

Prediction of dietary iron absorption: an algorithm for calculating absorption and bioavailability of dietary iron¹⁻³

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ABSTRACT

Background: Dietary iron absorption from a meal is determined by iron status, heme- and nonheme-iron contents, and amounts of various dietary factors that influence iron absorption. Limited information is available about the net effect of these factors.

Objective: The objective was to develop an algorithm for predicting the effects of factors known to influence heme- and nonheme-iron absorption from meals and diets.

Design: The basis for the algorithm was the absorption of iron from a wheat roll ($22.1 \pm 0.18\%$) containing no known inhibitors or enhancers of iron absorption and adjusted to a reference dose absorption of 40%. This basal absorption was multiplied by the expected effect of different amounts of dietary factors known to influence iron absorption: phytate, polyphenols, ascorbic acid, meat, fish and seafood, calcium, egg, soy protein, and alcohol. For each factor, an equation describing the dose-effect relation was developed. Special considerations were made for interactions between individual factors.

Results: Good agreement was seen when measurements of iron absorption from 24 complete meals were compared with results from use of the algorithm ($r^2 = 0.987$) and when mean iron absorption in 31 subjects served a varied whole diet labeled with heme- and nonheme-iron tracers over a period of 5 d was compared with the mean total iron absorption calculated by using the algorithm ($P = 0.958$).

Conclusions: This algorithm has several applications. It can be used to predict iron absorption from various diets, to estimate the effects expected by dietary modification, and to translate physiologic into dietary iron requirements from different types of diets. *Am J Clin Nutr* 2000;71:1147-60.

KEY WORDS Humans, iron absorption, heme iron, nonheme iron, algorithm, diet, meals, bioavailability, iron status, iron requirements, phytate, polyphenols, ascorbic acid, meat, soy protein, alcohol, eggs, calcium

INTRODUCTION

Knowledge about the absorption of iron from the diet and about factors influencing absorption has increased considerably since the extrinsic tag was introduced to label dietary iron in meals (1, 2). The amount of iron absorbed from a meal is determined by iron status, the content of heme and nonheme iron, and the bioavailability of the 2 kinds of iron, which in turn is deter-

mined by the balance between dietary factors enhancing and inhibiting the absorption of iron, especially nonheme iron (3). It is well known that the variation in dietary iron absorption from meals is due more to differences in the bioavailability of the iron, which can lead to a >10-fold variation in iron absorption, than to a variation in iron content.

Therefore, several attempts have been made to devise algorithms to estimate the bioavailability of the dietary iron content of meals. The aim of the first attempt was to illustrate the fact that the composition of meals greatly influences the absorption of dietary nonheme iron (4). Later, attempts were made to improve the algorithm (5, 6). A simpler method using a score system to estimate the expected bioavailability of dietary nonheme iron was also suggested (7). In this model, factors inhibiting iron absorption were also considered.

Several dietary factors (eg, ascorbic acid, meat, fish, and poultry) enhance iron absorption, whereas other factors [eg, inositol phosphates (phytate), calcium, and certain structures in polyphenols] inhibit iron absorption. In the present study, we analyzed the dose-response relation between amounts of these factors and their effects on nonheme-iron absorption. All of these factors must be considered in an algorithm to predict the amount of iron absorbed from a meal. For almost all of the factors, it has been possible to develop continuous functions related to the amounts of each in the meal. Moreover, interactions between different factors have been examined and considered.

The hypothesis tested in the present algorithm was that the bioavailability of iron in a meal is a product of all factors present in the meal that inhibit or enhance iron absorption. A starting point for the present work was to find a food or meal that contained no known inhibiting or enhancing components and then use this food

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as a basis for evaluating the effects of different factors added in different amounts. For many years we used, as a control, wheat rolls made of low-extraction wheat flour and fermented to such an extent that no inositol phosphates could be detected. Various factors to be tested were added in different amounts to such rolls and iron absorption was measured from the rolls, when served with or without a specific factor in known and various amounts, after the rolls were labeled with 2 different radioiron isotopes. Iron status in each fasted subject was measured by using the absorption from a standard reference dose of ferrous iron to describe the iron status of the individuals studied. The reference dose was introduced by Layrisse et al (8) and the entire procedure was described in detail (9). Iron absorption can also be related to log serum ferritin as suggested by Cook et al (10).

Numerous studies on factors influencing the bioavailability of dietary iron have been published by several research groups (discussed below), in addition to the studies by our group. It has only been possible, however, to use some of the data from their studies. This is true also for some of the older data from our laboratory. The reason is simply that there is a lack of information about the content of phytate and sometimes that of polyphenols in the meals studied.

METHODS

The method used to predict dietary iron absorption is based on an algorithm containing the value for iron absorption (relative to 40% of the absorption of the reference dose of iron) from a single basal meal ([low-extraction (40%) wheat flour] that contained no components known to inhibit or enhance iron absorption. This basal value was then multiplied by factors expressing the effect of different dietary components present in the meal known to influence iron absorption: phytate, polyphenols, soy protein, calcium, eggs, ascorbic acid, meat (including fish and seafood), and alcohol. For each factor, an equation was derived that also considered interactions between components in the meal.

Iron absorption from a basal meal

The basal meal was composed of wheat rolls served with margarine and water on 2 mornings while subjects were in a fasting state. The rolls were made of a special low-extraction (40%) wheat flour and the dough was fermented for 2 periods (30 + 10 min) to ensure that no inositol phosphates could be detected with a sensitive method (11). The iron content of the rolls was adjusted to 4.1 mg by adding ferrous sulfate to the dough. The rolls were labeled with an extrinsic radioiron tracer. Iron absorption was measured as described previously (9, 12).

The rolls were included in different studies of factors influencing iron absorption. Rolls were served with and without a factor to be studied in specific amounts and were labeled with 2 different radioiron isotopes (13–15). Iron absorption from these rolls was measured in 310 subjects (194 female and 116 male volunteers). In each subject, iron absorption from a reference dose containing 3 mg Fe as ferrous sulfate, given while subjects were in a fasting state on 2 consecutive mornings, was also measured. All absorption values were adjusted to correspond to an absorption of 40% from the reference dose. Thus, absorption measurements from the same meal could be pooled from different groups of subjects with different iron statuses. The mean (\pm SEM) absorption of iron from the rolls in all studies, adjusted to a 40% reference dose absorption, was $22.1 \pm 0.18\%$.

Effect of phytate and other inositol phosphates

The effect of different amounts of phytate on iron absorption was examined when wheat rolls were served with and without different amounts of added sodium phytate. Seven groups of subjects ($n = 63$) were studied and the added phosphorus as phytate (phytate-P) varied from 2 to 250 mg (14). A similar study was performed in another laboratory in which the basal wheat rolls contained 10 mg phytate-P ($n = 57$). Four different amounts of phytate-P (14–58 mg) were added (16). Because the effect of 10 mg phytate-P was examined in the previous study, it was possible to recalculate the effect of the added phytate-P. The effect of phytate was similar in the 2 studies. When the data from the 2 studies were pooled, the following relation was found:

$$\text{Log absorption ratio} \\ (\text{with/without phytate}) = -0.30 \times \log (1 + \text{phytate-P}) \quad (1)$$

where phytate-P is in milligrams. The correlation coefficient was $r^2 = 0.926$ ($n = 120$). Antilog of the log absorption ratio thus constitutes the phytate factor.

When the content of phytate-P in bread is determined, some of the inositol phosphates are present in forms with a fewer number of phosphate groups than the 6 groups present in phytate. In a previous study we found that the total number of phosphate groups bound to inositol, present in a bread, determines the degree of inhibition (11). This implies that the total inhibitory effect of inositol phosphates is better expressed as the number of phosphate groups bound to inositol than as moles of inositol. (Conversion factor: 1 mg phytate-P = 3.53 mg phytic acid = 5.56 μ mol phytic acid.)

