Meal effect on magnesium bioavailability from mineral water in healthy women

Magalie Sabatier, Maurice J Arnaud, Peter Kastenmayer, Andreas Rytz, and Denis V Barclay

ABSTRACT
Background: Magnesium intakes in many industrialized countries are below recommended daily allowances. Magnesium-rich mineral water may contribute to coverage of magnesium requirements by providing significant amounts of natural, energy-free, bioavailable magnesium.

Objective: The objectives were to determine magnesium bioavailability from magnesium-rich (110 mg/L) mineral water in healthy subjects when consumed alone and to evaluate the effect of simultaneous meal consumption.

Design: Magnesium bioavailability was measured in 10 healthy women with the use of a crossover design. Stable magnesium isotopes (28Mg and 26Mg) were administered orally with mineral water, which was consumed with or without a meal. Apparent magnesium absorption was determined by fecal monitoring, and magnesium retention was determined from urinary excretion of magnesium isotopes.

Results: The mean (±SD) magnesium absorption from mineral water consumed alone was 45.7 ± 4.6% (range: 40.2–55.5%) and was significantly greater (P = 0.0001) when it was consumed with a meal (52.3 ± 3.9%; 46.2–60.2%), a relative difference of 14.4%. Magnesium retention also was significantly greater (P = 0.0004) when mineral water was consumed with a meal (41.5 ± 4.2%; 35.2–50.6%) than when consumed alone (37.4 ± 4.0%; 31.3–47.0%), a relative difference of 11.0%.

Conclusions: In healthy young women, 50% of the magnesium from magnesium-rich mineral water was absorbed when consumed alone. Magnesium bioavailability from mineral water is enhanced when the water is consumed with a meal, perhaps because of a slower gastrointestinal transit time, the presence of digestion products from the meal, or both. Regular consumption of magnesium-rich mineral water could make a valuable contribution to magnesium requirements.

INTRODUCTION
Magnesium is an essential mineral for humans and plays key roles in many biological processes through its function in enzyme activities. All enzymes utilizing ATP need magnesium for substrate formation. It has been suggested that aging, stress, and various disease states may increase magnesium requirements. Inadequate intake and impaired absorption of magnesium are thought to contribute to various pathologies in humans, including osteoporosis, hypertension, and atherosclerotic vascular disease.

Dietary reference intakes (DRIs) of magnesium in the United States are 400–420 and 310–320 mg for men and women aged 19–30 and >31 y, respectively. The strong relation between intakes of energy and magnesium and the change in lifestyle since the middle of the 20th century have led to a decrease in dietary magnesium intake. It has been suggested that magnesium intakes are below dietary recommendations in industrialized countries because of increased consumption of processed foods. Magnesium intakes were assessed over 1 y in 5448 French subjects participating in the Supplement in Vitamins and Minerals Antioxidants (SU.VI.MAX) study. In that study, 77% of women and 72% of men had dietary magnesium intakes that were lower than the French recommended dietary allowances of 380 mg for men and 350 mg for women. Furthermore, 23% of women and 18% of men consumed less than two-thirds of these recommended dietary allowances.

Magnesium-rich mineral waters may provide significant amounts of energy-free magnesium. The mineral water chosen for the present study has the highest magnesium content (110 mg/L) of all mineral waters sold in France. The bioavailability of magnesium from mineral water was previously evaluated in rats with the use of 28Mg and classic balance techniques. With the use of 26Mg, magnesium absorption from mineral water containing 202 mg Mg/L calculated from fecal excretion ranged from 40% to 50% of the dose ingested. The balance study used a diet deficient in magnesium and the mean magnesium absorption value of 55% represented that from water and the diet. In contrast with calcium, for which several studies in humans showed high bioavailability from mineral waters, magnesium bioavailability has not been studied. Although it has been suggested that

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4 From the Perrier Vittel Water Institute, Vittel, France, and the Nestlé Research Center, Lausanne, Switzerland.
magnesium from water may be more available than that from food (9), experimental data supporting this view are limited (10). Thus, the 2 objectives of the present study were to evaluate magnesium absorption and retention from magnesium-rich mineral water and to show whether the simultaneous consumption of a meal with the mineral water has an effect on magnesium bioavailability.

