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Stable isotope labels as a tool to determine the iron absorption by Peruvian school children from a breakfast meal

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Abstract Fractional iron absorption from a breakfast meal was determined in Peruvian children employing stable iron isotopes as labels. Iron isotopic analysis was performed by the recently developed negative thermal ionization technique for high-precision iron isotope ratio measurements using FeF_4^- ions. By increasing the ascorbic acid content of the standard breakfast meal as served within the Peruvian school-breakfast program from 27 mg to 70 mg, it was possible to increase the geometric mean fractional iron absorption significantly from 5.1% (range 1.6–13.5%) to 8.2% (range 3.1–25.8%). Fractional iron absorption was calculated according to isotope dilution principles and by considering the non-monoisotopic character of the used spikes.

Introduction

Iron deficiency is the most common nutrient deficiency on a global scale and affects about 15% of the total world population [1]. With severe deficiency the hemoglobin level in blood is decreased. This condition is known as iron deficiency anaemia and is associated with problems of mental and psychomotor development in childhood, an increased morbidity and mortality of mother and child around childbirth, a decrease in work performance and a decreased resistance to infections [2–4].

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Iron deficiency in developing countries can be related to the low absorption of iron from the daily food, with women and children being the most vulnerable population groups [5]. In Peru, a school-breakfast program was initiated by the government to provide Peruvian children daily with a basic meal, fortified with iron and other nutrients. Ascorbic acid has been added to this meal (27 mg/meal) so as to enhance iron absorption [6]. The aim of the present study was to measure iron absorption in school children from one of the school-breakfast meals and to evaluate the possibility of increasing iron absorption by adding more ascorbic acid (70 mg/meal).

Stable iron isotopes [7, 8] and radioactive iron isotopes [9, 10] can both be used for labelling the iron in a test meal to evaluate its bioavailability, i. e. how much of the dietary iron is absorbed and utilized by the body. Stable iron isotopes were chosen for this study because of ethical concerns regarding the use of radioactive isotopes in children. When stable isotope labels are used, the amount of label absorbed from the test meal can be calculated from the shift in the iron isotopic abundances in the blood after red blood cell incorporation of the absorbed isotopic label, which can be measured approximately 14 days after test meal administration.

Since dietary iron absorption depends on the iron status of the body [11], large inter-individual variations in iron absorption can be expected even under highly standardized experimental conditions. For this reason, the iron in the two test meals was labelled with two different iron isotopes. By administration of the differently labelled test meals to each subject on consecutive days, each subject can act as his or her own control [8].

Experimental

Preparation of iron isotopic labels

For all work involving isotopically enriched labels and blood/iron samples, respectively, the principles of inorganic trace analysis were followed so as to minimize the alteration of their iron isotopic composition. Both isotopic labels were prepared from iron metal, isotopically enriched in ^{57}Fe (95.4% ^{57}Fe) and ^{58}Fe (93.1% ^{58}Fe), respectively. The isotopically enriched iron spikes were dissolved in 3 mol/L H_2SO_4 and diluted with water to yield a 1 mol/L H_2SO_4 solution. The iron isotopic composition of the spike solutions was determined by negative thermal ionization mass spectrometry (see below). The iron concentration of the spike solutions was determined against a commercially available iron standard solution by mass spectrometric isotope dilution analysis. Individual isotope doses were prepared by weighing the corresponding volume of the spike solution in Teflon containers, flushed with argon and tightly sealed for shipping. Iron doses of natural isotopic composition were

prepared in a corresponding way by dissolution of $FeSO_4 \cdot 7H_2O$ in 1 mol/L H_2SO_4.