Effect of ascorbic acid

Ascorbic acid is a strong promoter of iron absorption, as shown in several studies (see reference 16 for a review). In an extensive study by Cook and Monsen (17) in 1977 in which 6 different amounts of ascorbic acid (25–1000 mg) were added to a semisynthetic meal, a strong relation was seen between log amounts of ascorbic acid and the log absorption ratio ($r^2 = 0.958$; $n = 25$). The counteracting effect of ascorbic acid on phytate and polyphenols was also reported by other groups (18). In the study by Cook and Monsen, it was not mentioned whether an inhibitor was present in the control meals, which showed a very low absorption of iron ($\approx 0.75\%$). The enhancing effect of ascorbic acid is more marked in the presence of phytate or iron-binding polyphenols. In subsequent studies from the same group using the same liquid formula, it was noted that vanilla extract had been added to the formula, probably to improve the taste (19, 20). Recent analyses in our laboratory indicate that vanilla extracts contain appreciable amounts of iron binding polyphenols (**Appendix A**). This fact might explain the marked effect of ascorbic acid in Cook and Monsen's (17) comprehensive study. Addition of 100 mg ascorbic acid to the semisynthetic liquid formula increased iron absorption 4.14 times, whereas addition of the same amount of ascorbic acid to a so-called standard meal containing meat, potatoes, and milk increased iron absorption by only 67%. In another study from the same group, addition of 100 mg ascorbic acid to another but similar liquid formula containing 85 mg phytate-P increased iron absorption 3.14 times (20).

These findings suggest that the ability of ascorbic acid to reduce iron and thus to prevent the formation of less-soluble ferric compounds is probably an important mechanism of action for the absorption-promoting effect of ascorbic acid. An

enhancing effect of ascorbic acid on iron absorption, however, was also seen in the absence of phytate and polyphenols. Addition of 50 mg ascorbic acid, for example, to wheat rolls with no detectable phytate increased mean iron absorption from 22.4% to 37.6% (14).

These facts are taken into account in an algorithm describing the expected effect of ascorbic acid in the presence of phytate. The algorithm was calculated as follows:

- 1) Even in the absence of inhibitors, ascorbic acid increases iron absorption in a dose-dependent way: absorption ratio = $(1 + 0.01) \times$ ascorbic acid (in mg).
- 2) The more phytate that is present, the greater the effect of ascorbic acid. Linear relations were seen between the absorption ratio (with and without ascorbic acid) and log phytate-P. Five regression lines describing this relation had different linear slopes for different log amounts of ascorbic acid (5–500 mg). The squared correlation coefficients for the 5 lines varied from 0.837 to 0.877. The content of phytate varied from 0 to 250 mg. The 5 slopes of the regression lines were related to log amounts of ascorbic acid and showed a best fit in an exponential equation with an r^2 value of 0.995. The following general equation was thus derived:

$$\text{Absorption ratio} = [1 + 0.01 \text{ AA (in mg)} + \log \text{ phytate-P (in mg)} + 1] \times 0.01 \times 10^{0.8875 \times \log(\text{AA}+1)} \quad (2)$$

where AA is mg ascorbic acid and is mg in the meal. This equation is based on studies in 240 subjects in 24 studies. The enhancing effect of ascorbic acid was the same in meals with and without calcium and the same in meals with and without meat. These observations suggest that the mechanisms of action on iron absorption are different for ascorbic acid, meat, and calcium.

Effect of polyphenols

In earlier studies it was shown that tea inhibits the absorption of non-heme iron (21–23). Similarly, coffee (22–24) and red wines (25, 26) were reported to inhibit iron absorption. This inhibition was considered to be due to polyphenols present in these beverages. Addition of tannic acid to a meal was shown to reduce iron absorption (27). Further studies showed that gallic acid and tannic acid had identical inhibitory effects on iron absorption and identical iron binding properties (13). Galloyl groups with their 3 adjacent hydroxyl groups were found to be the main, common structure in polyphenols binding iron, probably by a direct chemical binding, especially of ferric iron, and presumably through the formation of chelates.

The strong binding of ferric iron to galloyl groups explains the counteracting effect of ascorbic acid on the inhibition of iron absorption by phenolic compounds. Iron binding polyphenols are widespread in foods because they occur naturally in a variety of cereals, vegetables, and spices, and in many beverages such as wine, coffee, and tea (13, 28). A chemical method for specifically determining galloyl groups has been designed (29).

The inhibition of iron absorption by coffee is explained mainly by its content of chlorogenic acid. The binding of iron to this compound is less strong than the binding of iron to galloyl groups. The relative inhibition by equimolar amounts of gallic acid and chlorogenic acid was found to be 1.6:1 (13). In Appendix A, tannic acid equivalents, chlorogenic acid, and total tannic acid equivalents (the sum of tannic acid and the amount of chlorogenic acid divided by 1.6) in various foods are reported.

Effect on iron absorption of the contents of polyphenols, ascorbic acid, and meat in meals

In calculating the effect of tannic acid on iron absorption it was necessary to consider both the amount of galloyl groups and the amount of ascorbic acid present in a meal. In studies in which different known amounts of tannic acid were added to a wheat roll (range: 5–200 mg), a linear relation was observed when the log absorption ratio was plotted (absorption with/without tannic acid) against the log amounts of tannic acid added to the rolls (13). The following equation ($r^2 = 0.978$ for the mean values) was based on measurements in 59 subjects:

$$\text{Log absorption ratio} = 0.4515 - 0.715 \times \log \text{ tannic acid (in mg)} \quad (3)$$

The slope of this regression line (-0.715) changed when different amounts of ascorbic acid were added. The regression lines for different amounts of ascorbic acid converged to the point log absorption ratio (0.4515) and log tannic acid (0).

The effect of ascorbic acid on the inhibition of iron absorption by tannins was reported in 2 studies (18, 30). Moreover, in developing the equations we also used recent unpublished data from our laboratory on the effect of ascorbic acid on the inhibition by phenolic compounds. Two studies of the effect of meat on the inhibition by tannic acid were conducted ($n = 20$ each). Other studies also showed that ≈ 100 g meat reduced the inhibition by tannic acid by half (24). The effect of meat on the inhibition by polyphenols is also included in the equation below.

The effect of polyphenols on iron absorption is expressed in the following equation, in which the amounts of tannic acid equivalents (TA; in mg), ascorbic acid (AA; in mg), and meat or fish (M ; in g) in the meal are considered:

$$\text{Absorption ratio} = (1 + 0.01M) \times 10^{0.4515 - [0.715 - 0.1825 \times \log(1 + AA)] \times \log(1 + TA)} \quad (4)$$

The absorption ratio should be ≤ 1 and corrected to 1 if it is not.

Effect of coffee and tea

Coffee and tea are widely consumed as beverages with meals or directly after meals. These beverages have a high content of phenolic compounds and have been shown to strongly inhibit the absorption of nonheme iron (13, 21, 22, 24). A cup of tea (≈ 200 mL) reduces iron absorption by ≈ 75 –80%. Variations in the results of different studies are probably related to the different amounts of phenolic compounds in the tea resulting from differences in the amounts, brands, and steeping time of teas used. A cup of coffee (≈ 150 mL) reduces iron absorption by ≈ 60 %. When tea or coffee was served with a meal containing ≈ 100 g meat, the inhibition of iron absorption was reduced by 50% (24). This agrees with the first part of equation 4 above (eg, when $M = 100$ g, $1 + 0.01M = 2.0$).

On the basis of its content of phenolic compounds, coffee is expected to reduce iron absorption even more than was observed. It is well known that coffee stimulates the gastric secretion of hydrochloric acid, which may explain the lower than expected effect. We tested this possibility by measuring the inhibition of iron absorption by coffee in patients with pentagastrin-proven achlorhydria and found that in these patients the inhibitory effect was twice as high (absorption ratio: 0.19 compared with 0.39) as that in healthy subjects and corresponded to the content of phenolic compounds in coffee (L Hulthén, L Hallberg, A Killander, unpublished observations, 1995).

