Health significance of drinking water calcium and magnesium

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Introduction

As far as the chemical quality of drinking water is concerned, such issues as endocrine disruptors, pesticides, disinfection by-products and other contaminants are the subject of interest while natural water constituents, non-toxic at usual concentrations and possibly beneficial to health, remain out of focus. Calcium and magnesium as major representatives of these constituents have been extensively studied for years, but surprisingly, the extensive data available and the knowledge acquired has had a negligible effect on the regulatory field.

If only a part of the findings on the beneficial effects of calcium (Ca) and magnesium (Mg) in drinking water are true, and most of the existing indices seem to support such opinion, possible regulatory measures concerning the minimum Ca and Mg contents of drinking water would be of higher benefit to public health than the effort not to exceed the maximum limits for some contaminants however justified such limitations are.

Furthermore, this issue is closely related to another weak point of the current regulatory approach to defining drinking water quality. A clearly negative definition has been used, insisting on the absence, more precisely on the strictly limited presence, of certain undesirable substances. Based on this approach, we can tell whether a given drinking water is safe but we cannot definitely tell whether it is really good and beneficial to health.

Therefore, distilled water or another pure liquid H_2O prepared by any other means would surely meet the criteria of the absence of any contaminants and could be considered as ideal in the light of the negative definition of quality. Nevertheless, such water is not representative of drinking water, let alone good drinking water. From the chemical point of view, drinking water is a complex system of mineral substances and gases dissolved in it. The present contribution summarizes the existing knowledge of health significance of drinking water Ca and Mg and the attempts to reflect it in regulation and suggests how to bridge the regulatory gaps in this field.

Calcium, magnesium and water hardness

If we want to work on calcium and magnesium in drinking water, a third parameter is to be taken into account: water hardness, even if this term is incorrect and obsolete from a strictly chemical point of view. That is to say that both of these elements largely have not been analysed individually in drinking water in the past, but just non-specifically in summary as hardness. This approach was applied in many studies focused on health effects of this “water factor”.

Since the definition of water hardness is approached either analytically or technologically, it was not and still has not been defined in a unified manner, and as with other parameters, multiple definitions have been available and multiple units have been used to express it (German, French, and English degrees; equivalent $CaCO_3$ or CaO in mg/l).

Initially, water hardness was understood to be a measure of the capacity of water to precipitate soap, which is in practice the sum of concentrations of all polyvalent cations present in water (Ca, Mg, Sr, Ba, Fe, Al, Mn, etc.); nevertheless, since the other ions (apart from Ca and Mg) play a minor role in this regard, later it has been generally accepted that hardness is defined as the sum of the Ca and Mg concentrations, determined by the EDTA titrimetric method, and expressed in mmol/l (ISO, 1984) or as $CaCO_3$ equivalent in mg/l (Standard Methods, 1998), less frequently as the CaO equivalent.

From the technical point of view, multiple different scales of water hardness were suggested (e.g. very soft – soft – medium hard – hard – very hard). Expectedly, both extreme degrees (i.e. very soft and very hard) are considered as undesirable concordantly from the technical and health points of view, but the optimum Ca and Mg water levels are not easy to determine since the health requirements may not coincide with the technical ones.

Calcium and magnesium presence in waters

Water calcium and magnesium result from decomposition of calcium and magnesium aluminosilicates and, at higher concentrations, from dissolution of limestone, magnesium limestone, magnesite, gypsum and other minerals. Anthropogenenic contamination of drinking water sources with calcium and magnesium is not common but drinking water may be intentionally supplemented with these elements while treated, as happens with deacidification of underground waters by means of calcium hydroxide or filtration through different compounds counteracting acidity such as $CaCO_3$, $MgCO_3$ and MgO, and possibly also with stabilization of low-mineralized waters by addition of CaO and CO_2.

In low- and medium-mineralized underground and surface waters (as drinking waters are), calcium and magnesium are mainly present as simple ions Ca^{2+} and Mg^{2+} , the Ca levels varying from tens to hundreds of mg/l and the Mg concentrations varying from units to tens of mg/l.

Magnesium is usually less abundant in waters than calcium, which is easy to understand since magnesium is found in the Earth's crust in much lower amounts as compared with calcium. In common underground and surface waters the weight concentration of Ca is usually several times higher compared to that of Mg, the Ca to Mg ratio reaching up to 10. Nevertheless, a common Ca to Mg ratio is about 4, which corresponds to a substance ratio of 2.4 (Pitter, 1999).

Physiological role of calcium and magnesium in the human body

Both of these elements are essential for the human body. Calcium is part of bones and teeth. In addition, it plays a role in neuromuscular excitability (decreases it), good function of the conducting myocardial system, heart and muscle contractility, intracellular information transmission and blood coagulability. Osteoporosis and osteomalacia are the most common manifestations of calcium deficiency; a less common but proved disorder attributable to Ca deficiency is hypertension. Based on newly acquired epidemiological data, implication of Ca deficiency in other disorders is currently being discussed. The recommended Ca daily intake for adults ranges between 700 and 1000 mg (Scientific Committee for Food, 1993; Committee on Dietary Reference Intake, 1997). Some population groups may need a higher intake.

Magnesium plays an important role as a cofactor and activator of more than 300 enzymatic reactions including glycolysis, ATP metabolism, transport of elements such as Na, K and Ca through membranes, synthesis of proteins and nucleic acids, neuromuscular excitability and muscle contraction etc. It acts as a natural antagonist of calcium. Magnesium deficiency increases risk to humans of developing various pathological conditions such as vasoconstrictions, hypertension, cardiac arrhythmia, atherosclerotic vascular disease, acute myocardial infarction, eclampsia in pregnant women, possibly diabetes mellitus of type II and osteoporosis (Rude, 1998; Innerarity, 2000; Saris *et al*, 2000). These relationships reported in multiple clinical and epidemiological studies have recently been more and more supported by the results of many experimental studies on animals (Sherer et al, 2001). The recommended magnesium daily intake for an adult is about 300-400 mg (Scientific Committee for Food, 1993; Committee on Dietary Reference Intake, 1997).

