Special Article

Factors influencing magnesium consumption among adults in the United States

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The negative health effects of inadequate magnesium intake are well established, but the extent of the problem of deficiency warrants further exploration. This review explores the dietary factors, such as changes in agricultural practices and dietary patterns, that affect magnesium consumption over time and examines the current adequacy of magnesium intake among adults in the United States. Large, cross-sectional, population-based data sets confirm over half the adult population in the United States does not consume adequate amounts of magnesium, although recent population-based studies show a steady and consistent recovery in magnesium consumption over the last several decades. Because there is no simple, rapid, accurate test to determine whole-body magnesium status, continued monitoring of magnesium consumption is essential to determine whether the trend of increasing magnesium consumption will continue. In the meantime, since the clinical consequences of inadequate magnesium status are well established, there are few reasons not to encourage increased magnesium intake in adults, especially since magnesium is found in healthy foods that should be consumed more often and there are no reported cases of hypermagnesemia from food alone.

INTRODUCTION

The clinical manifestations of inadequate magnesium intake are well established and include electrolyte, neuromuscular, neurologic, and cardiovascular abnormalities.[1–4] Adequate intake of magnesium is essential because magnesium plays a key role in energy production, prevention of dysrhythmia, blood pressure regulation, insulin resistance, and bone homeostasis.[2,5,6] There is no simple, rapid, accurate test for whole-body magnesium status. As a result, monitoring magnesium status is difficult,[7] but magnesium consumption among adults in the United States has reportedly decreased over the past century by 200 to 300 mg/d.[8–10] The possible reasons for this decrease are multifaceted and include changes in agricultural processes and food consumption patterns. Magnesium homeostasis in humans is influenced not only by dietary intake but also by absorption in the gastrointestinal tract and excretion by the kidneys.[11] However, further research is needed to draw any conclusions about the effect of these factors on net magnesium levels. If population-based studies, which use 24-hour recall data to track intake over time, indicate an increasingly magnesium-deficient population, the negative health effects become a public health concern.[4,7] The aim of this review is to explore the factors affecting magnesium consumption over time and to determine the current adequacy of magnesium intake in adults in the United States.

MAGNESIUM BASICS

Magnesium, as the fourth most abundant mineral and second most abundant cation in the human body, has numerous essential roles.[12] Besides being a cofactor for over 300 enzymes, it is essential for glycolysis,

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mitochondrial oxidative phosphorylation, regulation of potassium transport, and generation of anaerobic and aerobic energy and acts as nature's physiological calcium channel blocker.[13] It is an essential mineral that plays a role in the physiological function of the heart, brain, and skeletal muscles. The human body contains approximately 25 grams of magnesium, with 50% to 60% found in bone, which is responsible for maintaining normal extracellular magnesium concentrations, while the rest is found mostly in skeletal muscle and soft tissue.[6] The gastrointestinal tract and kidneys are the organs primarily responsible for magnesium homeostasis. When dietary intake of magnesium is low, the percent absorbed from the diet by the gastrointestinal tract increases and the amount excreted by the kidneys decreases to replenish stores.[6] After magnesium consumption, around 30% is absorbed by the intestine, 5% is eliminated in feces, approximately 30% is used to replenish stores in bone, muscle, and other parts of the body, 30% is excreted via urine, and small amounts are lost via sweat.[13]

ASSESSING MAGNESIUM STATUS

Bone and muscle are the 2 main compartments for magnesium storage. Because they are not easily or painlessly accessible, there is no accurate test for whole-body magnesium status.[7] Clinical laboratory tests for assessing magnesium status include total serum magnesium concentration and 24-hour urine excretion. The current reference range for serum magnesium, which is based on 1974 data, is 0.75 to 0.95 mmol/L (1.8–2.3 mg/dL).[6] Only 1% of total body magnesium is present in extracellular fluids, and only 0.3% is found in serum.[11] While measurement of serum magnesium is the most convenient and economical way to determine magnesium status, it does not reflect intracellular magnesium levels[14] or bone stores, which could be dangerously low if the body uses them to preserve serum levels.[6,15] The serum magnesium concentration can also be low while total body stores are adequate if a person is taking a drug that acutely increases excretion of magnesium.[16] Twenty-four hour urine excretion is readily available, but it is a better assessment of magnesium wasting by the kidneys and is not necessarily a test for assessing magnesium status.[16] Magnesium in urine most likely shows the current snapshot of intake, and a single 24-hour urinary test is not adequate for assessing magnesium status because urinary magnesium excretion changes rapidly in response to dietary intake.[7,15]

Other potential tests of magnesium status are not widely available. Measurement of serum concentrations of ionized magnesium, the biologically active form, may be the most reflective of current status,[7] yet very few clinical laboratories offer this service.[16] A magnesium retention test, which assesses the amount of magnesium excreted in urine after a parentally administered load test, is probably the best assessment of magnesium deficiency, since intracellular levels are physiologically representative.[16] However, it is more invasive, is usually limited to use in research studies, and is only appropriate for adults with adequate kidney and intestinal function.[6,17] Techniques of interest, but requiring additional research, include phosphorous nuclear magnetic resonance spectroscopy to measure brain magnesium and measurement of magnesium concentrations in total and free red blood cells.[16,18]

Table 1 **Published requirements for daily magnesium intake in the United States[6]**

Requirement and age group	Males	Females	Pregnant females	Lactating females
EAR				
19–30 y	330 mg	255 mg	290 mg	255 mg
31–50 y	350 mg	265 mg	300 mg	265 mg
51–70 y	350 mg	265 mg		
> 70 y	350 mg	265 mg		
RDA				
19–30 y	400 mg	310 mg	350 mg	310 mg
31–50 y	420 mg	320 mg	360 mg	320 mg
≥ 51 y	420 mg	320 mg		

Abbreviations: EAR, Estimated Average Requirement; RDA, Recommended Dietary Allowance.