SUBJECTS AND METHODS

Subjects

Ten healthy white women aged 25–45 y were recruited from the staff of the Nestlé Research Center in Lausanne, Switzerland. Volunteers were declared healthy after they completed a medical questionnaire and were examined by a physician. The subjects used no oral contraceptives and the magnesium bioavailability test was carried out while the subjects were not menstruating. No medication or vitamin-mineral supplements were allowed during the study. All but one subject were nonsmokers. Subjects were fully informed of the aims and methods of the study and gave their written, informed consent. The study protocol was approved by the Ethical Committee of the Nestlé Research Center.

Study design

As shown in Figures 1 and 2, a crossover design was used in which 2 groups of 5 subjects were matched for age and body mass index. One group began by consuming mineral water alone (group A) without a meal (test drink), whereas the other group began by consuming mineral water together (group T) with a meal (test meal). Thus, each subject in group A received alternately for 4 d the test drink on day 1, the test meal on day 2, the test drink on day 3, and the test drink on day 4. During a 15-d adaptation period before isotope administration began, subjects consumed 1 L magnesium-rich mineral water/d (Hépar; Perrier Vittel, France), corresponding to an additional daily intake of 110 mg Mg. The mineral composition of this water is shown in Table 1. Three days before isotope administration, subjects began consuming a standardized diet, which was maintained until the end of isotope administration. With the use of the French food composition table (11), it was calculated that this diet provided ≈8360 KJ (2000 kcal)/d, 16% of which was from protein, 34% from fat, and 50% from carbohydrate. The test meal was a breakfast consisting of 56 g toast, 10 g butter, and 30 g jam.

Magnesium absorption from mineral water was determined with the use of a fecal monitoring stable-isotope technique. Fasting subjects drank 500 mL magnesium-rich mineral water labeled either with 15 mg Mg as 25MgSO4 when consumed alone or with 26MgSO4 when consumed with a meal. Over the 4 d of alternate administration, subjects thus received a total of 30 mg of each stable isotope of magnesium. The mineral water was labeled with the stable isotope 30 min before administration, which began between 0730 and 0800. After consumption of the labeled mineral water alone, subjects received the standardized breakfast at 1045. After consumption of the labeled mineral water with the standardized breakfast, subjects consumed no other foods and beverages until lunch at 1300. Subjects consumed the standardized meals at the Nestlé Research Center, except for dinner, which was taken home for consumption. During the 4-d period, subjects had free access to another mineral water (Valvert; Perrier Belgium, Etalle, Belgium) that contained only 2 mg Mg/L.

Sample collection

A dysprosium fecal marker (2 mg DyCl3) was administered along with the stable isotopes to check the completeness of the...
fecal collections. On day 4, subjects also received 100 mg brilliant blue to determine the endpoint of the fecal collection. Venous blood samples were taken at the time of recruitment and on the day before isotope administration began (day −1) for determination of serum total magnesium and free magnesium (Mg$^{2+}$) concentrations. Before the study, subjects provided urine and fecal samples as references for the isotopic determinations. Starting from the time of the first isotope administration, complete urine and fecal samples were collected. Complete 24-h urine samples were collected and volumes were recorded for 10 d after isotope administration. Feces were collected individually for the same period of time. All samples were frozen at −20°C until analyzed.

### Stable-isotope labels

Stable magnesium isotopes were purchased from Chemgas (Boulogne, France). The 2 stable isotopes $^{25}$Mg and $^{26}$Mg were prepared from enriched $^{24}$MgO (97.9%) and $^{25}$MgO (98.8%); 411 mg $^{25}$Mg or 416 mg $^{26}$Mg was dissolved in a mixture of 10 L H$_2$O/L concentrated H$_2$SO$_4$ and diluted with ultrapure water to a concentration of 6 g Mg/L. The solutions were filtered through a 0.45-μm filter (MilllexHV4; Millipore AG, Zürich, Switzerland) and the pH was adjusted to 6.0 by adding sodium hydroxide. The isotopic composition of the labels was verified with the use of a thermal ionization quadrupole mass spectrometer (model THQ; Finnigan Mat, Bremen, Germany) equipped with a secondary electron multiplier, a 13-sample turret, and a reference pyrometer. Between the time of the first isotope administration, complete urine and fecal samples were collected. Complete 24-h urine samples were collected and volumes were recorded for 10 d after isotope administration. Feces were collected individually for the same period of time. All samples were frozen at −20°C until analyzed.

