

Update on the relationship between magnesium and exercise

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Abstract. Magnesium is involved in numerous processes that affect muscle function including oxygen uptake, energy production and electrolyte balance. Thus, the relationship between magnesium status and exercise has received significant research attention. This research has shown that exercise induces a redistribution of magnesium in the body to accommodate metabolic needs. There is evidence that marginal magnesium deficiency impairs exercise performance and amplifies the negative consequences of strenuous exercise (*e.g.*, oxidative stress). Strenuous exercise apparently increases urinary and sweat losses that may increase magnesium requirements by 10-20%. Based on dietary surveys and recent human experiments, a magnesium intake less than 260 mg/day for male and 220 mg/day for female athletes may result in a magnesium-deficient status. Recent surveys also indicate that a significant number of individuals routinely have magnesium intakes that may result in a deficient status. Athletes participating in sports requiring weight control (*e.g.*, wrestling, gymnastics) are apparently especially vulnerable to an inadequate magnesium status. Magnesium supplementation or increased dietary intake of magnesium will have beneficial effects on exercise performance in magnesium-deficient individuals. Magnesium supplementation of physically active individuals with adequate magnesium status has not been shown to enhance physical performance. An activity-linked RNI or RDA based on long-term balance data from well-controlled human experiments should be determined so that physically active individuals can ascertain whether they have a magnesium intake that may affect their performance or enhance their risk to adverse health consequences (*e.g.*, immunosuppression, oxidative damage, arrhythmias).

Key words: magnesium, exercise, physical performance, mineral

Nutritional status influences the ability to routinely perform vigorous physical activity, and physical activity influences nutrient use. Among the nutrients whose status relationship to physical activity or exercise has received significant attention is magnesium. This is not surprising because magnesium is involved in numerous processes that affect muscle function including oxygen uptake, energy production (ATP and phosphocreatine synthesis), and electrolyte (sodium, potassium, and calcium) balance. The effect of exercise on magnesium requirements and utilization, and the effect of magnesium deficiency and supplementation on performance of exercise have been reviewed numerous times [1-12] since it was reported in 1983 that magnesium supplementa-

tion alleviated muscle spasms occurring with intense exercise in a female tennis player [13]. These reviews present convincing evidence that exercise affects the metabolism and utilization of magnesium and a fair amount of evidence indicating that magnesium supplementation improves the physical performance of magnesium-deficient individuals and not of individuals with an adequate magnesium status. Information in these reviews, complemented when appropriate by information from pertinent older original articles, will be summarized to provide a background for recent findings providing some insight about the nutritional importance of magnesium for physically active individuals.

Magnesium requirements and intakes

Because of the lack of a relatively non-invasive simple status indicator, it is difficult to determine when an individual has a low or deficient magnesium status resulting in an impaired physical performance that may be improved by magnesium supplementation or increased dietary intake. Perhaps the best method for getting an indication of magnesium status is to assess whether magnesium intake is adequate. But even this is troublesome because of the lack of consensus as to what is considered an adequate intake. Dreosti [5] in 1995 found that the adult recommended dietary intakes for magnesium ranged from 220 to 400 mg/day throughout the world.

The problem with establishing a firm recommended intake or requirement for magnesium is the lack of data. This is exemplified by the following. In 1997, the U.S. Food and Nutrition Board, Institute of Medicine set the magnesium Recommended Dietary Allowances (RDAs) for men and women between ages 31 and 50 years at 420 and 320 mg/day [14], respectively, which are consistent with the recommendation of 6 mg/kg body weight/day suggested by Seelig [15] and Durlach [16]. The U.S. RDAs for men and women between ages 19 and 30 years were set slightly lower, 400 and 310 mg/day, respectively [14]. The RDA was defined as the average daily dietary intake sufficient to meet the requirement of nearly all (97-98%) individuals in a life stage and gender group or the Estimated Average Requirement (EAR) + 2 Standard Deviations of the EAR. The EAR was defined as the intake estimated to meet the requirement, determined by using a specified indicator of adequacy (*e.g.*, balance), for 50% of the individuals in a life stage and gender group. The EARs for men and women between ages 19 and 30 years were determined to be 330 and 255 mg/day, respectively. The magnesium RDAs and EARs were based almost exclusively on findings from one poorly controlled balance study performed in 1984 [17]. In that study, subjects consumed self-selected diets in their home environment and were responsible for the collection of their urine, feces and duplicate diet and beverage samples used in the balance determinations. The samples were only collected one week every season for one year. The magnesium content of the self-selected diets of nine men aged 20-35 years ranged from 190 to 595 mg/day and intakes ranging from 204 to 595 mg/day were sufficient to maintain balance in four men. The five men who did not maintain balance had magnesium intakes ranging from 190 to 526 mg/day. The magnesium content of self-selected diets of the eight women aged 20-35 years ranged

