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Iodine status of postpartum women and their infants aged 3, 6 and 12 months: Mother and Infant Nutrition Investigation (MINI)

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Abstract

To alleviate the re-emergence of iodine deficiency in New Zealand, two strategies, the mandatory fortification of bread with iodised salt (2009) and a government-subsidised iodine supplement for breast-feeding women (2010), were introduced. Few studies have investigated mother and infant iodine status during the first postpartum year; this study aimed to describe iodine status of mothers and infants at 3, 6 and 12 months postpartum (3MPP, 6MPP and 12MPP, respectively). Partitioning of iodine excretion between urine and breast milk of exclusive breast-feeding (EBF) women at 3MPP was determined. In total, eighty-seven mother–infant pairs participated in the study. Maternal and infant spot urinary iodine concentration (UIC) and breast milk iodine concentration (BMIC) were determined. The percentage of women who took iodine-containing supplements decreased from 46 % at 3MPP to 6 % at 12MPP. Maternal median UIC (MUIC) at 3MPP (82 (46, 157) μg/l), 6MPP (85 (43, 134) μg/l) and 12MPP (95 (51, 169) μg/l) were <100 μg/l. The use of iodine-containing supplements increased MUIC and BMIC only at 3MPP. Median BMIC at all time points were below 75 μg/l. Infant MUIC at 3MPP (115 (69, 182) μg/l) and 6MPP (120 (60, 196) μg/l) were below 125 μg/l. Among EBF women at 3MPP, an increased partitioning of iodine into breast milk (highest proportion 60 %) was shown at lower iodine intakes, along with a reduced fractional iodine excretion in urine (lowest proportion 40 %), indicating a protective mechanism for breastfed infants' iodine status. In conclusion, this cohort of postpartum women was iodine-deficient. Iodine status of their breastfed infants was suboptimal. Lactating women who do not consume iodine-rich foods and those who become pregnant again should take iodine-containing supplements.

Key words: Iodine deficiency: Postpartum women: Breastfed infants: Urinary iodine concentration: Breast milk iodine concentration

Iodine is an essential micronutrient for adequate production of thyroid hormones, including triiodothyronine (T_3) and thyroxine (T_4). Insufficient synthesis of thyroid hormones may impair the neurodevelopment of infants and children, particularly, in the first 3 years of life(1,2). During lactation, maternal iodine requirement increases to allow the secretion of iodine into breast milk and to maintain maternal thyroid hormone concentrations. Studies have suggested that during lactation, mammary glands are able to concentrate 20–50 times more iodine than maternal blood due to the active sodium–iodide symporter(3). However, limited research has investigated how iodine absorbed from the diet is partitioned for lactating women between the mammary gland, thyroid and kidney(4). It is unclear whether the mammary gland varies its iodine uptake in response to changes in dietary intake and prioritises iodine intake for infants. The WHO recommends exclusive breast-feeding (EBF) during the first 6 months of life and to continue to breastfeed for up to 2 years and beyond(5). Exclusively breastfed infants rely fully on their mothers for an adequate iodine supply to synthesise sufficient thyroid hormones during the first 6 months, thereafter infants obtain additional iodine from appropriate complementary foods(6).

The first postpartum year is important for women to re-adjust and meet their changing iodine requirements. Few studies have investigated iodine status at different time points from early lactation to the end of the first postpartum year(7–11). One small

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Abbreviations: BMIC, breastmilk iodine concentration; EBF, exclusive breastfeeding; 12MPP, 12 months postpartum; 3MPP, 3 months postpartum; 6MPP, 6 months postpartum; MINI, Mother and Infant Nutrition Investigation; MUIC, median urinary iodine concentration; UIC, urinary iodine concentration.

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study of New Zealand women (n 35) prior to the government introduction of mandatory fortification of bread with iodised salt (2009) reported median urinary iodine concentrations (MUIC) of 37 μg/l, 25 μg/l and 47 μg/l at 3, 6 and 12 months postpartum (3MPP, 6MPP and 12MPP, respectively), suggesting iodine deficiency(8). There continues to be a need for a more robust investigation into the iodine status of postpartum women and their infants.

New Zealand soil typically provides low levels of available iodine, which results in low iodine concentrations in local food supply(12). Endemic goitre was prevalent in New Zealand in the early 20th Century, due to iodine deficiency. A voluntary salt iodisation programme was established in 1938 which dramatically reduced goitre rates by the 1950s(13). An analysis of twenty different retail salt products in New Zealand reported 32–64 mg of iodine/kg of iodised table salt, while non-iodised salt contained only 1–5 mg of iodine/kg of salt(14). However, public health messages have led to reduced salt consumption to prevent high blood pressure and reduce the risks of other chronic medical conditions. The recent shifting from traditional home cooking with iodised salt to commercially prepared food with non-iodised salt has contributed to low use of iodised salt(15). Despite 70 % of retail salt sold in New Zealand being iodised(16), only 51 % of breast-feeding women used iodised salt either at table or in cooking (published results from the Mother and Infant Nutrition Investigation (MINI)(17)). Other possible reasons which may reduce population iodine intake include the cessation of using iodophors as cleaning agents in the New Zealand dairy industries which resulted in a drop of iodine content in milk(18), and the current dietary preferences of non-dairy milks made from soya, almond, rice and oat which contain low iodine $< 0{\cdot}02$ mg/kg(19). Re-emerging iodine deficiency was reported in the 1990s for adults(20) and schoolchildren(13), and also breastfed infants and toddlers(21).

To combat iodine deficiency, mandatory fortification of bread with iodised salt (25–65 mg iodine/kg salt) was introduced in New Zealand in September 2009, applicable to all commercial breads other than organic and unleavened(16). Recent studies in New Zealand have suggested that fortification has led to adequate intakes and status in the majority of schoolchildren(22,23) and adults(24,25). According to the 2016 New Zealand Total Diet survey, bread was the primary dietary source of iodine in the diet of an adult, although dairy products, fish, meat and eggs were also major contributors(18). However, fortification was predicted to be inadequate for pregnant and breast-feeding women due to their increased requirements. Thus, in 2010, the use of government-subsidised iodine-only supplements (150 μg/d) was recommended to all pregnant and breast-feeding women in New Zealand(26). A pilot study (n 36) suggested that breast-feeding women remain deficient(27) and reported mean breast milk iodine concentrations (BMIC, 63 μg/l)(27) lower than that suggested for adequacy (75 μg/l)(28), although iodine status of the breastfed infants was not investigated. Our own research reported that 86 % (75/87) of women took iodine-containing supplements (ranging from 150 to 270 μg iodine/d), with 79 % (59/75) consuming the government-subsidised iodine tablet of 150 μg/d during pregnancy. During lactation, the proportion of women taking an iodine-containing supplement was only 46 % (40/87) at 3MPP (ranging from 100 to 250 μg iodine/d), with 58 % (23/40) consuming the government-subsidised iodine tablet(17).