Beginnings of research into health significance of water hardness

That drinking water is also an important source of essential (i.e. essential to life) elements such as Ca and Mg was already known before world war II (Kabrhel, 1927; Widdowson, 1944). The significance of drinking water calcium for nutrition was underlined in the 1940's by a German nutritionist R.Hauschka who recommended sodium hydrogen sulphate to be added to water prior to boiling in order to maintain the level of dissolved calcium and to prevent loss of calcium due to precipitation (Hauschka, 1951).

Health significance of water hardness was directly evidenced in the late 1950's. The relationship between water hardness and the incidence of vascular diseases was first described by a Japanese chemist Kobayashi (Kobayashi, 1957) who showed, based on epidemiological analysis, higher mortality rates from cerebrovascular diseases (stroke) in the areas of Japanese rivers with more acid (i.e. softer) water compared to those with more alkaline (i.e. harder) water used for drinking purposes.

Several studies followed and most of them confirmed an inverse correlation between water hardness and mortality from cardiovascular diseases (CVD). Among the best known studies were those by H.A.Schroeder who demonstrated, among others, correlation between mortality from CVD in males aged 45-64 years and water hardness in 163 largest cities of the USA (Schroeder, 1960) and summarized his results using the following compelling dictum: „soft water, hard arteries". Other studies were published by Morris in Wales (Morris *et al*, 1961) and Canadian, Finnish, Italian, Swedish and other authors. A review of most relevant papers of the 1960's is given e.g. in a WHO Bulletin (Masironi *et al*, 1972) or by Sharrett and Feinleib (Sharrett *et al*, 1975).

An interesting British study (Crawford *et al*, 1971) focused on variation in mortality from CVD depending on water hardness in 11 British cities between 1950 and 1960. Water hardness increased in five cities and decreased in six cities. Within the given period mortality from CVD in the UK increased by 10% on average compared to 20% in the cities supplied with softer water than before and compared to 8,5% only in the cities supplied with harder water than before.

It is interesting to note that significant differences in cardiovascular pathology and the magnesium content of the cardiac muscle were found between males who had died from infarction and those who had been victims of traffic accidents and between those living in the areas with soft or hard water: harder water was associated with a higher magnesium content of the cardiac muscle (Crawford ***et al***, 1967; Anderson ***et al***, 1973; Neri ***et al***, 1975; and six other studies given in Rubenowitz ***et al***, 1999). Correlation between the water Mg level of and the Mg content of skeletal muscles is also described in a Swedish study of the late 1980's (Landin ***et al***, 1989).

Within the first two decades of research into water hardness in association with CVD more than 100 papers were published (Hewitt ***et al***, 1980).

From the very beginning the crucial question was what the „unknown water factor" responsible for the positive/negative effect on CVD morbidity was. Apart from the calcium and magnesium content alone as the major factor implicated in water hardness and possibly the Ca to Mg ratio, a role played by other trace elements both beneficial to health (Li, Zn, Co, Cu, Sn, Mn, Cr ...) and toxic (Pb, Cd, Hg) was considered; nevertheless, no significant correlation between the content of any of these elements in water and CVD morbidity was found or repeatedly confirmed in other studies. Attention was paid not only to the theory of the content of these elements at source but also to higher corrosive potential of soft water that can support higher leakage of toxic compounds from the water pipe network.

Over the years, evidence has accumulated that magnesium is the major beneficial agent involved, while calcium has only a supportive effect against CVD (Eisenberg, 1992). Although only two out of three studies have shown correlation between cardiovascular mortality and water hardness, the studies carried out on the water magnesium alone have practically all shown an inverse correlation between cardiovascular mortality and water magnesium level (Durlach ***et al***, 1985).

In the late 1970's, the issue of an optimum composition of drinking water, particularly if obtained by desalination, was in the centre of attention of the WHO. The WHO also emphasized the importance of mineral composition of drinking water and warned e.g. against the use of cation exchange sodium cycle softening in water treatment (WHO, 1978; WHO, 1979). An international group of experts who met in 1975 under the auspicies of the European Commission also concluded: „although it has not yet been possible to establish any relationship between the cause and effect, the existence on an association between water hardness and mortality cannot be dismissed" (Amavis ***et al***, 1976).

The 1980's and criticisms of the existing epidemiological studies

In the 1980's the wave of interest in the effect of water hardness on CVD morbidity rather subsided; it seemed that any new insight into the issue could not be expected. The focus was on confirming the role of magnesium as a crucial factor of hardness and on first attempts of more general quantification of its protective effect (see below).

What made a new challenge to publication of further studies in the 1990's were criticisms of the existing studies (e.g. Comstock, 1980). Such criticisms were partly justified since based on new epidemiological methods: they revealed methodical drawbacks of the previous studies that were mostly ecologic. This means that they evaluated morbidity at a population group-based level rather than at an individual-based level and did not establish individual exposure to calcium and magnesium from water. Some of the studies did not even analyse water for the calcium and magnesium content, but focused on water hardness only, and consequently, did not allow to specify the implication of either calcium or magnesium. In other studies, the confounders possibly involved in CVD morbidity such as age, socio-economic factors, alcohol consumption, eating habits, climatic conditions etc. were not adequately taken into account. Nevertheless, most studies dealing with individual exposure confirmed an inverse correlation between the drinking water Mg level and the risk to population of developing CVD as described in ecologic studies, e.g. a vast Finnish cohort study (Punsar *et al*, 1979), a case-control study carried out in the same country (Luoma *et al*, 1983), an American study (Zeighami *et al*, 1985) and a USSR study (Novikov *et al*, 1983).