from 132 to 350 mg/day and intakes ranging from 213 to 304 mg/day were sufficient to maintain balance in three women. The five women who did not maintain balance had magnesium intakes ranging from 132 to 350 mg/day. Similar data from subjects older than 35 years in the same experiment [14] were used to set the RDAs and EARs 20 and 10 mg/day higher for men and women older than 30 years, respectively. Because of the tenuous nature of the data used, the U.S. EARs and RDAs for adults have been appropriately questioned. For example, an expert consultation for the Food and Agriculture Organization/World Health Organization (FAO/WHO) concluded that evidence was lacking for nutritional magnesium deficiency occurring with the consumption of diets supplying a range of magnesium intakes sometimes considerably less than the U.S. RDA or the U.K. equivalent to the RDA called Recommended Nutrient Intake (RNI) [18]. Based on this conclusion, the expert consultation subjectively set RNIs for magnesium at 220 and 260 mg/day for women and men, respectively, age 19-65 years.

Some recent reports have given stronger data on which to determine an average intake that would result in magnesium-deficient status for the average person. Based on balance data and findings of heart rhythm changes and impaired physiologic function in men and postmenopausal women fed slightly less than 200 mg/day under controlled metabolic unit conditions [19, 20], consistent magnesium intakes less than the RNIs set by the FAO/WHO probably would result in a deficient status. Individuals engaged in intense exercise may become deficient at 10-20% higher intakes because of increased losses through sweat and possibly urine (see below).

The recent U.S. National Health and Nutrition Examination Survey (NHANES) 2001-2002 [21] and a French survey [22] indicated that a significant number of people routinely have magnesium intakes that may result in a deficient status. In France, the mean magnesium intakes of a large population of men and women were determined to be 369 and 280 mg/day, respectively [22], which are near the 75 percentiles for the U.S. [21]. The NHANES 2001-2002 also estimated that the magnesium intakes of 25% of adult males and females were 251 and 184 mg/day, respectively, and the intakes of 10% of adult males and females were 206 and 148 mg/day, respectively [21]. In reviews [9-11] of dietary surveys of highly trained male and female athletes participating in sports with high caloric requirements (*e.g.*, cyclists, skiers, and soccer and football players) it has been found that their magnesium intakes often exceeded 260 and 220 mg/day, respectively. A recent survey of the

dietary behavior of German adults engaging in different levels of physical activity also found that the median magnesium density was higher in the diets of active persons [23]. In contrast, reviews [9-11] of the literature revealed that athletes participating in sports requiring weight control (*e.g.*, wrestling, gymnastics) often consumed less than the FAO/WHO RNI. Thus, a significant number of physically active people apparently would find it beneficial to increase their intake of magnesium.

Effect of exercise on magnesium requirements

The effect of exercise on the distribution and excretion of magnesium has been extensively studied. Reviews [9, 10] of these studies found that exercise resulted in a redistribution of magnesium in the body and the type of exercise and magnesium status influenced the nature of this redistribution.

Early studies (see references in review by Bohl and Volpe [11]) indicated that short-term, high-intensity exercise transiently increased plasma or serum magnesium concentrations by 5-15%; the concentrations returned to baseline within a day. The increase was associated with a decrease in plasma volume. More recent studies also have found that sustained moderate physical exercise (80 km march of 18 hr duration) [24] and short-term high intensity (anaerobic) exercise [25] increased serum magnesium concentration. Instead of decreased plasma volume, muscle breakdown was suggested as the cause of increased serum magnesium found shortly after exercise [24] and this suggestion was supported by the finding of a concomitant small increase in serum creatine kinase activity [26]. Another possible contributor to the increased serum or plasma magnesium is the transfer of magnesium from muscle to the extracellular fluid during contraction similar to that known for potassium.