Based on the 2003/2004(29), 2009(30) and 2016 New Zealand Total Diet Survey(18), the iodine concentration in infant formula increased from 0·079 mg/kg in 2003/2004 to 0·133 mg/kg in 2009 and infant formula is suggested to be the major contributor (72 %) to the iodine intake in infants aged 6–12 months(18). The mandatory fortification of bread with iodine had the least impact on infant's iodine intake due to low consumption of bread(18); however, this research did not include the contribution of iodine from breast milk.

The aim of this MINI was to describe iodine status of supplement users and non-users (for both mothers and infants) at 3MPP, 6MPP and 12MPP. Further, it investigated partitioning of iodine excretion, between urine and breast milk, of EBF women at 3MPP.

Methods

Study population

MINI was an observational longitudinal cohort study spanning the first postpartum year in Palmerston North, in the North Island of New Zealand. Breast-feeding women aged 16 years and older were recruited, who had given birth to a healthy term singleton 3 months prior. Women were excluded: (1) if they had pre-existing or developed complicated health problems, such as metabolic disorders and cancer, and (2) if they had been diagnosed or treated at any time for hyperthyroidism or hypothyroidism. Recruitment spanned 19-month period between June 2016 and December 2017. Posters to promote the study were placed at selected sites (General Practitioner surgeries, midwifery clinics, pharmacies, antenatal classes, ultrasound clinics, maternal wards in hospitals, local community playgroups and early childhood centres, etc.). Local newspapers and social media sites were used to publicise the study. Local midwives, childbirth educators and lactation consultants were asked to raise awareness of the MINI study to their clients. Potential participants responded by recording an expression of interest online or via telephone/email. Prospective participants were provided with a study information sheet. Interested participants then completed a screening questionnaire to ensure eligibility. Details of the study methods have been published previously(31). The first study visit for each mother–infant pair was at approximately 3MPP, and follow-up assessments took place at 6 months (second study visit) and 12 months (third study visit) postpartum. Written informed consent was obtained from all participants before their enrolments in the study. Mothers also gave the written consent to their infants' participation in the study.

Ethics approval

All procedures performed in the MINI study involving human participants were in accordance with the ethical standards of the Health and Disability Ethics committee. The MINI study was approved by the Health and Disability Ethics Committee (reference: 15/NTA/172) in December 2015.

Sample size

The main outcome measure was UIC, and the sample size was calculated using G*Power 3.1 (Heinrich Heine University, Dusseldorf)(32) based on data (mean values and standard deviation) from a preliminary study of breast-feeding women(27). The analysis utilised one-way ANOVA with two groups (95 % power, alpha = 0·05, two-tailed) and three repeat measures. Eighty participants were sought, using expected mean daily UIC of 140 and 100 μg/l for iodine supplement users and non-users, respectively, with a SD of 60.

Assessment of iodine status

During each study visit, non-fasting spot urine samples were collected from each participating woman and her infant to assess iodine and creatinine excretion. A paediatric urine bag was placed inside the diaper and checked every 10 min during the study visit to collect infant urine samples. Women were asked to provide a breast milk sample (approximately 30–50 ml) using an electric breast pump if needed. Breast milk samples could be collected before, during or after a feed. All samples were collected before 12 noon on the study visit day. Samples were stored without preservative at –20°C. Breast milk samples were analysed for iodine concentration, allowing for estimations of daily excretion and infant iodine intake(33). The use of iodine-containing supplements was only determined within 24 h of the time of biological sample collections at each time point of the study visit (3MPP, 6MPP and 12MPP). Self-reported habitual use of these supplements was only assessed at 3MPP, 46 % (40/87) of women took iodine-containing supplements (ranging from 100 to 250 μg iodine/d), with 58 % (23/40) consuming the government-subsidised iodine tablet(17).

Iodine concentrations of urine and breast milk samples were determined by Hill Laboratories, Hamilton, New Zealand, using inductively coupled plasma MS(34). Quality Control procedures included analysis of blanks, analytical repeats and spiked samples in order to ensure accuracy and precision. Calibration standards and checks were undertaken on every run with the limit of detection at 0·001 mg/l. Standard uncertainty was calculated for each sample; mean values and standard deviation for maternal urine, breast milk and infant urine were 0·0082 (SD 0·0073), 0·0033 (SD 0·0037) and 0·0070 (SD 0·0094), respectively. Each batch (twenty-five samples) of urinary samples was analysed together with an external reference standard (Seronorm Trace Elements Urine, L-2) giving a mean iodine concentration of 286 (SD 12) μg/l (published value: 297 μg/l) with a CV of 4·2 % (*n* 14). Creatinine was measured in maternal urine using the Jaffe Method Flexor (Randox Assayed Multisera levels 2&3) at Massey University Nutrition Laboratory in Palmerston North. Each batch of breast milk samples was analysed together with an external reference standard (Skimmed milk powder, Elements in organic matrix, European) giving a mean iodine concentration of 1·603 (SD 0·029) mg/l (published value: 1·78 mg/l), with a CV of 4·9 % (*n* 6).

Iodine deficiency in a population is defined by a MUIC below 100 μg/l for lactating and non-lactating non-pregnant women, and children younger than 2 years(1). The WHO (2007) also recommends that for a population to be iodine sufficient, no more than 20 % should have a UIC <50 μg/l(1). There is no universal consensus on the optimal concentration for BMIC; however, >75 μg/l has been suggested to be sufficient for adequate infant iodine intake(28). There are no recommended cut-offs for lactating women to categorise excessive iodine intake; however, a median UIC ≥ 300 μg/l in infants was considered to indicate a risk of excessive iodine intake(1).

Infant anthropometry

At the initial visit, infant recumbent length was measured crown to heel using an infant length board and recorded to the nearest mm. Infant weight (without clothing and diapers) was measured, using a baby weighing scale (Nagata Scale Co. Ltd), and recorded to the nearest 10 g. Infant's weight-for-age Z-score and height-for-age Z-score were calculated by entering the data into WHO-Anthro software (https://www.who.int/childgrowth/software/en/)(35), using the formula: (observed value − median value of the reference population) divided by the standard deviation value of reference population(36). The median values for weight-for-age and length-for-age were based on the WHO child growth standards(37).

