Iron bioavailability of cocoa powder as determined by the Hb regeneration efficiency method

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Fe deficiency is a public-health problem worldwide, and effective measures for preventing Fe deficiency are needed. The aim of the present study was to determine the bioavailability of Fe in cocoa using the Hb regeneration efficiency (HRE) method. Thirty-five F344/N male weanling rats were fed a low-Fe diet for 4 weeks to deplete body Fe stores. Then, four groups of seven animals each were repleted for 20 d using a modified AIN-93G diet fortified with ferrous sulphate, ferric citrate or two brands of cocoa powder to provide a total dietary Fe concentration of 20 mg/kg. As a negative control, seven rats were maintained on the low-Fe diet. The HRE were 0.733, 0.350, 0.357 and 0.336 for ferrous sulphate, ferric citrate and the two brands of cocoa powder, respectively. The relative biological values (RBV), defined as the ratio of the sample HRE to that of ferrous sulphate, were 0.478, 0.488 and 0.459 for ferric citrate and the two brands of cocoa powder, respectively. The Fe bioavailability of cocoa was significantly less than that of ferrous sulphate and was similar to that of ferric citrate. The difference in Fe bioavailability between the two brands of cocoa powder was negligible. When the negative control was used to correct the data, estimates of the RBV derived from Hb gain were similar to those derived from the HRE. These results suggest that cocoa is a significant source of moderately bioavailable Fe.

Fe bioavailability: Cocoa powder: Rats: Hb regeneration efficiency method

Fe deficiency is one of the most important nutritional problems in the world today11. Many efforts are underway to develop effective measures for preventing Fe deficiency and anaemia12. Although chocolate drink powder and cocoa powder have been shown to be effective vehicles for dietary Fe fortification3–5, the bioavailability of Fe naturally occurring in cocoa has not been quantified. Cocoa powders contain high amounts of Fe6 and polyphenols, including epicatechin, catechin and their polymers (tannin)7, and phytate8. Polyphenols and phytate are potent inhibitors of Fe absorption9,10. Consistent with this, our previous studies showed that frequent consumption of tea (a source of tannin) and bran (a source of phytate) is associated with low-Fe stores in women11,12. The high level of polyphenols and phytate in cocoa powder may decrease the Fe bioavailability. However, fermentation of phytate-rich plant foods increases the Fe bioavailability13,14. To produce cocoa powder, cocoa beans are cured or fermented, dried and roasted before grinding15, which may increase the Fe bioavailability. The aim of the present study was to quantify the Fe bioavailability of cocoa powders using the Hb regeneration efficiency (HRE) method16 with minor modifications.

Materials and methods

The Fe bioavailability of cocoa powder was determined using the HRE method16,17 and thirty-five weanling F344/N male rats (Japan SLC, Shizuoka, Japan), with a mean weight of 50.4 g (SE 0.7 g). At the start of the study, each animal was weighed, blood was collected by tail-vein puncture and the Hb concentration of fresh blood samples was measured using the cyanmethaemoglobin method and an electronic counter (Cellucount MEK-5258, Nihon Kohden Co., Tokyo, Japan). The animals were individually housed in stainless steel cages with raised wire bases and maintained in a temperature- and light-controlled environment at 22°C and 50 % relative humidity with a standard light cycle (12 h light/12 h dark; lights on 07.00 hours). All the animals had free access to the experimental diets and deionised water during the entire periods.

Anaemia was induced in all animals by feeding them a low-Fe diet (3-6 mg Fe/kg) for 4 weeks. The diet consisted of an AIN-93G-purified rat diet without ferric citrate and contained (g/kg): maize starch, 397.486; casein, 200.000; dextrinised maize starch, 132.000; sucrose, 100.000; soyabean oil, 70.000; fibre (cellulose powder), 50.000; AIN-93G mineral mix (without ferric citrate), 35.000; AIN-93 vitamin mix, 10.000; l-cystine, 3.000; choline bitartrate, 2.500; tert-butylhydroquinone, 0.014. Casein, maize starch, fibre, AIN-93G mineral mix (without ferric citrate) and AIN-93 vitamin mix were obtained from the Oriental Yeast Japan Co. (Tokyo, Japan). Dextrinised maize starch was obtained from Nacalai Tesque Co. (Kyoto, Japan). Other ingredients were obtained from Wako Pure Chemicals (Osaka, Japan).