The criticisms also pointed out that not all studies then had found correlation between water hardness and CVD morbidity. This is less compelling since water hardness is only one - and probably not the crucial one – of multiple factors possibly involved in CVD morbidity. If other factors which are not taken into account prevail, the effect of water hardness may be biased. In some cases, such „failures“ to document water hardness effect were retrospectively explained by a low level of crucial magnesium in hard water and subsequent insignificant difference in the Mg content between soft and hard water (Bar-Dayan *et al*, 1997). Such explanation seems to be also applicable to the results of a Norvegian ecologic study (Flaten *et al*, 1991) showing even a slightly positive correlation between the magnesium content of drinking water and CVD morbidity, but all the areas studied had extremely soft water containing less than 2 mg Mg/l.

These criticisms seem to be at the origin of the WHO position adopted with respect to the last *Guidelines for drinking water quality* elaborated in 1990-1993. In spite of former enthusiastic opinion of the WHO on water hardness importance, the *Guidelines* cautiously admitted some weak relationships between hardness and health, but concluded: “the available data are inadequate to permit the conclusion that association is causal. No health-based guideline value for water hardness is proposed”. Only sensorial and technical disadvantages of extremely hard and extremely soft water were specified (WHO, 1993). Nonetheless, some studies on water hardness published in the 1980’s are referred to in the 2nd volume of the *Guidelines* (WHO, 1996); surprisingly, some less important or methodically less developed studies (e.g. Kubis, 1985) are listed among the references rather than other studies of highest epidemiological significance.

The 1990‘s: correlation with cardiovascular diseases confirmed and new knowledge

Most new epidemiological studies of the 1990’s were able to specify the effect of either calcium or magnesium and also focused on morbidity other than CVD; studies meeting the current methodical standards were published in high impact epidemiological journals. Protective effect of both drinking water magnesium and calcium against CVD was confirmed and more data on beneficial effect of these elements in drinking water on human health are presented. A review of all epidemiological studies of 1990-2000 and some older ones dealing with the relationship between drinking water composition and CVD is given by Sauvant and Pepin (Sauvant *et al*, 2002).

A Swedish ecologic study found a significant inverse correlation between water hardness and mortality from CVD for both males and females and a significant correlation between the drinking water magnesium level and mortality from CVD in males (Rylander *et al*, 1991). In all districts where the drinking water magnesium level was higher than 8 mg/l (but not higher than 15 mg/l), the CVD mortality rates were lower. Another Swedish case-control study focused on the effect of the drinking water Mg and Ca levels on mortality from acute myocardial infarction (AMI) in females showed a statistically significantly lower mortality rate (by 34%) in the areas supplied with water containing more calcium (> 70 mg/l) as compared to those where the drinking water calcium level was < 31 mg/l; a similar finding was presented independently for magnesium: the mortality rate was by 30% lower in the areas where the water Mg content was > 9,9 mg/l compared to those where the water Mg content was < 3,4 mg/l (Rubenowitz *et al*, 1999).

Another Swedish case-control study showed a significant correlation between male mortality from AMI the Mg content of water. Cases were 854 men from 17 municipalities in the southern part of Sweden who had died of AMI between ages 50 and 69 years during the period 1982-1989. The controls were 989 men of the same age in the same area who died from cancer during the same period. Only men who consumed water supplied from municipal waterworks were included in the study. The group with hard water (> 9,8 mg Mg/l) had a mortality rate from AMI by 35% lower as compared with the consumers of soft water (< 3,5 mg Mg/l). Any correlation with the water Ca content was not reported (Rubenowitz *et al*, 1996).

Another study of the same type and by the same authors focused on correlation between the drinking water Mg and Ca levels and morbidity and mortality from AMI in 823 males and females aged 50-74 years in 18 Swedish districts, who had developed AMI between October 1, 1994 and June 30, 1996 (Rubenowitz *et al*, 2000). The study took into account both individual exposure to Ca and Mg from water and food and other known risk factors for AMI likely to bias the correlation, if any. Although for calcium the correlation with AMI was not confirmed, magnesium proved to reduce the risk level by 7.6 % in the group of the quartile with the highest water Mg level (≥ 8,3 mg/l) compared to groups exposed to water containing lower levels of magnesium. Although the total AMI rates were similar in all four groups, the persons enrolled in the group with the highest water Mg level had a risk level of death from AMI by a third lower (odds ratio 0.64) as compared to the groups consuming water containing less Mg than 8.3 mg/l. Multivariate analyses showed that the correlation found is not caused by other known risk factors. This finding supports the hypothesis that magnesium prevents primarily sudden death from AMI, rather than all ischemic heart disease deaths or the risk of suffering an AMI.

Another ecologic Swedish study analyzing causes of a marked difference in anti CVD drugs consumption between two districts found the difference in water hardness to be one of possible causes in this regard (Oreberg *et al*, 1992). Another ecologic study from seven Central Swedish districts ascribes higher mortality rates from IHD (by 41%) and from stroke (by 14 %) to water softness (Nerbrand *et al*, 1992).

In contrast to this series of Swedish studies confirming the correlation mentioned above, another Swedish study surprisingly concluded that in cold areas in Sweden, the climate (more precisely the so-called cold index) has a higher effect on mortality from CVD than water hardness (Gyllerup *et al*, 1991).

An ecologic study of Tennessee (Erb, 1997) found mortality from CVD to be by 19% lower in the areas supplied with hard water (161 mg $CaCO_3$/l) compared to soft water (39 mg $CaCO_3$/l). Even more compelling were the conclusions of an extensive study (a total of 3013 cases of 1973-1983) carried out in the former German Democratic Republic: in an area supplied with very hard water (Mg content close to 30 mg/l) the incidence rate of AMI was 20.6 per 10000 population while in the areas supplied with soft water (Mg content about 3 mg/l) the rate was as high as 32.7; the difference was even higher in younger age categories

(Teitge, 1990). A Serbian environmental study (Maksimovic *et al*, 1998) also found out a marked difference in mortality from CVD between the population groups supplied with drinking water with a „low“ Mg level (less than 20 mg/l) and a high Mg level (52 to 68 mg/l).