General demographic and health information

At the initial visit, mode of infant feeding, maternal general health and demographic information (including age, ethnicity, educational attainment, household size and income) were collected. Potential changeable information including mode of infant feeding and general health was also sought at the second and third visits. EBF was defined as follows: infants fed only breast milk since birth with no water, formula or liquid supplements (excluding essential medication). Non-breast-feeding was defined when infants were not fed with any breast milk at the time of questioning; partial breast-feeding was defined when infants were fed with a mixed diet consisting of breast milk, infant formula and/or complementary food. Infants' birth information including gestational age at birth, date of delivery, method of delivery, birth weight and sex was collected at the first visit, from the 'Well Child Tamariki Ora' book (New Zealand child health record). Recorded date of delivery was used to calculate the age of infants on the day of study visit.

Statistical analysis

Data were analysed using IBM SPSS (Statistics Package for the Social Sciences; IBM) version 20. Data were tested for normality using Shapiro–Wilk test. Non-parametric data were expressed as median with interquartile range (25th, 75th percentile) and parametric data expressed as mean (standard deviation). Bivariate correlations were tested using the non-parametric Spearman's rho correlation coefficient. Non-parametric data were natural log-transformed for further analysis. A one-way mixed ANOVA with two groups was used to compare the mean differences between UIC of iodine-containing supplement users and non-users (based on iodine-containing supplement use at 3MPP) with a repeated measure at 3MPP, 6MPP and 12MPP. Differences in iodine status for women who were breast-feeding at all three time points, determined by UIC, urinary iodine:

creatinine ratio and BMIC between three measurement points, were tested by one-way repeated-measures ANOVA.

For EBF women, their daily maternal iodine excretion in urine was estimated based on 1·5 litres of urine/d(38). Total estimated daily iodine excretion was the sum of urinary and breast milk iodine excretions. The fractional excretions of iodine in urine and breast milk were calculated as percentages of total daily iodine excretions(4). Assuming 92 % of iodine consumed is excreted into urine and breast milk together(38), total estimated maternal iodine intake was calculated. The estimated total daily iodine intake of their exclusively breastfed infants was calculated based on daily urine volume assumed at 0·5 litres, with an assumption of 87 % iodine consumed is excreted in infants' urine(39). Independent *t* test was used to compare natural log-transformed maternal UIC, maternal urinary iodine:creatinine ratio and BMIC between EBF women who used iodine-containing supplements and non-users.

Results

Characteristics of mothers and their infants

In total, eighty-seven mother and infant pairs were recruited at 3MPP and followed up at 6MPP (*n* 78) and 12MPP (*n* 71). At 3MPP, the mean maternal age was 31·5 (SD 4·2) years. Most participants (77 %) were Caucasian and achieved tertiary education (Table 1). The majority had a vaginal delivery (78 %), and 44 % were delivering their first infant. All women were breast-feeding at 3MPP, and 96 % of women continued to breastfeed their infants at 6MPP, but only 46 % continued breast-feeding at 12MPP.

Maternal iodine status at 3, 6 and 12 months postpartum

Maternal MUIC (25th, 75th percentile) at 3MPP (82 (46, 157) μg/l), 6MPP (85 (43, 134) μg/l) and 12MPP (95 (51, 169) μg/l) < 100 μg/l suggest iodine deficiency. Further, >20 % of women had a UIC below 50 μg/l: 29 % at 3MPP; 27 % at 6MPP and 23 % at 12MPP. Median (25th, 75th percentile) BMIC was below the suggested concentration at all three time points (69 (52, 119) μg/l), (59 (39, 108 μg/l) and (35 (26, 54) μg/l). BMIC was moderately correlated with urinary iodine:creatinine ratio at all three time points ($r = 0{\cdot}441$, $P < 0{\cdot}001$ at 3MPP; $r = 0{\cdot}552$, $P < 0{\cdot}001$ at 6MPP; $r = 0{\cdot}577$, $P = 0{\cdot}001$ at 12MPP; online Supplementary Table). No significant differences between maternal iodine status measures were found among EBF, partial breast-feeding or non-breast-feeding women (Table 2).

Overall, among women who completed the study, 46 % (33/71) took iodine-containing supplements with 24 h of urine sampling at 3MPP; this reduced markedly to 11 % (8/71) at 6MPP, and 6 % (4/71) at 12MPP. Defining women as supplement users or non-users at 3MPP showed that there was no significant main effect of time points on natural log UIC (F (2,138) = 0·500, $P = 0{\cdot}607$, partial $\eta^2 = 0{\cdot}007$), with participants showing similar mean natural log UIC at 3MPP (4·36), 6MPP (4·97) and 12MPP (4·49). However, there was significant interaction between iodine supplement use and time points on the mean of natural log UIC (F (2,138) = 3·550, $P = 0{\cdot}031$, partial $\eta^2 = 0{\cdot}049$) (Fig. 1). At 3MPP, iodine-containing supplement users showed a higher MUIC (111 μg/l) when compared with non-users (66 μg/l). The subgroup of women who were breast-feeding at the three time points showed a significant reduction in BMIC from 3MPP to 6MPP to 12MPP (Table 3). However, there were no significant variations in UIC or maternal urinary iodine:creatinine ratio over the three time points.

Iodine status of infants aged 3, 6 and 12 months

In the current study, infant MUIC at the age of 3, 6 and 12 months were all above 100 μg/l with fewer than 20 % below 50 μg/l (Table 4), suggesting adequate iodine status. However, at 6 months, infants who were EBF had an MUIC (80 μg/l, *n* 13) which was below the 100 μg/l cut-off and significantly lower than infants who were mixed-fed with complementary food (147 μg/l, *n* 29, $P = 0{\cdot}033$). Exclusively breastfed infants at 3 months of age had a lower infant MUIC than those who were partial breast-feeding, but this was not statistically significant (Table 4). Infant UIC was significantly, moderately correlated with BMIC at 3MPP, 6MPP and 12MPP ($r = 0{\cdot}598$, $P < 0{\cdot}001$; $r = 0{\cdot}602$, $P < 0{\cdot}001$; $r = 0{\cdot}656$, $P = 0{\cdot}011$, respectively; online Supplementary Table).