Abbreviations: HRE, Hb regeneration efficiency; RBV, relative biological value.

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After the 28-d depletion period, each animal was weighed, blood was collected by tail-vein puncture and the Hb concentration was measured. The animals were then randomised into five groups (of seven rats each) based on the Hb concentrations.

The AIN-93G diet uses 35 mg Fe/kg in the form of ferric citrate, which has a lower Fe bioavailability than ferrous sulphate\(^\text{18}\). The dose–response curve for ferrous sulphate is linear up to 24 mg Fe/kg according to the Association of Official Agricultural Chemists method\(^\text{19}\). Therefore, we used repletion diets containing 20 mg Fe/kg to estimate the Fe bioavailability. Four repletion diets were prepared by replacing the maize starch component of the low-Fe diet with one of two brands of commercial cocoa powder (Cocoa A (Morinaga Brand Pure Cocoa; Morinaga & Co. Ltd, Tokyo, Japan) and Cocoa B (Van Houten Brand Pure Cocoa; Kataoka & Co. Ltd, Tokyo, Japan)), ferrous sulphate or ferric citrate (Wako Pure Chemicals). The cocoa powders were purchased from a local supermarket in Matsudo, Chiba, Japan. Cocoa A and Cocoa B contained 30.39 and 29.43 mg Fe/100 g, respectively. Therefore, the cocoa powders, diets and a National Institute of Standards and Technology (Gaithersburg, MD, USA) standard (ICPM-8500, Shimadzu Co., Kyoto, Japan) for Microsoft Windows. The data were analysed by Scheffe’s simultaneous multiple comparison test and Spearman’s rank correlation test using SYSTAT version 10.2 software (SPSS Inc., Evanston, IL, USA) for Microsoft Windows. \(P\) values less than 0.05 were considered significant.

The present study was approved by the Ethical Committee for Laboratory Animals of Seikatu University, Matsudo, Chiba, Japan. All animal care guideline and animal handling procedures followed were concordant with the standards relating to the Care and Management of Experimental Animals (notification no. 6, 1980, The Japanese Prime Minister’s Office).

**Results**

At the start of the depletion period, the mean Hb concentration was 123 (SE 1) g/l and mean body weight was 50.4 g (SE 0.7 g). At the end of the depletion period, the mean Hb concentration was 64 (SE 1) g/l and mean body weight was 130.6 g (SE 1.3 g). Body weights, and body-weight gains, feed intakes, feed efficiencies and Fe intakes during the repletion period are shown in Table 1. The mean Hb gain of the negative control was \(-11\) (SE 1) g/l. The mean Hb-gain of the negative control was 0.01 mg (SE 0.003 mg), signifying that the dietary treatment was effective in depleting Fe. Although the initial body weight of rats that were fed Cocoa A was slightly higher than that of the other groups, the differences were

\[
\text{Hb-gain} = \text{Hb (final)} - \text{Hb (initial)}.
\]

The RBV\textsubscript{Hb-gain} was calculated for each animal according to the following equation:

\[
\text{RBV}_{\text{Hb-gain}} = \frac{\text{Hb-gain (each animal)}}{\text{Hb-gain (average for ferrous sulphate)}}.
\]

We also calculated the RBV based on the Hb gain (RBV\textsubscript{HRE}) for a comparison with the RBV\textsubscript{HRE}, as recommended by Forbes \textit{et al.}\(^\text{16}\). The RBV\textsubscript{HRE} was calculated by dividing the individual Hb gains of the Fe sources by the mean Hb gain of ferrous sulphate.

