Degradation of phytic acid in cereal porridges improves iron absorption by human subjects[1–3]

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ABSTRACT

Background: Phytic acid in cereal-based and legume-based complementary foods inhibits iron absorption. Low iron absorption from cereal porridges contributes to the high prevalence of iron deficiency in infants from developing countries.

Objective: The objective was to measure the influence of phytic acid degradation on iron absorption from cereal porridges.

Design: An exogenous phytase was used to fully degrade phytic acid during the manufacture of 9 roller-dried complementary foods based on rice, wheat, maize, oat, sorghum, and a wheat-soy blend. Iron absorption from the phytate-free and native phytate porridges prepared with water or milk (wheat only) was measured in adult humans with an extrinsic-label radioiron technique. Ascorbic acid was added to some porridges.

Results: When the foods were reconstituted with water, dephytinization increased iron absorption from rice porridge from 1.73% to 5.34% ($P < 0.001$), from oat from 0.33% to 2.79% ($P < 0.0001$), from maize from 1.80% to 8.92% ($P < 0.0001$), from wheat from 0.99% to 11.54% ($P < 0.0001$), from the wheat-soy blend without ascorbic acid from 1.15% to 3.75% ($P < 0.005$), and from the wheat-soy blend with ascorbic acid from 2.40% to 8.46% ($P < 0.005$). Reconstituting wheat porridge with milk instead of water markedly decreased or completely removed the enhancing effect of dephytinization on iron absorption in the presence and absence of ascorbic acid. Dephytinization did not increase iron absorption from high-tannin sorghum porridge reconstituted with water but increased iron absorption from low-tannin sorghum porridge by ≈2-fold ($P < 0.01$).

Conclusions: Phytate degradation improves iron absorption from cereal porridges prepared with water but not with milk, except from high-tannin sorghum. *Am J Clin Nutr* 2003;77:1213–9.

KEY WORDS Iron absorption, phytic acid, cereal porridges, ascorbic acid, complementary food, developing countries, human subjects

INTRODUCTION

Iron nutrition is particularly important during the weaning period, when the infant is growing rapidly and has a high demand for iron. In developing countries, the intake of absorbable iron by infants is often low, and iron deficiency anemia is common. A major consequence is retarded psychomotor and mental development, with possible long-term negative effects on school performance (1). Cereal porridges are common complementary foods during the weaning period and often provide much of the dietary iron intake because the iron contribution from human milk is low.

Cereal porridges are based on common grains, such as rice, maize, wheat, oat, or sorghum. They are often combined with milk or with leguminous seeds, such as soy, to provide infants with both adequate protein and energy. In developing countries, the cereals or cereal legume mixtures are first cooked and then fed as a watery gruel. In industrialized countries, the cereals are precooked industrially and dried by roller-drying or extrusion and then reconstituted with milk, commercial infant formula, or water before consumption. Both cereal grains and legume seeds are rich in phytic acid (myo-inositol-6-phosphate), a compound that strongly inhibits the absorption of iron and other essential minerals (2, 3). Some sorghum varieties are also rich in phenolic compounds (4), which—like phytate—strongly inhibit iron absorption (5).

Because of the high phytate content of cereal porridges, iron absorption of native iron and fortification iron may be very low (6). Absorption can be increased by the addition of ascorbic acid (4, 6–8), by the addition of EDTA (9), and by the degradation or removal of phytic acid (10). Phytic acid is highest in whole-grain flours and can be decreased considerably by removing its hull (11). Iron absorption is still low, however, even from porridges made from low-extraction flours (6), because small amounts of phytate inhibit iron absorption (10). Phytic acid in cereal foods can be degraded completely by phytases, enzymes that successively remove the phosphate groups from phytic acid until it no longer binds iron. Phytic acid has been completely degraded in weaning cereals by adding commercial exogenous phytases (12) or by activating the native phytases by a combination of soaking, germinating, and fermenting (13).