Iodine status of exclusive breast-feeding women and their infants at 3 months postpartum

The MUIC for EBF women was 78 μg/l, below 100 μg/l, suggesting iodine deficiency (Table 2). Median BMIC was 68 μg/l also below the suggested 75 μg/l. Median estimated maternal iodine intake was 212 (138, 331) μg/d (Table 5), below the recommended dietary intake of 270 μg/d, and 46 % (33/72) had intakes below the estimated average requirement of 190 μg/d(40). Only 44 % (32/72) of EBF women took iodine-containing supplements (range 150–250 μg iodine/d). Women who used iodine-containing supplements showed significantly higher MUIC (105 *v.* 66 μg/l, $P = 0{\cdot}027$), urinary iodine:creatinine ratio (173 *v.* 94 μg/l, $P < 0{\cdot}001$) and BMIC (84 *v.* 61 μg/l, $P < 0{\cdot}001$), when compared with those who did not use iodine-containing supplements.

Based upon a visual inspection of the scatter plot of the partitioning of maternal UIC and BMIC in total daily iodine excretion (Fig. 2), it demonstrates when total daily iodine excretion was below 300 μg, an increased partitioning of BMIC (the highest proportion of 60 %) was observed, together with a reduced fractional iodine excretion in urine (the lowest proportion of 40 %). When total daily iodine excretion was higher than 300 μg, a constant proportion of excretion was observed in urine (80 %) and breast milk (20 %).

Discussion

Iodine sufficiency and deficiency during the first postpartum year

The MINI study found women who used iodine-containing supplements at 3MPP had a significantly higher MUIC than non-users (111 *v.* 68 μg/l). A post-fortification study of Australian breast-feeding women (*n* 60) at around 3 months after

Table 1. Description of breast-feeding participants and their infants at 3 months postpartum (3MPP) (*n* 87)
(Mean values and standard deviation; numbers and percentages)

	Total (*n* 87)		Iodine-containing supplement users (*n* 35)		Iodine-containing supplement non-users (*n* 52)	
Maternal characteristics at 3MPP	*n*	%	*n*	%	*n*	%
Maternal age (years)						
Mean	31·5		32·3		30·9	
SD	4·2		3·3		4·6	
Tertiary education	67	77	31	89	37	71
Ethnicity – Maori	9	10	4	11	5	10
Ethnicity – Caucasian	66	76	26	74	40	77
Ethnicity – Asian	9	10	5	14	4	8
Annual household income (Above median)*	54	62	23	66	31	60
Primiparity	38	44	15	43	23	44
Caesarean delivery	19	22	8	23	11	21
Infants characteristics						
Gestational age at birth (weeks)						
Mean	39·4		39·3		39·4	
SD	1·5		1·7		1·46	
Age of infants (d)						
Mean	88·5		90·1		87·4	
SD	14·8		15·6		14·3	
Male	52	60	19	54	33	63
Birth weight (kg)						
Mean	3·6		3·5		3·7	
SD	0·6		0·5		0·7	
Weight-for-age Z-score						
Mean	−0·049		−0·777		−0·029	
SD	1·050		0·989		1·098	
Height-for-age Z-score						
Mean	0·066		0·025		0·092	
SD	1·386		1·318		1·442	

* Median annual household income based on Statistics New Zealand was 75 995 New Zealand dollars for the year ended June 2016[53].

Table 2. Maternal markers of iodine status during the first postpartum year by mode of infant feeding
(Numbers; medians and 25th and 75th percentiles)

	3MPP		6MPP		12MPP	
	EBF	PBF	EBF	PBF	PBF	NBF
Number samples	72	15	24	51	33	38
UIC (µg/l)						
Median	78	117	81	93	91	104
25th, 75th percentile	45, 150	46, 174	47, 148	42, 134	58, 156	43, 171
Number samples	65	14	24	47	29	33
Maternal urinary iodine:creatinine ratio (µg/g)						
Median	125	107	130	133	127	111
25th, 75th percentile	76, 219	91, 270	99, 214	75, 190	90, 173	88, 206
Number samples	72	15	23	49	33	n/a
BMIC (µg/l)						
Median	68	80	78	59	35	
25th, 75th percentile	52, 108	50, 139	32, 113	41, 94	26, 54	

3MPP, 3 months postpartum; 6MPP, 6 months postpartum; 12MPP, 12 months postpartum; EBF, exclusive breast-feeding; PBF, partial breast-feeding; NBF, none breast-feeding; UIC, urinary iodine concentration; BMIC, breast milk iodine concentration.

parturition showed a similar significant positive effect of taking iodine-containing supplements on maternal MUIC (206 *v.* 97 µg/l)[41]. However, in the current study, there was no difference in MUIC at 6MPP and 12MPP based on supplement use at 3MPP. This is unexpected, although could be due to the low proportion of women actually using iodine-containing supplements in later lactation 11 % (8/71) at 6MPP and 6 % (4/71) at 12MPP. The low use is unsurprising, and the lack of awareness of the need for iodine supplementation during lactation in this population has been reported[17]. The low use of iodine-containing supplements during later breast-feeding is especially concerning for women who do not consume iodine-rich foods

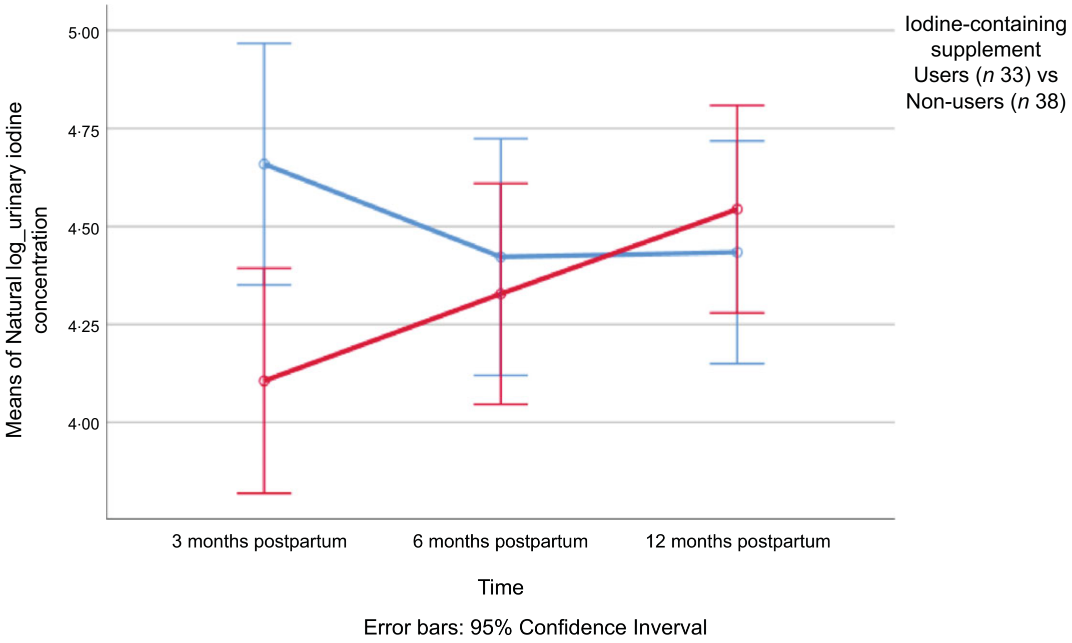

Fig. 1. Urinary iodine concentration of women who completed three study visits (n 71). ▬ Users; ▬ Nonusers. Median urinary iodine concentration: 3 months postpartum: 111 μg/L (users) vs 66 μg/L (non-users); 6 months postpartum: 71 μg/L (users) vs 89 μg/L (non-users); and 12 months postpartum: 98 μg/L (users) vs 93 μg/L (non-users).