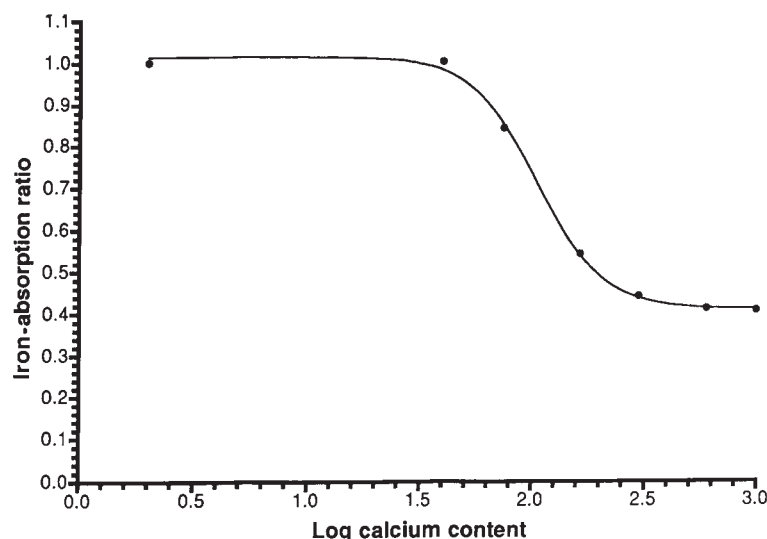


FIGURE 1. Relation between the log calcium content in a meal and the ratio of iron absorption from a meal served with or without different amounts of calcium. The equation describing the relation is given in the text.

To circumvent the problem encountered when the algorithm was applied to coffee and tea, because of variations in the content of iron binding polyphenols and different extraction times of the beverages, we used a factor of 15 mg tannic acid equivalents for one cup of regular coffee and 30 mg tannic acid equivalents for one cup of tea. These values apply to beverages consumed with a meal or up to a few hours after a meal (24). We are aware that strong coffee may reduce iron absorption even further (eg, 50 mg tannic acid equivalents gives a tannic acid factor of 0.17) and that other strengths of tea or other kinds of tea may reduce iron absorption even more. We found for a common green tea, for example, a tannic acid factor of 0.17 (Appendix A)—a reduction in iron absorption of 83%.

Effect of calcium

A strong dose-effect relation between the amount of calcium in a meal and the reduction in nonheme-iron absorption has been observed (15). The relative reduction of iron absorption was the same for the same amount of calcium given as a calcium salt, milk, or cheese. No inhibition was seen when the amount of calcium in a meal was <50 mg (10 mg native and 40 mg added Ca) and the inhibition was maximal at a content of ≈ 300 –600 mg. Moreover, calcium also inhibited the absorption of heme iron similarly (31), suggesting a common step in the transport of these 2 kinds of iron; therefore, the effect was not located in the intestinal lumen but within the mucosal cell. The observed relation between the absorption ratio (absorption with/without calcium) and the amount of calcium in a meal had a clear sigmoid curve, suggesting one-site competitive binding at a receptor (**Figure 1**). Such a step may be located in the active transport pathway for calcium (32). An equation was tested describing such a relation for the present data [$n = 7$ (mean values); $r^2 = 0.9984$].

$$\text{Absorption ratio} = 0.4081 + \left\{ \frac{0.6059}{1 + 10^{-[2.022 - \log(\text{Ca} + 1)] \times 2.919}} \right\} \quad (5)$$

where Ca is the calcium content in the meal (in mg). The calculations are based on the computer program GRAPHPAD

PRISM (version 2.0; Intuitive Software for Science, San Diego). Iron absorption increased after the addition of ascorbic acid to a meal containing calcium (33); however, the relative increase was the same as would have occurred had no calcium been present.

Effect of meat, poultry, and fish and seafood

Several studies have shown that meat, poultry, and fish and other seafood increase the absorption of nonheme iron. It was first noted by Layrisse et al (34). For a review, *see* reference 3. Despite numerous studies of the effect of meat on iron absorption by several groups, there is still insufficient information about the magnitude of the effect of meat in different types of meals and the possible mechanisms for the absorption-promoting effect of meat and fish.

In developing an algorithm for the effect of meat and fish on iron absorption, results from several absorption studies were pooled. The effect was measured as the absorption ratio when meals were served with and without meat or fish (19, 20, 35–37). The effect of meat was calculated in the following steps. In the first step, the effect of meat was measured in meals not containing phytate. The relation between the amount of meat and the absorption ratio ($r^2 = 0.899$) was examined in 135 subjects from 15 studies.

$$\text{Absorption ratio} = 1 + 0.00628 \times \text{amount of meat and fish (in g)} \quad (6)$$

In the second step, we analyzed the effect of phytate on the slope of this relation. In 10 studies in which meat with different amounts of phytate was served, we found that the factor influencing the slope in the first relation could be expressed as $(1 + 0.006) \times \text{amount of phytate-P (in mg)}$; $r^2 = 0.877$. The final meat factor obtained was thus as follows:

$$\text{Absorption ratio (with/without meat)} = 1 + 0.00628 \times M \times [1 + 0.006 \text{ phytate-P (in mg)}] \quad (7)$$

where M is meat, fish, and seafood expressed as grams of uncooked food. According to the previous model of Monsen and

Balintfy (5), 1.3 g raw weight is equivalent to 1.0 g cooked weight of meat, poultry, and fish.

Several investigators examined the effect of both meat and fish but direct comparisons have not been reported. The balance of evidence suggests that meat and fish are interchangeable in this equation. Meat has the clear nutritional advantage because it also provides considerable amounts of heme iron.

Effect of soy protein

In several studies it was observed that soy protein reduced the fraction of iron absorbed from a meal (38, 39). The high content of phytate in soy products led the researchers to suspect that the inhibition by soy might be related to phytate. Reduction of the phytate content by repeated washings with acidic solutions, however, did not totally abolish the inhibition (39, 40).

In a recent comprehensive study in which almost all of the phytate in soy was removed by enzymatic degradation with a phytase, however, the inhibition by soy proteins was markedly reduced (41). Four groups of subjects were studied ($n = 32$). Iron absorption was measured from semisynthetic meals, each containing 30 g protein as soybean-protein isolates or egg white as a control. A significant inhibitory effect on iron absorption by soy protein remained. The egg white contained 96 mg Ca/meal compared with 19.2, 27.4, and 44 mg Ca/meal in the soybean-protein isolates. It can be estimated from Equation 5 that the higher calcium content in the control meals would reduce iron absorption by 25%. The average absorption ratio of iron from the soy meals and the control meals was 0.33 after correction for the higher calcium content in the control meals. The inhibitory effect on iron absorption per gram of soy protein (x) would thus be as follows: $1 - 30x = 0.33$. Solving the equation gives $x = 0.022$ and the soy-factor absorption ratio would thus be as follows:

$$\text{Absorption ratio} = 1 - 0.022 \times \text{soy protein (in g)} \quad (8)$$

This equation is valid up to ≈ 20 g soy protein. For a hamburger that might contain a commercial soy-protein isolate containing phytate, it is necessary to consider in the algorithm the amounts of pure meat, soy protein, and phytate-P present in the hamburger.

Effect of eggs

In an early study of the effect of eggs on iron absorption in 28 humans, white-wheat bread was given with eggs together with coffee or tea (42). A reference dose (5 mg Fe) was also given in this study. It is possible to estimate iron absorption from this meal corresponding to a reference dose absorption of 40%. About 16% could be estimated to have been absorbed had tea or coffee not been fed. Relating this absorption to 22.1% absorption from the basal wheat-roll meal (*see above*) at the same iron status, the egg factor would be $16/22 = 0.73$, ie, a reduction in iron absorption of 27%.