In the current study, phytic acid was fully degraded in roller-dried complementary foods prepared from rice, wheat, maize, oat, sorghum, and a wheat-soy blend by adding an exogenous phytase. The iron-fortified cereal porridges were fed after reconstitution with water or milk (wheat porridge only). Ascorbic acid was added to some porridges. Iron absorption was measured in adult human subjects by using the dual-extrinsic-label radioiron technique.

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SUBJECTS AND METHODS

Subjects

Iron absorption was measured in 78 subjects aged 21–38 y ($\bar{x}$: 25 y). The composite group included 34 males and 44 females. All subjects were in good health and denied a history of disorders known to influence the gastrointestinal absorption of iron. Serum ferritin concentrations ranged from 3 to 326 μg/L, indicating a wide variation in iron status. Fourteen of the subjects, 1 male and 13 females, were iron deficient as defined by a serum ferritin concentration < 12 μg/L. None of the subjects were anemic, defined as a hemoglobin concentration < 120 g/L in women and < 130 g/L in men. Written informed consent was obtained from each volunteer before the investigation began, and all experimental procedures were approved by the Human Subjects Committee at the University of Kansas Medical Center. The subjects were allocated to the studies in the order in which they volunteered.

Iron absorption measurements

Nine iron absorption studies were performed, during which 2–4 separate iron absorption measurements were made in each of 6–11 subjects by using radioiron tracers administered sequentially. All meals were fed between 0700 and 0900 after an overnight fast, and nothing but water was allowed for 3 h after the meal. The test meals were fed with a radioiron label providing either 37 kBq ^{59}Fe or 74 kBq ^{55}Fe, and iron absorption was measured on the basis of incorporated erythrocyte radioactivity as previously described (14).

On the morning preceding the administration of the first test meal, 25 mL nonfasting blood was collected from each subject for the measurement of background radioactivity, packed cell volume, and plasma ferritin (15). The first and second test meals (meals A and B), labeled with ^{55}Fe and ^{59}Fe, respectively, were fed on days 2 and 3 of the study. Fourteen days after the administration of the second of these meals (day 17), 30 mL blood was drawn for the measurement of incorporated red blood cell radioactivity. A third and fourth test meal (meals C and D), labeled with separate radioiron labels, were fed on days 17 and 18, and a final blood sample (30 mL) was obtained on day 32 to determine the increase in red blood cell radioactivity. Measurements of blood radioactivity were performed on duplicate 10-mL samples of whole blood according to a modified version of the method of Eakins and Brown (16). Percentage absorption was calculated on the basis of blood volume estimated from height and weight (17, 18) and an assumed red blood cell incorporation of 80% (19).

Roller-dried cereal porridges

Eighteen different roller-dried cereal porridges were prepared either at the Nestlé Research Center, Lausanne, Switzerland, or at the Nestlé Product Technology Center, Orbe, Switzerland. Nine of the cereal porridges contained their native phytate concentrations and the other 9 were the same porridges after dephytinization. The dried porridges were prepared from the flours of 8 different cereal grains and from a blend of wheat and soy flour. The wheat-soy blend was prepared from a mixture of 60% extraction wheat flour and defatted soybean flour. The cereal flours included ground polished rice, 60% extraction wheat flour, partly degermed whole-white maize, oat flour prepared from dehulled oat grain (treated first with steam to deactivate the lipase and then roller-dried, flaked, and ground into a flour), and 4 different sorghum flours. Two sorghum varieties originated from Sudan and were obtained from Larry Butler (Purdue University, Lafayette, IN): sorghum A (IS 8260) was described as a conventional high-tannin, bird-resistant sorghum, and sorghum B (Hagen Dura 1) was described as a hybrid sorghum completely devoid of tannins. The second 2 sorghum varieties, sorghum C (DC-75) and sorghum D (SV-2), originated from Zimbabwe and were obtained from Nestlé Ltd, Harare, Zimbabwe.