Past (see references in review by Bohl and Volpe [11]) and recent studies [27, 28] found that prolonged endurance exercise (*e.g.*, marathon running or cross-country skiing), in contrast to short-term, high-intensity exercise, decreased plasma and serum magnesium concentrations. This decrease generally returned to baseline within a day and has been attributed to the movement of magnesium into other body compartments and an increase in excretion through sweat and urine. Regardless of the nature of the effect, the change in extracellular magnesium apparently reflects that the body is responding to exercise by redistributing magnesium to locations with increased metabolic need for such processes as

energy production and counteracting oxidative stress. Because extracellular magnesium is only 1% of total body magnesium, it is unlikely that a transient change in plasma magnesium during exercise is an indication of an altered magnesium status. This notion is supported by findings from a recent study [29] indicating that magnesium status affects the magnitude and direction of the shift in plasma magnesium. Ten female subjects performed a standardized 9-minute cycle ergometry program before and after being placed on a "high" magnesium diet (257 mg/day) for 10 days. Before the diet change, only small increases or decreases occurred in plasma magnesium in response to exercise, and the changes did not correlate with the basal magnesium concentration. After the diet change, plasma magnesium increased and the changes in plasma magnesium induced by exercise were 13 times greater and correlated with the basal magnesium concentration. Similar findings have been observed with dietary zinc restriction [30]. Men were fed diets containing 8.6, 3.6 and 33.6 mg/day of zinc and underwent maximal exercise testing. Compared to an adequate zinc intake (≈ 9 mg/day), pre- and post-exercise plasma zinc concentrations decreased significantly with low zinc, and increased significantly with supplemental zinc. After correction for exercise-induced changes in hematocrit, plasma zinc content declined from +1.8 to -7.4 and rebound to +6.9% when dietary zinc changed from adequate to restricted to supplemental intakes. This finding indicates zinc mobilization from tissue stores when zinc intake is adequate, and mobilization is impaired when dietary zinc is inadequate. Similarly, small increases or decreases in plasma magnesium with exercise may indicate a deficient magnesium status and a relatively large transient decrease in serum magnesium during exercise most likely indicates a normal magnesium status and not magnesium deficiency during exercise.

If the decrease in serum magnesium is not transient, it may indicate that exercise increases the magnesium requirement to a point where intake is inadequate and thus results in a sub clinical or deficient status. Some studies found that prolonged sustained (*e.g.*, 12 months) moderate physical training decreased serum magnesium to concentrations that may be considered deficient (*i.e.*, 0.689 mmol/L compared to reference values of 0.8-1.2 mmol/L) [24, 31]. Unfortunately, the dietary magnesium intakes in these studies were not fastidiously assessed, but some intakes of the military trainees may have been marginal because it was estimated they ranged from 270-340 mg/day. The suggestion that the decreased

serum magnesium concentration indicated the development of magnesium deficiency is supported by the finding of concomitant long-term decreases in cellular (*e.g.*, lymphocyte and erythrocyte) magnesium concentrations. Lymphocyte [24] and erythrocyte [20, 32] magnesium concentrations have been suggested to be indicators of altered magnesium status.

The body compartment that is most responsible for the transient decrease in extracellular magnesium has not been definitively identified. Erythrocytes, adipocytes, and myocytes have each been suggested to be the primary site to which magnesium is transferred from serum or plasma. Based on the need for magnesium for biochemical processes involved in increased physical activity, perhaps all sites are involved.

Early studies (see references in review by Bohl and Volpe [11]) found that a bout of cross-country skiing or marathon running increased erythrocyte magnesium concentration, and similarly to the associated decreased serum magnesium, the concentration returned to baseline within a day. It was suggested that the increase in erythrocytes occurred because magnesium was needed for glycolysis and NADPH production. One study, however, found decreased erythrocyte magnesium after a marathon race [34], and more recently, it was reported that anaerobic exercise (stepwise treadmill ergometer test) did not change total magnesium but increased ionized magnesium in erythrocytes (and thrombocytes) while decreasing total and ionized magnesium in serum [35]. The lack of a change (or decrease) in total intracellular magnesium suggests that a total magnesium shift between the intracellular and extracellular compartments of blood is not responsible for the decrease in serum magnesium during exercise. Nonetheless, the increase in the fraction of ionized magnesium located intracellularly supports the suggestion that exercise changes intracellular signaling and metabolic processes involving magnesium in the erythrocyte.