\[
\text{RBV}_{\text{HRE}} = \frac{\text{HRE (each animal)}}{\text{HRE (average for ferrous sulphate)}}.
\]
The relationship between the Hb gain and the body-weight gain and that between the Hb gain and the feed intake are shown in Fig. 1. The body-weight gain was significantly correlated with the Hb gain and feed intake during the repletion period (Spearman’s \( r = 0.864, n = 35, P<0.001 \); Spearman’s \( r = 0.880, n = 35, P<0.001 \), respectively). The feed intake was significantly correlated with the Hb gain (Spearman’s \( r = 0.714, n = 35, P<0.001 \)).

**Discussion**

According to the International Cocoa Organization, the revised estimate of world cacao bean grindings for the 2006–2007 cocoa year was 3 641 000 tons (22). Cocoa grinding was bioavailable. Buijsse et al. (24) investigated the relationship between the cocoa intake and blood pressure among elderly men in The Netherlands. They found that one-third of the population did not consume cocoa powder and that the median and the 92nd percentile intakes of cocoa powder from various sources were 0.92 and 6.1 g/d, respectively.

Considering measurement errors, the RBV as determined by the modified HRE method was similar to that for ferric citrate and the two brands of cocoa powder, and the difference between the two brands of cocoa powder was negligible. The Fe bioavailability of cocoa is similar to that of lime-treated cocoa powder. The Fe bioavailability of cocoa powder was bioavailable. Buijsse et al. (24) investigated the relationship between the cocoa intake and blood pressure among elderly men in The Netherlands. They found that one-third of the population did not consume cocoa powder and that the median and the 92nd percentile intakes of cocoa powder from various sources were 0.92 and 6.1 g/d, respectively.

### Table 1. Body-weight gain, feed intake, feed efficiency and Fe intake of rats during Fe repletion

(Mean values with their standard errors)

<table>
<thead>
<tr>
<th></th>
<th>Negative control</th>
<th>Ferrous sulphate</th>
<th>Ferric citrate</th>
<th>Cocoa A*</th>
<th>Cocoa B†</th>
<th>ANOVA P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Body weight (g)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td></td>
</tr>
<tr>
<td>132.5</td>
<td>2.5</td>
<td>126.9</td>
<td>2.7</td>
<td>129.0</td>
<td>2.7</td>
<td>136.2</td>
</tr>
<tr>
<td>Gain</td>
<td>28.7a</td>
<td>2.0</td>
<td>78.4a</td>
<td>3.6</td>
<td>57.2a</td>
<td>2.2</td>
</tr>
<tr>
<td>Feed intake (g)</td>
<td>177.9a</td>
<td>4.1</td>
<td>257.1a</td>
<td>8.9</td>
<td>216.7a</td>
<td>5.1</td>
</tr>
<tr>
<td>Feed efficiency</td>
<td>0.162a</td>
<td>0.01</td>
<td>0.304b</td>
<td>0.004</td>
<td>0.264a</td>
<td>0.008</td>
</tr>
<tr>
<td>Fe intake (mg)</td>
<td>0.64a</td>
<td>0.01</td>
<td>6.07b</td>
<td>0.21</td>
<td>5.12c</td>
<td>0.12</td>
</tr>
</tbody>
</table>

### Table 2. Bioavailability for rats of ferric citrate and Fe in commercial cocoa powder using the AIN-93G diet

(Mean values with their standard errors)