Design of the study

Nine healthy, non-aneamic 6 year old children were recruited in Lima, Peru. None of the children were taking any iron medication. Before the first test meal administration, blood samples were drawn for analysis of iron status indices (hemoglobin, ferritin). Standardized school-breakfast meals were prepared by mixing 50 g of the cereal/milk powder in 200 g hot deionized water and weighing 42 g of white wheat bread per serving. This school-breakfast meal was identical with the regular breakfast of the school-feeding program except that no ascorbic acid and no iron were added during processing. Test meal A was prepared by adding the ^{58}Fe isotopic label (2.6 mg Fe as ^{58}Fe enriched $FeSO_4$) and 27 mg ascorbic acid to the standardized meal. In test meal A, the ascorbic acid content corresponded to the level at which the regular school-breakfast meal is ascorbic acid fortified. Test meal B was prepared by adding the ^{57}Fe isotopic label (7.0 mg Fe as ^{57}Fe enriched $FeSO_4$) and 70 mg ascorbic acid to the standardized school-breakfast meal. The added iron per test meal was made up to 14 mg with iron of natural isotopic composition (test meal A: 11.4 mg Fe as $FeSO_4$; test meal B: 7.0 mg Fe as $FeSO_4$) to obtain an iron content as given in the regular school-breakfast meal. The iron isotope labels and the iron doses of natural isotopic composition were added in solution to the cereal/milk drink immediately before administration. The ascorbic acid dose was added to the drink as a freshly prepared aqueous solution. Test meal A and test meal B were given to each subject on consecutive days in a randomized order. No food or drink was allowed for 3 h after intake of the labeled breakfasts. After incorporation of the absorbed isotopic label into the red blood cells (14 days after test meal administration), venous blood samples were drawn, frozen and shipped for iron isotopic analysis to Zurich, Switzerland. The study protocol was approved by the ethical committee at the Instituto de Investigacion Nutricional, Lima, Peru.

Preparation of blood samples for iron isotopic analysis

Each blood sample was prepared and isotopically analyzed in duplicate. The mineralization of an aliquot of the thawed blood sample (0.5 mL) was performed by microwave digestion using 5 mL conc. HNO_3 and 2 mL H_2O_2 (30%). After mineralization, the solution was dried down and redissolved in 5 mol/L HCl for iron separation by ion-exchange chromatography using the strongly basic ion-exchange resin AG1-X8 (200–400 mesh) [8, 12]. The solution was transferred to the top of a column (7 mm inner diameter) filled with the ion-exchange resin to a height of 70 mm. The column was rinsed with 20 ml 5 mol/L HCl after loading and the sample iron was eluted with 15 ml 1 mol/L HNO_3 from the column. After evaporating the iron solution to dryness, the sample iron was redissolved in 5 mol/L HCl and rerun through a second column as described above. Likewise, the solution containing the eluted iron from the second column was dried down and dissolved again in 500 µL 6 mol/L HCl. The iron was extracted from this solution in three steps into diethylether using 300 mL of the solvent each time. The combined organic phases were finally evaporated to dryness and stored for mass spectrometric analysis. With each batch of samples, a known amount of pure ^{57}Fe spike was passed through the entire sample preparation procedure to check for sample contamination.

Mass spectrometry

The iron isotopic composition of the isotopic labels and the prepared samples was determined by negative thermal ionization mass spectrometry (NTIMS) using FeF_4^- molecular ions and a rhenium double-filament ion source. The evaporation filament as well as the ionization filament were coated with BaF_2 to promote the formation of negatively charged ions. The sample iron was loaded as FeF_3 in HF (40%) on top of the BaF_2 layer on the evaporation filament and coated with a solution of $AgNO_3$ in HF (20%). All mass spectrometric measurements were carried out with a single-focusing magnetic sector field mass spectrometer (MAT 262, Finnigan MAT, Bremen, Germany) and simultaneous ion beam detection. The details of the employed mass spectrometric technique are given elsewhere [13]. Because of the low abundances of ^{54}Fe and ^{56}Fe in the used isotopic labels and the very low amounts of isotopic labels finally present in the blood samples, a shift in the $^{54}Fe/^{56}Fe$ isotope ratio of the blood samples could not be resolved within the reproducibility of the isotope ratio measurement. Therefore, it was possible to normalize the measured $^{54}Fe/^{56}Fe$ isotope ratios in the blood samples for the natural isotope ratio $^{54}Fe/^{56}Fe$ = 0.06370 [14] to correct for isotopic fractionation effects. Iron isotope ratios in the blood of the subjects before test meal administration were identical with the isotope ratios determined by Taylor et al. in a metal iron sample [14] within the reproducibility of the analysis. The average internal (in-run) precision (1 SD) after normalization of the isotopic data was 0.006% for the $^{57}Fe/^{56}Fe$ isotope ratio and 0.03% for the $^{58}Fe/^{56}Fe$ isotope ratio for a run consisting of 50 individual isotope ratio measurements. For six independent runs of a sample, external (between-run) precisions (1 SD) of 0.006% for the $^{57}Fe/^{56}Fe$ isotope ratio and 0.02% for the $^{58}Fe/^{56}Fe$ isotope ratio were obtained for normalized data sets.

