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Dietary Magnesium: Supply, Requirements and Recommendations – Results From Duplicate and Balance Studies in Man

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The average magnesium uptake recommendation for an adult is in the range of 300 to 400 mg/day. During recent years dietary reference intakes in the USA and also in Germany/Austria/Switzerland have been slightly increased from the respective nutrition societies up to 400 mg/day for young men. The basis for these recommendations, among others, are balance studies. During the last years a series of balance and duplicate studies have been performed to determine magnesium uptake and balance in German and Mexican adults, in vegetarians, and in lactating women. In addition, the effect of supplementing a normal diet with 100 mg magnesium from a multimineral/multivitamin preparation was tested in a double blind, placebo controlled study in young women and in women during lactation. Daily magnesium intake from a self-selected diet in Germany was determined in duplicate studies in 1988/1992/1996 to be about 200 mg for women and 250 mg for men. Compared to these data a self-selected Mexican diet provided an average of 301 mg magnesium/day to women and 318 mg to men. Female and male vegetarians consumed 376 respective 474 mg magnesium/day. Balance studies that were performed over a period of 7 days showed no significant net uptake or net loss of magnesium. Supplementing the daily diet with 100 mg magnesium also did not lead to a changed balance. The higher intake was reflected by an increased urinary magnesium excretion, showing that about 20 to 40 % of the additional magnesium had been absorbed. Serum magnesium concentrations were not changed in young lactating and non-lactating women.

In addition to these magnesium balance studies in various test populations it could be shown that during aging a significant amount of magnesium (up to 50 %) is lost from the bones which represents the main storage compartment for magnesium.
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Key words: magnesium, diet, balance, supplement, human

Magnesium is an essential mineral that is needed in sufficient amounts for numerous physiological processes. Under steady state conditions, magnesium uptake should be high enough to compensate for daily losses, occurring mainly via the urine. Increasing or decreasing magnesium renal excretion primarily regulates the extracellular magnesium concentration, the mechanisms underlying these regulatory processes have been reviewed in detail [1]. Increased extracellular magnesium concentrations could occur after redistribution of magnesium from intracellular to extracellular space. Intracellular magnesium losses are caused by activation of magnesium efflux systems when intracellular free magnesium concentrations are increased. This is the case after excessive breakdown of Mg-ATP, as ADP binds magnesium with lower affinity than ATP [2]. When the increased extracellular magnesium concentration is decreased by renal excretion, part of the intracellular magnesium is lost from the body. When the intracellular ATP content is regenerated magnesium is taken up into the cells again, resulting in decreased extracellular magnesium concentration that has to be replenished by magnesium absorption from the intestines.

Diets low in magnesium can induce magnesium deficiency in animals and humans [3]. In growing rats very low plasma magnesium concentrations occur within a few days after feeding a magnesium deficient diet. In adult humans however, low plasma magnesium concentrations are observed only after prolonged ingestion of food with a low magnesium content [3]. During recent years dietary reference intakes for magnesium have been revised by the US Institute of Medicine [4] and also by the German, Austrian and Swiss nutrition societies [5] (Table 1). For adults the recommended intakes of magnesium are between 300 and 420 mg per day. These recommendations are based on a few balance studies with women and men consuming different diets, with different magnesium contents, and for some age groups no data from balance studies are available [4]. The recommendations are thus based on relatively few small studies, without taking into account either regional differences or differences due to race.

The actual intake of magnesium in various populations has been determined in various duplicate, shopping basket and balance studies with or without using supplemental magnesium. This article reviews the results of several magnesium balance and duplicate studies [6–10].