<table>
<thead>
<tr>
<th></th>
<th>Negative control</th>
<th>Ferrous sulphate</th>
<th>Ferric citrate</th>
<th>Cocoa A*</th>
<th>Cocoa B†</th>
<th>ANOVA P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hb (g/l)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
</tr>
<tr>
<td>63</td>
<td>1</td>
<td>63</td>
<td>2</td>
<td>64</td>
<td>2</td>
<td>64</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11a</td>
<td>0.4</td>
<td>62</td>
<td>3</td>
<td>19c</td>
<td>22c</td>
<td>21c</td>
</tr>
<tr>
<td>Hb-Fe (mg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
<td>Mean SE</td>
</tr>
<tr>
<td>2.11</td>
<td>0.07</td>
<td>2.01</td>
<td>0.05</td>
<td>2.06</td>
<td>0.09</td>
<td>2.1a</td>
</tr>
<tr>
<td>Gain</td>
<td>0.01a</td>
<td>0.03</td>
<td>4.45b</td>
<td>0.21</td>
<td>1.79</td>
<td>0.13</td>
</tr>
<tr>
<td>HRE</td>
<td>0.016a</td>
<td>0.040</td>
<td>0.733b</td>
<td>0.025</td>
<td>0.350c</td>
<td>0.023</td>
</tr>
<tr>
<td>RBVHRE</td>
<td>0.022a</td>
<td>0.055</td>
<td>1.000a</td>
<td>0.034</td>
<td>0.478c</td>
<td>0.032</td>
</tr>
<tr>
<td>RBVHb-gain</td>
<td>-0.177a</td>
<td>0.007</td>
<td>1.000a</td>
<td>0.036</td>
<td>0.302c</td>
<td>0.037</td>
</tr>
<tr>
<td>Corrected RBVHb-gain</td>
<td>-0.004a</td>
<td>0.006</td>
<td>1.000a</td>
<td>0.039</td>
<td>0.367c</td>
<td>0.032</td>
</tr>
</tbody>
</table>

**HRE**, Hb regeneration efficiency; **RBVHRE**, relative biological value based on HRE; **RBVHb-gain**, relative biological value based on Hb gain.

* Morinaga Brand Pure Cocoa (Morinaga & Co., Tokyo, Japan).  
† Van Houlen Brand Pure Cocoa (Kataoka & Co., Tokyo, Japan).
maize flour (RBV 0·51) and wheat flour with 70–72 % extraction (RBV 0·55), as determined using the HRE method by Hernández et al. (28), and is better than that of ferric phosphate (RBV 0·23) reported by Whittaker & Vanderveen (26). These results indicate that the Fe in cocoa is moderately bioavailable and would be a significant Fe source if the results of animal studies were applicable to human subjects.

Cocoa contains considerable amounts of Fe absorption inhibitors. According to Natsume et al. (27), the total polyphenol or tannin content of pure cocoa is 3·02–4·73 %. Aremu et al. (8) reported that five brands of Nigerian cocoa beverage contained 68–146 mg of oxalate and 590–750 mg of phytate per 100 g of DM. On the other hand, cocoa is a fermented food. During fermentation by yeasts, lactic acid bacteria and acetobacters, significant amounts of polyphenols and alkaloids in cacao beans are metabolised and lost (28). Effective yeast fermentation, which degrades phytate, increases the bioavailability of Fe in whole-meal bread (13,29). Further studies are necessary to determine whether cocoa Fe bioavailability in human subjects is similar to that in rodents.

In addition to information on the bioavailability of cocoa Fe, the present results also emphasise the significance of methodological aspects of the HRE method. The International Nutritional Anemia Consultative Group Task Force reported that the RBV values derived using the HRE method are greater than those derived using the modified Association of Official Agricultural Chemists method or the Hb gain method, especially for lower RBV or less bioavailable compounds (16). The task force mentioned the shorter depletion period and the compensation of the body-weight-gain factor as possible causes of the apparent overestimates of the RBV of less bioavailable compounds.