The same processing method was used to prepare all of the dried cereal porridges containing native phytate. The cereal flours were mixed with sucrose and water (1:10, wt:vol) to give a slurry with ≈40% (wt:vol) dry matter. The slurry was cooked by steam injection (≈135 °C) and roller-dried. No other ingredients were added. The dephytinized cereal porridges were prepared in a similar way. They were dephytinized by adding phytase (Finase S40; Alko Ltd, Helsinki) to the aqueous slurry, adjusted to pH 5.0–5.5, and holding at 40 °C until all the phytate had been degraded (≈2 h).

Analytic methods

The phytic acid content of the roller-dried porridges made from rice, wheat, oat, maize, and sorghum was measured by a modification of the Makover (20) method in which cerium replaced iron in the precipitation step. The phytic acid content of the cereal-soy blend was measured by an HPLC method (21, 22). Sorghum grains were analyzed for condensed tannins by the vanillin method (23).

Test meals

Studies 1–4 investigated the influence of phytate degradation on iron absorption from iron-fortified rice, oat, maize, and wheat porridges (**Table 1**). All test meals contained 50 g roller-dried cereal and 0.5 g salt and were mixed into a porridge with 300 mL hot water. The wheat porridge and dephytinized wheat porridge were additionally fed mixed with 300 mL hot, homogenized whole milk. In studies 1–3, the native phytate and the dephytinized porridges made from the same cereal were fed to the same subject on consecutive days as meals A and B or meals C and D labeled with either ^{55}Fe or ^{59}Fe. Study 4 compared the absorption of the 4 dephytinized porridges directly. The radioiron label was added to the porridge as a 1-mL solution containing 2.5 mg Fe as ferrous sulfate heptahydrate and either 74 kBq $^{55}FeCl_3$ or 37 kBq $^{59}FeCl_3$ in 0.01 mol HCl/L. Sugar (10 g) was sprinkled on top of the porridge before it was served. To ensure complete ingestion of the radioiron labels, the feeding bowls were carefully rinsed with water after consumption of the porridge, and the rinsing water was consumed.

The influence of phytate degradation on iron absorption from Sudan sorghums A and B was investigated in study 5 and from Zimbabwe sorghums C and D in study 6 (Table 1). All test meals contained 50 g sorghum cereal and 0.5 g salt and were mixed to a porridge with 150–250 mL hot water. All porridges were fed with a similar thick, creamy texture. The amount of water necessary to give this texture varied and was less for the phytate-free cereals. The native and phytate-free sorghum porridges were fed on 2 consecutive days. The radioiron label was added to the porridge as a 1-mL solution containing 0.1 mg Fe as ferric chloride with either 74 kBq ^{55}Fe or 37 kBq ^{59}Fe in 0.01 mol HCl/L. The sorghum porridges contained no fortification iron. Sugar (10 g) was sprinkled onto the top of the porridge before it was served.

Studies 7–9 investigated the influence of the dephytinization of wheat porridge reconstituted with water or milk and fed with or without ascorbic acid and the dephytinization of a wheat–soy flour

TABLE 1
Influence of phytic acid degradation on iron absorption from rice, oat, maize, wheat, and sorghum porridges