The difference in the drinking water Mg level as the most probable explanation for different rates of myocardial calcifications in persons who died from AMI is reported by authors of a study carried out in Salt Lake City and Washington D.C. (Bloom *et al*, 1989). The significance of a low drinking water magnesium level as a risk factor for CVD particularly in males is underlined by Rylander's review article (Rylander, 1996).

Multiple past and recent epidemiological studies reported lower rates of sudden deaths from CVD (including sudden deaths in infants) in the areas with harder water (Crawford *et al*, 1972; Anderson *et al*, 1975; Eisenberg, 1992; Bernardi *et al*, 1995; Garzon *et al*, 1998). It is hypothesized that magnesium deficiency is implicated in cardiovascular spasms and cardiac arrhythmias leading to death.

Only a statistically slightly significant link between water hardness and geographical differences in mortality from cerebrovascular diseases was revealed in a study of North Dakota (Dzik, 1989); similar findings were reported by a French environmental study not only for cerebrovascular diseases but also for IHD (Sauvant *et al*, 2000); nevertheless, water hardness was taken as a general factor regardless of Ca to Mg levels.

While health effects of most chemicals commonly found in drinking water manifest themselves after a long exposure only, the effects of calcium and in particular those of magnesium on the cardiovascular system are believed to reflect the current exposure which means that a couple of monts are sufficient for „adaptation“ to a new source of water with low content of magnesium and/or calcium. Adaptation here does not mean adaptation of the organism to the water of an inadequate composition but time within which the intake of drinking water of inadequate composition may manifest itself by a disorder of consumer's health (Rubenowitz *et al*, 2000). Illustrative are cases among Czech and Slovak population who started to use reverse osmosis-based systems for final treatment of drinking water at their home outlets in 2000-2002 and several weeks later reported different health complaints suggestive of acute magnesium deficiency.

New knowledge of protective effects of drinking water calcium and magnesium

Calcium alone probably has a positive protective effect against some neurological disturbances in the elderly as evidenced by a French case study. The results in a region supplied with drinking water containing Ca > 75 mg/l were by 20% more favourable compared to a drinking water Ca level < 75 mg/l (Jacqmin *et al*, 1994). A Mallorca study reported that children in the areas supplied with drinking water containing higher calcium levels showed statistically significantly lower incidence of fractures compared to those supplied with water poorer in calcium, if drinking water fluorides and socio-economic conditions were taken into account (Verd Vallespir *et al*, 1992).

While in males no study evidenced that the water calcium level could have an effect on the risk for death from myocardial infarction, in females a low water calcium level proved to be one of the risk factors in this regard (Rubenowitz *et al*, 1999). Reality of such relationship is supported by the known fact that calcium deficiency may cause hypertension. Meta-analysis of several studies including almost 40 thousand population showed an inverse correlation between the calcium intake from food and blood pressure (Capuccio *et al*, 1995). Moreover, several mechanisms are known by which the calcium implication in blood pressure fall can be explained (Rubenowitz *et al*, 1999).

An inverse correlation between the calcium intake with food and blood pressure was also described in pregnant women in whom calcium supplementation is effective in blood pressure reduction. Higher intake of calcium is believed to decrease smooth muscle contractility and tonus, which clinically results in lower blood pressure and lower rate of pre-term births. In this light, an epidemiological combined ecologic case-control study was carried out in Taiwan in 1781 females: relationship between the drinking water calcium level and birth weight of first borns was analyzed. Drinking water calcium was found to be a beneficial protective factor statistically significantly reducing the risk for pre-term birth and low birth weight (Yang *et al*, 2002).

An inverse correlation between the intake of an element with food and blood pressure was confirmed in most studies also for magnesium (Mizushima *et al*, 1998).

A low magnesium content of drinking water was found to be a risk factor for motor neuron disease (Iwami *et al*, 1994) and preeclampsia in pregnant women (Melles *et al*, 1992). Discordant results were obtained in the studies dealing with correlation between the drinking water magnesium level and the incidence of diabetes mellitus. Although a Taiwan study (Yang *et al*, 1999a) reported protective effect of magnesium or lower incidence of diabetes mellitus in the areas supplied with water with higher magnesium levels, an American study (Joslyn *et al*, 1990) did not find such a correlation.

A low intake of Ca and Mg with drinking water seems to be a risk factor for amyotrophic lateral sclerosis (Yasui *et al*, 1997), while higher levels of these elements in drinking water may have protective effect against caries and periodontal disease even if the fluorides content of water is low (Skljar *et al*, 1987). Russian epidemiological studies (predominantly of ecologic type) found significantly higher incidence rates of hypertension, IHD, adrenergic function disturbances, gastric and duodenal ulcer and other diseases in the areas with soft water (less than 1.5 mmol/l) (Loseva *et al*, 1988; Plitman *et al*, 1989; Lutai, 1992).

German study did not find any correlation between the incidence of endemic goitre and the drinking water calcium and magnesium levels (Sauerbrey *et al*, 1989), while a Russian ecologic study reported higher incidence of goitre in the population supplied with low-mineralized water (Lutai, 1992).

Water hardness and cancer. In the late 1990's several epidemiological studies were carried out in Taiwan to focus on relationships between drinking water hardness and mortality from various diseases showing significant geografical variation. Magnesium was found to have protective effect against cerebrovascular diseases (Yang, 1998) and hypertension (Yang *et al*, 1999b), water hardness showed protective effect against CVD (Yang *et al*, 1996), cancer of oesophagus (Yang *et al*, 1999c), cancer of pancreas (Yang *et al*, 1999d), cancer of rectum (Yang *et al*, 1999e) and breast cancer (Yang *et al*, 2000), drinking water calcium proved protective against colorectal cancer (Yang *et al*, 1997) and gastric cancer (Yang *et al*, 1998). These were combined ecologic case-control studies. Further studies from other countries are needed to confirm these results. Although previous studies dealing with relationships between water hardness and the incidence of cancer elsewhere in the world were mostly suggestive of protective effect of hard water, the results were ambiguous as stated in a review paper

(Cantor, 1997) underlining the need for further studies in this promising field. The epidemiological findings are supported by the clinical discussion on positive role of calcium in both food and water in colorectal cancer prevention (Pence, 1993).