Some studies have found that strenuous exercise decreased erythrocyte or monocyte [24] magnesium concentration and the decrease persisted during a season of training. Instead of redistribution resulting from a change in immediate metabolic need, this finding may have been indicating a reduced magnesium status caused by increased sweat and urinary losses. Decreased erythrocyte magnesium has been found to indicate a decreased magnesium status in controlled magnesium deprivation studies [20, 32]. Also, exercise has been found to amplify the

decrease in erythrocyte magnesium concentration in marginally magnesium-deficient rats [36].

The basis for the suggestion that magnesium is shifted from serum to adipocytes during a prolonged strenuous exercise activity is that free fatty acids reportedly increase in serum at the completion of endurance exercise (see review by Bohl and Volpe [11]). This apparently occurs because lipolysis is exaggerated towards the end of endurance exercise when muscle glycogen becomes depleted. Magnesium is taken up by adipocytes during lipolysis that produces the free fatty acids.

The basis for the suggestion that a transient shift of magnesium to myocytes from the extracellular fluid occurs during prolonged strenuous exercise includes reports that magnesium apparently slowly increases in exercising muscle in parallel to decreases in plasma magnesium [37], and that prolonged exhaustive exercise increased muscle magnesium [38]. Animal experiments also have shown that magnesium increases in muscle (and liver) after maximal exercise [39] and physical training [40]. The increased myocyte magnesium may be the result of increased need for high-energy phosphorus and to counteract oxidative stress caused by high oxygen utilization during muscle contraction.

Recent research confirms past research reviewed by Resina *et al.* [41]. Magnesium fluxes occur during and after aerobic exercise (*figure 1*). Magnesium moves from the plasma into adipocytes and active skeletal muscle during physical activity. The degree of the translocation of extracellular magnesium into these sites is modulated by the level of aerobic energy production or use. Immediately following aerobic exercise, a redistribution of magnesium from tissues to the circulation occurs. Magnesium is mobilized from bone, as well as soft tissues, muscle

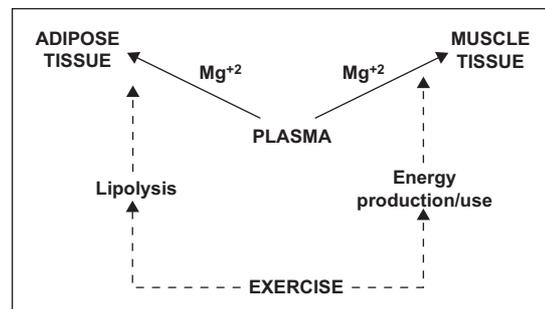


Figure 1. Magnesium fluxes of during aerobic physical activity. Solid arrows indicate magnesium fluxes. Abbreviated arrows reflect modulating factors (adapted from [41]).

and adipose tissue, to restore pre-exercise plasma magnesium concentrations (*figure 2*). The degree of muscle damage, which is a function of the intensity and duration of the exercise bout, is a factor in magnesium release from skeletal muscle. Although tubular reabsorption mechanisms act to minimize urinary losses of magnesium, post-exercise excretion of magnesium in the urine is elevated compared to pre-exercise values because of increased circulating lactic acid concentrations.

Thus, the transient redistribution of magnesium from extracellular fluid to other body compartments after an acute or prolonged strenuous exercise activity should be considered an indication that magnesium is being transferred to tissues where it is urgently needed, and not that the exercise is causing a magnesium-deficient state. But long-term reduction in plasma or serum magnesium concentration in parallel with decreased erythrocyte magnesium concentration during long-term strenuous exercise or training may indicate that the exercise has increased magnesium requirements, such that intake is inadequate for maintaining an optimal magnesium status. Confirmation of a depressed magnesium status would be improved oxygen utilization and physical performance upon increasing magnesium intake either by diet or supplementation.

The judgment that exercise may result in an increased magnesium requirement has been prompted by reports of increased sweat loss and urinary excretion of magnesium after both short-term high-intensity and long-term strenuous exercise

or training. Major sweat losses of magnesium may occur in individuals exercising in a hot humid environment; a study described in 1963 found that 12% of magnesium excreted daily was through sweat [42], another study in 1977 indicated that between 18 and 60 mg magnesium/L of sweat may be lost [37], under such an environment. Other studies have found much lower concentrations of magnesium in sweat in a hot dry environment (3.4 mg/L) [43] and under hot humid conditions (12.2 mg/L) [44], but the amount lost apparently is still significant in individuals performing intense exercise with a high amount of sweating.