DAILY REQUIREMENTS

The response by the body to ensure magnesium homeostasis (increased intestinal absorption and decreased urinary excretion) makes it difficult to determine daily requirements.[19] The Estimated Average Requirements (EARs) and Recommended Dietary Allowances (RDAs) for magnesium intake are based on age and sex (Table 1). Current reference values were determined by measuring serum magnesium concentrations in healthy normal individuals during data collection for the National Health and Nutrition Examination Survey I (NHANES I) in 1974.[20] Between 1971 and 1974, the average serum magnesium level in adults in the United States was 0.85 mm/L.[20] In this same population, a serum magnesium deficiency of 21% in women and 1.5% in men was reported.[7,20] Since then, there have been changes in the food supply and in the prevalence of diseases such as diabetes that affect magnesium status, which may indicate a need to reevaluate daily requirements.[7] The validity of the EAR has been questioned in several reviews.[4,7,15,21] Population studies conducted over the past few decades that assessed both food and supplemental sources of magnesium show a majority of adults in the United States consume amounts below the EAR (Table 2).[22–26] In fact, magnesium was listed as a

Table 2 **Percentage of US adult population with intake below the Estimated Average Requirement (EAR) for magnesium**

Reference	NHANES years represented	Magnesium source	Ages included	Percent below EAR
Moshfegh et al. (2005)[22]	2001–2002	Food	$\geq$ 19 y	
Male				64
Female				67
Moshfegh et al. (2009)[23]	2005–2006	Food	$\geq$ 19 y	
Male				53
Female				56
Tarleton & Littenberg (2015)[24]	2007–2010	Food & supplements	$\geq$ 20 y	54
Papanikoloau et al. (2015)[25]	2007–2010	Food & supplements	$\geq$ 19 y	
White				43
Male				44
Female				41
Black				69
Male				69
Female				69
Cifelli et al. (2016)[26]	2007–2010	Food	$\geq$ 19 y	56

Abbreviation: NHANES, National Health and Nutrition Examination Survey.

shortfall nutrient in the *2015–2020 Dietary Guidelines for Americans*,[27] signifying that magnesium status in the United States is a public health concern. Women consume less magnesium than men, and black men and women consume less than their white counterparts, a trend that is well documented back to the 1970s.[20]

CLINICAL SIGNIFICANCE OF DEFICIENCY

The clinical consequences of inadequate magnesium status have been reviewed extensively.[1–4] Hypomagnesemia is associated with electrolyte, neuromuscular, neurologic, and cardiovascular abnormalities.[28] Magnesium plays a role in production of myocardial energy, prevention of dysrhythmias, and promotion of vasodilation.[5] Increased consumption of magnesium can aid in treatment of cardiovascular disease (CVD) and prevention of sudden cardiac death.[2,4] Correcting magnesium status can help control blood pressure and reduce risk factors for CVD, especially in those with hypertension and those with magnesium depletion due to use of diuretics or poor dietary intake.[2] Magnesium intake and serum magnesium concentrations are inversely proportional to C-reactive protein levels.[4] C-reactive protein, a measure of inflammation, is associated with risk of CVD, metabolic syndrome, and diabetes.[4] This relationship with inflammation may help explain why inadequate magnesium intake and hypomagnesemia are associated with CVD, arrhythmias, heart failure, diabetes, and metabolic syndrome.[2,29–32] An elevated risk of certain diseases, even at a serum magnesium concentration higher than the present clinical cutoff for deficiency, raises further doubt about the adequacy of the current reference intervals.[7] Latent, or subclinical, deficiency is likely associated with risk of chronic diseases such as hypertension, CVD, diabetes, and osteoporosis.[33]

The varied functions of magnesium in the body have prompted research into magnesium's role in other chronic health conditions as well. The association between magnesium intake and depression is well documented.[24,34,35] Magnesium plays a role in many of the pathways involved in the pathophysiology of depression and is found in several enzymes, hormones, and neurotransmitters.[36] Depression is also associated with inflammation.[37] Recent randomized clinical trials have found that supplementation with magnesium improves symptoms of depression in patients with hypomagnesemia,[38] regardless of baseline magnesium status.[39] Magnesium is involved in bone cell growth, and inadequate intakes can lead to decreased bone formation and loss of bone mass. Animal studies have shown that magnesium levels at 10%, 25%, and 50% of adequate intake lead to bone loss, decreased numbers of osteoblasts, and increased osteoclast activity.[4] Adults with migraines tend to be magnesium deficient, and since magnesium functions as a smooth muscle relaxant, ensuring adequate status may be important for alleviating symptoms of asthma.[5] Recommendations for magnesium supplementation to alleviate symptoms of these clinical consequences of deficiency are currently under investigation.