### Sample preparation and analyses

#### Serum

After being collected, blood was left at room temperature for 1 h to coagulate and was then centrifuged for 15 min at 1800 × g at 4°C. The serum obtained was divided into 2 aliquots and the Mg$^{2+}$ concentration was immediately analyzed in 100-μL samples with an ion selective electrode (Mercury 8 Analyzer; Nova Biomedical, Les Ulis, France). This analyzer was calibrated with standard solutions containing 1.39, 0.59, and 0.3 mmol Mg$^{2+}$/L as described by the manufacturer. Between-run precision was assessed by analyzing a 3-level control material (Nova Biomedical) daily (12). Results were adjusted to a pH of 7.40 with the use of a built-in computer and an appropriate algorithm. Total magnesium concentrations were measured in duplicate by flame atomic absorption spectrophotometry (SpectrAA 400; Varian, Mulgrave, Australia) under the operating conditions recommended by the manufacturer. Serum was diluted in 0.5% LaCl$_3$ (1:100, by vol). The instrument was calibrated with the use of magnesium standards of 0.1, 0.2, and 0.4 mg/L. Human reference serum (Seronorm; Nycomed Pharma, Oslo) was analyzed with the samples for quality control.

#### Diet, feces, and urine

Duplicates of all food items included in each menu were weighed, homogenized with weighed amounts of ultrapure water, and freeze-dried. Fecal samples from each subject were divided into 2–3 pools, depending on the amount of feces weighed. The fecal samples were then autoclaved and homogenized and the aliquots were freeze-dried. Twenty-four–hour urine samples were collected and weighed and the specific gravity was measured. Aliquots were then kept frozen at −20°C until analyzed.

Duplicate freeze-dried samples (=500 mg) were ashed in silica Erlenmeyer flasks in a muffle furnace at 520°C for 48 h. Ash was dissolved in 4 mL concentrated HCl and was diluted to 25 mL with ultrapure water. The total magnesium concentration was measured in urine and in ashed food and fecal samples by atomic absorption spectrophotometry as described above. The dry weight of food and fecal samples was measured after the samples were dried at 105°C for 24 h. The accuracy of analysis was controlled for by analyzing the standard reference materials (SRMs) of the National Institute of Standards and Technology (Gaithersburg, MD): SRM 1548 (total diet), SRM 1577b (bovine liver), and a pooled human fecal sample as laboratory standard. The CVs for the analysis of magnesium for the pooled fecal sample were 2.7% ($n = 10$) and 6.0% for SRM 1548 ($n = 5$).

The amounts of dysprosium excreted in feces and of the $^{25}$Mg and $^{26}$Mg labels excreted in feces and urine were determined by inductively coupled plasma mass spectrometry (ICP-MS) with an Elan 6000 equipped with a GemTipTM cross-flow nebulizer and a Scott-type double-pass spray chamber (Perkin-Elmer Europe, Mulgrave, Australia) under the operating conditions recommended by the manufacturer. Excellent agreement was found between isotope abundances given in the suppliers certificate for the $^{25}$Mg ($^{24}$Mg: 1.83%; $^{25}$Mg: 97.86%; $^{26}$Mg: 0.31%) and $^{26}$Mg ($^{24}$Mg: 0.84%; $^{25}$Mg: 0.37%; $^{26}$Mg: 98.79%) and the mean (±SD) values ($n = 4$) measured by thermal ionization quadrupole mass spectrometry for $^{25}$Mg ($^{24}$Mg: 1.83 ± 0.01%; $^{25}$Mg: 97.90 ± 0.01%; $^{26}$Mg: 0.265 ± 0.001%) and $^{26}$Mg ($^{24}$Mg: 0.847 ± 0.006%; $^{25}$Mg: 0.371 ± 0.001%; $^{26}$Mg: 98.783 ± 0.007%).
Rotkreuz, Switzerland). Ashed fecal samples were evaporated to dryness under nitrogen and redissolved to give concentrations of dysprosium ranging from 10 to 30 μg/L in 0.5 mol HNO₃/L. Rhodium, at a concentration of 20 μg/L, served as the internal standard. The ICP-MS settings used for dysprosium analysis were as follows: RF power, 1000 W; nebulizer argon flow rate, 0.83 L/min; sample uptake rate, 1.2 mL/min; selected isotope, ¹⁶³Dy; detector mode, pulse counting; scanning mode, peak hopping; dwell time, 20 ms; sweeps, 50; and replicates, 5 per integration. Within-run precision for dysprosium analysis was <1% for all of these variables between groups (Student’s t test).