Exercise may also significantly increase the loss of magnesium through urine. Both prolonged and short-term, high-intensity exercise have been found to increase urinary magnesium excretion; urinary magnesium excretion returned to pre-exercise values the day after the short-term exercise [11, 25]. Other studies, however, have found that urinary excretion of magnesium is decreased after exercise. For example, Monterio *et al* [45] found that urinary magnesium excretion was reduced two hours after a treadmill exercise and returned to baseline level 48 hours later. Other studies found that urinary magnesium excretion was decreased after a full-marathon race [27, 28] and high intensity bicycle ergometry [46]. Tubular reabsorption rate of magnesium was elevated for one week after a marathon race [28]. Women participating in karate excreted less magnesium in urine than controls [47]. Still, significant evidence exists to indicate that long-term strenuous exercise increases magnesium loss through urine. Women participating in handball, basketball and running had increased urinary excretion of magnesium (means ranged between 26 to 52 mg higher) compared to controls [47]. Rowing athletes participating in extended and intensive training loads also exhibited increased urinary magnesium excretion [48]. A recent study with horses in race training also supports the concept that the predominant effect of long-term strenuous exercise is an increase urinary magnesium excretion [49]. The reason for high-intensity exercise, and perhaps long-term exercise, apparently increasing urinary magnesium excretion is open to speculation. The horse study suggests that the increased excretion is not the result of increased intestinal absorption efficiency [49]. It has been suggested that renal tubular reabsorption of magnesium is reduced [11]. Among the suggested initiators of this reduction are increases in hormones such as aldosterone and antidiuretic hormone, which are increased during strenuous exercise. But one study found no correlation between the circulatory level of

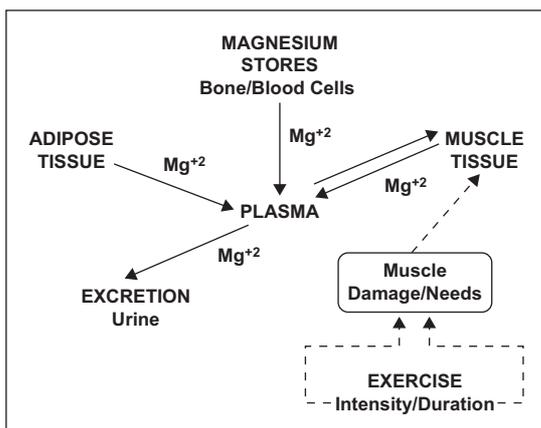


Figure 2. Magnesium fluxes following aerobic exercise. Solid arrows indicate magnesium fluxes. Abbreviated arrows reflect modulating factors (adapted from [41]).

these hormones and tubular reabsorption rate of magnesium after a full marathon race [28]. Thus, hormone changes may have a limited impact on urinary magnesium excretion with long-term strenuous exercise. Increased lactic acid production resulting in a metabolic acidosis which causes magnesuria also has been suggested as a cause for hypothesized decreased tubular reabsorption. This hypothesis is supported by the finding that the percent increase in urinary magnesium correlated with blood lactate concentration after short-term, high-intensity exercise and also with oxygen consumption during recovery [50].

Based on the preceding sweat and urinary excretion findings, one may suggest that an individual routinely participating in strenuous exercise has a magnesium requirement 10-20% higher than the average sedentary person of the same age and sex.

Effect of magnesium deficiency on exercise performance

Based on findings from experimental animals and in humans made deficient by drugs or disease, severe magnesium deficiency results in muscle weakness, neuromuscular dysfunction, and muscle cramping or spasms (see reviews [1-12]). However, it is unlikely that a severe magnesium-deficiency will occur in a healthy exercising individual consuming a varied diet. But, as indicated above, marginal magnesium deficiency is a distinct possibility for some strenuously exercising individuals consuming magnesium-poor foods (*e.g.*, meat, eggs, and refined carbohydrates) instead of magnesium-rich foods (*e.g.*, whole grains, pulses, legumes and green leafy vegetables), and may impair exercise performance. The possibility of marginal magnesium deficiency impairing performance is supported by the finding that marginally magnesium-deficient rats exhibited reduced exercise capacity or endurance on a treadmill [1]. Also, a marginal magnesium-deficiency was found to impair exercise performance in untrained postmenopausal women in a controlled metabolic unit study [20]. Heart rate and oxygen consumption increased significantly during submaximal exercise when the women were fed 150 mg *versus* 320 mg/d. Further support is provided by two reported cases of muscle cramps or spasms resolved by magnesium supplementation in strenuously exercising individuals [13, 51]. In one case, magnesium supplementation also normalized neuromuscular excitability and decreased lactate dehydrogenase and creatine kinase activities [51]. These individuals were deter-

mined to be magnesium-deficient before supplementation began. There is a lack of reports showing that magnesium supplementation improved performance of individuals with established magnesium-adequate status.