Antitoxic effect of calcium and magnesium

Calcium and to a lower extent also magnesium in both drinking water and food were previously found to have a beneficial antitoxic effect since they prevent – via either a direct reaction resulting in an nonabsorbable compound or competition for binding sites – absorption or reduce harmful effects of some toxic elements such as lead, cadmium etc. (Thompson, 1970; Levander, 1977; Oehme, 1979; Hopps *et al*, 1986; Nadeenko *et al*, 1987; Plitman *et al*, 1989; Durlach et al, 1989). Nevertheless, this protective effect is limited quantitatively.

Disproportion between the high protective effect and low nutritive contribution of drinking water Mg and Ca

A detailed critical analysis of the studies on the drinking water magnesium level and the incidence of IHD was presented by Marx and Neutra (Marx *et al*, 1997). As in other studies (Neutra, 1999), the authors focus on how the relatively low magnesium intake with drinking water (usually less than 10 % of the total daily magnesium intake) can reduce mortality from CVD by even 30 %. Several explanations are possible and several causes may be implicated at a time.

It is generally known that modern refined food does not contain enough magnesium and that most adult population either fail to cover or just cover the recommended daily intake of magnesium and therefore live close to the permanent Mg deficiency. These conclusions were concordantly drawn from surveys carried out in many industrialized countries. For instance, the Ministry of Agriculture of the USA, based on surveys among 37 thousand population in the late 1970's, reported the recommended daily intake of magnesium to be met or exceeded in 25 % of them only; in contrast, as many as 39 % of population had lower magnesium intake than 70 % of the recommended daily intake (Marier, 1986). Subsequent studies confirmed these findings and reported that most Americans intake less Ca and Mg than recommended and that even many subjects took less than 80% of the recommended dietary allowances (RDA) for Mg – it is to be noted that in general, *„as of this date, RDAs have not addressed prevention of chronic diseases"* (Marx *et al*, 1997). In the Czech Republic, the calcium and magnesium intake with food is close to the lower limit of the recommended daily intake and the deficiency may easily manifest itself in some population groups. In the year 2000, the the recommended daily intakes for Mg and Ca were covered to 83 % and 91 %, respectively (Ruprich *et al*, 2001). In Germany, insufficient intake of magnesium was recorded in 15 % of children on average: it reached 25 % in children in northern Germany supplied usually with soft water, i.e. was 3 to 4 times higher as compared with the percentage in southern regions supplied mostly with water rich in magnesium and calcium (Schimatschek, 2003).

Under such conditions, even the relatively low intake of Mg with drinking water may be of relevance for prevention or reduction of Mg deficiency. Let's have a closer insight into that „low intake". In Ontario, it was found that the difference in Mg intake from the hardest and the softest drinking waters was 53 mg Mg/day (Marier *et al*, 1985), which is definitely more than 10% of the total intake. Absorption of magnesium from food in the intestine is about 30%, while magnesium from water where it is present in free cation form is absorbable to a higher extent - from 40 % to 60 % as reported (Durlach *et al*, 1985; Durlach, 1988; Neutra, 1999; Sabatier *et al*, 2002), i.e. Mg absorbability from water is by 30 % higher compared to dietary magnesium (Marx *et al*, 1997). Drinking water is also a relatively more suitable source of Mg and Ca than food since it is generally true that the higher the amount of these elements is available, the lower proportion of them is absorbed (Böhmer *et al*, 2000; Sabatier *et al*, 2002).

Soft water was proved to reduce markedly the content of different elements (including Mg and Ca) in food if used for cooking vegetables, meat and cereals (WHO, 1978; Haring *et al*, 1981; Oh *et al*, 1986; Durlach, 1988). Up to 60% for magnesium and calcium! In contrast, if used for cooking, hard water is responsible for much lower loss of elements or may even fortify the calcium content of the food prepared. Therefore, in the areas supplied with soft water, we have to take into account not only a lower intake of magnesium and calcium from drinking water but also a lower intake of magnesium and calcium from food due to cooking in such water. All these aspects contribute to better understanding of the „relatively low intake“ of magnesium from drinking water. Anyway, protective effect of drinking water magnesium may not be linearly (quantitatively) proportional to the share of drinking water in the total intake of this element.
Durlach (Durlach, 1988; Durlach *et al*, 1989) repeatedly underlines the so-called qualitative importance of water magnesium. Its higher bioavailability as compared with food magnesium is not due only to its increased GIT absorption (better biodisposability), but also to its increased utilization probably resulting from the biologically advantageous (hexahydrated) form of water magnesium (Theophanides *et al*, 1990).
Repeated tests on animals yielded highly surprising results: the animals given the element studied (i.e. Zn or Mg) with drinking water showed statistically significantly higher increase of this element in the serum than those given a much higher amount of these elements with food and demineralized water to drink. Based on experiments and clinical observation that mineral deficiency in patients receiving balanced intravenous nutrition (to be diluted with distilled water) where intestinal absorption does not need to be considered, the authors presume that demineralized water intake is responsible for increased elimination of minerals from the organism (Robbins *et al*, 1981). A similar mechanism could also apply to soft low-mineralized water.

Some researchers say that the differences in mortality from CVD (or those in the incidence of other diseases) could be explained by the effect of other confounders such as physical activity, eating habits, obesity, alcohol consumption, socio-economic conditions etc. and that these confounders may give a false positive idea of the effect of calcium or magnesium in water. The most compelling counter-argument to these objections is that there is no reason to expect that there could be any correlation between the lifestyle factors mentioned above and water hardness resulting from the environmental conditions.