### Stable magnesium isotopes

Aliquots of digested fecal samples were evaporated to dryness under nitrogen and redissolved in 0.5 mol HNO₃/L to give a concentration of 100 μg Mg/L. Urine samples were diluted to the same concentration with the use of 0.5 mol HNO₃/L. The instrument settings used for magnesium isotope ratio analysis by ICP-MS were as follows: dwell time of 24Mg, 50 ms; dwell time of ²⁵Mg and ²⁶Mg, 100 ms; sweeps, 100; and replicates, 5 per integration. Instrumental bias was corrected for by measuring the magnesium isotope ratios in a standard solution (100 μg Mg/L; Merck) with natural isotopic composition. The ratio correction factor was calculated from the error in 10 samples. Within-run precision (5 replicates) was 0.5–1.2% for ²⁵Mg:²⁴Mg and ²⁶Mg:²⁴Mg. After correction for instrumental bias, isotope ratios for unenriched urine and fecal samples were within 0.8% of the accepted International Union of Pure and Applied Chemistry values (13). Accuracy was also verified by adding known amounts of highly enriched ²⁵Mg or ²⁶Mg to basal urine and fecal sample. Repeatability, determined by measuring baseline samples several times over 4 h on the same day, was <0.5% for both isotope ratios in feces and urine (n = 30). The detection limits of ²⁵Mg and ²⁶Mg enrichments in urine and feces were determined from the same measurements by using the definition that the detection limit for measuring a change in an isotope ratio is 3 times the SD of the baseline value (14). The detection limits of ²⁵Mg and ²⁶Mg enrichments in the present study were 1.3% and 1.5% in urine and 0.7% and 1.9% in feces, respectively.

All acids were purified by subboiling distillation. Other chemicals were of analytic grade purity. All flasks used for sample collection and manipulation were acid washed in 1 mol HNO₃/L for 24 h and then rinsed in ultrapure water. Only ultrapure water (18 MΩ; Millipore AG, Zurich, Switzerland) was used.

### Calculations

The amounts of ²⁵Mg and ²⁶Mg excreted in urine and feces were calculated by using the total magnesium content and magnesium isotope ratios in feces and urine samples, similar to the method used by Walczyk et al (15) for iron. The calculations are given in detail in Appendix A. Apparent absorption was then calculated according to the following equation:

\[
\text{Apparent magnesium absorption} = \frac{[(\text{dose} - M_\text{s})/\text{dose}] \times 100}{(1)}
\]

where the dose is the amount of enriched ²⁵Mg or ²⁶Mg administered orally and M_s is the amount of enriched ²⁵Mg or ²⁶Mg excreted in feces. The retention of ²⁵Mg and ²⁶Mg was calculated by subtracting the total amounts of ²⁵Mg and ²⁶Mg excreted in urine and feces over 10 d from the administered dose.

### Statistics

In general, crossover designs can induce 2 types of bias as a result of sequence and period effects, which can be analyzed with the use of classic analysis of variance techniques (16). The sequence and period effect appeared to be insignificant; therefore, magnesium absorption and retention from the mineral water consumed alone or with a meal were compared by using Student’s paired t tests. P values <0.05 were considered to indicate significant differences.