Differences in magnesium status may be the reason for the numerous conflicting reports about the effect of magnesium supplementation on exercise performance. Because many studies did not assess, and others used insensitive methods to assess, the magnesium status of individuals before supplementation started, positive effects may have been found only in individuals that had a deficient magnesium status. For example, a magnesium supplement of 360 mg/day compared to a placebo decreased serum creatine kinase after training in competitive female athletes with plasma magnesium concentrations at the low end of the range of normal values [4]. Also, in a study of young men participating for seven weeks in a strength-training program and consuming about 250 mg magnesium/day (most likely an inadequate intake), a greater increase in peak knee-extension torque was found in those fed an additional 250 mg/day than those fed a placebo [52]. Similar types of intakes by moderately trained adults resulted in those receiving a supplemental 250 mg magnesium/day (instead of a placebo) having improved cardiorespiratory function during a 30-minute submaximal exercise test [53]. Recently it was found that football players with a regular plan of training of 8 hours/week did not show a change in serum magnesium concentration after a cycle ergometer test which suggests they had a low or deficient magnesium status (see above) [54]. Magnesium supplementation decreased serum ammonia concentration which suggests a better use of carbohydrates during exercise and thus a beneficial response of an exercising individual with a low magnesium status. Dietary magnesium has been found to be a significant predictor of improvement in 100-yard swim performance of male and female collegiate swimmers [10].

In contrast to these studies, a study of marathon runners with adequate magnesium status showed that they did not benefit from supplemental magnesium [55]. Trained runners, supplemented with 365 mg/d of magnesium for six weeks showed no improvement in running performance, no increase in resistance to muscle damage, and no improvement in skeletal muscle function. The likelihood that the runners were magnesium-adequate was supported by the finding that the supplementation did not increase muscle magnesium. In a crossover-designed experiment, it was found that a 212 mg magnesium/day

supplement as magnesium oxide compared to a placebo for 4 weeks had no effect on exercise performance and recovery of physically active women [56]. Many of the women in this experiment probably were not magnesium-deficient at the initiation of magnesium supplementation because of the crossover experimental design. This inference is supported by findings from a controlled magnesium deprivation experiment with postmenopausal women using a crossover design [57]. After several weeks of consuming a diet supplying about 400 mg magnesium/day, an intake of about 120 mg/day took several weeks to have an effect on variables indicating magnesium deficiency.

The reasons for marginal magnesium deficiency impairing exercise performance measures have not been clearly defined. Deficiency experiments with experimental animals suggest that the impairment is not caused by a single lesion but is multifactorial. An early proposal for the mechanism through which magnesium deficiency impairs performance was the reduction of erythrocyte 2,3-diphosphoglycerate synthesis, which would reduce the delivery of oxygen to the working muscle [58]. However, an experiment with rats discounted this hypothesis [36]. Recently it was suggested that the finding of less efficient use of oxygen by magnesium-deficient individuals performing exercise may result from augmented mitochondrial respiratory activity and enhanced neuromuscular excitability [20]. Support for this suggestion is that decreased skeletal muscle magnesium and serum magnesium was associated with a partial uncoupling of the respiratory chain and a reduced ADP to oxygen ratio in rat liver mitochondria [59]. The neuromuscular excitability increase may be caused by increased intracellular calcium. Recent controlled metabolic unit studies have shown that magnesium deprivation increases calcium retention [60, 61]. Some of this calcium may be retained in muscle because animal experiments have shown that magnesium deficiency increases muscle calcium [62]. This increase apparently occurs because magnesium deficiency impairs the calcium pump and sodium/calcium exchange across the cell membrane [63]. The calcium pump transports calcium ions from the cytosol to the stores of sarcoplasmic reticulum after muscle contraction. This pump uses a high amount of energy – one ATP per two calcium ions, and the calcium transport-ATPase is magnesium-dependent. Also, one ATP is needed to move one calcium ion out of a cell during the sodium/calcium exchange. The end result of increased intracellular calcium is excessive oxygen and ATP consumption, and hyperexcitability that

may lead to such things as muscle cramps and fatigue.