Table 1. Recommended dietary allowances (USA, 1997) and reference intakes (Germany, Austria, Switzerland, 2000) for magnesium (mg/day)

US-RDA 1997			D-A-CH reference intake 2000		
Age	**Females**	**Males**	**Age**	**Females**	**Males**
1–3	80	80	1–4	80	80
4–8	130	130	4–7	120	120
9–13	240	240	7–10	170	170
14–18	360	410	10–13	230	250
			13–15	310	310
			15–19	350	400
19–30	310	400	19–25	310	400
31–50	320	420	25–51	300	350
51–70	320	420	51–65	300	350
>70	320	420	>65	300	350
Pregnancy	+40		Pregnancy	310	
Lactation	+0		Lactation	390	

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Methods

Studies were carried out in 17 test groups from Germany and Mexico which consisted of at least 7 women and 7 men between the ages of 20 and 69 years. If possible, 10 women and 10 men participated per study with 2 women and men per decade. The test subjects collected the duplicates of all consumed foods, beverages and sweets on 7 consecutive days. All of them were asked not to change their eating habits. The test subjects kept a daily record of the food consumed, allowing not only the calculation of the magnesium intake (basket method) but also a comparison of this method with the findings of the duplicate method. The balance studies were carried out in 1996 and 1997.

As well as collecting food duplicates in these studies, urine and faeces, and in two groups the milk as well, were collected every day from the test subjects and analysed. Dry weight of the samples was determined after drying at 60 °C until weight constancy. Analysis of magnesium was carried out after dry ashing of the samples at 450 °C and dissolution of the ashes in 2.5 % HCl. Magnesium was determined by atomic absorption spectrophotometry (AAS3, Carl Zeiss Jena, Jena, Germany) or ICP-OES (Spectroflame D, Spectro Analytical, Kleve, Germany). Analytical precision was determined by using reference materials with certified magnesium content. Magnesium contents determined with both methods varied by ±5 %.

Duplicate studies were carried out in Germany during various years: 1988 (in the GDR before unification), 1992 (2 years after unification) and 1996, to allow an estimate of changed food choice after unification. In addition, samples of a duplicate study performed in two rural regions of Mexico were available to make a comparison between magnesium intakes under different living conditions.

Studies were done with omnivores and ovo-lacto vegetarians. In addition a study was done with young non-pregnant women receiving a magnesium-containing multimineral/multivitamin supplement or placebo. A further study compared magnesium balance of lactating women who had received either the multimineral/multivitamin supplement or placebo from the 8th month of pregnancy until the 35th day of lactation. The daily supplement provided 100 mg magnesium as magnesium oxide together with various minerals (Ca, Fe, Zn, Cu, Mn, I, Se) and vitamins (C, E, D, niacine, panthotenic acid, B6, B1, B2, B12, folic acid, biotin, β-carotene). The non-pregnant women took the supplement over a period of 21 days and the balance study was done from the 15th to the 21st day of supplementation. Pregnant women received the supplement or placebo from the 8th month of pregnancy until the 35th day of lactation. The balance study was done from the 29th to the 35th day of lactation. In the supplementation studies plasma magnesium concentration was also determined. Table 2 summarises the number of test groups and the number of subjects in each test group of the different studies.

The magnesium content of human bone was determined in human accident casualties of various ages. Samples from rib were removed, dried, and ashed and magnesium content measured by atomic absorption spectrophotometry. The study was approved by the local ethic committee.

Table 2. Overview about the different studies: duplicate and/or balance, number of test groups and number of participating individuals in every test group in the different studies

	Number of groups tested/number of participants Women	Number of groups tested/number of participants Men
Germany, 1988 (GDR before unification) duplicate	4/7	4/7
Germany, 1992 duplicate	6/7	6/7
Germany, 1996 duplicate and balance	4/3 × 7, 1 × 10	4/ 3 × 7, 1 × 10
Germany, 1996 vegetarians duplicate and balance	1/10	1/10
Mexico, 1996 duplicate	2/7	2/7
Germany, 1997 young women supplementation study duplicate and balance	2/7	–
Germany, 1997 lactating women supplementation study duplicate and balance	2/7	–

Results

Magnesium intake from self-selected diets of adults in Germany in the years 1988, 1992, and 1996 is shown in Table 3. There is an increase in magnesium intake from 1988 to 1996, but despite this, the recommended dietary intakes were not met. The increase in magnesium uptake from 1988 to 1992 might be explained by the broader availability of different foods in the former GDR after unification.