In our studies of iron absorption from different breakfast meals, the introduction of a boiled egg reduced the absorption by 28%, from 9.3% to 7.6% in 12 subjects (43). In one of the studies by Cook and Monsen (35), powdered eggs were fed to 10 subjects in an amount corresponding to 2.9 eggs, each weighing 60 g. When eggs are substituted for other proteins in a standard meal, the absorption ratio with or without eggs was reduced to 0.22 (a reduction of 78%). For one egg this corresponds to a reduction of 27% ($0.78/2.9 = 0.27$). The results on the inhibiting effects of eggs by different groups are thus aston-

ishingly consistent. The effect of eggs has been studied in a total of 50 subjects.

When the data were pooled assuming a proportional inhibition of iron absorption to the amount of eggs included in a meal, the following equation was derived:

$$\text{Absorption ratio} = 1 - 0.27 \times \text{number of eggs} \quad (9)$$

The number of eggs can also be expressed as grams (one egg = 60 g). Equation 9 is valid only for ≤ 3 eggs/meal. Check that the absorption ratio for eggs is not < 0.2 (equivalent to the inhibition by 3 eggs).

Effect of alcohol

Studies in humans have shown that alcohol increases the absorption of ferric but not of ferrous iron (44). This increase has been attributed to an enhancement of gastric acid secretion. In a study serving a hamburger meal with or without 23.8 g alcohol (as a 40% solution), a statistically significant 23% increase in iron absorption was seen when alcohol was given with the meals (23). When the same meal was served with red wine, no significant increase was seen, possibly because of the simultaneous inhibiting effect of iron binding polyphenols present in red wine. In a study of the effect of different wines on iron absorption, a dinner roll was served with or without different wines, some of which had a markedly reduced alcohol content because of vacuum distillation (26). Adjustment for differences in iron status made it possible to make 4 pairwise comparisons of iron absorption from meals served with the same type of wine but with different alcohol contents (low or high). The mean absorption ratio between the meal with the low-alcohol compared with the high-alcohol content was 1.33 ± 0.14 ($P = 0.039$). The amount of alcohol served with the rolls was 12.6 g, which was about half the amount served with the hamburger meals mentioned above (23). Assuming that the effect of alcohol is related to stimulation of gastric acid secretion, it is possible that with a meal containing meat, more acid is formed than when a bread roll is served. The further stimulation of gastric secretion by alcohol may thus be lower from a full meal than from the meal containing only a roll. The studies strongly indicate, however, that alcohol also enhances iron absorption from composite meals (23). After careful consideration, we provisionally decided to use a single factor of 1.25 for the stimulation of iron absorption by alcohol. We also provisionally decided to use this factor for meals consumed together with, for example, 1–2 glasses of wine or 1–2 alcoholic beverages. The inhibitory effect of red wine on iron absorption, related to the content of iron binding polyphenols, should be considered separately in the calculation of the tannic acid factor.

Effect of other factors

It is reasonable to assume that there are other factors in meals influencing iron absorption that have not been considered in the present algorithm. For example, some soy sauces may enhance iron absorption (45), whereas some flavonoids, especially myricetin, may inhibit iron absorption. Myricetin has a molecular structure similar to that of the galloyl group in polyphenols, which we know inhibits iron absorption via chelation with ferric iron. In our food analyses, we based the inhibiting effect of polyphenols on the content of such groups. Flavonoids with a similar structure may therefore be expected to have the same inhibitory effect on iron absorption (13, 29).

Formula for log heme-iron absorption and the computer program

Iron absorption from single meals

The formula is the product of the basal factor 22.1 multiplied by one or more of the 8 dietary factors present in each meal: the phytate factor, the ascorbic acid factor, the polyphenol factor (or, tannic acid factor), the calcium factor, the meat factor, the soy-protein factor, the egg factor, and the alcohol factor. The value obtained is thus the percentage absorption of the nonheme iron present in a meal at an iron status corresponding to a reference dose absorption of 40%. The percentage absorption of heme iron was adjusted to the same iron status by using a formula presented in a previous study (46).

$$\text{Log heme-iron absorption (\%)} = 1.9897 - 0.3092 \times \text{log serum ferritin} \quad (10)$$

Heme-iron absorption is then corrected for the content of calcium in the meal by using the same calcium factor as used for nonheme-iron absorption (*see above*) (31).

To obtain the amount of iron absorbed from a meal, the percentage absorption of nonheme and heme iron have to be multiplied by the amounts of the 2 kinds of iron present in the meal. For nonheme iron it is important to consider any fortification iron present in the meal and to what extent this iron is potentially bioavailable. Similarly, if food components are contaminated with iron (eg, from soil), the fraction of such iron that is potentially absorbable (or, exchangeable with an extrinsic radioiron tracer) should be considered. A method is available to quantify this fraction (47). In Appendix A, the fraction of heme iron present in different kinds of meat and meat products is provided.

Iron absorption from the whole diet

The amount of iron absorbed from the whole diet is obtained by summing the amounts of iron absorbed from all the single meals and snacks for a certain period of time, eg, a single day or several days. Potential interference between meals is discussed below.

Use of computer programs for the calculations

We used Microsoft's EXCEL program (Redmond, WA) for the calculations. To avoid problems with calculating some of the factors based on logarithmic functions, we used a value of 1 in equations 1, 3, 4, and 7. In equation 4, an absorption ratio > 1 had to be changed to 1.

Validation studies

The validity of the present algorithm was examined in 2 ways. In study 1, the observed absorption of nonheme iron from 24 single meals in 3 previous studies (43, 48, 49) was compared with the absorption values estimated by using the algorithm. These 3 studies were performed > 15 y ago. At that time, no sufficiently sensitive method for measuring small amounts of phytate and no specific method for measuring iron binding polyphenols was available. At the time of the studies, for example, we were not aware of the rather high contribution of phytate from potatoes in many meals (200 g potato contains 14 mg phytate-P) or of the fact that commercial products for making mashed potatoes also contained appreciable amounts of calcium from dried milk powder. Similarly, the content of polyphenols in different vegetables, spices, and beverages was not known, nor were the effects of polyphenols on iron absorption. New analyses had to be per-

formed to estimate the probable contents of phytate, polyphenols, ascorbic acid, and calcium in the meals. The variation in contents of iron and energy and amounts of nonheme iron absorbed from the 24 meals are provided in **Table 1**.

In study 2, a comparison was made between the estimated total amount of iron absorbed by using the algorithm in 31 men served 4 different meals for 5 d and the actual total iron absorption measured in these men by using 2 radioiron tracers. One tracer was given as intrinsically labeled radioiron to label hemoglobin and the other as inorganic iron to label nonheme iron. All meals were labeled with the 2 tracers to ensure a homogenous specific activity of both nonheme and heme iron in all meals. The total absorption of heme and nonheme iron was determined by using a whole-body counter to determine ⁵⁹Fe and a blood sample to analyze the ratio of ⁵⁵Fe to ⁵⁹Fe. The method used and the menus given were described in detail previously (46, 50, 51).

RESULTS

Study 1

The result of the comparison of observed and calculated nonheme-iron absorption is shown in **Figure 2**. The main finding was the remarkably good agreement between observed and estimated nonheme absorption. The observed mean (\pm SEM) percentage absorption of nonheme iron in the 24 meals was $12.91 \pm 1.84\%$ and the corresponding value for the absorption calculated by using the algorithm was $13.33 \pm 1.95\%$. There was no significant difference between the mean values. The correlation coefficient was high and the slope of the regression line was not significantly different from the line of equality. We also made the interesting observation that minor food components, such as a correct amount of calcium (cheese, vegetables, and milk) or a correct value for phytate content had a marked effect on the absorption calculated. The same was true for the amount of ascorbic acid served. Detailed knowledge of meal composition is thus essential to achieve reasonably good estimates of the iron absorption by using the algorithm. The average compositions of the 24 meals in studies 1 and 2 are shown in **Table 2**.

Study 2

The calculated iron absorption from the 20 different meals varied considerably between meals and days as shown in **Table 3**. The composition of these meals was also described in detail previously (51). Among the 31 men, there were 4 patterns in the choice of beverages (coffee, tea, and water) with the breakfast meals and the evening snacks; therefore, analyses were conducted separately in these 4 groups.