Table 3. Markers of maternal iodine status of continuous breast-feeding women
(Numbers; medians and 25th and 75th percentile, n 33)

	3MPP		6MPP		12 MPP		P*
	Median	25th, 75th percentile	Median	25th, 75th percentile	Median	25th, 75th percentile	
Iodine-containing supplement users							–
n	17		5		2		
%	52		15		6		
UIC (μg/l)	69	46, 106	80	41, 133	91	58, 156	0·259
Maternal urinary iodine:creatinine ratio (μg/g)	132	82, 243	148	98, 199	127	90, 173	0·420
BMIC (μg/l)	71	52, 102	61	36, 100	35	26, 54	0·001

3MPP, 3 months postpartum; 6MPP, 6 months postpartum; 12MPP, 12 months postpartum; UIC, urinary iodine concentration; BMIC, breast milk iodine concentration.
* One-way ANOVA.

and those who become pregnant again. In Morocco, a randomised double-blinded placebo-controlled trial (n 241 mother–infant pairs) compared the effectiveness of using maternal supplementation, either with a single dose of 400 mg iodised oil or supplementing infants (aged ≤ 8 weeks) directly with a single dose of 150 mg. This study found that maternal supplementation is more effective in ensuring adequate infant iodine status and maintaining BMIC levels until at least 6MPP(42). Achieving adequate maternal iodine status throughout lactation is critical for infants' growth(43) and also optimal fetal neurodevelopment(44).

Overall iodine deficiency was present in a group of women during the first postpartum year based on the WHO epidemiology criteria(1). The UIC did not change significantly over the three time points. Our results showed an improvement of maternal iodine status, when compared with the results reported in a pre-fortification study of postpartum women in the South Island of New Zealand in 2001 (37 μg/l, 25 μg/l and 47 μg/l at 3MPP, 6MPP and 12MPP, respectively)(8). The trend for increase in MUIC across three time points in the MINI study was also found in a study of Sudanese breast-feeding women (n 47) living in an area with 17·5 % goitre rate, where MUIC increased from 3 (51 μg/l) to 9 (63 μg/l) months postpartum(7). Similarly, a recent large Norwegian longitudinal study of postpartum women (n 915) reported the lowest MUIC at 6 weeks postpartum (57 μg/l), which increased through 6, 12 and 18 months postpartum (70 μg/l, 79 μg/l and 87 μg/l, respectively)(10). The Norwegian authors suggested that the increase was possibly due to an assumed decrease of iodine excretion in breast milk during the postpartum period. However, these studies on Norwegian and Sudanese women did not measure BMIC.

In the current study, among women who continued to breast-feed, iodine secreted into breast milk significantly decreased from the highest concentration of 71 μg/l at 3 months, to 61 μg/l at 6 months, and with the lowest concentration of

Table 4. Infant urinary iodine concentration (UIC) from infants aged 3, 6 and 12 months
(Numbers; medians and 25th and 75th percentile)

	3 months			6 months			12 months		
	Urine samples (*n*)	Median	25th, 75th percentile	Urine samples (*n*)	Median	25th, 75th percentile	Urine samples (*n*)	Median	25th, 75th percentile
UIC total (μg/l)	67	115	69, 182	43	120	60, 196	33	118	62, 220
UIC < 50 μg/l									
n		10			5			4	
%		15			12			12	
UIC EBF (μg/l)	55	111	61, 182	13	80	36, 128	–	–	
UIC PBF (μg/l)	12	127	104, 245	29	147	78, 215	14	129	70, 300
UIC NBF (μg/l)							19	106	54, 210
*P**		0·280			0·033*			0·872	

EBF, exclusive breast-feeding; PBF, partial breast-feeding; NBF: none breast-feeding.
* Mann–Whitney *U* test.

Table 5. Estimated daily iodine excretions and intakes in mothers and their infants at 3 months postpartum (3MPP)
(Median values and 25th and 75th percentiles)

	Mothers (EBF) (*n* 72)		Infants (EBF) (*n* 55)	
	Median	25th, 75th percentile	Median	25th, 75th percentile
Estimated daily iodine excretion				
Based on maternal UIC (μg/d)*	116	68, 225		
Based on BMIC (μg/d)	53	41, 84		
Total (μg/d)	195	127, 305		
From urine %total	69	53, 76		
From breast milk % total	31	24, 47		
Estimated daily iodine intake total (μg/d)	212	138, 331		
Estimated iodine intake, based on infant UIC (μg/d)†			64	35, 105
Estimated iodine intake, based on BMIC (μg/d)			53	41, 84

EBF, exclusive breast-feeding; UIC, urinary iodine concentration; BMIC, breast milk iodine concentration.
* Calculated for each mother as UIC × 1·5 litres (the assumed daily urine volume in lactating women)(4).
† Calculated for each infant as (UIC × 0·5 litres (the assumed daily urine volume in infants aged 0–6 months))/0·87 (the assumed iodine intake excreted in urine with negligible excretion in faeces)(4).

35 μg/l at 12MPP. This pattern suggests reduced transport of iodine to breast milk. Similar observations were made in a cohort of New Zealand iodine-deficient lactating women without iodine supplementation during the first 6MPP in 2004–2005 decreasing from 43 μg/l in week 1 to 25 μg/l in week 24(45). A reduction of BMIC from 3 months (60 μg/l) to 9 months (26 μg/l) was also reported in Moroccan mothers who were supplemented with one oral dose (400 mg) of iodine after delivery(42). Research has reported a sharp decrease of iodine concentration from colostrum to mature milk, which could be due to the low volume of colostrum(46). The further reduction of BMIC from 6MPP to 12MPP observed in the current study must be interpreted with caution due to the small number of samples at 12 months. However, for breastfed infants, breast milk is still an important iodine source. Therefore, it is important for lactating women to achieve adequate iodine status.