Calculation of fractional iron absorption

Based on the iron isotopic shifts in the blood sample after incorporation of the administered isotopic label into the red blood cells, the fractional absorption (A_f) of the isotopic label was calculated as the amount of isotopic label absorbed relative to the amount of isotopic label ingested. This calculation is based on isotope dilution principles and is described in the appendix.

The same principles were applied to estimate in advance the minimum oral isotope doses necessary to obtain a resolvable iron isotopic shift in the blood of the subjects. For the definite detection of an iron isotopic shift, it was assumed that the mean of the respective iron isotope ratios in the blood sample had to differ from its natural mean value by at least ten times the external standard deviation obtainable for independent iron isotope ratio measurements. The calculation of the isotope doses was based on the lowest expected fractional absorption of the isotopic label which was 1.5% for test meal A and 2.0% for test meal B, respectively.

Results and discussion

The fractional absorption of the iron label from test meal A and test meal B, respectively, is presented in Fig. 1 for each individual subject. As expected, the intra-individual variation in iron absorption is large (see the figure). However, a statistically significant increase (paired t-test, $p = 0.02$) was observed when the ascorbic acid content in the test meal was increased from 27 mg (test meal A) to 70 mg (test meal B). The geometric mean of the fractional Fe absorption was 5.1% for test meal A (range 1.6% to 13.5%) versus 8.2% for test meal B (range 3.1% to 25.8%). In Fig. 1, the fractional Fe absorption ratio A_f (test

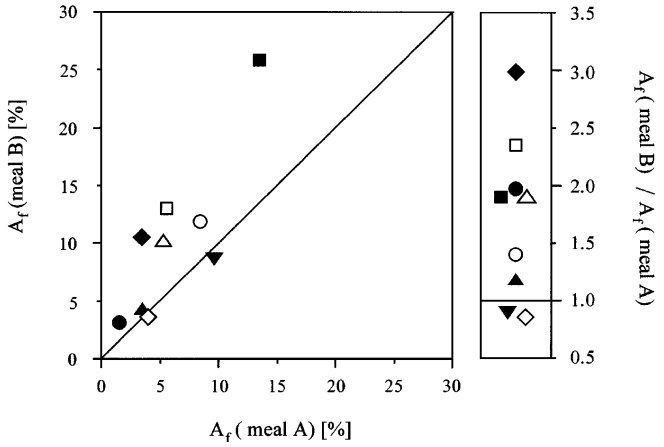

Fig. 1 Fractional iron absorption *(A_f)* from the Peruvian school-breakfast meal. Test meal A was fortified with 27 mg ascorbic acid and test meal B with 70 mg ascorbic acid at an identical iron content. Each symbol represents an individual child. The diagonal line corresponds to an identical fractional iron absorption from both test meals

meal A)/A_f (test meal B) is given in addition. The geometric mean of this ratio was found to be 1.60, which indicates that an increase of the ascorbic acid content in the school-breakfast meal from 27 mg to 70 mg could be a useful approach to enhance the iron absorption from the school-breakfast meal and, hopefully, would have an impact on the iron status of the Peruvian children.