Hypermagnesemia, on the other hand, is not a concern. Overconsumption of magnesium from food intake alone has never been documented and rarely occurs following intakes of supplemental magnesium in people with adequate kidney function.[6]

PATTERNS OF MAGNESIUM CONSUMPTION

The negative health effects of inadequate magnesium intake are irrefutable, but the extent of the problem of deficiency warrants further exploration. The clinical significance of magnesium deficiency in a majority of the US population is not inconsequential. There is no

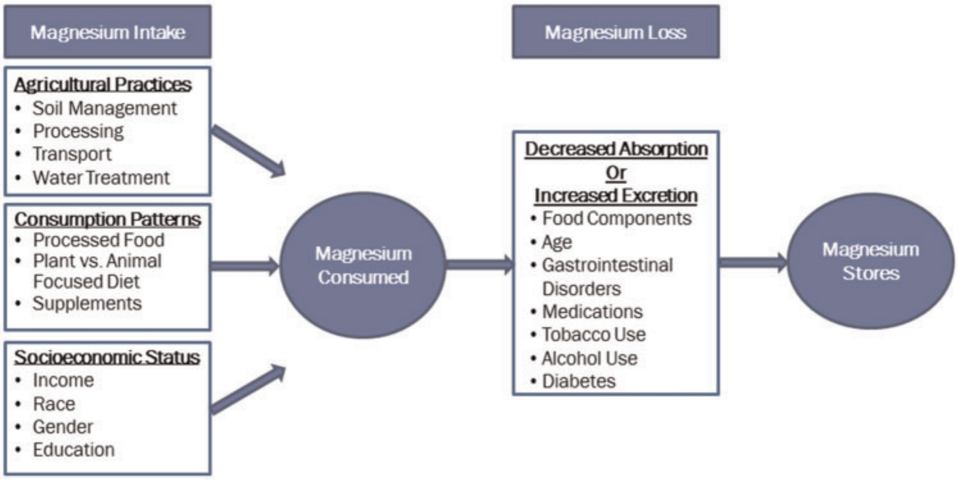

Figure 1 **Factors influencing magnesium homeostasis.**

reliable and convenient clinical test to document changes in magnesium status over time. Researchers rely on results from population-based studies to study changes in daily consumption over the past century. Daily intake has decreased from 400 to 500 mg/d in the early 20th century to 200 to 300 mg/d in the 21st century.[8–10] Dietary magnesium intake is directly related to kilocalorie intake. As energy intake increases, so does total magnesium intake. In addition, consumption of magnesium is influenced by the amount of magnesium available in the soil. Higher amounts in the soil lead to adequate absorption by the plant, which, in turn, leads to higher amounts available for consumption. Low magnesium status may be an indicator of other suboptimal dietary and lifestyle patterns, such as inadequate intake of whole grains, fruits, and vegetables.[7] Unhealthy dietary patterns are often influenced by socioeconomic status.[40] Figure 1 illustrates the factors influencing magnesium homeostasis. The next sections focus on factors affecting magnesium consumption over the past century (Box 1). If the majority of the US adult population is magnesium deficient, the reasons for decreased consumption of magnesium may prove to be an area for public health interventions.

Box 1 **Dietary factors negatively influencing consumption of magnesium, 20th–21st century**

Decreased magnesium in soil
Decreased magnesium in crops
Decreased consumption of plant-based diets
Decreased consumption of dairy products
Increased consumption of soft water and bottled water
Increased reliance on animal protein
Increased use of refined sugar and oils
Increased consumption of processed grains and vegetables

MAGNESIUM IN SOIL AND CROPS

A decrease of magnesium in the food supply is likely a major contributor to inadequate consumption of magnesium and, perhaps, to chronic latent deficiency.[7] The mineral content of plants differs according to the mineral content of the soil in which plants are grown, the manner in which plants are grown and harvested, and the amount of processing the plants undergo prior to consumption. Wild plant foods consumed by early hunter gatherers generally contained higher micronutrient concentrations than do their domesticated counterparts.[41] Historical data on soil fertility indicate changes in concentrations of minerals in produce from the 1940s to the end of the 20th century. Some studies report median declines of 5% to 40% or more of minerals in fruits and vegetables over the past 50 to 70 years.[13,42] Magnesium concentrations have decreased by 20% in cheese and by 15% in meat, owing to decreased amounts of magnesium in animal feed.[43] Exact changes in magnesium concentrations in foods are difficult to quantify because of differences in the methods of purchasing, pretreating, and analyzing food items by different researchers.[44] Nonetheless, changes in the amount of magnesium in the soil are reflected in the magnesium content of crops. To increase the amount of magnesium in food, there needs to be more magnesium available in the soil.

Change in the amount of magnesium in crops is hypothesized to stem from changes in agricultural processes that result in genetic dilution and environmentally related soil dilution.[42,43] Soil dilution occurs as the result of environmental changes such as fertilization and irrigation, which tend to cause decreases in concentrations of minerals in plants.[42] Phosphorus from fertilizers can be beneficial to magnesium concentrations in the plant at low doses but detrimental at very high rates of application.[43] Genetic dilution occurs when plant yield increases as a result of selective breeding.[43] This process came about during the so-called Green Revolution in the 1960s and 1970s, which encouraged increased yield of grains and other crops by 2- to 3-fold in developed countries.[42,45] For example, in fruits, vegetables, and grains, approximately 80% to 90% of the dry weight yield is carbohydrate. When breeders select for a high yield, they are selecting for high carbohydrate yield, with no assurance that any other nutrients are increasing in the same proportion.[42] Magnesium content in the food supply is affected by these agricultural processes. Twentieth century wheat can contain almost 30% less magnesium than wheat consumed in the 19th century.[45] Increasing grain yields over the past 40 years have provided additional food for the human population, but with a corresponding decrease in the availability of essential nutrients.