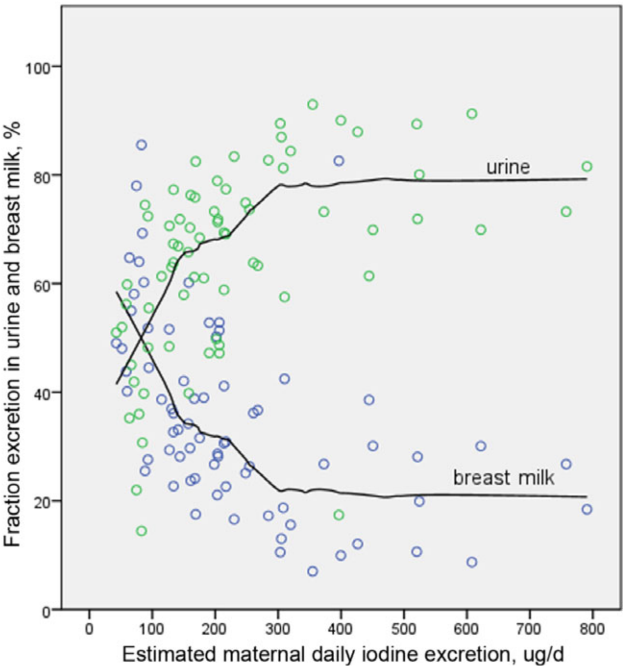

Fig. 2. Fractional iodine excretion in urine and breast milk in relation to total estimated daily iodine excretion (*n* 72). Blue bubble indicate proportion of iodine in breastmilk and green bubble indicate proportion of iodine in urine

Adequate infant iodine status was observed at three time points of this current study, using the WHO epidemiological criteria(1). However, the calculated iodine intake from a UIC of 100 μg/l is 57 μg/d (based on approximately 0·5 litres daily urine volume and 87 % of dietary iodine excreted into urine)(4). This is much lower than the Institute of Medicine suggested adequate intake of 110 μg/d for infants up to age of 6 months(47). Delange suggests that infant MUIC between 180 and 225 μg/l(48) are necessary to achieve the WHO recommended iodine intake of 90 μg/d(1). Further, results from a recent dose–response crossover iodine balance study of euthyroid term Swiss infants with iodine sufficiency suggested 125 μg/l as a cut-off for infant MUIC (based on the estimated average requirement of 72 μg/d for infants aged 2–5 months)(39). Using this cut-off, the MUIC for infants aged 3 (115 µg/l) and 6 months (120 µg/l) in the current study would indicate iodine deficiency, which was consistent with the estimated suboptimal intake from BMIC. Further, infants aged 6 months who were exclusively breastfed had an MUIC (80 µg/l) lower than 125 µg/l suggesting iodine insufficiency, which was significantly lower than those who were partially breastfed (147 µg/l). This shows the importance of adequate maternal iodine status for those infants who are exclusively breastfed at 6 months of age.

In the present study, despite differing amounts of breast-feeding and ages of infants, BMIC was moderately correlated with infant UIC. This finding is supported by a systematic review of fourteen eligible studies(46), which suggested BMIC was the primary indicator of iodine status in breastfed infant iodine status due to the positive association between BMIC and infant UIC. In the current study, median BMIC at 3MPP and 6MPP (69 µg/l and 59 µg/l, respectively) suggested inadequate infant iodine intake. Further analysis from a South Australia post-fortification study in 2017 found that infants from mothers with lower BMIC (<100 µg/l) were less likely to achieve adequate iodine status (infant UIC > 100 µg/l), when compared with those with higher BMIC (≥100 µg/l)(49). The Australian authors suggest that achieving adequate iodine status for lactating women is essential to ensure sufficient iodine supply to their breastfed infants.

Iodine status of exclusive breast-feeding women and their infants at 3 months postpartum

This current MINI study found iodine deficiency was present in EBF mothers at 3MPP. The current MUIC remained similar to the value (74 µg/l in 2011) previously reported from the same region in New Zealand(27), although it showed a marked improvement from 34 µg/l in 2009 (prior to government interventions)(27). Women who reported consuming iodine-containing supplements at 3MPP were more likely to achieve adequate iodine status when compared with those who did not use such supplements, this has been discussed in detail previously(17). Exclusively breastfed infants fully rely on their breast milk intake for thyroid function. The MUIC of exclusively breastfed infants at 3 months of age was 111 µg/l, below the suggested cut-off of 125 µg/l(39) indicating iodine deficiency. Lack of iodine intake may interrupt the motor and neurodevelopment of these infants at this crucial time.

The present study suggests that among this cohort of EBF women who were iodine-deficient, increased partitioning of iodine secretion into breast milk (the highest proportion of 60 %) occurred when total daily iodine excretion was low (<300 µg/d). This partitioning potentially provides a protective effect to ensure iodine supply to their breastfed infants. In comparison, a similar partitioning pattern (increased fraction of iodine into breast milk but decreased iodine in urine when total daily iodine excretion < 300 µg/d) was observed from a large multi-centre study of lactating women (iodine sufficient based on median BMIC) in China (*n* 386), Philippines (*n* 371) and Croatia (*n* 109)(4). This pattern may be due to an enhanced capacity of sodium–iodide symporter transportation by mammary glands during early lactation(50), which may ensure adequate iodine supply to exclusively breastfed newborn infants(4). However, in the MINI study, when total daily iodine excretion was higher than 300 µg, a constant partitioning of excretion was observed in urine (80 %) and breast milk (20 %), which differed from the previous multi-centre study showing a continuous decreased excretion in breast milk but a measurable increase in urine(4). This may be due to the smaller number of participants in the current study whose total iodine excretion was above 300 µg/d; thus, the current results need to be interpreted with caution.

Strengths and limitations

This study is the first longitudinal cohort study in New Zealand to assess the iodine status simultaneously of both mothers and infants, subsequent to the introduction of mandatory fortification of bread with iodised salt (2009) and the recommended government-subsided iodine supplement (150 µg/d) for breast-feeding mothers (2010).

The study examined the iodine status of mother–infant pairs during the transitional period from exclusive, to partial, and in some cases, cessation of breast-feeding throughout the first postpartum year, which enhances the existing available knowledge of iodine status throughout postpartum period. Maternal iodine status was measured in both urine and breast milk to provide a thorough measure of each participant's iodine status. The study also contributes to the limited knowledge on the fractional uptake of iodine from the mammary gland in response to variations in iodine intake while EBF.