The present study can be used to demonstrate the advantages of the recently developed NTIMS technique for iron isotopic analysis using molecular FeF_4^- ions [13] instead of atomic Fe^+ ions when applied in iron bioavailability studies using stable isotopes. In principle, the miniumum doses of iron isotopes necessary to obtain resolvable iron isotopic shifts in the blood of a subject are governed by the reproducibility at which the iron isotopic analysis can be performed. Within bioavailability studies using stable isotopes, it is of general interest to keep the isotope doses in the test meals as low as possible to be in a physiologically meaningful range and/or because of the high costs of stable isotopes (e. g. approximately 15 US$ per mg ^{57}Fe and 200 US$ per mg ^{58}Fe). Thus, isotope ratio measurements at the highest attainable precision are essential for this particular application of inorganic mass spectrometry.

At the time the study was designed, the novel NTIMS technique for iron was not yet available. Isotope doses for administration were therefore calculated according to the reproducibility of the isotopic analysis achievable at this time using the conventional positive thermal ionization (PTI) technique for iron [8]. By the NTIMS approach for iron, it was possible to improve the reproducibility of iron isotope ratio determinations significantly [13]. Thus, substantially lower isotope doses could have been administered within the present study. In Table 1, the recalculated isotope doses are compared for the different mass spectrometric techniques.

As can be seen from Table 1, a reduction of the isotope doses by a factor of 3 to 4 would have been possible by using the NTIMS approach for iron isotopic analysis. Because of the high isotopic enrichment of the used spikes and the low amounts of spikes finally present in the blood of the subjects, it was possible to normalize the collected data sets using the negligibly altered ^{54}Fe/^{56}Fe isotope ratio. Using internally normalized data sets and NTIMS for iron isotopic analysis, it would have been possible to further reduce the isotope doses and thus the costs for stable isotopes for the present study by a factor of 10.

Table 1 Calculated minimum isotope doses to obtain resolvable isotopic shifts (> 10 SD) in the blood of children (present study) according to the chosen mass-spectrometric method. PTIMS and NTIMS data refer to a magnetic sector field instrument and simultaneous ion beam detection [13]. ICPMS data refer to a quadrupole instrument [23]

Mass spectrometric method	Normalization	RSD [%]		Required dose [mg]	
		^{57}Fe/^{56}Fe	^{58}Fe/^{56}Fe	^{57}Fe	^{58}Fe
PTI-MS	No	0.1	0.2	7.0	2.6
	Yes	0.02	0.06	1.4	0.8
NTI-MS	No	0.03	0.06	2.1	0.8
	Yes	0.006	0.02	0.4	0.3
ICP-MS	–	0.2	0.6	14.0	9.8

Numerous applications published over the last years reflect the enormous potential of inductively coupled plasma mass spectrometry (ICPMS) as a tool for inorganic trace analysis. In addition to its use for element determinations, increasing attention is being paid by the analytical community to use ICPMS for isotope ratio determinations [18–22]. When directly compared with TIMS as a well-established technique for isotopic analysis, the ease of sample preparation is mostly the prominent advantage of ICPMS besides its multi-element capabilities and the speed of isotopic analysis. However, because the ionization method itself is element non-selective and molecular ions are formed in the plasma, isobaric interferences with the mass spectrum of the element of interest are common. This strongly limits the accuracy and the reproducibility of isotope ratio determinations attainable by ICPMS. A typical example is the case of iron. The predominant interferences with the iron mass spectrum are related to argon molecular ions formed in the argon-plasma ($^{54}Fe^+/^{40}Ar^{14}N^+$, $^{56}Fe^+/^{40}Ar^{16}O^+$, $^{57}Fe^+/^{40}Ar^{17}O^+$, $^{57}Fe^+/^{40}Ar^{16}OH^+$, $^{58}Fe^+/^{40}Ar^{18}O^+$). In addition, the interferences $^{54}Fe^+/^{37}Cl^{16}OH^+$, $^{54}Fe^+/^{54}Cr^+$ and $^{58}Fe^+/^{58}Ni^+$ have also to be considered. Nevertheless, a careful optimization of instrumental parameters to supress the formation of argon molecular ions, as well as highly standardized experimental conditions, allow iron isotope ratio determinations using ICPMS at a reproducibility sufficient to perform iron bioavailability studies with stable isotope labels. Based on the optimum reproducibilities published at the present time for iron isotopic analysis by ICPMS [23], the necessary isotope doses for the present study were recalculated. As shown in Table 1, the administration of approximately 35 times higher isotope doses would have been necessary within the present study, if ICPMS would have been chosen instead of NTIMS for isotopic analysis. Thus, the possible advantages of using ICPMS for isotopic analysis within iron bioavailability studies are counteracted at the present time by the substantially higher isotope doses required. These higher doses may be prohibitively expensive or outside the meaningful physiological range.