Study (no. of subjects, sex, and age)	Mean packed cell volume	Serum ferritin[1]	Meals	Iron absorption[2]	Absorption ratio versus native phytate[2,3]
	%	μg/L		% of dose	
1) Rice (*n* = 6 M, 3 F; 25 y)	45	53 (10–326)	A: rice, native phytate	1.73 (1.20, 2.49)	—
			B: rice, dephytinized	5.34 (3.72, 7.68)	3.09[4] (2.55, 3.74)
2) Oat and maize (*n* = 3 M, 7 F; 25 y)	43	27 (8–119)	A: oat, native phytate	0.33 (0.25, 0.44)	—
			B: oat, dephytinized	2.79 (2.37, 3.28)	8.36[5] (6.67, 10.48)
			C: maize, native phytate	1.80 (1.44, 2.25)	—
			D: maize, dephytinized	8.92 (7.33, 10.85)	4.96[5] (4.07, 6.05)
3) Wheat (*n* = 5 M, 6 F; 25 y)	43	28 (7–125)	A: wheat, native phytate	0.99 (0.80, 1.23)	—
			B: wheat-milk, native phytate	1.30 (1.00, 1.68)	—
			C: wheat, dephytinized	11.54 (8.29, 16.07)	11.60[5] (9.11, 14.77)
			D: wheat-milk, dephytinized	1.63 (1.10, 2.42)	1.26 (0.91, 1.75)
4) Oat, rice, wheat, and maize (*n* = 6 M, 3 F; 24 y)	42	34 (6–98)	A: oat, dephytinized	3.19 (2.34, 4.36)	—
			B: rice, dephytinized	7.08 (5.31, 9.45)	—
			C: wheat, dephytinized	10.20 (7.70, 13.51)	—
			D: maize, dephytinized	8.61 (6.02, 12.33)	—
5) Sudan sorghum (*n* = 1 M, 7 F; 27 y)	42	15 (3–79)	A: sorghum A, native phytate	0.94 (0.64, 1.37)	—
			B: sorghum A, dephytinized	1.26 (0.85, 1.85)	1.34 (1.10, 1.64)
			C: sorghum B, native phytate	1.39 (1.08, 1.80)	—
			D: sorghum B, dephytinized	2.49 (1.87, 3.31)	1.79[6] (1.58, 2.02)
6) Zimbabwe sorghum (*n* = 2 M, 7 F; 24 y)	42	26 (4–193)	A: sorghum C, native phytate	1.52 (1.01, 2.27)	—
			B: sorghum C, dephytinized	3.10 (2.08, 4.63)	2.04[4] (1.78, 2.34)
			C: sorghum D, native phytate	1.37 (1.01, 1.87)	
			D: sorghum D, dephytinized	2.56 (1.68, 3.92)	1.87[6] (1.61, 2.17)

[1] Geometric $\bar{x}$; range in parentheses.
[2] Geometric $\bar{x}$; −1 SE and +1 SE in parentheses.
[3] Absorption ratio calculated as iron absorption from meal with no phytic acid divided by iron absorption from the same meal containing its native phytic acid.
[4] $P < 0.001$.
[5] $P < 0.0001$.
[6] $P < 0.01$.

blend fed with or without ascorbic acid (**Table 2**). In study 7, native phytate and dephytinized wheat porridge, with 25 mg added ascorbic acid, was prepared with either hot water (meals A and C) or hot milk (meals B and D). In study 8, the native phytate and dephytinized wheat porridge was prepared with milk and fed either with no added ascorbic acid (meals A and C) or with 25 mg added ascorbic acid (meals B and D). In study 9, the native phytate or dephytinized wheat-soy blend was prepared with water and

TABLE 2
Influence of dephytinization on iron absorption from wheat porridges also containing ascorbic acid, milk, or soy