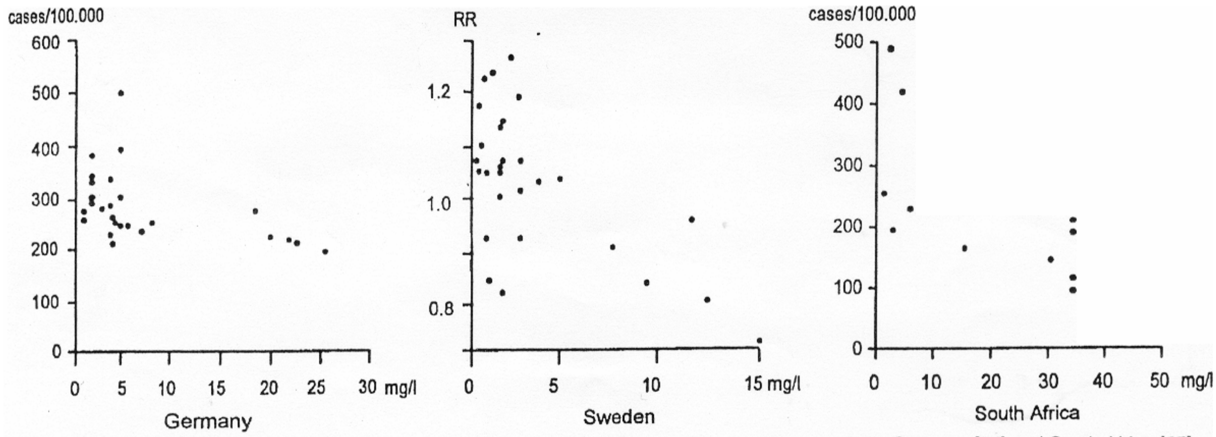
Magnesium: dose (concentration in water) – response relationship

First attempts to quantify the protective effect of water magnesium date back to the 1960’s. For instance, based on Schroeder’s American studies, it was estimated that an increase in the water magnesium level by about 8 mg/l led to reduction of mortality from all CVD by about 10%; similarly, based on a South African study, it was estimated that an increase in drinking water magnesium by 6 mg/l led to reduction of mortality from IHD equally by about 10% (Marier *et al*, 1985). An extensive East German study reported an even lower value: if drinking water magnesium is reduced by about 4.5 mg/l, the incidence of myocardial infarction increases by 10% (Teitge, 1990).

Pocock et al. (1980) described a negative non-linear relationship between CVD mortality and water hardness, based on the data from a British Regional Heart Study (regional variations in cardiovascular mortality in 253 towns during 1969-73). The adjusted standardised mortality ratios decreased steadily in moving from a hardness of 0.1 to 1.7 mmol/l (10 to 170 mg $CaCO_3$/l) but changed little in moving from 1.7 to 2.9 mmol/l (170 to 290 mg/l) or more. The model estimated that in the range below 1.7 mmol/l an increase in total hardness of 1 mmol/l – say from 0.5 to 1.5 mmol/l – while keeping other variables constant should result in a 7.2 % decrease in CVD mortality, whereas there was no evidence of an equivalent decrease beyond 1.7 mmol/l.

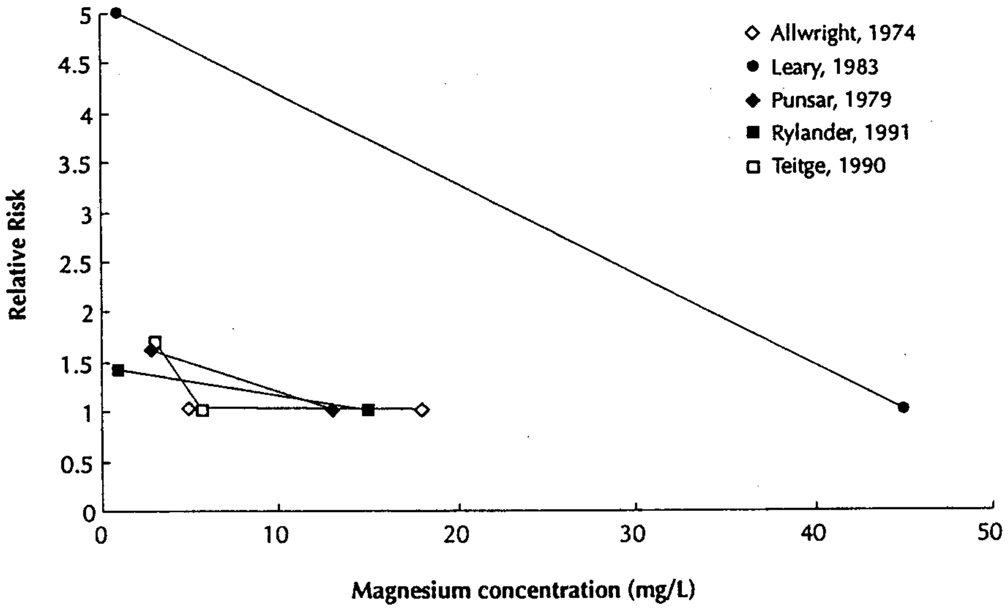
Out of six studies analyzed by Marx and Neutra (Marx *et al*, 1997) the decrease in the absolute cardiovascular mortality ranged from 0.1 per mg (of Mg) per 100,000 population in a Los Angeles study (Allwright *et al*, 1974) to 20.0/mg/100,000 in a Finnish study (Punsar *et al*, 1979). The relative risk decrease ranged from 0.001 to 0.034 per mg of magnesium. Several authors attempted to represent this relationship diagrammatically.

Figure 1 taken from Rylander (Rylander, 1996) shows correlation between CVD mortality in males and drinking water magnesium levels, based on German (Teitge, 1990), Swedish (Rylander *et al*, 1991) and South African (Leary *et al*, 1983) studies.



Relation between cardiovascular death among men and drinking water magnesium levels in Sweden [36], Germany [34] and South Africa [35].