In addition to the amount of magnesium available to the plant from the soil, factors related to the presence of other nutrients and the growth of the plant affect the magnesium content of crops. The amount of magnesium is influenced by competition with other ions (such as calcium), elevated concentrations of aluminum (which decreases magnesium uptake[46]), and other factors that restrict the size of the root system.[43] Magnesium is found in high concentrations in the chlorophyll of plants,[2] but the developing layer (endodermis) of the plant actually becomes a barrier to absorption, and less magnesium is absorbed as the plant grows.[43] Magnesium intake can also be determined by which portion of a plant is edible. Root crops store 25% to 33% of their magnesium content in the tap root, which is usually not consumed.[43] Up to 50% of magnesium is stored in the reproductive organs of plants, ie, in the seed or grain, and is removed during processing.[43]

MAGNESIUM IN WATER

Hard water is frequently considered an important source of magnesium[43] and can account for up to 10% of daily intake.[2] The amount of magnesium consumed from water varies greatly, depending on the mineral content of the water supply.[1,5] Distilled water contains fewer minerals than tap water.[7] To meet the growing need for potable water, the use of desalination has increased, and the magnesium content of desalinated water (0.8 mg/L) is lower than that of hard water (20–30 mg/L).[47] Geography also plays a role in the amount of magnesium in the water supply. North American bottled and tap water contains much lower levels of magnesium than European counterparts.[48] Levels of magnesium in water differ significantly between US states and even within areas of the same city.[48] Tap water accounts for two-thirds of the water consumed at home but only half of the water consumed away from home.[49] Per capita consumption of bottled water in the United States has increased from just under 2 gallons in 1976 to over 36 gallons in 2015, an increase of about 6% per year.[50,51] Filtered and bottled water contain less magnesium than tap water, although mineral and spring waters are often good sources of magnesium, depending on the source.[48]

CHANGES IN DIETARY PATTERNS

There are no excellent sources (defined as providing $\geq$ 40% of the RDA per serving) or good sources (defined as providing $\geq$ 25% of the RDA per serving) of magnesium in the US food supply.[52] The highest levels of magnesium are found in green vegetables, beans, peas, legumes, nuts, and whole unrefined grains. Meat, fish, and fat contain little magnesium.[53] The amount of magnesium in the US food supply changed from 408 mg per capita per day in the early 1900s to 349 mg in 1980, a 14% decrease.[54] Increased intake of processed grains and potatoes paired with increases in dairy, meat, poultry, and fish is thought to be a major reason for this decrease. Between the early 1900s and 1980, the supply of protein from vegetables decreased by 33% while protein from animals increased by 24%, leading to a net reduction in magnesium in the US food supply.[54]

The current Western-style diet, which has 72% of total energy coming from dairy products, refined cereals, refined vegetable oils, and alcohol, is a poor source of magnesium and often contains only 30% to 50% of the RDA for magnesium.[2,55] Magnesium intake is directly related to kilocalorie intake, except when energy comes from high amounts of alcohol or refined sugars and oils.[1] As a result, the typical American diet needs to include either higher amounts of kilocalories or supplemental magnesium to meet recommendations for magnesium intake.[56] In some cases, achieving adequate intake of magnesium from diet alone may require at least 3000 kcal/d, which exceeds the energy needs of the average adult.[57]

Sugar plus refined oil makes up over 36% of the US diet.[41] Adults in the United States consume a large proportion of total energy from energy-dense, refined sugars such as cakes, cookies, pies, sodas, and soft drinks, and consuming large amounts of these foods reduces the total vitamin and mineral density of the diet.[58] Between the early 1900s and 1980, the use of sugars and other sweeteners increased by 50%[54] and continued to climb. Per capita consumption of refined sugars in the United States increased from 55.5 kg in 1970 to 69.1 kg in 2000.[41] More recently, mean daily intake has decreased slightly from 21 teaspoons per day in 2003–2004 to just over 18 teaspoons in 2011–2012.[59] From 1909 to 1999, per capita consumption of oils increased as follows: vegetable oil by 130%, shortening by 136%, and margarine by 410%.[41] Changes in animal husbandry practices and decreased consumption of wild animals over the past 2 centuries led to the large-scale addition of refined oils to the food supply.[41] Fat storage depots of wild animals are mostly saturated fatty acids, while muscle and organ tissues supply mostly poly- and monounsaturated fats. Year-round dietary intakes of high amounts of saturated fat are not possible with diets that rely on wild animals for meat, owing to the seasonal cyclic depletion of saturated fat. Animal husbandry has made it feasible to prevent this seasonal decline in body fat and to slaughter at peak body fat percentage. The development of processing procedures that allow for the storage of products with high concentrations of animal-based saturated fats (cheese, butter, tallow, salted fatty meats) allows for year-round consumption of these high-fat products.[41]