The introduction of high-resolution ICPMS (HR-ICPMS) has sharply reduced the omnipresent problem of isobaric interferences in ICPMS. Using a double-focusing sector field mass spectrometer instead of a quadrupole filter, isobaric interferences with the mass spectrum of the element of interest can be resolved [24]. Recent investigations have demonstrated that the precision of magnesium, lead and copper isotope ratio measurements can be significantly improved by using HR-ICPMS instead of quadrupole ICPMS [22, 25]. However, the use of a secondary electron multiplier for ion detection, as given for most commercially available ICPMS instruments, has limited the attainable precision of isotope ratio measurements due to

ion-counting statistics. In this respect, the use of a set of several Faraday cups for simultaneous ion detection in HR-ICPMS is a landmark approach to further narrow the gap in attainable precision between ICPMS and TIMS [26]. This will certainly open the possibility to fully use the advantages of ICPMS for high-precision isotope ratio measurements. Nevertheless, it is likely that TIMS will remain the most powerful tool for high-precision isotope ratio measurements in inorganic mass spectrometry, at least for those elements/applications where internal normalization techniques can be applied to correct for mass dependent isotopic fractionation effects in the ion source.

Appendix

The calculation of the amount of isotopic label present in the blood of the subject is based on the shift of the isotopic ratios in the blood after red cell incorporation of the absorbed isotopic label. When the circulating amount of isotopic label is known, the amount of label absorbed from the test meal and thus the fractional iron absorption can be calculated. Fomon et al. simplified this calculation by the assumption that the used isotopic label is monoisotopic [7]. However, a systematic error is introduced by this assumption because commercially available spikes enriched in ^{57}Fe or ^{58}Fe usually contain significant amounts of other iron isotopes up to several percent. For this reason, Kastenmayer et al. [8] modified the formula by Fomon et al. [7] to consider the amount of ^{57}Fe in the ^{58}Fe label and vice versa, provided that the contribution from one isotopic label is negligible. Within the presented study, the fractional iron absorption was calculated using a more generally applicable formula which considers both the non-monoisotopic character of the two isotopic labels and cross-over contributions. This calculation also considers the significant differences in the atomic weight of natural iron and the administered iron isotopic labels.

After red blood cell incorporation of the isotopic labels, the molar amount of iron of natural isotopic composition in the isotope diluted blood is n_{nat} while the molar amount of the ^{58}Fe isotopic label and the ^{57}Fe isotopic label are given by n_A and n_B, respectively. According to Eqns. (1–4), the molar amount of a certain iron isotope $n(^mFe)_{blood}$ in the blood (with m being the mass number of the respective iron isotope) is given by its natural isotopic abundance (a^m_{nat}), its isotopic abundance in the ^{57}Fe isotopic label (a^m_A) and by its isotopic abundance in the ^{58}Fe isotopic label (a^m_B).