Study (no. of subjects, sex, and age)	Mean packed cell volume	Serum ferritin[1]	Meals	Iron absorption[2]	Absorption ratio versus native phytate[2,3]
	%	μg/L		% of dose	
7) Wheat (*n* = 3 M, 4 F; 23 y)	44	48 (30–77)	A: wheat, ascorbic acid, native phytate	2.91 (2.37, 3.56)	—
			B: wheat-milk, ascorbic acid, native phytate	2.32 (1.87, 2.87)	—
			C: wheat, ascorbic acid, dephytinized	10.10 (7.96, 12.83)	3.48[4] (2.47, 4.89)
			D: wheat-milk, ascorbic acid, dephytinized	2.58 (1.79, 3.71)	1.11 (0.85, 1.46)
8) Wheat (*n* = 6 M; 25 y)	45	88 (54–175)	A: wheat, milk, native phytate	0.58 (0.48, 0.71)	—
			B: wheat, milk, ascorbic acid, native phytate	0.89 (0.72, 1.09)	—
			C: wheat, milk, dephytinized	1.47 (1.03, 2.11)	2.53[4] (1.98, 3.24)
			D: wheat, milk, ascorbic acid, dephytinized	2.25 (1.70, 2.96)	2.53[4] (1.90, 3.34)
9) Wheat-soy blend (*n* = 2 M, 7 F; 24 y)	41	21 (4–69)	A: wheat-soy, native phytate	1.15 (0.77, 1.71)	—
			B: wheat-soy, dephytinized	3.75 (2.46, 5.72)	3.26[5] (2.55, 4.20)
			C: wheat-soy, ascorbic acid, native phytate	2.40 (1.61, 3.58)	—
			D: wheat-soy, ascorbic acid, dephytinized	8.46 (5.64, 12.70)	3.52[5] (2.74, 4.53)

[1] Geometric $\bar{x}$; range in parentheses.
[2] Geometric $\bar{x}$; −1 SE and +1 SE in parentheses.
[3] Absorption ratio calculated as iron absorption from meal with no phytic acid divided by iron absorption from the same meal containing its native phytic acid.
[4] $P < 0.05$.
[5] $P < 0.005$.

TABLE 3
Phytic acid content of cereal porridges[1]

Porridge	Phytic acid
	%
Rice	0.16
Oat	0.67
Maize	0.26
Wheat	0.12
Sudan sorghum A	0.87
Sudan sorghum B	0.89
Zimbabwe sorghum C	0.43
Zimbabwe sorghum D	0.71
Wheat-soy blend	0.30

[1] Dephytinized porridges contained 0.002% to ≤0.001% phytic acid, except the dephytinized wheat-soy blend, which contained 0.02% phytic acid.

fed with no added ascorbic acid (meals A and B) or with 25 mg added ascorbic acid (meals C and D). All meals contained fortification iron added as ferrous sulfate, either 2.5 mg/meal (studies 7 and 8) or 5 mg/meal (study 9). All test meals contained 50 g cereal and 0.5 g salt and were mixed to a porridge with 300 mL hot water or whole, homogenized milk. The radioiron label was added to the porridge as a 1-mL solution containing 2.5 or 5-mg Fe as ferrous sulfate heptahydrate and either 74 kBq $^{55}FeCl_3$ or 37 kBq $^{59}FeCl_3$ in 0.01 mol HCl/L. Sugar (10 g) was sprinkled onto the porridge before it was served. When ascorbic acid was added, 25 mg was mixed carefully into the hot porridge immediately before the sugar was added and the porridge served.

Statistical analysis

Values expressed as a percentage of absorption were converted to logarithms to calculate geometric means and for statistical analysis. Original values were recovered by reconverting the results to antilogarithms (24). Comparison of iron absorption for any given pair of test meals within each study was made by a paired *t* test to determine whether the log absorption ratio differed from zero. When the effect of dephytinization was tested among all of the cereal porridges, the absorption ratios comparing iron absorption from cereal porridges with and without phytic acid (−PA/+PA) were compared by using analysis of variance with Tukey's multiple comparison test. To test the effectiveness of ascorbic acid to enhance iron absorption from dephytinized wheat porridge prepared with milk, the absorption ratios (−PA/+PA) were pooled for studies 3, 7, and 8. In all cases, P values < 0.05 were considered significant. Statistical analysis was performed with the use of GRAPHPAD PRIZM (Graph Pad Software, San Diego).

