugar contributes to obesity, which is a significant problem in Kiribati, as in other Pacific Island nations.[24] Likewise, salt is associated with hypertension, and there have been several strategies aimed at curbing sodium intakes in the Pacific Islands.[25] Concerns have been expressed that fortifying "unhealthy foods" will cause their consumption to increase.[26,27] However, there is no evidence that fortifying a food leads to increased consumption, especially when fortification is mandatory. Moreover, the WHO has indicated that increasing the availability of fortified salt is compatible with sodium reduction strategies.[26] We hope that the consumption of salt and sugar decreases to align with WHO guidelines. Nevertheless, ongoing monitoring and evaluation required for fortification would show if salt or sugar consumption patterns change and adjustments to fortification levels could be made. For example, if salt consumption declines, the amount of thiamine added could be increased.

Excessive alcohol consumption can also lead to beriberi by inhibiting the absorption of thiamine and displacing thiamine-containing foods.[3] Self-reported alcohol consumption was low, with very few women, and only 11% of men, indicating they consumed alcohol in the month before. Alcohol is not commercially available on Kuria but is homemade by fermenting sugar. Given the self-reported nature of the data, our finding of low rates of alcohol consumption may be subject to social desirability and response bias. We did not assess other potential factors that may have affected thiamine status among our survey population, including the consumption of antithiamine compounds naturally occurring in foods, such as raw fish (thiaminase) and betel nut chewing.[3] Consumption of raw fish is common in Kiribati, and while betel nut is not grown in Kiribati, it may be imported from Papua New Guinea.

The strengths of this study include that every eligible family participated in the survey, and the use

of repeat multiple-pass 24-h recalls to collect nutrient and food vehicle intakes. Also, energy intakes were as predicted, indicating that underreporting, often inherent in dietary studies, was likely low. A limitation was the small number of participants, especially pregnant women, on the atoll. Furthermore, we did not assess the intakes of infants and children, as well as other members of the population. However, beriberi typically occurs when infants are breastfeeding, so improving breastmilk thiamine levels through improved maternal intakes should reduce risk in this lifecycle group. Also, we did not consider the fortification of multiple food vehicles. However, Kiribati likely does not have the resources to monitor fortification of multiple food vehicles and overfortification might occur. Kuria is just one atoll of many in Kiribati, and our modeling cannot be extrapolated to other places in Kiribati. In South Tarawa, for example, where most of the population lives, a greater variety of foods, including more bread made from fortified flour, is more commonly consumed.

Conclusion

The only long-term solution to preventing thiamine deficiency in Kiribati is through mandatory food fortification. Modeling showed that rice fortification would allow the most people to achieve their required intake, but technical issues and a large number of suppliers limit its feasibility. Sugar fortification allows similar coverage and there are a limited number of suppliers; however, thiamine-fortified sugar is not currently available. While coverage is not as complete with sugar and rice, our modeling shows that increasing the amount of thiamine in wheat flour would improve thiamine intakes and is feasible. Kiribati is small and has limited resources; thus, a regional approach to fortify salt or sugar may be needed as a means of preventing future beriberi outbreaks.

Acknowledgments

Author contributions

L.A.H. and T.J.G. designed the research; L.A.H., K.C.W., T.J.G., and R.B. conducted the field work; L.D. and T.J.G. analyzed the data; and L.D., L.A.H., and T.J.G. wrote the paper. T.J.G. has primary responsibility for the final content. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