With the algorithm, the absorption of heme and nonheme iron from each meal was calculated separately and summed for the whole period. Nonheme-iron absorption in each subject was that expected at an iron status corresponding to a reference dose of 40%. For each individual, nonheme-iron absorption was then adjusted to the individual serum ferritin concentration and body weight according to equation 11 (*see below*). The individual amounts of heme-iron absorption expected were calculated by using equation 10. The calculated total amounts of iron absorbed in the 31 subjects were then obtained by adding the amounts of heme- and nonheme-iron absorption calculated in all meals. These figures were then compared with the actual absorption obtained when total iron absorption was measured directly. It was thus possible to compare the observed amounts of iron absorbed with the

TABLE 1

Study 1: observed absorption of nonheme iron before and after adjustment to a reference dose absorption of 40%, and the calculated absorption with the algorithm¹

Type of meal and reference ²	Nonheme iron	Energy	Iron absorption		
			Observed	Adjusted to 40% of reference dose absorption	Algorithm calculation
			mg (%)	mg (%)	%
Galician meat soup (48)	7.2	980 (4100)	0.96 (13.4)	1.16 (16.2)	17.2
Spaghetti with cheese (48)	4.9	1020 (4268)	0.54 (11.0)	0.59 (12.1)	11.6
Hamburger meal (48)	3.9	1030 (4310)	0.54 (13.8)	0.48 (12.2)	13.0
Soup, steak, and kidney pie (48)	5.7	1010 (4226)	1.09 (19.2)	1.08 (18.9)	18.9
Pizza (48)	4.2	1040 (4351)	0.38 (9.0)	0.33 (7.9)	9.6
Vegetable soup (48)	7.0	1010 (4226)	0.50 (7.2)	0.55 (7.9)	8.0
Pancake and jam (49)	5.1	630 (2636)	0.09 (1.7)	0.18 (3.3)	3.2
Breakfast basal (43)	2.8	320 (1339)	0.21 (7.6)	0.16 (5.7)	5.0
Breakfast + orange juice (43)	3.1	390 (1632)	0.25 (8.0)	0.40 (12.9)	13.1
Breakfast + egg (43)	4.1	405 (1695)	0.31 (7.6)	0.19 (4.6)	3.6
Breakfast + egg + bacon (43)	4.2	410 (1715)	0.30 (7.1)	0.25 (6.0)	5.9
Breakfast + corn flakes (43)	3.6	555 (2322)	0.19 (5.4)	0.16 (4.4)	3.1
Sauerkraut + sausage (43)	2.0	470 (1966)	0.91 (45.8)	0.90 (45.0)	41.4
Beetroot soup + meat (51)	2.8	300 (1235)	0.85 (30.3)	0.81 (29.1)	26.4
Sole au gratin (49)	2.1	330 (1381)	0.39 (18.7)	0.38 (18.0)	18.2
Brown beans + pork (49)	5.4	750 (3138)	0.22 (4.0)	0.43 (7.8)	5.5
Roast beef meal (49)	3.1	480 (2008)	0.36 (11.6)	0.58 (18.7)	17.7
Spaghetti with meat sauce (51)	2.7	600 (2510)	0.31 (11.3)	0.31 (11.1)	12.5
Cod (48)	7.8	1050 (4393)	0.63 (8.1)	0.80 (10.4)	10.9
Gazpacho and chicken (48)	7.6	1040 (4351)	1.10 (14.5)	1.35 (17.6)	17.1
Meatballs (49)	2.6	600 (2510)	0.19 (5.4)	0.29 (11.1)	10.6
Shrimp and beef (48)	6.2	980 (4100)	0.95 (15.3)	0.94 (15.1)	14.0
Antipasti misti and meat (48)	7.8	1150 (4812)	1.55 (18.0)	1.80 (23.1)	23.0
Vegetarian meal "low" (48)	5.8	730 (3054)	0.14 (2.5)	0.13 (2.3)	0.4

¹The study included 24 meals. Details of meals are described in individual references.

²"Breakfast" encompasses coffee, white-wheat bread, margarine, cheese, and marmalade.

amounts estimated by using the algorithm (Table 4). The mean total iron absorption obtained with the 2 methods was not statistically different on the basis of a *t* test; the difference between the means with both methods was only 0.06 mg (or 3.4%) and was not statistically significant ($t = -0.588$, $P = 0.561$).

Application of the algorithm for different levels of iron status

The present calculations are based on absorption values adjusted to a reference dose absorption of 40%. Because the relation between reference dose absorption and log serum ferritin is known, it is possible to convert the algorithm to any iron status (Appendix A).

$$\text{Iron absorption (mg)} = \text{iron absorption (alg mg)} \times 23^{0.94/\text{SF}} (\mu\text{g/L}) \quad (11)$$

where iron absorption (alg mg) is the absorption calculated (mg) by using the algorithm, ie, at a reference dose absorption of 40%, and SF is serum ferritin.

DISCUSSION

It has been nearly 20 y since the first simple algorithm for estimating iron absorption was published (4). Since then, much new knowledge has accumulated about dietary iron absorption, as emphasized in a recent review (52). It is thus probable that new information will lead to modifications of the present algorithm. Instead of waiting for the "final version," we developed an algo-

ri thm based on as much present knowledge as possible and we think the present algorithm has many practical applications.

Note that the method of measuring iron absorption from the whole diet with tracers has been validated. In each subject, a comparison was made between the absorption measured and iron requirements. In men, requirements were calculated from body weight and in women from body weight and measured menstrual losses of iron (53). The comparison in study 1 clearly showed that iron absorption estimated with the algorithm agreed well with measured iron absorption.

Nonheme-iron absorption was estimated for the 24 meals in study 1 by using the 2 previously published algorithms, in which effects of both enhancers and inhibitors were included. In the earliest study (7), there was a significant relation between observed and estimated absorption ($r^2 = 0.192$, $P = 0.032$). There was also a significant relation between observed and estimated nonheme-iron absorption ($r^2 = 0.256$, $P = 0.0116$) when a more recent algorithm was used (6). These correlation coefficients are thus considerably lower than that obtained with the present algorithm ($r^2 = 0.987$) for estimated and observed nonheme-iron absorption. Probable reasons are that, in contrast with the 2 previous algorithms mentioned, the present algorithm 1) is based on continuous variables for content of enhancers and inhibitors, 2) takes into consideration interactions between factors, and 3) includes more factors. In study 2, the same mean heme- and nonheme-iron absorption values were seen despite the expected markedly varying bioavailability of iron in the 20 different meals included (Table 3).

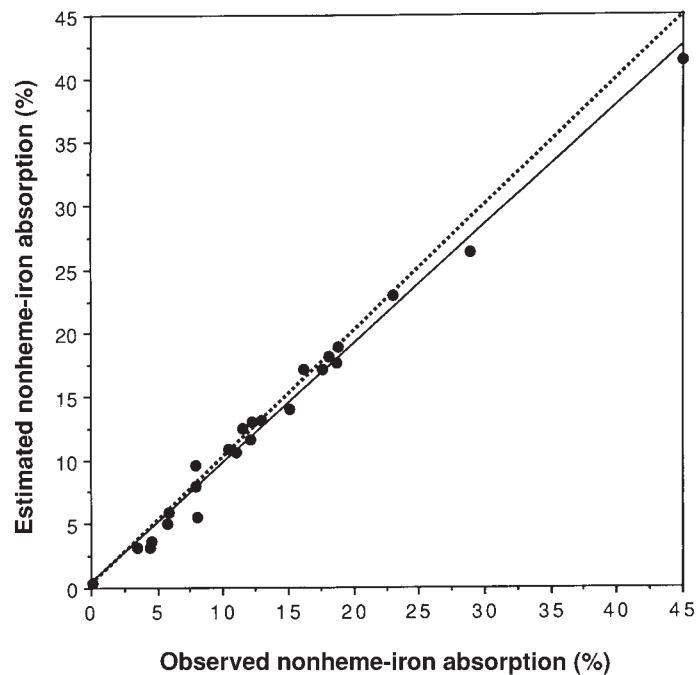


FIGURE 2. Relation between observed and estimated nonheme-iron absorption in study 1 with use of the algorithm. Data reflect the mean values from 24 studies in 243 subjects. $y = 0.43 + 0.94x$; $r^2 = 0.987$

An important difference between the 2 validation studies was that each absorption value in study 1 was the mean of 10 subjects (observed and calculated by using the algorithm; Table 1), whereas each absorption value in study 2 was the mean of 31 subjects measured over 5 d (Table 4). In study 1 the slope of the regression line did not differ from the identity line and there were no statistically significant differences between observed absorption and absorption estimated by using the algorithm at the same iron status. In study 2, the total amounts of observed and calculated (algorithm) iron absorbed from the whole diet were not significantly different after adjustment to the same iron status (Table 4).