RESULTS

The phytic acid contents of the dried cereal porridges are shown in **Table 3**. The native phytate in the dried porridges ranged from 0.12% for the wheat porridge to 0.89% for the Sudan sorghum B porridge. Phytic acid degradation with the phytase enzyme was very efficient, and phytic acid was decreased to ≤0.002% in all dephytinized porridges except the dephytinized wheat-soy blend, which contained 0.02% phytic acid (reduced from 0.3%). Sudan sorghum A was a high-tannin variety and contained 3.36% condensed tannins compared with <0.01% in Sudan sorghum B. The Zimbabwe sorghums C and D both had a low concentration of tannins (0.039% and 0.030%, respectively).

Iron absorption from the rice, oat, maize, and wheat porridges prepared with water and containing their native phytate content was relatively low, ranging from 0.33% for oat to 1.8% for maize (studies 1–3; Table 1). Iron absorption from the cereal porridges was increased significantly by the degradation of phytic acid, although the magnitude of the increase differed markedly. Dephytinization had no influence on iron absorption of wheat porridge reconstituted with milk (absorption ratio: 1.26; $P > 0.05$). Study 4 compared iron absorption from the dephytinized oat, rice, wheat, and maize porridges directly (Table 1). Mean iron absorption values for the individual dephytinized cereals reconstituted with water were similar to those obtained in studies 1–3. Iron absorption from the dephytinized oat was one-third to one-half of that from other cereals.

Dephytinization had no influence on iron absorption from the high-tannin Sudan sorghum A porridge reconstituted with water (absorption ratio: 1.34; $P > 0.05$) but significantly increased absorption by ≈2-fold from low-tannin sorghum porridges (Table 1).

The interaction between the enhancing effect of dephytinization and the negative effect of milk on iron absorption from wheat porridge was further investigated in studies 7 and 8 (Table 2). Study 7 was identical to study 3, except that each meal contained 25 mg added ascorbic acid. As in study 3, dephytinization significantly increased absorption when the wheat porridge was prepared with water (absorption ratio: 3.48) but had no influence on iron absorption when the porridge was prepared with milk (absorption ratio: 1.11; $P > 0.05$). On the other hand, in study 8, dephytinization of wheat porridge prepared with milk modestly but significantly increased iron absorption 2.5-fold when consumed without ascorbic acid and again by 2.5-fold when consumed with ascorbic acid (Table 2).

In study 9, phytate degradation increased iron absorption 3.26-fold from the wheat-soy blend in the absence of ascorbic acid and 3.52-fold in the presence of 25 mg ascorbic acid (Table 2).

DISCUSSION

Mean iron absorption in nonanemic adult humans (with a wide range of iron stores) from precooked, roller-dried, cereal-based complementary foods reconstituted with water was very low, ranging from 0.33% to 1.80%, and was similar to what has been previously reported (6). When the phytic acid in the complementary foods was almost completely degraded by adding a commercial phytase during manufacture, iron absorption increased 2–12-fold (**Figure 1**). Dephytinization, with the use of the same commercial phytase, was previously reported to increase iron absorption from soy (5) and pea (25) infant formula fed to adults and from soy formula fed to infants (12).

There were large differences between grains in the magnitude of the improvement in iron absorption on dephytinization. Iron absorption from wheat porridge increased 12-fold, which was significantly higher than that from all of the other cereal porridges except oat. The 3–5-fold increases in absorption observed on dephytinization of the rice, wheat-soy, and maize porridges were not significantly different from each other. The 5–8-fold increases in absorption on dephytinization of maize and oat were also not significantly different from each other. Phytic acid degradation of low-tannin sorghum porridges increased iron absorption only