References

1. Nilles, E.J., A. Manaia, B. Ruaia, *et al.* 2018. Re-emergence of thiamine deficiency disease in the Pacific islands (2014–15): a case–control study. *PLoS One* **13**. e0198590.
2. Gibson, R.S. & T. Cavalli-Sforza. 2012. Using reference nutrient density goals with food balance sheet data to identify likely micronutrient deficits for fortification planning in countries in the Western Pacific region. *Food Nutr. Bull.* **33**: S214–S220.
3. Whitfield, K.C., M.W. Bourassa, B. Adamolekun, *et al.* 2018. Thiamine deficiency disorders: diagnosis, prevalence, and a roadmap for global control programs. *Ann. N.Y. Acad. Sci.* **1430**: 3–43.
4. Mosnier, E., F. Niemetzky, J. Stroot, *et al.* 2017. A large outbreak of thiamine deficiency among illegal gold miners in French Guiana. *Am. J. Trop. Med. Hyg.* **96**: 1248–1252.
5. Institute of Medicine. 1998. *Dietary Reference Intakes for Thiamin, Riboflavin, Niacin, Vitamin B6, Folate, Vitamin B12, Pantothenic Acid, Biotin, and Choline*. Washington, DC: National Academies Press.
6. Dror, D.K. & L.H. Allen. 2018. Overview of nutrients in human milk. *Adv. Nutr.* **9**: 278S–294S.
7. Mimouni-Bloch, A., H. Goldberg-Stern, R. Strausberg, *et al.* 2014. Thiamine deficiency in infancy: long-term follow-up. *Pediatr. Neurol.* **51**: 311–316.
8. Allen, L.H., B. de Benosit, O. Dary, *et al.* 2006. *Guidelines on Food Fortification with Micronutrients*. Geneva: World Health Organization.
9. Aburto, N.J., M. Abudou, V. Candeias, *et al.* 2014. Effect and safety of salt iodization to prevent iodine deficiency disorders: a systematic review with meta-analyses. WHO eLibrary of Evidence for Nutrition Actions (eLENA). World Health Organization, Geneva.
10. Houghton, L.A. & T. Green. 2018. Consultancy on beriberi, thiamine deficiency, its causes and potential solutions Kiribati. World Health Organization, Geneva.
11. Whitfield, K.C., T.J. Smith, F. Rohner, *et al.* 2021. Thiamine fortification strategies in low- and middle-income settings: a review. *Ann. N.Y. Acad. Sci.* **1498**: 29–45.
12. Department of Foreign Affairs and Trade Australia. 2020. Kiribati country brief. Accessed December 31, 2020. https://www.dfat.gov.au/geo/kiribati/Pages/kiribati-country-brief.
13. de Onis, M., A.W. Onyango, J. Van den Broeck, *et al.* 2004. Measurement and standardization protocols for anthropometry used in the construction of a new international growth reference. *Food Nutr. Bull.* **25**: S27–S36.
14. Gibson, R.S. & E.L. Ferguson. 2000. *An Interactive 24-Hour Recall for Assessing the Adequacy of Iron and Zinc Intakes in*

Developing Countries. Washington, DC: World Health Organization.

15. Dignan, C., B. Burlingame, S. Kumar, *et al.* 2004. The Pacific Islands food composition tables. Rome.

16. Sivakumaran, S., L. Huffman & S. Sivakumaran. 2018. The New Zealand Food Composition Database: a useful tool for assessing New Zealanders' nutrient intake. *Food Chem.* **238:** 101–110.

17. Haytowitz, D.B. & P.R. Pehrsson. 2018. USDA's National Food and Nutrient Analysis Program (NFNAP) produces high-quality data for USDA Food Composition Databases: two decades of collaboration. *Food Chem.* **238:** 134–138.

18. Black, A.E. 2000. Critical evaluation of energy intake using the Goldberg cut-off for energy intake:basal metabolic rate. A practical guide to its calculation, use and limitations. *Int. J. Obes. Relat. Metab. Disord.* **24:** 1119–1130.

19. Institute of Medicine. 2006. *Dietary Reference Intakes: the Essential Guide to Nutrient Requirements*. Washington, DC: National Academies Press.

20. Harttig, U., J. Haubrock, S. Knüppel, *et al.* 2011. The MSM program: web-based statistics package for estimating usual dietary intake using the Multiple Source Method. *Eur. J. Clin. Nutr.* **65**(Suppl. 1): S87–S91.

21. Imhoff-Kunsch, B., I. Shakya, S.A.D. Namohunu, *et al.* 2019. Potential dietary contributions from rice and wheat flour fortification in the Solomon Islands: results from the

22. Arroyave, G., L.A. Mejía & J.R. Aguilar. 1981. The effect of vitamin A fortification of sugar on the serum vitamin A levels of preschool Guatemalan children: a longitudinal evaluation. *Am. J. Clin. Nutr.* **34:** 41–49.

23. Chan, K., J. Gallant, S. Leemaqz, *et al.* 2021. Assessment of salt intake to consider salt as a fortification vehicle for thiamine in Cambodia. *Ann. N.Y. Acad. Sci.* **1498:** 85–95.

24. Aldwell, K., C. Caillaud, O. Galy, *et al.* 2018. Tackling the consumption of high sugar products among children and adolescents in the Pacific Islands: implications for future research. *Healthcare (Basel)* **6**. 81.

25. Christoforou, A., W. Snowdon, N. Laesango, *et al.* 2015. Progress on salt reduction in the Pacific Islands: from strategies to action. *Heart Lung Circ.* **24:** 503–509.

26. World Health Organization. 2013. Salt reduction and iodine fortification strategies in public health: report of a joint technical meeting convened by the World Health Organization and the George Institute for Global Health in collaboration with the International Council for the Control of Iodine Deficiency Disorders Global Network, Sydney, Australia. Geneva: World Health Organization.

27. Meltzer, H.M., A. Aro, N.L. Andersen, *et al.* 2003. Risk analysis applied to food fortification. *Public Health Nutr.* **6:** 281–291.

2012–2013 Household Income and Expenditure Survey. *Food Nutr. Bull.* **40:** 71–86.