Vegetables contain a high amount of magnesium but are consistently underconsumed in the United States. Processing and boiling of certain vegetables, such as green leafy vegetables, leads to the loss of 80% to 90% of the magnesium content.[1,13] The use of processed vegetables in the United States increased 4-fold during the 20th century, while consumption of fresh vegetables increased only during the first half of the century.[54] From 1976–1980 (NHANES II) to 1988–1994 (NHANES III), the percentage of adults consuming 3 or more servings of vegetables per day increased from 27% to 35%.[60,61] NHANES data from 1999 to 2002 indicate a small but significant ($P = 0.03$) decrease in mean daily intake, with only 33% of adults consuming at least 3 servings of vegetables per day.[61] Other population-based studies confirm that vegetable intake stalled and then decreased in the late 1990s. Data from the Behavioral Risk Factor Surveillance System from 1990 to 1994 are consistent with the NHANES data from the early 1990s, ie, the percentage of US adults meeting the guideline of 5 servings of fruits and vegetables per day increased from 19% in 1990 to 22% in 1994, but then increased to only 23% in 1996.[62] Behavioral Risk Factor Surveillance System data from 1994 to 2005 show an overall significant decrease in the frequency of daily consumption of vegetables by US adults, from 2.03 times per day to 1.91 times per day (95%CI, −1.12 to −0.10; $P < 0.001$).[63] The intake of vegetables remains poor, according to more recent data from the Behavioral Risk Factor Surveillance System. From 2007 to 2010, 13% of the adult population met the recommendations for daily vegetable intake of at least 1.5 cups per day; by 2013, this percentage had decreased to 9%.[64]

Adults following a vegetarian diet tend to have higher intakes of magnesium from food.[8] Varying degrees of vegetarianism (ie, lacto-ovo, or pesco-vegetarian) result in magnesium consumption higher than that obtained from a typical Western diet. Compared with a typical US diet, a strict vegetarian diet significantly increases the amount of magnesium consumed (mean intake of 267 mg/d vs 346 mg/d; $P < 0.001$).[65] The higher magnesium intake most likely results from higher intakes of vegetables and legumes.[65] The percentage of US adults following a vegetarian diet has decreased from 2.3% in 2006 to 1.8% in 2016.[66]

Breakfast consumption was associated with a predicted increase in daily fruit and vegetable servings in a rural US population (coefficient 0.255; $P < 0.001$).[67] Magnesium intake is lowest and prevalence of inadequacy is highest in people who do not eat breakfast, and adequate intake is highest in those who consume ready-to-eat cereals.[68] The adequate intake seen with consumption of breakfast is thought to result from the inclusion of whole grains and dairy products. Although dairy is not a rich source of magnesium, it is consumed so frequently that is acts as a significant source of magnesium in US diets. Dairy and dairy products provided 18% of daily magnesium in the National Food Consumption Survey of 1977–1978 and over 10% of daily magnesium for adults in the Continuing Survey of Food by Individuals (1989–1991).[69,70] While dairy is still a large part of the Western diet, dairy intake has decreased over time. Between 2001 and 2004, 15% of Americans consumed the recommended daily servings of dairy, but between 2007 and 2010, only 11% met the recommendation.[71] Changes in the diet to meet the recommended servings of dairy predict a decrease in the percentage of US adults with inadequate magnesium intake, from approximately 56% to 33%. The predicted benefits would be especially beneficial for older adults.[71]

In the later part of the 19th century, the nutritional characteristics of milled grain changed as a result of the germ and bran being removed during the milling process.[41] Only 16% to 18% of the original magnesium in many ready-to-eat cereals remains in the refined product.[18] Diets high in processed carbohydrates result in a significantly lower intake of magnesium.[72] For example, a potato without the skin contains a third less magnesium than one with skin.[43] White bread and cooked white rice contain almost a third less magnesium than their whole-grain counterparts.[53] From 2003–2004 to 2011–2012, a small but significant increase in the consumption of whole grains was seen in the US population (0.6 to 0.9 gram equivalent per day; $P < 0.01$). Nevertheless, consumption is still far below the recommendation to consume 50% of grains as whole.[59]

Intake of beans, legumes, nuts, and seeds has remained mostly constant throughout the 21st century.[54] Between 2009 and 2010, 40% of US adults consumed nuts on a given day, but only 6% of the US population consumes tree nuts regularly.[73] Tree nuts are a great source of shortfall nutrients. Ninety-two percent of people who eat tree nuts consume the EAR for magnesium, compared with 40% of nonconsumers, and tree nut consumers exhibit a dietary pattern of higher quality and nutrient adequacy overall.[55] Between 2005 and 2012, daily consumption of nuts and seeds increased slightly (0.6–0.7 ounce equivalents), as did the intake of legumes (0.09–0.12 cups).[74] Consumption of tree nuts offers the potential to improve nutrient adequacy in the US diet.

MAGNESIUM SUPPLEMENTS

Supplements can contribute significantly to overall vitamin and mineral intake. In 1986, 15% of the adult population took an over-the-counter magnesium supplement. The most common amount was 100 mg, although daily intake and the form of magnesium was not confirmed.[6] A review of magnesium supplement intake in the decades since then, using NHANES data, shows that, as of 2011–2012, magnesium supplement use has increased to 28% of the population, although this is down from a high of 37% in 2005–2006.[75] Use is consistently higher in females[6,75] and increases with age.[76] People using supplements tend to consume healthier diets and have higher intakes of magnesium from food as well.[49,76] Older adults taking supplements are 3 times more likely to have adequate intake than those who do not take supplements, and older adults consuming a supplement also consume twice as much magnesium from food alone.[49]