### RESULTS

Subject characteristics and serum magnesium concentrations at screening and on day −1 are shown in Table 2. The mean (±SD) body mass indexes (kg/m²) of groups A and T were 21.0 ± 1.9 and 21.2 ± 2.3, respectively; the group’s mean ages were 32.8 ± 7.7 and 31.8 ± 7.3 y, respectively. Mean serum total magnesium concentrations for all subjects at screening and on day −1 were 0.859 ± 0.050 and 0.855 ± 0.049 mmol/L, respectively. Corresponding serum Mg²⁵ concentrations were 0.535 ± 0.063 and 0.489 ± 0.061 mmol/L. There were no significant differences in any of these variables between groups A and T. Individual total magnesium and Mg²⁵ concentrations in serum were in the normal range for all but one subject, who, despite having a normal total magnesium concentration, had a low Mg²⁵ concentration.

The total daily dietary intake of magnesium during the test period, including that from mineral water and the stable isotope labels, was 329 ± 54 mg, as determined by atomic absorption spectrometry of duplicate samples of the foods consumed. The total magnesium content of the breakfast consumed with a meal was 17.0 ± 0.3 mg.

Analysis of dysprosium in feces indicated excellent subject compliance with stool collection. The mean dysprosium recovery was 102 ± 3%, with individual values ranging from 97% to 105% of the administered dose.

The absorption and retention of magnesium from mineral water consumed with and without a meal are reported in Table 3. There was no significant difference between groups A and T resulting from the crossover design; ie, the order of administration of the test drink and test meal had no significant influence on magnesium absorption and retention. For all subjects, magnesium absorption

### Table 2

<table>
<thead>
<tr>
<th>Group A</th>
<th>Group T</th>
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<tr>
<td>n = 5</td>
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<tr>
<td><strong>BMI (kg/m²)</strong></td>
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<td>0.836 ± 0.042</td>
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<td>0.554 ± 0.034</td>
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<td>0.470 ± 0.079</td>
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</table>

All values are mean (±SD). There were no significant differences between groups (Student’s t test).

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from water consumed with the test meal was higher than from water alone (range of absolute differences: 1.6–10.6%), resulting in a significant increase of 6.6 ± 3.2% (P = 0.0001) with the meal, or a relative increase of 14.4%. There was also a small but significant increase in the urinary excretion of labeled magnesium, from 18.2% to 20.6% of the absorbed dose (P = 0.019), when water was coingested with the meal. The absolute increase in magnesium retention when the mineral water was consumed with a meal was 4.1 ± 2.7% (P = 0.0004), which represents a relative increase of 11.0%. No correlations were observed between serum total magnesium or Mg^{2+} and magnesium absorption or retention.

**DISCUSSION**

This is the first study reporting on the bioavailability of magnesium from mineral water in humans and the effect of a light meal consumed with water on the absorption and retention of magnesium from water. Magnesium absorption is dose dependent and may also vary as a function of the composition of the diet, which may contain either enhancers or inhibitors of absorption (4, 17, 18). Magnesium retention depends not only on absorption but also on homeostatic mechanisms at the level of the kidney and on individual magnesium status. The most accurate methods for assessing magnesium status are magnesium loading tests and analyses of magnesium in muscle biopsies. These methods are invasive and not readily usable by most clinicians; as a consequence, the measurement of serum magnesium concentrations is the most widely available and commonly applied test of magnesium status (19). In the present study, the serum total magnesium concentration was measured. Furthermore, the serum Mg^{2+} concentration, which has been suggested to be a better indicator of magnesium status, was also measured. Although Mg^{2+} is considered as the physiologically active and homeostatically regulated fraction, some studies report that concentrations can change rapidly, and that low concentrations may not necessarily represent magnesium deficiency (20). For all subjects, serum total magnesium and Mg^{2+} concentrations were in the normal range, except for the Mg^{2+} concentration in one subject who was a heavy smoker (>20 cigarettes/d). It was previously shown that serum Mg^{2+} concentrations in smokers are below the normal range (21). However, it was also shown that the effect of smoking on serum Mg^{2+} concentrations may be method dependent, and that smoking may induce a factor in serum that negatively interferes with the response of the magnesium ion selective electrode used (22). The one subject in our study with low serum Mg^{2+} concentrations had values for serum total magnesium, magnesium absorption, and magnesium retention within the ranges obtained for the other subjects. To our knowledge, no studies have been reported in the literature on the effect of smoking on magnesium absorption and retention. Consequently, we decided to include the results of this subject.