$$n(^{54}Fe)_{blood} = a^{54}_{nat} \cdot n_{nat} + a^{54}_A \cdot n_A + a^{54}_B \cdot n_B \quad (1)$$

$$n(^{56}Fe)_{blood} = a^{56}_{nat} \cdot n_{nat} + a^{56}_A \cdot n_A + a^{56}_B \cdot n_B \quad (2)$$

$$n(^{57}Fe)_{blood} = a^{57}_{nat} \cdot n_{nat} + a^{57}_A \cdot n_A + a^{57}_B \cdot n_B \quad (3)$$

$$n(^{58}Fe)_{blood} = a^{58}_{nat} \cdot n_{nat} + a^{58}_A \cdot n_A + a^{58}_B \cdot n_B \quad (4)$$

The isotope ratio $R_{57/56} = n(^{57}Fe)_{blood}/n(^{56}Fe)_{blood}$ in the isotope diluted blood sample of the subject can be expressed using Eqns. (2) and (3).

$$R_{57/56} = \frac{a^{57}_{nat} \cdot n_{nat} + a^{57}_A \cdot n_A + a^{57}_B \cdot n_B}{a^{56}_{nat} \cdot n_{nat} + a^{56}_A \cdot n_A + a^{56}_B \cdot n_B} \quad (5)$$

Likewise, Eqns. (2) and (4) can be used to express the isotope ratio $R_{58/56} = n(^{58}Fe)_{blood}/n(^{56}Fe)_{blood}$ in the blood sample.

$$R_{58/56} = \frac{a^{58}_{nat} \cdot n_{nat} + a^{58}_A \cdot n_A + a^{58}_B \cdot n_B}{a^{56}_{nat} \cdot n_{nat} + a^{56}_A \cdot n_A + a^{56}_B \cdot n_B} \quad (6)$$

Eqns. (5) and (6), respectively, can be transformed to yield the molar amount of ^{57}Fe isotopic label in the blood:

$$n_A = n_{nat} \cdot \frac{a^{57}_{nat} - a^{56}_{nat} \cdot R_{57/56}}{a^{56}_{nat} \cdot R_{57/56} - a^{57}_A} + n_B \cdot \frac{a^{57}_B - a^{56}_B \cdot R_{57/56}}{a^{56}_A \cdot R_{57/56} - a^{57}_A} \quad (7)$$

$$n_A = n_{nat} \cdot \frac{a^{58}_{nat} - a^{56}_{nat} \cdot R_{58/56}}{a^{56}_A \cdot R_{58/56} - a^{58}_A} + n_B \cdot \frac{a^{58}_B - a^{56}_B \cdot R_{58/56}}{a^{56}_A \cdot R_{58/56} - a^{58}_A} \quad (8)$$

By equating Eqn. (7) and (8), the molar amount of ^{58}Fe isotopic label in the blood can be obtained by transformation.

$$n_B = n_{nat} \cdot \frac{\alpha - \beta}{\gamma - \delta} \quad (9)$$

In Eqn. (9), the variables α, β, γ and δ are defined by the following equations:

$$\alpha = \frac{a^{58}_{nat} - a^{56}_{nat} \cdot R_{58/56}}{a^{56}_A \cdot R_{58/56} - a^{58}_A} \quad (10)$$

$$\beta = \frac{a^{57}_{nat} - a^{56}_{nat} \cdot R_{57/56}}{a^{56}_A \cdot R_{57/56} - a^{57}_A} \quad (11)$$

$$\gamma = \frac{a^{57}_B - a^{56}_B \cdot R_{57/56}}{a^{56}_A \cdot R_{57/56} - a^{57}_A} \quad (12)$$

$$\delta = \frac{a^{58}_B - a^{56}_B \cdot R_{58/56}}{a^{56}_A \cdot R_{58/56} - a^{58}_A} \quad (13)$$

According to Eqn. (9) the molar amount of the ^{58}Fe isotopic label in the blood can be calculated by the isotope ratios $R_{57/56}$ and $R_{58/56}$ in the blood sample. The circulating molar amount of ^{57}Fe isotopic label can be obtained by Eqn. (7) or (8) using the molar amounts of ^{58}Fe isotopic label as calculated. However, for both calculations the molar amount of iron of natural isotopic composition in the blood of the subject has to be known.