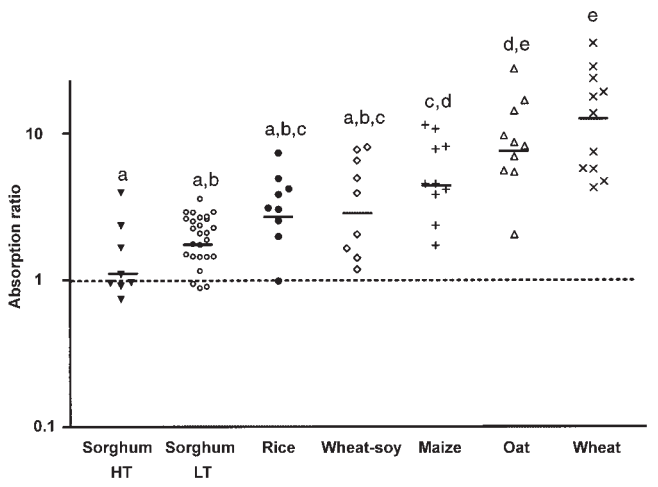

FIGURE 1. Influence of dephytinization on iron absorption from cereal porridges. Means with different letters are significantly different. Results for high-tannin (HT) sorghum are from sorghum A, study 5. For low-tannin (LT) sorghum, the results from studies 5 and 6 (sorghums B, C, and D) were combined. The absorption ratio was calculated as iron absorption from the meal with no phytic acid divided by iron absorption from the same meal containing its native phytic acid. The horizontal line indicates geometric means.

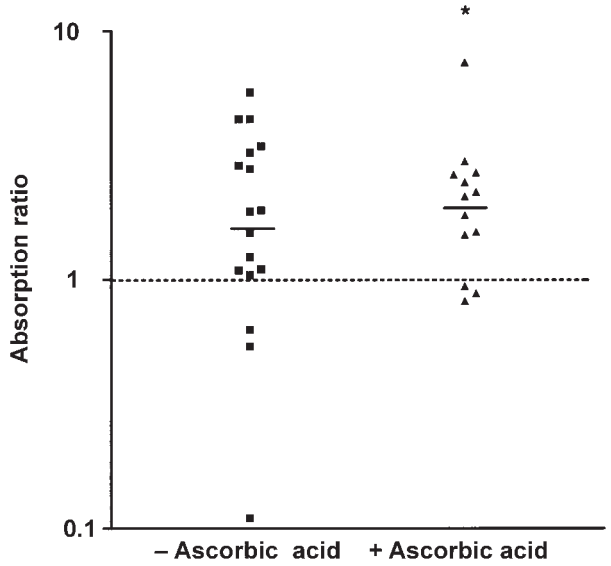

FIGURE 2. Effect of dephytinization on wheat-milk porridges with (+) and without (−) added ascorbic acid. The absorption ratio was calculated as iron absorption from the meal with no phytic acid divided by iron absorption from the same meal containing its native phytic acid. The horizontal line indicates geometric means. *Log ratio is significantly different from zero, $P < 0.005$.

2-fold, and no improvement in iron absorption was observed on dephytinization of high-tannin sorghum (absorption ratio: 1.34). This latter finding was presumably due to the strong inhibitory effect of phenolic compounds (4, 5). The magnitude of the observed change in iron absorption on dephytinization could be related to the initial level of iron absorption from the native phytate–containing porridge and to differences in composition of the grains. Phenolic compounds, certain proteins, and calcium could inhibit iron absorption from cereal foods (26).

Another finding of the present study was that the enhancing effect of dephytinization on iron absorption was greatly decreased or even completely removed by preparing the wheat porridges with milk instead of water (studies 3, 7, and 8). When the results from these studies were pooled (**Figure 2**), dephytinization of wheat-milk porridge in the absence of ascorbic acid resulted in a small nonsignificant 1.6-fold increase in iron absorption, whereas dephytinization of wheat-milk porridge with added ascorbic acid resulted in a small but significantly different ($P < 0.005$) 1.9-fold increase. When the 2 outliers (Figure 2) were omitted from the calculation, dephytinization of wheat-milk porridge significantly improved iron absorption both in the absence (1.9-fold; $P < 0.005$) and presence (1.7-fold; $P < 0.005$) of ascorbic acid. Nevertheless, in the presence of milk, the influence of dephytinization on iron absorption is at best modest. We previously reported that dephytinization of commercial infant cereals made from low-extraction wheat and milk and containing ascorbic acid did not improve iron absorption in human infants (12). The inhibitory effect of cow milk on iron absorption is thought to be mainly related to its high concentration of calcium (27) and casein (28).