The fractional absorption of ingested magnesium by healthy individuals is influenced by the amount of magnesium in the diet and, to a variable extent, by the presence of inhibiting and enhancing dietary components (23). There are limited data on magnesium absorption from different diets in humans. The most frequently used methods for measuring magnesium absorption include the chemical balance technique and, as in the present study, stable-isotope techniques that incorporate fecal monitoring. Mean apparent magnesium absorption from the water consumed alone by the women in our study was 45.7%. The average daily magnesium intake was 329 ± 54 mg, which is close to the recently revised US DRI of 320 mg (3). Comparable values have been published for magnesium absorption from different diets at similar magnesium intakes. In a balance study in healthy young men, apparent magnesium absorption from a mixed Western diet containing 18 g fiber/d was 46.3% (24). Knudsen et al (25) evaluated apparent magnesium absorption from a fiber-rich diet in a group of healthy young men and women with the use of fecal monitoring with a ^26Mg tracer. They found a mean magnesium absorption of 46%. In another study, magnesium absorption from milk was measured in 9–14-y-old adolescents with the use of a multitracer stable-isotope technique. Magnesium absorption from milk was 42.8% in girls and 45.3% in boys and was not significantly different between sexes (26). Magnesium absorption from mineral water in our study was therefore in the same range as values established for magnesium absorption from food. This indicates that the major anion in the mineral water (ie, sulfate) had no inhibitory effect on magnesium absorption.

When mineral water was coingested with a light breakfast, magnesium absorption and retention were significantly greater than after consumption of mineral water alone, despite a slightly greater total magnesium intake from the breakfast test meal (70 compared with 87 mg). To our knowledge, no other published studies address this subject. This increase in magnesium absorption and retention may be explained either by a direct interaction at the level of the gastrointestinal tract or by the presence of food constituents. The study was not designed to distinguish between these 2 factors or to establish the exact mechanism of the meal effect. However, several explanations are possible. Meals are known to stimulate gastric acid secretion and to slow down stomach emptying. A 10–30% increase in calcium absorption from milk and orange juice when the liquids were consumed with a breakfast meal was previously reported (27). The authors attributed the enhancing effect mainly to slower stomach emptying because calcium in milk and orange juice already has good solubility, which is not likely to be greatly influenced by the additional gastric acid produced by the meal. Similarly, in the present study, magnesium was already solubilized in water; therefore, acid secretion should not have played an important role in enhancing magnesium absorption. Another possible explanation for the observed effect could be the slower transit time due to the meal, leading to an increased exposure of magnesium to the mucosal cells of the intestine.

The composition of the meal may also provide an explanation for the enhancement of magnesium absorption. The breakfast fed in our study contained ~62% carbohydrate. It was previously shown that some carbohydrates (eg, lactose, fructose, and glucose

<table>
<thead>
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<th>Table 3: Magnesium absorption and retention from the mineral water consumed with and without a meal</th>
<th>Value</th>
<th>%</th>
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<tbody>
<tr>
<td>Magnesium absorption</td>
<td>Without a meal</td>
<td>45.7 ± 4.6 (40.2–55.5)</td>
</tr>
<tr>
<td></td>
<td>With a meal</td>
<td>52.3 ± 3.9 (46.2–60.2)</td>
</tr>
<tr>
<td>Magnesium retention</td>
<td>Without a meal</td>
<td>37.4 ± 4.0 (33.1–47.0)</td>
</tr>
<tr>
<td></td>
<td>With a meal</td>
<td>41.5 ± 4.2 (35.2–50.6)</td>
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</table>

\(^1\) ± SD; range in parentheses. The mineral water was Hépar (Perrier Vittel, Vittel, France).

\(^2\) Significantly different from without a meal, P < 0.05 (Student’s t test).
polymers) can increase magnesium absorption in humans (28–30). The mechanism by which the effect occurs is unknown. Although magnesium absorption occurs by different mechanisms, it has been suggested that diffusion and solvent drag are most important at normal magnesium intakes (31), such as those in the present study. In a concentration-dependent manner, glucose may modulate tight junction permeability and thus increase solute absorption by enhancement of the solvent drag mechanism (32).