Compared to omnivores, magnesium intake was significantly higher in ovo-lacto vegetarians (Tab. 3); vegetarian women consumed 83 % and men 78 % more magnesium. Moreover, a population of Mexicans, eating a more plant based diet had an increased magnesium intake compared to German omnivores, +47 % in women and +20 % in men (Tab. 3). Generally, intake in men is higher than in women. This is related to the higher intake of dry mass (data not shown) and not due to a different choice of food and drink by men.

Balance studies showed that with an intake of 205 mg magnesium/day in women and 266 mg magnesium/day in

Table 3. Mg intake (mg/day; mean ± SD) of adults eating self-selected diets, measured by duplicate studies

	Year	Women	Men
Germany	1988	193 ± 56	248 ± 69
	1992	213 ± 79	260 ± 104
	1996	205 ± 72	266 ± 92
Germany, Vegetarians	1996	376 ± 101	474 ± 199
Mexico	1996	301 ± 95	318 ± 122

Table 4. Magnesium intake, excretion and balance (mg/day) of adult omnivores and vegetarians in a duplicate study (mean ± SD)

	Omnivores		Vegetarians	
	Women	Men	Women	Men
Mg intake	205 ± 72	266 ± 92	376 ± 101	474 ± 199
Mg excretion:				
urine	75 ± 48	90 ± 45	104 ± 50	130 ± 51
faeces	137 ± 123	175 ± 167	283 ± 164	333 ± 186
Mg balance	–7	+1	–11	+11

men no significant net uptake or loss of magnesium from the whole body could be detected (Tab. 4). The same result was achieved with vegetarians consuming 376 (women) or 474 (men) mg magnesium/day (Tab. 4). Most of the ingested magnesium was excreted via the faeces, 67 % and 66 % in omnivore women and men respectively. The relative amount of magnesium in the faeces was increased to 75 % in vegetarian women and 70 % in vegetarian men. Urinary excretion was 39 % higher in female and 44 % higher in male vegetarians compared to omnivores.

Supplementing 100 mg magnesium/day as magnesium oxide to young women did not result in a changed magnesium balance (Tab. 5). Both the supplemented and the unsupplemented group had a negative magnesium balance (magnesium loss: 32 mg/day). Magnesium balance was positive in supplemented (+4 mg) and unsupplemented (+32 mg) lactating women (Tab. 6). Magnesium excretion in milk was not significantly different in both groups, whereas urinary excretion was 70 % higher in supplemented women. Plasma magnesium concentrations were low (mean 0.7 mmol/l) in all women whether taking a supplement or not, but not significantly changed by supplementing magnesium, in either non-pregnant or in lactating women (data not shown).

A clear cut decrease of the magnesium content of human rib with increasing age could be observed from about 3500 mg/kg dry mass at age 0–1 years to less than 2000 mg/kg dry mass at age 80–89 years (Fig. 1).

Discussion

The results of these studies show that in adult healthy women and men an uptake of 205 resp. 266 mg magnesium per day is sufficient to maintain the normal magnesium homeostasis, as there was no significant net uptake or loss of magnesium from the body. It cannot be concluded from these data however, if the magnesium content in the food is just enough to remain in homeostasis or is sufficient to compensate for earlier losses. The daily magnesium requirement is caused by magnesium losses via urine, excretion into the gut and possibly losses via sweat. Together these losses add up to about 100 mg/day, an amount that must be absorbed daily for the individual to stay in magnesium balance. The usual magnesium content of the diet seems to be sufficient to fulfil the needs of the body. In addition, the body is able to adapt to a wide variety of intakes, by reducing or increasing the loss of magnesium.

If homeostatic mechanisms are adequate, then magnesium deficiency should be rare. However, an epidemiological study in Germany [11] showed that low serum magnesium concentrations are found in about 5–8 % of the overall population of various ages; in young women however, between the ages of 18–22 the incidence was much higher, being 20 %. A low serum magnesium concentration is associated with magnesium deficiency [12]. In agreement with this are the results with the young women in our study who had serum magnesium concentration below the normal range. Even though the women had a magnesium intake of 248 mg/day, even higher than the intake in the balance study of 1996 (205 mg), all women lost magnesium. The reason for this is not clear, but it might have been caused by some failure of magnesium-homeostatic mechanisms. Although these women lost magnesium, a magnesium supplement providing 100 mg magnesium per day, did not improve magnesium balance. 100 mg supplement, also did not increase the serum magnesium concentration, despite the fact that part of this magnesium was obviously absorbed, as urinary magnesium excretion was increased. Since an increased absorption from the intestine was unable to compensate for loss of magnesium, the main regulatory mechanisms for extracellular magnesium in these women, cannot be located in the gut.