SOCIOECONOMIC STATUS

Individuals with a higher socioeconomic status consume healthier diets.[77] Higher income and education are associated with higher intakes of reduced or nonfat milk, lean meats, and whole grains and with consumption of at least 5 servings of fruits and vegetables per day, while low socioeconomic status is associated with higher consumption of refined grains and added fats.[40,61,77] Low educational status is associated with low earning potential, low purchasing power, and food insecurity.[40] The prevalence of food insecurity has remained stable, at just over 14%, since the beginning of the 21st century.[27] Food costs are a barrier to consumption of nutrient-dense foods in populations with low socioeconomic status.[77] Food-insecure adults consume vegetables fewer times per month than food-secure adults (69 vs 76 times; $P < 0.05$).[78] The need to maximize energy intake and minimize food waste leads not only to the consumption of highly processed, shelf-stable foods but also to a minimal variety of foods.[77] Over the past 20 years, the price of fruits and vegetables has increased more than the price of foods high in sugar and fat.[77,78] Increases in food prices affect those living in poverty to a greater extent and reduce access to healthy food. The disparity between socioeconomic status and fruit and vegetable intake has increased over time. Results from the 5 A Day for Better Health Program, which encourages consumption of fruits and vegetables, indicate that, although awareness of the program in the 1990s increased, intake declined in nonwhite racial and ethnic groups.[79] This finding may help explain the change in vegetable intake at the end of the 20th century. Americans living in poverty are more likely to be food insecure.[78]

Groups with higher socioeconomic status tend to consume higher amounts of most vitamins, minerals, and fiber, regardless of overall energy intake.[77,80] According to National Food Consumption Survey from the 1970s through the 1990s, individuals living in poverty consume less magnesium.[69] Sex, race, age, income, and education level, as well as poverty level, are all associated with magnesium intake.[22,23,25,80] NHANES III (1988–1994) data indicate older adults experiencing food insecurity consume only 58% of the RDA for magnesium, while their food-secure counterparts consume 77% of the RDA ($P < 0.05$).[78] Older adults in the United States with higher income meet the EAR for magnesium to a significantly higher extent than those with low income (39% vs 22%; $P < 0.05$), owing to a healthier overall dietary pattern.[40] NHANES 2011–2012 data show that the prevalence of US adults meeting the EAR is greater for those with the highest income (≈72%) than for those living in poverty (≈50%; $P < 0.001$), and those living in poverty are less likely to take any dietary supplement (63% of those with higher income vs 52% in the lowest poverty group; $P < 0.001$).[81] Nevertheless, it is important to note that some studies found over half the adults in the high-income group consumed less than the EAR.[82] In either scenario, a significant portion of well-educated, healthy adults also consume inadequate amounts of magnesium.

CHANGES IN MAGNESIUM INTAKE OVER TIME

The data thus far support the idea of a population with less access to and lower consumption of magnesium compared with the previous century's population. However, comparison of the National Food Consumption Survey from 1977 to 1978 with the NHANES from 2013 to 2014 shows that mean magnesium intake in men 20 years and older increased from 283 mg/d to 345 mg/d, and mean intake in women of the same age increased from 204 mg/d to 268 mg/d (Figure 2 and Table S1 in the Supporting Information online) (J.D. Goldman, Food Surveys Research Group, Agricultural Research Service, United States Department of Agriculture, personal communication, April 2017). The data are consistent with research showing mean magnesium consumption among US adults to be 200 to 300 mg/d, a decrease from a mean of 400 to 500 mg/d a century ago.[8–10] Yet, despite evidence to the contrary, Figure 2 indicates overall magnesium intake among US adults may be returning to levels seen a century ago. These surveys confirm that women consume less magnesium than men and that older adults and females aged 20 to 29 years do not currently meet the EAR, although mean intakes in these age groups continue to increase along with intakes among the rest of the population.

EVIDENCE OF INADEQUATE MAGNESIUM STATUS

The information available on magnesium intake among US adults is often contradictory. According to several population-based studies investigating magnesium intake among US adults since the start of the 21st century, a majority do not consume the EAR. Yet 24-hour recall data from population-based surveys indicate an overall increase in magnesium intake among adults, with mean intake reaching the EAR as of 2014. Results of population-based studies should be interpreted with caution, however, as consumption data from such studies have known limitations. Over the years, the manner in which intake data are analyzed has changed or has differed by investigator, making it difficult to compare results. Some studies group foods according to conceptually and nutritionally similar characteristics but do not disaggregate food mixtures.[83] The result is potentially inflated values for some macro- and micronutrients.[70] Other studies separate food mixtures into individual ingredients and are then able to assess the nutrient contribution of each food, which results in a more accurate portrayal of percent distribution.[70] Comparing studies that used differing methods may result in flawed conclusions about changes in consumption over time. Survey methods themselves can make it difficult to compare data if they do not properly use weighting adjustment (which assigns an adjustment weight to each survey respondent).[84] The 24-hour recall is the most commonly used instrument for dietary data collection used in surveillance and is the tool used in What We Eat in America, the dietary component of the NHANES.[85] A limitation of the 24-hour recall is that intake varies greatly from day to day and is not indicative of long-term intake, although at the population level the 24-hour recall is thought to provide valid estimates of nutrient intake.[86] Inadequate interviewer training and lack of inter-rater reliability are additional limitations of 24-hour recalls. Decisions about the degree of probing for additional details for foods or recipes, as well as the use of default ingredients in recipes, affect the results. Trained interviewers are utilized for What We Eat in America and methods are validated.[87]