The increase in the consumption of processed foods during the 20th century has led to a decrease in the average daily intake of magnesium from 410 to <300 mg, and significant proportions of populations have intakes below recommended amounts and may be at risk of chronic, latent magnesium deficiency (19, 33). In France, 72% of men and 76% of women in the SU.VI.MAX study cohort had magnesium intakes lower than the French recommended dietary allowances (5). Widespread inadequate magnesium intakes may represent potential health risks. For example, studies in several countries showed inverse correlations between magnesium concentrations in drinking water and the prevalence of cardiovascular mortality (33). Regular consumption of magnesium-rich mineral waters such as those used in the present study could make a significant contribution to the coverage of magnesium requirements. One liter of this mineral water consumed daily would provide 110 mg Mg, equivalent to 31% and 26% of the new US DRI for women and men, respectively.

The results of the present study, which used a stable-isotope technique to determine magnesium bioavailability, showed that magnesium from a magnesium-rich mineral water was highly bioavailable. Magnesium absorption and retention were further enhanced when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed enhanced when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed improved when the mineral water was consumed with a light meal; therefore, it is recommended that mineral water be consumed.

We are very grateful to A Berthelot (University of Besançon, France) for advice on the design of the study, to F Dubois (University of Nancy, France) for the analysis of ionized magnesium, to the staff of the Nestlé Research Center (J Barholdi (a nurse at the metabolic unit) for help with subject screening and blood sampling, B Decarli for the analysis of meal composition and help in menu planning, PA Jaquier (head cook at the restaurant) for help in menu planning and to his staff for meal preparation, and to C Mettraux for assistance with the study design) and to the subjects for making this study possible.

REFERENCES

APPENDIX A

Calculation of the amount of $^{25}$Mg and $^{26}$Mg excreted in feces and urine

After administration of the isotopic labels, the molar amount of the natural isotopic composition of magnesium in the excreted sample (feces or urine) is $n_{\text{nat}}$, whereas the molar amount of the $^{25}$Mg and $^{26}$Mg isotopic labels are given by $n_{25T}$ and $n_{26T}$. On the basis of Equations A1–A3, the molar amount of a certain magnesium isotope $n$ ($^{n}\text{Mg}_{\text{sample}}$) in the sample (with $m$ being the mass number of the respective magnesium isotope) is given by its natural isotopic abundance $a_{n}\text{nat}$, its isotopic abundance in the $^{25}$Mg isotopic label $a_{n}^{25T}$, and by its isotopic abundance in the $^{26}$Mg isotopic label $a_{n}^{26T}$.

\[ n^{(24)}\text{Mg}_{\text{sample}} = a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T} \]  
\[ (A1) \]

\[ n^{(25)}\text{Mg}_{\text{sample}} = a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T} \]  
\[ (A2) \]

\[ n^{(26)}\text{Mg}_{\text{sample}} = a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T} \]  
\[ (A3) \]

The total amount of magnesium is calculated as follows:

\[ n_{\text{total}} = n_{\text{nat}} + n_{25T} + n_{26T} \]  
\[ (A4) \]

The isotope ratio $R_{25:24}$ in the isotope-diluted sample can be expressed by using Equations A1 and A2.

\[ R_{25:24} = \frac{n^{(25)}\text{Mg}_{\text{sample}}}{n^{(24)}\text{Mg}_{\text{sample}}} = \frac{a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T}}{a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{24T} \times n_{24T} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T}} \]  
\[ (A5) \]

Likewise, Equations A3 and A1 can be used to express the isotope ratio $R_{26:24}$ in the sample.

\[ R_{26:24} = \frac{n^{(26)}\text{Mg}_{\text{sample}}}{n^{(24)}\text{Mg}_{\text{sample}}} = \frac{a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T}}{a_{n}\text{nat} \times n_{\text{nat}} + a_{n}^{24T} \times n_{24T} + a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T}} \]  
\[ (A6) \]