To examine the impact of iodine supplements on iodine status, participants were defined as iodine-containing supplement users or non-users based on data collected at 3MPP; this may have diluted the effect of iodine supplements, as fewer women were taking iodine supplements after 3MPP. Although the use of iodine-containing supplements within the last 24 h was likely to be reflected in their UIC, this method could incorrectly classify habitual users who did not use the supplement on the day of assessment into the non-user group. Other limitations of this study also include that the self-selected participants were predominantly well-educated with a relatively high household income; thus, the sample may not be representative of the overall New Zealand population. If these women were iodine-deficient, iodine status of women who are less educated and of low income may be of even greater concern. In addition, the use of a spot urine samples may introduce intra-individual variability due to the variation in maternal hydration status and substantial variation in daily iodine intake. Urinary creatinine values were used to reduce the variation due to maternal hydration. To determine habitual intake, using repeated measuring could have better predicted iodine status(51). Newborn TSH can be used as another indicator of infants' iodine status by following a standardised protocol(52). However, potential confounding factors including maternal iodine status, mode of delivery, sampling time and maternal exposure to iodine-containing antiseptics may limit the use of newborn TSH measurement(52).

Conclusions

In conclusion, after two New Zealand government interventions in 2009 and 2010, this cohort of women throughout the first postpartum year was iodine-deficient irrespective of the amount or duration of breast-feeding. Despite that an increased fractional iodine excretion into breast milk was observed in lactating women with low iodine intake, the low use of iodine-containing supplements during later breast-feeding is concerning, especially for lactating women on a diet containing few iodine-rich foods and those who become pregnant again. Iodine status of their breastfed infants aged 3 and 6 months may be inadequate. For breastfed infants, breast milk is still an important iodine source. Therefore, it is crucial for lactating women to achieve adequate iodine status throughout lactation. Further studies to assess maternal and infants' iodine status with their thyroid function, and infant neurodevelopment outcomes are needed, to ensure optimal health of both mothers and their future offspring.

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References

1. World Health Organization, UNICEF & ICCIDD (2007) Assessment of iodine deficiency disorders and monitoring their elimination. https://apps.who.int/iris/bitstream/handle/10665/43781/9789241595827_eng.pdf (accessed November 2020).
2. Bougma K, Aboud FE, Harding KB, *et al.* (2013) Iodine and mental development of children 5 years old and under: a systematic review and meta-analysis. *Nutrients* **5**, 1384–1416.
3. Semba RD & Delange F (2001) Iodine in human milk: perspectives for infant health. *Nutr Rev* **59**, 269–278.
4. Dold S, Zimmermann MB, Aboussad A, *et al.* (2017) Breast milk iodine concentration is a more accurate biomarker of iodine status than urinary iodine concentration in exclusively breastfeeding women. *J Nutr* **147**, 528–537.
5. World Health Organization Breastfeeding recommendations. https://www.who.int/health-topics/breastfeeding#tab=tab_2 (assessed November 2020).
6. Eastman C, Ma G & Li M (2019) Optimal assessment and quantification of iodine nutrition in pregnancy and lactation: laboratory and clinical methods, controversies and future directions. *Nutrients* **11**, 2378.
7. Eltom A, Eltom M, Elnagar B, *et al.* (2000) Changes in iodine metabolism during late pregnancy and lactation: a longitudinal study among Sudanese women. *Eur J Clin Nutr* **54**, 429–433.
8. Thomson CD, Packer MA, Butler JA, *et al.* (2001) Urinary selenium and iodine during pregnancy and lactation. *J Trace Elem Med Biol* **14**, 210–217.
9. Andersson M, Aeberli I, Wüst N, *et al.* (2010) The Swiss iodized salt program provides adequate iodine for school children and pregnant women, but weaning infants not receiving iodine-containing complementary foods as well as their mothers are iodine deficient. *J Clin Endocrinol Metab* **95**, 5217–5224.
10. Aakre I, Morseth MS, Dahl L, *et al.* (2021) Iodine status during pregnancy and at 6 weeks, 6, 12 and 18 months post-partum. *Matern Child Nutr* **17**, e13050.
11. Manousou S, Augustin H, Eggertsen R, *et al.* (2021) Inadequate iodine intake in lactating women in Sweden: a pilot 1-year, prospective, observational study. *Acta Obstet Gynecol Scand* **100**, 48–57.
12. Thomson CD (2004) Selenium and iodine intakes and status in New Zealand and Australia. *Br J Nutr* **91**, 661–672.
13. Skeaff SA, Thomson CD & Gibson RS (2002) Mild iodine deficiency in a sample of New Zealand schoolchildren. *Eur J Clin Nutr* **56**, 1169–1175.
14. Thomson B (2009) Levels of Iodine in New Zealand Retail Salt. Prepared as Part of a New Zealand Food Safety Authority Contract for Scientific Services. https://www.mpi.govt.nz/dmsdocument/22690/direct#:~:text=Iodisedsaltisdefinedby,)(FSANZ%2C2009) (accessed March 2021)
15. Ershow AG, Skeaff SA, Merkel JM, *et al.* (2018) Development of databases on iodine in foods and dietary supplements. *Nutrients* **10**, 1–20.
16. Ministry for Primary Industries (2014) Update report on the dietary iodine intake of Zealand children following fortification of bread with iodine. https://www.mpi.govt.nz/dmsdocument/4596/direct (accessed November 2020).
17. Jin Y, Coad J, Zhou SJ, *et al.* (2020) Use of iodine supplements by breastfeeding mothers is associated with better maternal and infant iodine status. *Biol Trace Elem Res* (In the Press).
18. Pearson A, Gibbs M, Lau K, *et al.* (2016) New Zealand Total Diet Study. https://apo.org.au/sites/default/files/resource-files/2018–05/apo-nid173731.pdf (accessed November 2020).
19. The New Zealand Institute for Plant and Food Research and New Zealand Ministry of Health (2018) New Zealand Food Composition Data. Mistry of Health. https://www.foodcomposition.co.nz/ (accessed October 2020).
20. Thomson CD, Colls AJ, Conaglen JV, *et al.* (1997) Iodine status of New Zealand residents as assessed by urinary iodide excretion and thyroid hormones. *Br J Nutr* **78**, 901–912.
21. Skeaff SA, Ferguson EL, McKenzie JE, *et al.* (2005) Are breastfed infants and toddlers in New Zealand at risk of iodine deficiency? *Nutrition* **21**, 325–331.
22. Skeaff SA & Lonsdale-Cooper E (2012) Mandatory fortification of bread with iodised salt modestly improves iodine status in schoolchildren. *Br J Nutr* **190**, 1109–1113.
23. Jones E, Mclean R, Davies B, *et al.* (2016) Adequate iodine status in New Zealand school children post-fortification of bread with iodised salt. *Nutrients* **8**, 298.
24. Edmonds J, McLean R, Williams S, *et al.* (2015) Urinary iodine concentration of New Zealand adults improves with mandatory fortification of bread with iodised salt but not to predicted levels. *Eur J Nutr* **25**, 1201–1212.
25. Ministry for Primary Industries (2016) Mandatory Iodine Fortification in New Zealand : Supplement to the Australian Institute of Health and Welfare 2016 Report- Monitoring the Health Impacts of Mandatory Folic Acid and Iodine Fortification. https://www.aihw.gov.au/reports/food-nutrition/folic-acid-iodine-fortification-aus-nz-supplement/contents/table-of-contents (accessed November 2020).