Additional concerns for the magnesium-deficient exercising individual

Magnesium deficiency may amplify other undesirable effects of exercise. In addition to performance, the importance of adequate magnesium status for optimal immune function and recovery from oxidative damage or stress in the physically active individual has received some attention.

Strenuous physical exercise induces oxidative stress or the production of reactive oxygen species. The physiological processes involved in reactive oxygen species production during exercise has been reviewed by Laires and Monteiro [9]. This review also presents some possible mechanisms through which magnesium deficiency may amplify oxidative damage caused by strenuous exercise, or vice versa because magnesium deficiency has been shown to cause increased reactive oxygen species in experimental animals [64]. The increase has been associated with ultrastructural damage in skeletal muscle (*i.e.*, swollen mitochondria and disorganized sarcoplasmic reticulum) [64]. Also, dietary magnesium deficiency has been shown to induce a pro-oxidant/pro-inflammatory response in rodents characterized by enhanced free radical (lipid radicals and nitric oxide) production, accumulation of oxidation products and pro-oxidant metals, depletion of endogenous antioxidants (*e.g.*, glutathione), and elevated circulating inflammatory mediators including substance P [65, 66]. Increased circulating substance P was found to be an early response to magnesium deprivation, or may be considered a response to marginal magnesium deficiency. The increased substance P has been postulated to be the result of increased intracellular calcium, which also apparently is induced by marginal magnesium deficiency (see above). Increased circulating substance P after an exercise test has been observed in humans [67]. The provocative findings suggesting a relationship between oxidative stress induced by exercise and marginal magnesium deficiency such that one may amplify the adverse effects of the other evinces the desirability for further studies to determine whether a relationship exists.

The effect of exercise on immune function also has been reviewed [9, 68]. Intense physical exercise has been associated with immunosuppression. Immunosuppression has been attributed to decreased helper/suppressor T-cell ratio and natural killer (NK)

cell activity and elevated stress hormones. Also, circulating amounts of various types of white blood cells have been shown to change after prolonged strenuous exercise. For example, white blood cells were increased during a three-day cross country ski race [69]. Exercise to exhaustion increased circulating granulocytes and post-exercise lymphopenia [68]. It has been found that magnesium status influences some of these changes induced by exercise. A sustained moderate physical training that decreased serum magnesium concentrations to concentrations considered marginal or deficient decreased circulating monocyte numbers [24]. In contrast, magnesium supplementation of magnesium-adequate individuals did not affect exercise-associated changes in immune cell function or numbers [70]. Thus, magnesium deficiency may amplify decreased immune responses induced by strenuous exercise, but magnesium supplementation will not prevent those that occur when magnesium status is adequate.

Finally, it should be noted that controlled metabolic unit studies with post-menopausal women have shown that marginal magnesium deficiency may result in arrhythmias and induce changes in potassium metabolism that may affect heart function [32, 33, 60]. High potassium gradients are characteristic for cells with high metabolic activity [63]. In addition to skeletal muscle, the myocardium has high metabolic activity. Strenuous exercise may amplify undesirable cardiovascular changes induced by a marginal magnesium deficiency by exacerbating the marginal deficiency or by increasing metabolic activity impaired by magnesium deficiency.

Conclusion

Exercise induces a redistribution of magnesium in the body to accommodate metabolic needs. This redistribution accounts for changes in magnesium concentrations in extracellular fluids, blood cellular components, myocytes and adipocytes. Most evidence indicates that strenuous exercise increases urinary and sweat magnesium losses. Based on dietary surveys and recent human experiments, a magnesium intake less than 260 mg/day for male and 220 mg/day for female athletes may result in a magnesium-deficient status. Marginal magnesium deficiency has been shown to impair performance and amplify the negative consequences of strenuous exercise. Thus, magnesium supplementation or increased dietary intake of magnesium could be beneficial to physically active individuals with a low or deficient magnesium status. Magnesium supplementa-

tion of physically active individuals with an adequate magnesium status has not been shown to enhance physical performance. Activity-linked RNIs or RDAs based on long-term balance data from well-controlled experiments are needed for magnesium.

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