Equations A5 and A6, respectively, can be transformed to yield the molar amount of $^{25}$Mg in the blood.

\[ n_{25T} = n_{\text{nat}} \times \frac{a_{n}^{25T} \times n_{25T} + a_{n}^{26T} \times n_{26T} - R_{25:24} \times a_{n}^{24T} \times n_{24T} - a_{n}^{25T} \times n_{25T}}{R_{25:24} \times a_{n}^{24T} \times n_{24T} - a_{n}^{25T} \times n_{25T}} \]  
\[ = \beta \]  
\[ (A7) \]

\[ n_{25T} = n_{\text{nat}} \times \frac{a_{n}^{26T} \times n_{26T} + a_{n}^{25T} \times n_{25T} - R_{26:24} \times a_{n}^{24T} \times n_{24T} - a_{n}^{26T} \times n_{26T}}{R_{26:24} \times a_{n}^{24T} \times n_{24T} - a_{n}^{26T} \times n_{26T}} \]  
\[ = \alpha \]  
\[ (A8) \]

Equations A7 and A8 can be written as

\[ n_{25T} = n_{\text{nat}} \times \beta + n_{26T} \times \gamma \]  
\[ (A9) \]

With the use of a modified Equation A4, in which $n_{\text{nat}}$ is replaced by $n_{\text{tot}}$ in Equations A9 and A10

\[ n_{\text{tot}} = n_{\text{tot}} - n_{25T} - n_{26T} \]  
\[ (A11) \]

we obtain

\[ n_{25T} = n_{\text{tot}} \times \frac{\beta}{1 + \beta} + n_{26T} \times \gamma - \beta \]  
\[ (A12) \]

\[ n_{25T} = n_{\text{tot}} \times \frac{\alpha}{1 + \alpha} + n_{26T} \times \gamma - \alpha \]  
\[ (A13) \]

With the use of Equations A12 and A13, we obtain

\[ n_{26T} \left( \frac{\gamma - \beta - \delta - \alpha}{1 + \gamma - \delta - \alpha} \right) = n_{\text{tot}} \left( \frac{\alpha}{1 + \alpha} - \frac{\beta}{1 + \beta} \right) \]  
\[ (A14) \]

and

\[ n_{26T} = n_{\text{tot}} \times \frac{\alpha}{1 + \alpha} + n_{26T} \times \gamma - \delta - \alpha \]  
\[ (A15) \]

In Equation A15, the variables $\alpha$, $\beta$, $\gamma$, and $\delta$ are defined by the following equations:

\[ \alpha = \frac{a_{n}^{26T} - R_{26:24} \times a_{n}^{24T}}{R_{26:24} \times a_{n}^{24T} - a_{n}^{26T}} \]  
\[ (A16) \]

\[ \beta = \frac{a_{n}^{25T} - R_{25:24} \times a_{n}^{24T}}{R_{25:24} \times a_{n}^{24T} - a_{n}^{25T}} \]  
\[ (A17) \]

\[ \gamma = \frac{a_{n}^{25T} - R_{25:24} \times a_{n}^{26T}}{R_{25:24} \times a_{n}^{26T} - a_{n}^{25T}} \]  
\[ (A18) \]

\[ \delta = \frac{a_{n}^{26T} - R_{26:24} \times a_{n}^{26T}}{R_{26:24} \times a_{n}^{24T} - a_{n}^{26T}} \]  
\[ (A19) \]

On the basis of Equation A15, the molar amount of $^{26}$Mg in the sample can be calculated by using isotope ratios $R_{25:24}$ and $R_{26:24}$ and the total amount of magnesium determined by atomic absorption spectrometry in the sample. The molar amount of the $^{25}$Mg can then be obtained by using Equations A7 or A8. The magnesium isotopic abundances used for the study are given in Table A1.

**TABLE A1**

<table>
<thead>
<tr>
<th>Natural abundance</th>
<th>$^{25}$Mg tracer</th>
<th>$^{26}$Mg tracer</th>
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</thead>
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<tr>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>$a_{n}^{24T}$</td>
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<tr>
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<tr>
<td>$a_{n}^{26T}$</td>
<td>98.78</td>
<td>$a_{n}^{26T}$</td>
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