26. New Zealand Ministry of Health (2011) Supplement (Tablet) to Take When Pregnant or Breastfeeding. https://www.healthed.govt.nz/system/files/resource-files/HE4147%20Folic%20acid%20and%20iodine.pdf (accessed November 2020).
27. Brough L, Jin Y, Shukri NH, *et al.* (2015) Iodine intake and status during pregnancy and lactation before and after government initiatives to improve iodine status, in Palmerston North, New Zealand: a pilot study. *Matern Child Nutr* **11**, 646–655.
28. Azizi F & Smyth P (2009) Breastfeeding and maternal and infant iodine nutrition. *Clin Endocrinol* **70**, 803–809.
29. Vannoort RW & Thomson BM (2005) 2003/04 New Zealand Total Diet Survey - Agricultural Compound Residues, Selected Contaminants and Nutrients. New Zealand Food Safety Authority. https://www.mpi.govt.nz/dmsdocument/22189/direct (accessed November 2017).
30. Vannoort RW & Thomson BM (2009) New Zealand Total Diet Study: Agricultural Compound Residues, Selected Contaminant and Nutrient Elements. Ministry of Agriculture and Forestry. https://www.mpi.govt.nz/dmsdocument/4004/direct (accessed November 2020).
31. Jin Y, Coad J, Zhou SJ, *et al.* (2020) Mother and Infant Nutrition Investigation in New Zealand (MINI Project): protocol for an observational longitudinal cohort study. *JMIR Res Protoc* **9**, e18560.
32. Faul F, Erdfelder E, Buchner A, *et al.* (2009) Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behav Res Methods* **41**, 1149–1160.
33. da Costa THM, Haisma H, Wells JCK, *et al.* (2010) How much human milk do infants consume? data from 12 countries using a standardized stable isotope methodology. *J Nutr* **140**, 2227–2232.
34. Fecher P, Goldmann I & Nagengast A (1998) Determination of iodine in food samples by inductively coupled plasma mass spectrometry after alkaline extraction. *J Anal Spectrom* **13**, 977–982.
35. WHO World Health Organization (2007) *AnthroPlus for Personal Computers. Manual: software for Assessing Growth of the World's Children*. Geneva: WHO.
36. De Onis M & Blössner M (1997) *WHO Global Database on Child Growth and Malnutrition*. Geneva: WHO.
37. De Onis M, Onyango A, Borghi E, *et al.* (2006) WHO Child Growth Standards: Length/Height-for-Age, Weight-for-Age, Weight-for-Length, Weight-for-Height and Body Mass Index-for-Age:Methods and Development. https://www.who.int/publications/i/item/924154693X (accessed November 2006).
38. National Academy of Science Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc. http://www.nap.edu/catalog/10026.html (accessed November 2020).
39. Dold S, Zimmermann MB, Baumgartner J, *et al.* (2016) A dose-response crossover iodine balance study to determine iodine requirements in early infancy. *Am J Clin Nutr* **104**, 620–628.
40. New Zealand Ministry of Health (2006) Nutrient Reference Values for Australia and New Zealand. Vol 085. Commonwealth of Australia. https://www.nrv.gov.au/ (accessed March 2021).
41. Axford S, Charlton K, Yeatman H, *et al.* (2011) Improved iodine status in breastfeeding women following mandatory fortification. *Aust N Z J Public Health* **35**, 579–580.
42. Bouhouch RR, Bouhouch S, Cherkaoui M, *et al.* (2014) Direct iodine supplementation of infants versus supplementation of their breastfeeding mothers: A double-blind, randomised, placebo-controlled trial. *Lancet Diabetes Endocrinol* **2**, 197–209.
43. Ellsworth L, Mccaffery H, Harman E, *et al.* (2020) Breast milk iodine concentration is associated with infant growth, independent of maternal weight. *Nutrients* **12**, 1–13.
44. Velasco I, Bath SC & Rayman MP (2018) Iodine as essential nutrient during the first 1000 days of life. *Nutrients* **10**, 1–16.
45. Mulrine HM, Skeaff SA, Ferguson EL, *et al.* (2010) Breast-milk iodine concentration declines over the first 6 mo postpartum in iodine-deficient women. *Am J Clin Nutr* **92**, 849–856.
46. Dror DK & Allen LH (2018) Iodine in human milk: a systematic review. *Adv Nutr* **9**, 278S–294S.
47. Institute of Medicine (IOM) (2000) *DRI Dietary Reference Intakes: applications in Dietary Assessment*. Washington, DC: National Academies Press.
48. Delange F (2007) Iodine requirements during pregnancy, lactation and the neonatal period and indicators of optimal iodine nutrition. *Public Health Nutr* **10**, 1571–1580.
49. Huynh D, Condo D, Gibson R, *et al.* (2017) Iodine status of postpartum women and their infants in Australia after the introduction of mandatory iodine fortification. *Br J Nutr* **117**, 1656–1662.
50. Vermiglio F, Presti L, Battiato S, *et al.* (1992) Enhaneed iodine concentrating capacity by the mammary gland in iodine defieient lactating women of an endemie goiter region in Sieily. *J Endocrinol Invest* **15**, 137–142.
51. Konig F, Andersson M, Hotz K, *et al.* (2011) Ten repeat collections for urinary iodine from spot samples or 24-hour samples are needed to reliably estimate individual iodine status in women. *J Nutr* **141**, 2049–2054.
52. Li M & Eastman CJ (2010) Neonatal TSH screening: is it a sensitive and reliable tool for monitoring iodine status in populations? *Best Pract Res Clin Endocrinol Metab* **24**, 63–75.
53. Statistics New Zealand (2018) Household Income and Housing-Cost Statistics: year Ended June 2016. https://www.stats.govt.nz/information-releases/household-income-and-housing-cost-statistics-year-ended-june-2017 (accessed October 2020).