The availability of reliable food composition databases to analyze 24-hour intake data, in addition to the use of appropriate statistical modeling to calculate the distribution of usual intake in a population, is essential for producing accurate dietary recall data.[85] Evidence shows that magnesium levels in food have decreased over time. The amount of magnesium in food varies with the season and with agricultural practices and can change frequently, depending on manufacturer reformulations of products. Food composition data for analysis of dietary intake must be continuously updated to reflect these changes. The US Department of Agriculture (USDA) Agricultural Research Service provides the food and nutrient databases used for population-based analyses. The National Nutrient Database for Standard Reference is the main source of food composition data in the United States.[88] It is updated annually, and data are derived from USDA-contracted analyses, the food industry, and the scientific literature. The Food and Nutrient Database for Dietary Studies provides nutrient values and weights for typical food portions and is the underlying database for analyzing 24-hour recalls from survey responders in What We Eat in America.[88] The Food and Nutrient Database for Dietary Studies contains no missing values, and it is updated biennially. The nutrient values for the Food and Nutrient Database for Dietary Studies are derived from the National Nutrient Database for Standard Reference. Food composition data are integral to the success of all federal dietary surveys by the USDA and the US Department of Health and Human Services. The ability of these agencies to keep pace with changes in the US food system is commendable, but the databases are limited by the high cost of food analysis, coupled with funding constraints.[89]

The Nutrition Data System for Research is a Windows-based program designed for the collection

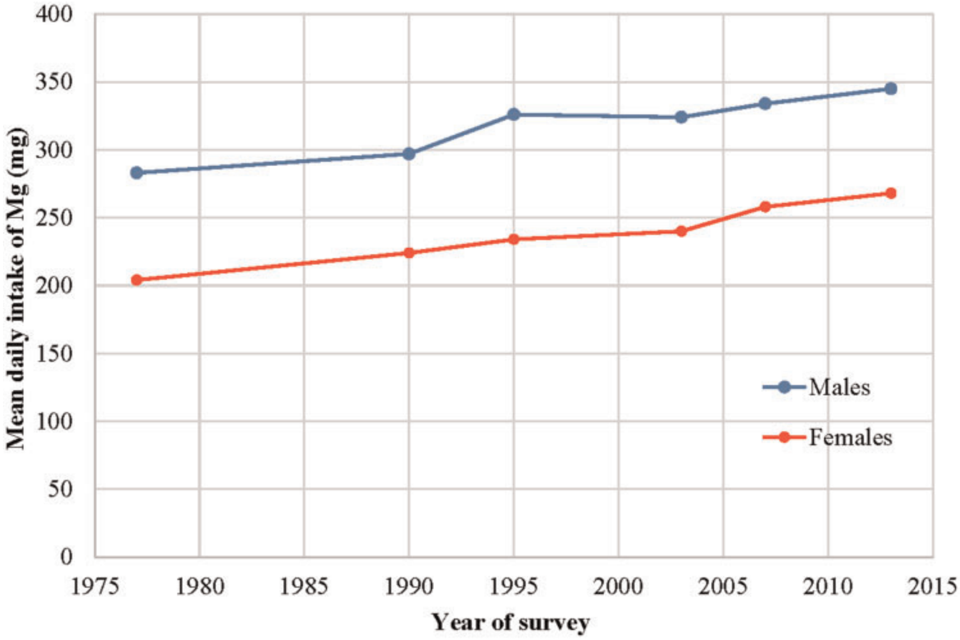

Figure 2 **Magnesium intake among US adults over time.** Based on data from historical USDA food intake surveys in Table S1 available in the Supporting Information online. Source data provided by J.D. Goldman, Food Surveys Research Group, Agricultural Research Service, United States Department of Agriculture (personal communication).

and analysis of 24-hour dietary recalls, food records, menus, and recipes. It combines data from the USDA Agricultural Research Service, food manufacturers, and scientific literature and includes more individual products than the Food and Nutrient Database for Dietary Studies.[89] The database, developed and supported by the Nutrition Coordinating Center at the University of Minnesota, is used frequently in nutrition research The importance of having accurate values for the nutrient content of food items prompted a recent study that compared phosphorous values reported in Nutrition Data System for Research for 46 products with results from a food analysis laboratory.[90] The results indicated 78% of the products contained levels of phosphorous that exceeded the Nutrition Data System for Research reference values. This small study investigated the potential effects of inaccuracies in the nutrient database on study results. While it involved only a single nutrient, it points to the possible limitations of current nutrient databases used in research; such limitations could diminish the ability to use study results to make decisions about the nutritional status of the population. Aware of the limitations of the National Nutrient Database for Standard Reference, the USDA Agricultural Research Service now complements the foods available in the USDA National Nutrient Database with the USDA Branded Food Products Database.[91] This addition greatly expands the number of food items in the database, but many of the branded foods do not include information on magnesium content, making it difficult to monitor the population's magnesium intake.