Ascorbic acid is a well-known enhancer of iron absorption in the presence of phytic acid (6) and is usually added to commercial infant foods together with fortification iron to ensure adequate absorption (29). Ascorbic acid also enhances iron absorption from foods such as infant formulas containing no phytic acid. The magnitude of the response depends on the amount of ascorbic acid added and the food matrix (30). In our studies 8 and 9 (Table 2), 25 mg ascorbic acid further increased iron absorption from the phytate-free wheat-soy blend from 3.75% to 8.46% ($P < 0.05$) but not from the phytate-free wheat-milk porridge (1.47% compared with 2.25%; $P > 0.05$), perhaps because of the inhibitory nature of milk.

Although the current studies investigated the influence of dephytinization of complementary foods on iron absorption in adults, not infants, we previously showed that iron absorption in infants is inhibited by phytic acid in a way similar to iron absorption in adults (31). The current studies, however, were single-meal studies, which have been reported to overemphasize the influence of enhancers and inhibitors on iron absorption in comparison with multimeal studies (32); therefore, care should be taken in the interpretation of these results. Nevertheless, the findings of the current studies confirm the very low iron absorption from cereal porridges and indicate that phytate degradation would be a useful means for improving iron absorption from cereal-based complementary foods, provided that these foods are fed mixed with water, not milk. In industrialized countries, most dried infant cereals are prepared with cow milk or cow milk–based infant formula, and, with these products, the addition of ascorbic acid and not phytate degradation would be the best means of ensuring adequate iron absorption (29). Industrially manufactured weaning foods containing blends of cereals and pulses, however, would be expected to have a substantially improved iron bioavailability if the phytic acid were degraded.

The main advantage of dephytinization is seen in developing countries, where infant porridges are usually consumed with water and where infants have difficulty obtaining an adequate supply of absorbable iron. Phytic acid degradation, however, is not suited

for home-prepared complementary foods and is best achieved on an industrial scale by adding commercial phytases (12, 29) or by activating native phytase (33) and then drying. Traditional food-processing methods will also activate cereal phytases, and soaking of pounded maize flour was reported to decrease the phytate content by 49% (34), whereas germinating and dehusking rice and mung beans reduced phytic acid by 92% (13) and a combination of soaking, germinating, and fermenting degraded phytic acid in sorghum completely (35).

One mole of phytic acid binds 6 mol ferric iron so that even relatively small quantities of residual phytate are still strongly inhibitory (10). Hallberg et al (36) found that adding 10 mg/100 g phytic acid to bread rolls decreased iron absorption by 20% and that adding 20 mg/100 g decreased iron absorption by 40%. More recently, Mendoza et al (37, 38) reported little or no improvement in iron absorption from maize meals prepared from maize that had been genetically modified to contain 30–50% less phytic acid.

In conclusion, the magnitude of iron absorption from cereal-based porridges depends on the contents of the different components that enhance or inhibit iron uptake. Phytic acid, polyphenolic compounds, and milk are the major inhibitors, whereas ascorbic acid enhances iron absorption. In the absence of milk and polyphenols, phytic acid degradation greatly improves iron absorption from cereal-based complementary foods and, in developing countries, dephytinization should be considered as a major strategy to improve iron nutrition during the weaning period.

The study and the protocols were designed by all authors under the direction of RFH, and RFH wrote the manuscript with the input of all authors. MBR conducted all of the feeding studies and radioiron measurements in collaboration with JDC, who was also responsible for the iron-status measurements. M-AJ manufactured the phytate-free cereals and was responsible for the phytate analysis. The results were evaluated by all authors. At the time the study was conducted, M-AJ and RFH were employed by Nestec Ltd, who financed the study. MBR and JDC had no affiliation with Nestec Ltd.

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