Effect of meal size and iron content of meals

It may seem obvious that the size of a meal should be taken into account in an algorithm for estimating iron absorption. A cer-

tain amount of ascorbic acid, for example, should be expected to have a greater effect in a small meal than in a large meal because the concentration would be higher in the small meal. Meal size, however, is an ambiguous concept because it can be interpreted in terms of volume, weight, or content of energy or iron. The concentration of a nutrient may also be influenced by the amount of beverage consumed with the meal. Another factor that can influence absorption is the rate of gastric emptying and, in turn, the volume of the meal and its fat content. Meal size as well as body size can influence the absorption of iron from a specific meal; however, we did not observe either in our adult volunteers.

There was almost a 4-fold variation in the content of both energy and iron and a 3-fold variation in nutrient density (nonheme iron/energy) in the meals in study 1 (Table 1). Despite these variations, the relation between calculated and observed

TABLE 2

Descriptive characteristics of the 24 different meals included in study 1 and the 20 different meals included in study 2

	Study 1			Study 2		
	$\bar{x} \pm SD$	Median	Range	$\bar{x} \pm SD$	Median	Range
Energy (MJ)	3.03 \pm 1.21	2.85	1.26–4.81	2.52 \pm 0.46	2.51	1.63–3.26
Nonheme iron (mg)	4.74 \pm 1.92	4.2	2–7.8	2.75 \pm 1.32	2.2	1.2–5.1
Heme iron (mg)	0.38 \pm 0.44	0.1	0–1.2	0.73 \pm 0.83	0.2	0.04–2.7
Total iron (mg)	5.07 \pm 1.93	4.6	2.2–8.4	3.48 \pm 1.95	2.63	1.25–6.8
Ascorbic acid (mg)	15.9 \pm 23.8	4	0–85	23.2 \pm 29.0	5	0–95
Meat and fish (g)	59.6 \pm 53.3	60	0–175	68 \pm 71.2	55	0–175
Calcium (mg)	171.8 \pm 160.5	130	0–600	226 \pm 183	229.5	30–409
Phytate phosphorus (mg)	26.8 \pm 56.3	8	0–271	18.3 \pm 10.5	12.8	11.4–52
Tannic acid equivalents (mg)	13.8 \pm 23.1	4	0–100	28.9 \pm 33.1	19.5	0–80
Eggs (<i>n</i>)	0.21 \pm 0.388	0	0–1	0	—	—
Soy	0	—	—	0	0	—
Alcohol factor	1.03 \pm 0.08	1	0.73–1	1.0	—	—

TABLE 3

Total amounts of heme and nonheme iron absorbed from different meals on different days in Study 2 in 11 of the 31 subjects having an identical pattern in the consumption of beverages with the meals

Day	Heme- + nonheme-iron absorption (mg)				
	Breakfast	Lunch	Dinner	Evening	Whole day
	<i>mg</i>				
1	0.082	1.87	2.66	0.083	4.70
2	0.045	1.32	1.11	0.082	2.56
3	0.076	1.51	1.11	0.058	2.75
4	0.055	2.01	2.09	0.081	4.24
5	0.076	1.39	1.84	0.098	3.40
\bar{x}	0.067	1.62	1.76	0.080	3.53
Median	0.076	1.51	1.84	0.082	3.40
SD	0.0159	0.304	0.665	0.014	0.925
CV	23.8	18.8	37.8	17.8	26.2

absorption was more similar than we had expected. Thus, the balance of evidence indicates that meal size per se had no major systematic effect on the validity of the algorithm. The algorithm may need modification when used in infants and small children. In a recent study, however, direct comparison of iron absorption from a formula given to adults and infants showed no difference in absorption (54). Moreover, a 3-fold increase in meal size (and iron content) in adults did not change fractional iron absorption (54). It is thus reasonable to assume that the algorithm will also be useful in infants.

A linear relation was observed between log amounts of iron administered and log amounts of iron absorbed (*see* references 55 and 56 for a review). Most of these studies used therapeutic doses of iron or pure iron solutions; iron given with food seems to behave differently. In one of our early studies, we found that the percentage iron absorption from a meal was the same despite an almost 5-fold difference in iron content (57). This result is thus compatible with the results mentioned above (54), probably because the concentration of iron in the gastrointestinal lumen is many times lower when a certain amount of iron is present in a meal than when the iron is provided as a salt without food.

Iron absorption from single meals compared with that from the whole diet

To estimate iron absorption from the whole diet, absorption measurements from all the single meals consumed over a certain time period are summed. Almost all studies of factors influencing iron absorption are based on single meals served in a fasting state, with and without a factor to be studied given in different amounts. Note that direct measurements have shown that a preceding meal has no effect on the absorption of iron from a subsequent meal. In studies of 4 diets, it was shown that iron absorption from a meal served in the morning after an overnight fast was the same as that from a meal eaten during the day at lunch or supper (58). Similarly, we found that iron absorption was the same from a hamburger meal served in the morning or after breakfast (with or without added calcium) 2 or 4 h earlier (59).

It has been suggested that the variation in iron absorption from single meals under laboratory conditions would exaggerate the variation in iron absorption from the whole diet (7). The variation in iron absorption between single meals of different compositions may be much greater than the variation in iron absorp-

tion from whole diets composed of several single meals. The iron content and bioavailability of single meals varies markedly, whereas iron absorption from whole diets is the mean absorption of several single meals. The expected lower variation in iron absorption from the whole diet than from single meals was documented previously (7) and in the 3 studies of iron absorption from whole diets in our laboratory (46, 50, 51).

Some investigators seem to have misinterpreted these results and assumed that the absorption of iron from single meals per se, for some unknown reason, would be falsely high or low. The present result that the sum of the calculated iron absorption from 4 different meals served for 5 d (ie, 20 meals in 31 men for a total of 620 meals) did not differ significantly from that obtained from meals in which heme and nonheme iron were homogeneously labeled with 2 different tracers, clearly indicates the validity of basing total dietary iron absorption on the sum of iron absorption from single meals. This issue was also discussed in our previous review (53).

Some applications of the algorithm

The algorithm can be used to evaluate the nutritional value of meals with respect to iron, for example, in school-lunch programs, in catering programs for the elderly, and for military services. The algorithm may be used to translate data from dietary surveys into amounts of iron expected to be absorbed. The main requirement for such calculations is that detailed information is available about the meal composition and its variation over a representative and sufficiently long period of time. A 7-d record, for example, may not represent the iron absorption from the habitual diet.