Figure 2 taken from the study by Marx and Neutra (Marx *et al*, 1997) shows relative risk of ischemic heart disease as a function of water magnesium concentration in five rate-based studies (Allwright *et al,* 1974; Leary *et al,* 1983; Punsar *et al*, 1979; Teitge, 1990; Rylander *et al*, 1991).



Swedish researchers presume that the protective effect of drinking water magnesium against CVD mortality is of a threshold nature, more precisely that it starts working from the values above about 8 mg/l (Rubenowitz *et al*, 2000). This conclusion is drawn from Swedish studies (Rylander *et al*, 1991; Rubenowitz *et al*, 1996, 1999 a 2000), one South African study (Leary *et al*, 1983) and one German study (Teitge, 1990). Nevertheless, this does not mean that different magnesium levels either above or below this limit would be associated with the same risk. The opinion may be a point of departure for possible recommendations for drinking water magnesium levels or legislative measures.

Significance of the magnesium to calcium ratio

Since the 1960's, some authors consider the absolute content of both elements in water (diet) to be of the same importance as the magnesium to calcium ratio (Seelig, 1964; Karppanen, 1981; Durlach *et al*, 1989). Durlach's recommendation that the Mg to Ca total intake ratio should be 1 to 2 (Durlach, 1989) as required for the best Mg absorption has still been valid. Theoretical derivation of the recommended Mg to Ca ratio in water can be supported by several epidemiological studies suggestive of negative effects of variations in this ratio in both directions: decrease in the Mg to Ca ratio was associated with increasing risk for mortality from IHD and AMI (Itokawa, 1991; Rubenowitz *et al*, 1996) while the increase in the Mg to Ca ratio was associated with increasing risk for gastric cancer (Sakamoto *et al*, 1997). Nevertheless, any definitive conclusions or recommendations cannot be drawn from the data available; a low water Mg to Ca ratio was always associated with a low water Mg level and the water Mg level has proved to play a more important role in risk reduction (e.g. for AMI) as compared with the Mg to Ca ratio (Rubenowitz *et al*, 1996).

Bioavailability of drinking water calcium and magnesium

Some non-professionals are of opinion, supported and spread mainly by the manufacturers of devices for production of distilled and demineralized water (Bragg *et al*, 1998), that the human body is not able to use the essential minerals from drinking water, which in contrast clog up the body (similarly as happens to the pipes) and cause harm to it. Nevertheless, no study is available to support such idea. On the other hand, multiple studies have shown that intestinal absorption of calcium from drinking or mineral water is as effective or even more effective as compared with that from dairy products (e.g. Halpern *et al*, 1991; Heaney *et al*, 1994; Couzy *et al*, 1995; Van Dokkum *et al*, 1996; Wynckel *et al*, 1997; Guillemant *et al*, 1997). Meta-analysis of the studies published in 1966 – 1998 even evidenced that calcium absorption from mineral water is statistically significantly higher than that from dairy products (Böhmer *et al*, 2000). Based on this evidence, it was recommended to use waters richer in calcium as an important additional source of calcium in menopausal women, lactose intolerant people or those avoiding dairy products because of their taste or high fat content.

Not only absorbability is in question. Many studies have documented that water calcium can be easily used by the body: intake of drinking water rich in calcium correlated with higher bone density in elderly women in France (Aptel *et al*, 1999); similar results were obtained in an experiment with mineral water in menopausal women in Italy (Gennari, 1996; Cepollaro *et al*, 1999); lower bone resorption and osteoporosis were observed in women after drinking calcium rich water (Costi *et al*, 1999; Guillemant, 2000). The already mentioned Spanish study (Verd Vallespir *et al*, 1992) found a lower incidence of fractures in small school children of the areas supplied with harder water.

Bioavailability of water magnesium was documented by the studies of the 1960's and 1970's that found a positive correlation between the drinking water magnesium level and the magnesium content of the heart muscle (Crawford *et al*, 1967; Neri *et al*, 1975); among more recent papers we can quote e.g. a Swedish study (Rubenowitz *et al*, 1998). Three-week drinking of magnesium rich water (120 mg/l) resulted in 79 patients in lower pain intensity and frequency of migraine (Thomas *et al*, 1992). Similar results were obtained in a more recent study by the same authors (Thomas *et* al, 2000) with 29 migraine patients and 18 controls. Two-week drinking of water containing 110 mg Mg /l confirmed good usability of water magnesium leading to higher levels of intracellular magnesium and conservation of the serum magnesium level. Some balneological studies reported positive effects of magnesium rich water, but it is to be noted that these were based on short-term experiments (not longer than several weeks) focused on therapeutic effects, in many cases with waters rich in total dissolved solids and therefore, the results should be interpreted with caution with relation to drinking water.

Water hardness and urolithiasis

The key role of water in urinary stone formation is generally accepted by the public; nevertheless, only the quantitative facet of this idea is justified – insufficient intake of water and other liquids, i.e. permanent dehydration, even if slight, surely increases the risk for urolithiasis of all types. On the other hand, qualitative assessment shows that the content of water minerals, more precisely of magnesium and calcium, plays a less important role. Urinary stone formation is a process involving multiple factors, i.e. not only intake of liquids, but also genetic predisposition, eating habits, climatic and social conditions, gender, etc.

Several studies documented that higher water hardness is associated with higher incidence of urolithiasis among the population supplied with such water; in contrast, more studies found softer water to be associated with higher risk for urolithiasis. Nevertheless, most recent epidemiological studies explain those controversial results by differences in the study designs and say that water hardness ranging between the values commonly reported for drinking water is not a significant factor in urolithiasis (Singh *et al*, 1993; Ripa *et al*, 1995; Kohri *et al*, 1993; Kohri *et al*, 1989). Any correlation between water hardness, or the drinking water calcium or magnesium level, and the incidence of urolithiasis was not found in the last vast USA epidemiological study with 3270 patients (Schwartz *et al*, 2002).