Women during their lactation period had a positive magnesium balance. This, possibly, reflects an increased magnesium requirement as magnesium has to be taken up by the growing foetus leading to a probable magnesium deficiency in the mother. This magnesium deficit must be corrected during the postnatal period, and the magnesium content of the normal diet was high enough to allow for the positive magnesium balance. Any surplus of magnesium given as a supplement to these young women (lactating or not) without any overt signs of magnesium deficiency was either not absorbed or the kidneys excreted the absorbed part. Urinary magnesium excretion was also increased in vegetarians, showing that in spite of the lower bioavailability of magnesium from vegetarian food (possibly due to the high amount of phytic acid) more magnesium was absorbed than in omnivores. The different magnesium content of vegetarian food compared to mixed food, however, did not lead to a changed magnesium balance.

These results are in agreement with the concept that intracellular magnesium, representing about 40 % of total body

Table 5. Magnesium intake, excretion and balance (mg/day) in a placebo-controlled double-blind supplementation study in young women (100 mg Mg/day, 3 weeks supplementation, duplicate and balance study from day 15 to 21; mean ± SD)

	Supplement (n = 7)	Placebo (n = 7)
Mg intake	363 ± 76	248 ± 79
Mg excretion		
urine	97 ± 35	77 ± 35
faeces	298 ± 198	203 ± 153
Mg balance	–32	–32

Table 6. Magnesium intake, excretion and balance (mg/day) in a supplementation study in pregnant/lactating women (100 mg Mg/day from the 8th month of pregnancy to the 35th day of lactation; duplicate and balance study: day 29 to 35 of lactation; mean ± SD)

	Supplement (n = 7)	Control (n = 7)
Mg intake	421 ± 67	242 ± 85
Mg excretion		
milk	28 ± 6	32 ± 8
urine	104 ± 38	61 ± 29
faeces	285 ± 217	117 ± 123
Mg balance	+4	+32

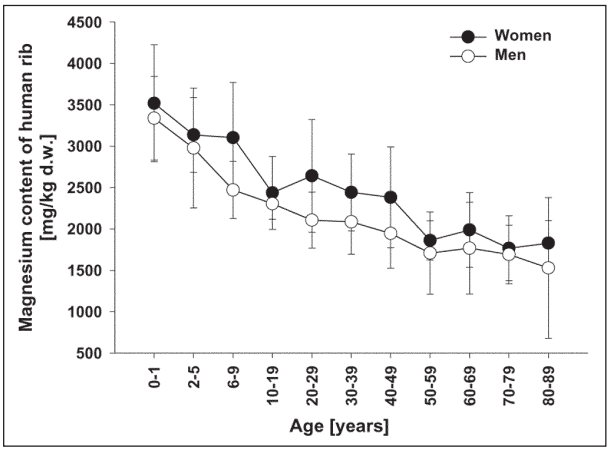

Figure 1. Magnesium content of human bone (rib); mean ± SD, n=10

magnesium, is very well maintained. In animal experiments it has been shown that a reduction of total intracellular magnesium can only be achieved by feeding fast growing animals a severely magnesium deficient diet [13]. Only when the plasma magnesium concentrations were reduced to below 0.2 mmol/l could a slight reduction of intracellular magnesium content be detected.