FUTURE DIRECTIONS

In early 2015, as a result of the Dietary Guidelines Advisory Committee listing magnesium as a shortfall nutrient, a working group convened in the United States to assess the evidence for the need to revise the serum magnesium reference level. The group concluded that adequate scientific data exist to warrant an increase in the reference level to improve clinical care and public health.[7] To define the reference level, a validated biomarker that most reflects magnesium status is needed; whether it is a dietary, urinary, serum, or combination marker is still undetermined. Other recommendations from the group include addressing methods of improving the content of magnesium in crops and packaged foods, increasing public awareness and education on the importance of magnesium in the diet, and developing systems to monitor magnesium insufficiency.[7] While the development of a validated biomarker is essential, it will not be achieved quickly. The other recommendations are either already being implemented as part of larger public health initiatives or could be implemented relatively easily.

Increasing the nutrient content of crops, minimizing nutrient loss during processing, and preserving nutrients during transport is possible. The amount of magnesium that plant foods provide can be greatly improved by increasing the availability of magnesium during growth and production.[92] Magnesium applications to the soil take time to become incorporated into crops; however, foliar sprays of Epsom salts can increase the magnesium content of plants within 6 weeks.[93] Agronomic practices that encourage supplying adequate nutrients to the plant during vegetation, increasing the percentage of edible plant parts, and using high-efficiency fertilizer along with methods to minimize leaching are additional suggested techniques for increasing magnesium in food.[43] The quality and nutrient content of fruits and vegetables is determined by the characteristics of the supply chain (time since harvest and type of processing).[94] Preservation methods can reduce the nutritional losses and increase shelf life, thereby minimizing the impact of "food miles."[94]

Consuming a variety of foods high in magnesium should be encouraged in all adults, regardless of the presence of lifestyle factors or chronic diseases that increase the risk of deficiency. Eating more whole grains, vegetables, legumes, nuts, and seeds can lead to higher intakes of magnesium and other shortfall nutrients. Decreased reliance on refined sugar and oils decreases the risk of magnesium deficiency. Modeling of various dietary scenarios indicates increasing plant foods by 100% of current intake and eliminating animal products decreases the percentage of people with inadequate magnesium intake by 5% to 8%.[26] Increasing dairy products by 100% without changing the amount of intake from plant foods decreases the rate of inadequate magnesium by 12%, but this model also increases energy intake by almost 200 kcal/d.[26] An increase in total kilocalorie intake with increased dairy intake would need to be counterbalanced with other dietary or lifestyle changes. The total amount of calcium consumption should be considered when recommending dairy to increase magnesium intake, since calcium—at very high levels—competes with magnesium for absorption.[56]

Increasing the magnesium concentration in the plant, thereby increasing how much magnesium is consumed, might be more feasible than changing eating patterns, since evidence that simply increasing awareness and knowledge of good nutrition practices leads to long-term behavior change is lacking.[95] Education level affects purchasing power as well exposure to and understanding of dietary information and healthy behavior messages.[80] Strategies to encourage healthy eating patterns must be continually evaluated and revised to stay current with consumer needs and changes in the market. Since magnesium intake is lower in minority groups, future programs aiming to improve dietary patterns and, thus, to increase magnesium intake should focus not only on raising awareness of the health benefits of vegetables, legumes, nuts, and seeds but also on the cultural aspects of dietary preferences.[96,97]

Not addressed by the working group is the use of supplements to fill the gap between magnesium from food intake and the RDA. There have been no reported cases of hypermagnesemia from food alone, even in people with inadequate kidney function, and toxicity from supplements is rare.[6] Supplements can play a large role in meeting magnesium needs.[82] Adults whose diet or medical history puts them at higher risk for deficiency may benefit from magnesium supplements in highly absorbable forms, such as magnesium salts. Supplements are generally tolerated in doses below the upper tolerable limit of 350 mg/d in those with adequate kidney function, though higher doses can cause gastrointestinal upset.[6] Gastrointestinal upset acts as a limiting factor in the amount of magnesium that is consumed and leads to decreased intake or termination of consumption prior to reaching toxicity levels. Changes in the serum magnesium concentration occur within weeks of initiation of magnesium supplementation.[16]

Hypomagnesemia is rarely caused by inadequate dietary intake of magnesium.[14] As discussed, this may partly be due to the body's ability to utilize stores and maintain an adequate serum magnesium concentration in times of deficiency. Many causes of magnesium insufficiency are not well understood or are not easily modifiable. Magnesium absorption and excretion may be affected by any of the following: compounds in food, such as phytic acid, oxalic acid, and protein; chronic conditions such as diabetes and gastrointestinal disorders; behaviors such as smoking and alcohol consumption; medications; and aging.[6,44,98–101] More research is needed to determine the overall effect of these factors on net magnesium levels. At this time, increasing magnesium intake through changes in agricultural processes and by encouraging consumption of whole foods is likely a more realistic approach to ensuring adequate magnesium status in adults in the United States.

CONCLUSION

Until a valid biomarker for magnesium status is discovered, continued monitoring of magnesium intake via future population-based studies is essential. Despite the potential for decreased magnesium intake as a result of changes in agricultural practices and dietary patterns, mean magnesium intake in adults in the United States has improved over the past 40 years. However, positive dietary trends can stall and then decline, so continued monitoring is necessary. In the meantime, since the health consequences of inadequate magnesium are well established, there are few reasons not to encourage increased magnesium intake from food, especially since magnesium is found in healthy foods adults should consume more often and there are no reported cases of hypermagnesemia from food alone.

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Supporting Information

The following Supporting Information is available through the online version of this article at the publisher's website.

Table S1 **Mean daily magnesium intake (in milligrams) in US adults based on data obtained from USDA food intake surveys**

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