The algorithm can be used to estimate the expected effects of different dietary modifications that can be considered realistic in both developed and developing countries. In developed countries, the main concerns are low energy expenditure and, thus, low energy intakes. To adequately provide for high iron needs, especially in infants, adolescents, and menstruating women, a high nutrient density and a high bioavailability is required. The algorithm can also be used to examine the overall effects of a higher extraction of flour (increasing the intake of both intrinsic phytate and iron) on bioavailability and iron content. It can be used to estimate the expected effects of iron

TABLE 4

Iron absorption from the whole diet¹

	Calculated absorption from the algorithm			
	Iron intake	At 40% of the reference dose		Observed absorption ³
		absorption ²	Adjusted to actual iron status ³	
	<i>mg</i>	<i>mg</i>	<i>mg</i>	<i>mg</i>
Nonheme iron	11.0	2.61	1.24 ± 0.22	1.23 ± 0.19
Heme iron	2.94	1.05	0.52 ± 0.02	0.52 ± 0.03
Total	13.94	3.65	1.77 ± 0.19	1.76 ± 0.21

¹*n* = 31 healthy men. Absorption was calculated by using the algorithm. The original calculation is based on an iron status corresponding to a reference dose absorption of 40%. For each subject, this absorption was then adjusted to the individual iron status based on the serum ferritin concentration and was compared with the actual observed absorption by using whole-body counting (*see text*).

² \bar{x} .

³ $\bar{x} \pm \text{SEM}$.


fortification or increased intakes of fruit, vegetables, and meat in the diet. In developing countries, the problems are similar but the knowledge about the chemical composition of foods and its variation is even more limited; for example, knowledge is limited about the contents of phytate and iron binding polyphenols in common foods, including spices and condiments. Evaluation of the expected effects on iron absorption and iron balance resulting from modification of food-preparation methods may also be required.

An important use of the algorithm would be to translate physiologic iron requirements into dietary requirements under different dietary conditions known to prevail in a certain population. In the Food and Agriculture Organization/World Health Organization recommendations, 3 levels of bioavailability (5%, 10%, and 15%) were used arbitrarily for this translation (60). The validity of choices of representative bioavailability values can be tested by using the algorithm. It is obvious from the present results that there is marked variation in the bioavailability of different types of diets in developed countries. The recommended dietary allowances (61) for different groups of subjects with different physiologic iron requirements should, therefore, not be given as single values, but rather as 3–4 values adjusted for different types of diets (eg, vegan or vegetarian, low-meat, and high meat). The algorithm can then be used to make rough estimates of the bioavailability of diets in some groups in the population with different dietary habits. The algorithm may be useful in the future search for realistic recommendations to be used in food-based strategies to improve iron nutrition in developing countries. However, more knowledge about the composition and properties of diets in developing countries is needed.

In the screening for unknown dietary factors influencing iron absorption, new starting points can be obtained by comparing actual absorption values from a certain meal with absorption values estimated from the content of presently known factors. A significant discrepancy would indicate that some unknown nutritionally important factor is present.

Importance of correct values for the factors included in the algorithm

One problem with the application of the algorithm is limited knowledge about the content of factors such as phytate and iron binding polyphenols in different foods. An extensive report on the phytate content in foods was published previously (62). Note that even low phytate contents play an important role in the bioavailability of iron, but are often not detectable with the current method used by the Association of Official Analytical Chemists, which was used in that report. A simple modification of the current method of the Association of Official Analytical Chemists was made to determine low phytate contents in foods and was calibrated against HPLC (11).

Another practical problem in applying the algorithm is the difficulty in estimating the ascorbic acid content in a meal at the time of consumption because cooking times and food-preparation methods markedly influence the final phytate content. In Appendix A, we provide data for some common foods. Appendix A also contains data from our laboratory about the content of total iron and heme iron in different kinds of meat. More detailed food-composition tables are needed. The lack of knowledge of the presence of different factors in different foods is even more obvious when the algorithm is applied to diets in developing countries. 

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APPENDIX A

Observed iron absorption at a certain iron status adjusted to the absorption expected at another iron status

The relation between log serum ferritin and the reference dose absorption was examined in 1066 subjects in whom an adequate serum ferritin standard had been used in the calibration. In these studies we found that a reference dose of 40% corresponded to a serum ferritin concentration of 23 $\mu\text{g/L}$. Data from a recent study of iron absorption from whole diets in men ($n = 31$) showed that there is a linear relation between log iron absorption and log serum ferritin (SF) ($r^2 = 0.720$):

$$\begin{aligned} \text{Log iron absorption} \\ (\mu\text{g Fe} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}) &= (2.9251 - 0.94049) \\ &\times \log \text{SF } (\mu\text{g/L}) \end{aligned} \quad (A1)$$

The constant in the equation (2.9251) is valid for a diet with a high bioavailability (1). The slope of this regression line (0.94) was the same for different diets but the intercept on the y axis varied, implying that different diets are represented by different parallel regression lines. A general formula for such regression equations is as follows:

$$\begin{aligned} \text{Log iron absorption} &= (C \text{ for a certain diet} \\ &- 0.94049) \times \log \text{SF} \end{aligned} \quad (A2)$$

where *C* is a constant. This formula assumes that the iron absorption from this diet was as calculated in equation A3 below at an iron status expressed as the SF₁ corresponding to a reference dose absorption of 40%. We know that this reference dose absorption corresponds to a serum ferritin concentration of 23 µg/L. Another data pair from the same diet would be used to calculate iron absorption:

$$\text{Log absorption 1} = (C - 0.94049) \times \log SF_1 \quad (A3)$$

To calculate iron absorption from the same diet but at a different SF concentration (SF₂) than used in equation A3, the following equation would be used:

$$\text{Log absorption 2} = (C - 0.94049) \times \log SF_2 \quad (A4)$$

In equations A3 and A4, iron absorption can be expressed as µg Fe/kg body wt or as mg. *C* is eliminated by subtracting equation A3 from equation A4 and the following equation is obtained:

$$\begin{aligned} \text{Log absorption 2} \\ - \text{log absorption 1} &= (-0.94 \times \log SF_2) \\ &+ (0.94 \times \log SF_1) \end{aligned} \quad (A5)$$

Log absorption 2 can then be calculated. The equation can be written in a simpler way by an antilog-transformation, which gives the following equation:

$$\begin{aligned} \text{Log absorption 2} &= \text{log absorption 1} \\ &\times [SF_1 \times (0.94/SF_2)] \end{aligned} \quad (A6)$$

To adjust the iron absorption from a reference dose absorption of 40% to a certain SF concentration, SF₁ is set at 23 µg/L. Log absorption 1 is the observed absorption at this iron status and log absorption 2 is the calculated absorption at the corresponding known SF₂ concentration.

TABLE A1

Phytate and iron binding polyphenols in vegetables, legumes, fruit, berries, beverages, spices, nuts, seeds, soy products, and cereal and cereal products

	Phytate phosphorus ¹	Tannin equivalents	Chlorogenic acid	Total tannin equivalents
	<i>mg/100 g dry matter</i>			
Root, leaf, and stem vegetables, and legumes				
Aubergine, whole	3	7	51	31
Asparagus				
Green	2	—	—	—
White	3	—	—	—
Beans				
Black	262	0	—	0
Brown	195	0	—	0
Green	15	—	—	—
Mung	188	140	—	140
Red	271	1	—	1
White	269	0	—	0
Beetroot	2	3	—	3
Broccoli	10	1	40	20
Brussels sprouts	11	0	—	0
Cabbage				
Chinese	2	—	—	—
White	1	0	—	0

(Continued)

TABLE A1 (Continued)