In the present study, we modified the HRE method of Forbes et al. (16) by extending the depletion period from 7–8 to 28 d and the repletion period from 9–10 to 20 d, and calculated the RBV based on the Hb gain method for comparison. However, we did not check the RBV using the Association of Official Agricultural Chemists method. The RBVHRE was significantly greater than the RBVHb-gain for ferric citrate and Cocoa A (P<0·01 according to Scheffé’s simultaneous comparison test). By contrast, there were no significant differences between the RBVHRE and the corrected RBVHb-gain for all Fe sources. The Fe deficiency decreases the body-weight gain and the feed intake in rats (30–32). Concordant with this, there were strong positive correlations between the Hb gain, the body-weight gain and the feed intake (Fig. 1; Table 1). Ferric citrate resulted in the smallest Hb gain, body-weight gain and feed intake among the materials tested (excluding the negative control). We assume that the slightly lower bioavailability of ferric citrate according to the RBVHb-gain may have contributed to the lower feed intake and body-weight gain of rats fed this compound. The Hb gain, body-weight gain and feed intake are used to calculate the RBVHRE. We suspect that the overestimation of the RBV of low bioavailable compounds by the HRE method compared with the Hb gain method is an inherent feature of the formula used to calculate the RBVHRE (Appendix).

During the depletion period, the negative control rats either gained Hb-Fe or did not lose Hb-Fe. They gained body weight, whereas their Hb level decreased reciprocally. We believe that the zero-point correction of the RBVHb-gain using the negative control data is an effective means of avoiding underestimates of the RBV by the Hb gain method relative to the estimates derived using the HRE method. In the present study, the Hb gain-derived RBV and the HRE-derived RBV resulted in similar estimates of the Fe bioavailability for the various Fe sources. However, there were insufficient data to establish whether data correction using the negative control data is relevant to the conditions in which depletion is more severe or in which shorter depletion and repletion periods are applied.

In conclusion, these results suggest that the Fe bioavailability of cocoa powder as determined using a rodent model is moderate and similar to that of ferric citrate. Cocoa powders may be significant Fe sources for human subjects.

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Fe bioavailability of cocoa powder

sulfate and predicted by iron solubility and particle surface area. J Nutr 133, 3546–3552.

Appendix

Hb gain, feed intake and body-weight gain during the repletion period are highly correlated in rats used for estimating the relative biological values of various Fe sources by the Hb regeneration efficiency method. Although the assumption of exact proportionality between these measures is somewhat of an oversimplification, it is useful for unveiling the hidden relationship between the RBV_{HRE} and the RBV_{Hb gain}.

Assuming an exact proportionality between the Hb gain, the feed intake and the body-weight gain, i.e. \( Hb_g = m \cdot FI \) and \( BW_g = n \cdot FI \), HRE becomes

\[
HRE = \frac{b \cdot Hb_i \cdot BW_f - b \cdot Hb_0 \cdot BW_i}{a \cdot FI},
\]

where FI is the feed intake; \( a \) is the Fe content of feed; \( b \) is the Fe content of Hb multiplied by blood volume per unit body weight; \( BW_i \) is the initial body weight; \( BW_f \) is the final body weight;
BW is the body-weight gain; HB is the initial Hb concentration; HB is the final Hb concentration; HB is the Hb gain; and m and n are the slopes of the regression equations.

Substituting HB with HB + HB,

\[
\frac{b}{a} \left( \frac{HB + HB}{FI} \right)
\]

Substituting BW with BW + BW,

\[
\frac{b}{a} \left( \frac{HB + HB}{FI} \right)
\]

Substituting HB with m FI and BW with n FI,

\[
\frac{b}{a} \left( \frac{mFI}{FI} \right) BW + \frac{b}{a} \left( \frac{nFI}{FI} \right) HB
\]

Substituting HRE with Hb/m,

\[
\frac{bn}{a} \left( \frac{Hb}{mFI} \right) BW + \frac{bn}{a} \left( \frac{Hb}{mFI} \right) HB
\]

Since BW and HB are equalised among rats fed different Fe sources, the second term can be replaced by the constant C,

\[
HRE = \frac{bn}{a} Hb + C
\]

Therefore, the discrepancy between the RBVHRE and the RBVHB-gain is larger for compounds with low-Fe bioavailability because the contribution of the constant C to HRE is relatively larger at a low HB.