The molar amount of natural iron circulating in the subject can be derived from the blood volume *(BV)* and the hemoglobin concentration *(Hb)* in the blood. The latter is only experimentally accessible, while the blood volume of the subject can be determined both experimentally, e. g. by the injection of dyed red blood cells [15], or by applying an appropriate, empirically derived formula. Within this study, the blood volume of male children was estimated according to Eqn. (14) and of female children according to Eqn. (15) with W being the weight and H the height of the individual child [16]:

$$\log BV = 0.6459 \cdot \log W + 0.002743 \cdot H + 2.0324 \quad (14)$$

$$\log BV = 0.6412 \cdot \log W + 0.001270 \cdot H + 2.2169 \quad (15)$$

When the hemoglobin concentration in the blood and the blood volume of the subject is known, the molar amount of iron of natural isotopic composition circulating in the body can be calculated. In the following equation, $F_{Fe/Hb}$ represents the iron concentration in hemoglobin which is 0.00347 g Fe/g hemoglobin. Because of the low isotopic enrichment of the iron in the isotope diluted blood, the atomic weight of the iron of natural isotopic composition $A_r(Fe_{nat})$ can be employed to obtain a molar quantity.

$$n_{nat} = \frac{BV \cdot Hb \cdot F_{Fe/Hb}}{A_r(Fe_{nat})} \quad (16)$$

In the human body, not all absorbed iron is incorporated into red blood cells. In children, as an example, it can be assumed that only 90% of the absorbed iron is finally present in the red blood cells [17]. To consider this, an incorporation factor F_{inc} of 0.90 was used within this study to obtain the total amount of absorbed isotopic label. With $A_r(Fe_A)$ and $A_r(Fe_B)$ being the atomic weights of the isotopic labels, the total masses of the isotopic labels m_A and m_B the body can be derived. The fractional absorption (A_f) of the administered iron isotopic labels can be calculated as the total mass of the isotopic labels m_A and m_B absorbed by the body relative to the mass of the respective isotopic label administered:

$$m_A = \frac{n_A \cdot A_r(Fe_A)}{F_{inc}} \quad (17)$$

$$m_B = \frac{n_B \cdot A_r(Fe_B)}{F_{inc}} \quad (18)$$

Within iron bioavailability studies using stable isotopes, the accuracy of the calculated fractional iron absorption values is strongly limited by the accuracy at which the amount of circulating body iron of natural isotopic composition is determined. Furthermore, inaccuracies in the factor used to consider an incomplete red blood cell incorporation of the isotopic labels also result in a systematic error of the fractional absorption value. However, these inaccuracies cancel out for the individual subject when the two differently labelled test meals are administered on consecutive days and the fractional iron absorption from both test meals is evaluated relative to each other.

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Trace analysis of glasses by magnetically enhanced rf GDMS

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Abstract A radiofrequency (rf) glow discharge ion source coupled to a commercial double-focusing mass spectrometer was used for the direct trace element analysis of glass samples. By utilizing an additional ring-shaped magnet located behind the flat sample in an rf glow discharge ion source compared with a configuration without a magnet, the sputtering and ionization efficiency of glass samples was enhanced and the detection power for trace elements was improved. The detection limits for elements determined by rf glow discharge mass spectrometry at low mass resolution ($m/\Delta m = 300$) are 10–100 ng/g. Possible interferences of atomic ions of analyte and molecular ions which limited the determination of some elements (e.g. Ti, Mn, Fe, Ni, Co, Cu, Zn) could be resolved at the mass resolution of $m/\Delta m = 3000$. The detection limits for these elements were found to be about 100 ng/g. Relative sensitivity factors (RSFs) for all elements of interest with respect to Sr (internal standard element) were determined in the range of 0.2–3.

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Introduction

The application of non-conducting materials – such as ceramics and glasses – in modern technology requires the development of analytical techniques for determining trace elements at the µg/g and sub-µg/g concentration range. Rf glow discharge