	Phytate phosphorus ¹	Tannin equivalents	Chlorogenic acid	Total tannin equivalents
	<i>mg/100 g dry matter</i>			
Carrot	4	0	28	13
Cauliflower	3	0	—	0
Celeriac	5	0	—	0
Chicory	2	0	—	0
Corn	24	—	—	—
Cucumber	1	0	0	0
Garden cress	7	—	—	—
Garlic	4	0	7	3
Horseradish	13	—	—	—
Kohlrabi	2	—	—	—
Leek	4	0	11	5
Lentils				
Brown	142	190	—	190
Red	122	0	—	0
Lettuce, iceberg	0.5	—	—	—
Mushrooms	13	1	—	1
Olives, black	3	—	—	—
Onion				
Red	5	10	—	10
Yellow	16	6	—	6
Parsley leaves	8	—	—	—
Parsnips	9	0	20	9.5
Peas				
Chickpeas	140	0	—	0
Green peas	175	0	0	0
Yellow peas	270	—	—	—
Peppers				
Sweet green	2	0	—	0
Sweet red	0.5	0	—	0
Sweet yellow	1	0	—	0
Potato	7	0	0	0
Radish				
White	4	0	—	0
Black	1	—	—	—
Rutabaga	1	0	—	0
Sauerkraut	1	0	—	0
Skorzonera (black salsify)	—	0	—	0
Spinach	2	20	12	26
Squash, summer	3	—	—	—
Tomato	2	0	—	0
Fruit and berries				
Apple	0.1	160	—	160
Apricot	—	0	—	0
Avocado	1	0	—	0
Banana	0.4	40	—	40
Blackberry	4	390	—	390
Blueberry	6	80	—	80
Currant				
Black	78	—	—	—
Red	55	—	—	—
Dates	—	5	—	5
Figs	—	0	—	0
Kiwi	10	0	0	0
Cowberry	5	3	250	122
Mango	1	—	—	—
Melon, honey	0.6	—	—	—
Orange	2	0	—	0
Pears	0.2	4	70	37
Raspberry	4	70	61	99

(Continued)

TABLE A1 (Continued)

	Phytate phosphorus ¹	Tannin equivalents	Chlorogenic acid	Total tannin equivalents
	<i>mg/100 g dry matter</i>			
Rhubarb	0.2	0	16	8
Strawberry	4	—	—	—
Beverages				
Coffee, brewed ²	—	21	71	55
Tea				
English breakfast ³	—	53	14	60
Green ⁴	—	26	17	35
Herb	—	18	—	18
Peppermint ⁴	—	20	23	31
Cacao powder				
Marabou	504	4400	520	4648
De Zaan ⁵	513	—	—	—
De Zaan low fat	342	—	—	—
Fazer ⁶	481	—	—	—
With sugar	93	380	69	413
Beer				
Light lager	—	0.4	—	0.4
Strong	—	0.1	—	0.1
Whiskey, Cutty Sark ⁷	—	2.9	—	2.9
Wine				
White	—	0	4	2
Red ^{5,8}	—	0.2–2.3	20–40	10–21
Fruit syrup, sloe	—	6.2	—	6.2
Spices ⁹				
Allspice	—	0	—	0
Basil	—	2.7	7.9	6.5
Black pepper	—	2	—	2
Caraway	—	2.8	6.4	5.8
Cardamom	—	0.3	—	0.3
Chervil	—	0.4	2	1.4
Chili pepper	—	0.4	0.8	0.8
Cinnamon	—	43	14.3	50
Clove	—	95	—	95
Cumin	—	2.8	6.4	5.8
Curry	—	6.2	9.9	10.9
Fennel	—	0.3	—	0.3
Ginger	—	0.2	—	0.2
Green pepper	—	1.4	—	1.4
Marjoram	—	6.4	9.9	11.1
Oregano	0.2	21	6	24
Thyme	—	12	4.4	14.1
Turmeric	—	34	0.7	34
Vanilla	—	0.7	—	0.7
White pepper	—	0.4	—	0.4
Nuts, seeds, and soy products				
Brazil nut	—	10	—	10
Cashew nut	—	0	—	0
Hazel nut	—	256	—	256
Peanut	—	0	—	0
Walnut	303	1400	—	1400
Sweet almond	296	43	—	43
Linseeds	296	14	—	14
Sesame seeds	576	—	—	—
Sunflower seeds	393	120	—	120
Soy sauce				
Kikkoman ¹⁰	4	—	—	—
Tamari ¹¹	15	—	—	—
Chinese mushroom ¹²	5	—	—	—
Cereals and cereal products				
Bran				

TABLE A1 (Continued)

	Phytate phosphorus ¹	Tannin equivalents	Chlorogenic acid	Total tannin equivalents
	<i>mg/100 g dry matter</i>			
Barley	185	—	—	—
Oat	399–628	0	—	0
Wheat	680–1189	0	58	28
Wheat, coarse	1338	3	—	3
Crisp bread				
Rye, thin	72–86	—	—	—
Rye, fiber	114–193	—	—	—
Graham	192	—	—	—
Oat	166	—	—	—
Rice cakes	113	—	—	—
Rice flour	27	—	—	—
Long grain	53–64	—	—	—
Parboiled	71	—	—	—
Wild, brown	181–215	0	—	0
Starch				
Lentil	3	—	—	—
Maize	3	—	—	—
Rice	1–37	—	—	—
Wheat	0	—	—	—
Corn flakes	12	—	—	—
Millet	217	—	—	—
Oats, rolled	282	0	—	0
Semolina	19	—	—	—
Sorghum				
Red	279	480	—	480
White	389	15	—	15
Spaghetti				
Buitoni ¹³	6	—	—	—
Barilla ¹⁴	71	—	—	—
Wheat germ	467	0	—	0

¹ See reference 2. 1 mg phytate phosphorus = 3.5 mg phytic acid = 5.56 μmol phytic acid.

² 3.3 g coffee/100 mL water.

³ 1 g tea/100 mL water.

⁴ 1.4 g tea/100 mL water.

⁵ Droste, Harlem, Netherlands.

⁶ Fazer AB, Solna, Sweden.

⁷ Berry Brothers and Rudd, Edinburgh.

⁸ Ranges given.

⁹ Values are per 1 g.

¹⁰ Kikkoman (s) PTE, Ltd, Singapore.

¹¹ Kung Markatta AB, Örebro, Sweden.

¹² CHE-BE Trading AB, Stockholm.

¹³ Milano, Italy.

¹⁴ Parma, Italy.

(Continued)

TABLE A2

Phytate phosphorus, ash, and total iron contents of flour and bread

	Ash content	Total iron	Phytate phosphorus		
			In flour	In bread baked with water	
				In dry substance	In bread as eaten
<i>% of dry matter</i>	<i>mg/100 g dry matter</i>		<i>mg/100 g dry matter</i>		
Corn flour	—	—	70–265 ¹	—	—
Rye flour ²	1.41	2.8	175–244 ¹	86 [44]	50 [26]
Wheat flour	0.38	0.4	13	—	—
Wheat flour	0.45	0.6	22	9	5
Wheat flour	0.63	1.1	61	10	6
Wheat flour	0.72	—	65	—	—
Wheat flour ³	0.76	1.6	86	19 [81]	11 [48]
Wheat flour	1.38	3.4	181	98	58
Wheat flour	1.60	3.6	227	154	90
Wheat flour	2.34	5.9	364	289	170
Wheat flour	2.50	6.3	348	—	—
Wheat flour	2.74	7.3	404	350	205

¹Ranges.²Values in brackets reflect sourdough fermentation.³Values in brackets reflect milk as an ingredient.**TABLE A3**Phytate and iron binding phenols in cooked meat and meat products¹

	Total iron	Heme iron	Heme iron
	<i>mg/100 g dry matter</i>	<i>% of total iron</i>	<i>mg/100 g dry matter</i>
Beef			
Rump steak	2.9	52	1.5
Sirloin steak	2.5	52	1.3
Round steak	3.2	50	1.6
Topside, round	2.5	48	1.2
Ground	2.5	40	1.0
Corned beef (brisket)	2.0	25	0.5
Roast, sliced	1.7	35	0.6
Pork tenderloin	1.3	23	0.3
Chicken	0.6	0	0
Lamb, leg	3.1	55	1.7
Deer meat	4.5	51	2.3
Moose loin	2.7	41	1.1
Processed meat products			
Sausage (Falú)	0.8	0	0
Sausage, veal	0.7	0	0
Ham, boiled and sliced	0.7	0	0
Liver paste and paté	5.0	16	0.8
Fish			
Cod	0.2	0	0
Mackerel	0.7	0	0
Salmon	0.6	17	0.1
Mussels	4.6	48	2.2

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