In spite of being in magnesium balance, it was found that the magnesium content of bones declines with age. As the main part of body magnesium is located within the bones this reflects a continuous loss of magnesium from the body. This loss of magnesium, however, might be so small on a daily basis that it cannot be detected with balance studies that are prone to large methodological variations. Part of the bone magnesium is in equilibrium with the extracellular magnesium [14]. In growing animals magnesium deficiency induced a rapid loss of bone magnesium [15]. Bone magnesium, therefore, represents a magnesium reservoir that buffers extracellular magnesium concentration. In humans this magnesium buffering capacity is obviously reduced with increasing age. This might be explained by slight changes in acid-base balance at increasing age. Due to a reduced ability to excrete acid together with an increased nutritional acid load a general loss of minerals from the skeleton occurs with increasing age [16]. The normal content of magnesium in the diet seems not to be high enough to avoid this magnesium loss from the bones, as over a lifetime nearly half of the magnesium content of bone is lost. There is evidence that a decreased magnesium content in bone also contributes to the problem of osteoporosis [17] as animal experiments [18] and human studies [19, 20] have shown a positive effect of supplementing magnesium on bone density and bone absorption parameters. The main effects of magnesium deficiency (ie neuromuscular hyperexcitability, cardiac arrhythmias) are caused by changes in extracellular magnesium concentrations producing direct membrane effects and magnesium/calcium interactions [21], and not due to changes in intracellular magnesium. Moreover, the pharmacological actions of magnesium infusions can also be mainly explained by an extracellular effect of the increased plasma magnesium concentration [22].

Even though the magnesium content in the diet seems to be high enough to stay in magnesium balance these studies provide little information concerning the regulation of the plasma magnesium concentration. Magnesium in plasma represents only a small part (less than 1 %) of total body magnesium stores. Magnesium concentration in plasma is a resultant of absorption from the intestines, excretion by the kidney and release or uptake from intracellular stores and bone. It is not clear how the extracellular magnesium concentration is regulated. Divalent cation sensing receptors of the blood vessels in the kidney might be involved by regulating reabsorption of ultrafiltrated magnesium [1]. The normal range of plasma magnesium concentration is 0.75 to 1 mmol/l [23]; but concentrations less than this are often found [11]. These low plasma magnesium concentrations may not necessarily result from a negative magnesium balance but could be caused by a changed regulation of extracellular magnesium without affecting intracellular stores.

Although in general, serum magnesium concentration is a bad predictor of the probability of disease (see Elwood and Pickering, this Journal) Liao et al. [24] showed that the probability of coronary heart disease was significantly reduced in subjects having a high normal plasma magnesium concentration; the higher the magnesium concentration the lower the probability of myocardial infarction. The recommendations in the US or in Germany, Austria and Switzerland (Table 1) are sufficient for individuals to stay in a magnesium balance. However, the concept of avoiding a magnesium deficiency does not take into account the possible benefits of a high plasma magnesium concentration.

Investigation into the possible diet in Palaeolithic hunter/gatherer societies showed a magnesium uptake of about 600 mg magnesium/day, much higher than today [25]. The homeostatic mechanisms regulating the plasma magnesium concentration and our genome are still the same as those of our ancestors, which probably means that our metabolism is best adapted to a high magnesium intake. The magnesium intake although sufficient to avoid overt magnesium deficiency in most of the population might not be high enough to provide the possible risk reduction of a higher than normal plasma magnesium concentration. In agreement with this is that numerous studies have shown that at least 300 mg magnesium/day must be given in addition to the normal magnesium content of the diet to establish significantly increased serum magnesium concentrations [26].

In conclusion, the concept of widespread magnesium deficiency in our population seems to be inappropriate, since the normal physiological mechanisms are able to adapt to a wide variation in magnesium intake. However, there could be a subgroup in the population who are unable to stay in magnesium balance with the normal magnesium content of the diet. This might be either because of genetical differences in magnesium homeostatic mechanisms and/or because of age-dependent changes in magnesium homeostasis. It remains to be established how to detect this subgroup and how to treat them. In individuals with genetically determined magnesium deficiency an uptake of more than 1000 mg magnesium per day is sometimes required to avoid symptoms of magnesium deficiency [27]. Finally, since an increased plasma magnesium concentration could contribute to a risk reduction in coronary artery disease or osteoporosis it might be considered worthwhile trying to achieve this. However, a much higher magnesium intake than the current recommendations would be required to accomplish this aim.

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