The quoted Japanese studies did not found that the water calcium or magnesium levels alone had an effect on the incidence of urolithiasis but did found that the Mg to Ca ratio had: one study reported the lower Mg to Ca ratio to be associated with a higher risk for urolithiasis regardless of type and the incidence of urolithiase to correlate with the type of geological subsoil (Kohri *et al*, 1989) and another study found correlation between the higher Mg to Ca ratio and higher incidence of infectious phosphate urolithiasis (Kohri *et al*, 1993).

Many experimental studies document that higher water hardness does not pose any risk for urolithiasis (which is not true of extreme water hardness beyond the range to be considered for drinking water – see below) and confirm concordantly that intake of calcium rich water (or magnesium rich water) reduces risk for calcium oxalate urolithiasis (Rodgers, 1997; Rodgers, 1998; Caudarella *et al*, 1998; Marangella *et al*, 1996; Gutenbrunner *et al*, 1989; Ackermann *et al*, 1988; Sommariva *et al*, 1987). Intake of such water is associated with higher urinary calcium elimination and at the same time with lower urinary oxalate elimination probably due to oxalate bond to calcium in the intestine with subsequent prevention of oxalate absorption and enhanced oxalate elimination through feces.

Nevertheless, these conclusions do not apply to patients after urinary stone removal. Isolated experiments suggested that intake of softer drinking water resulted in a lower rate of recurrent urolithiasis (Bellizzi *et al*, 1999; Coen *et al*, 2001; Di Silverio *et al*, 2000) but admitted at the same time that the results could not be generalized and depended on multiple factors, e.g. whether water was given between meals as in one of the studies above or during meals when, in contast, harder water intake may have been associated with a lower rate of recurrences (Bellizzi *et al*, 1999). Genetic predispositions and eating habits may play a relevant role in this regard.

High hardness (>5 mmol/l) which is not typical of drinking water may be associated with higher risk for urinary and salivary stone formation as documented by a Russian epidemiological study (Mudryi, 1999). The author says that a long-term intake of drinking water harder than 5 mmol/l results in a higher local blood supply in the kidneys and subsequent adaptation of the filtration and resorption processes in the kidney. This is believed to be protective reaction of the human body which may lead, if the conditions persist, to alteration of the body‘s regulatory system with possible subsequent development of urolithiasis and hypertension. Risk for urolithiasis was also associated with intake of water of a hardness of 10.5 mmol/l (Ca 370 mg/l) as documented by the already quoted Italian study (Coen *et al*, 2001).

Cases of urolithiasis and other complications, otherwise rarely reported at low age, were described in infants whose feeding was prepared exclusively with calcium rich mineral water (Ca 555 mg/l, Mg 110 mg/l, water hardness 18.4 mmol/l) and whose calcium daily intake was consequently several times higher than recommended (Saulnier *et al*, 2000).

Harmful effects of hard water

No evidence is available to document harm to human health from harder drinking water. Perhaps only a high magnesium content (hundreds of mg/l) coupled with a high sulphate content may cause diarrhoea. Nevertheless, such cases are rather rare; other harmful health effects due to high water hardness (e.g. the effects on the eliminatory system as mentioned above) were observed in waters rich in dissolved solids (above 1000 mg/l) showing mineral levels which are not typical of most drinking waters.

In the areas of the Tula region supplied with drinking water harder than 5 mmol/l, higher incidence rates of cholelithiasis, urolithiasis, arthrosis and arthropathies as compared with those supplied with softer water were reported (Muzalevskaya *et al*, 1993). Another epidemiological study carried out in the Tambov region found hard water (more than 4-5 mmol/l) to be possible cause of higher incidence rates of some diseases including cancer (Golubev *et al*, 1994). The results of the studies concerning the relationship between water hardness and tumours are discordant, but most of them are supportive of protective effect of harder water (see above). The quoted Russian studies did not assess possible effect of higher levels of other dissolved minerals in drinking water (increasing water hardness is usually coupled with the increasing total content of dissolved solids).

Hard water is also reported to cause increase in the risk for atopic eczema in school children (McNally *et al*, 1998) which can probably be explained by its higher drying effect on the skin (similar to that of overchlorinated water), but in this case water is used externally and is not intended for consumption.

Sensorial disadvantages of hard and soft water

Higher water hardness may worsen sensorial (organoleptic) characteristics of drinking water or drinks and meals prepared with such water: formation of a layer on the surface of coffee or tea, loss of aromatic substances from meals and drinks (due to bonding to calcium carbonate), unpleasant taste of water itself for some consumers (calcium taste threshold is about 100 - 300 mg/l, unpleasant taste starts from 500 mg/l, but it also depends upon the presence of other ions; the magnesium content exceeding 170 mg/l together with the presence of chloride and sulphate anions are responsible for the bitter taste of water). According to some data, increasing water hardness needs increasing time for vegetables and meat to be cooked.

Very soft water, such as distilled and rain water as two extreme examples, is of unacceptable taste for most people who usually report it to be of unpleasant to soapy taste. A certain minimum content of minerals, the most crucial of which are calcium and magnesium salts, is essential for the pleasant and refreshing taste of drinking water. At least for this reason, demineralized drinking water should be fortified with minerals if obtained by desalination from sea water on a ship or by ultrafiltration from waste water on a spaceship.

Optimum drinking water hardness (Ca and Mg levels) from the health point of view

For the health reasons given above, we prefer harder water but it is not absolutely true the harder the water, the better. An optimum is hard to set; perhaps, the following ranges could be given:

- for magnesium, a minimum of 10 mg/l (Novikov *et al*, 1983; Rubenowitz *et al*, 2000) and an optimum of about 20-30 mg/l (Durlach *et al*, 1989; Kozisek, 1992),
- for calcium a minimum of 20 mg/l (Novikov *et al*, 1983), an optimum about 50 (40-80) mg/l (Rachmanin *et al*, 1990; Kozisek, 1992),
- for a total water hardness of 2 to 4 mmol/l (Plitman *et al*, 1989; Lutai, 1992; Golubev *et al*, 1994) – drinking water in this range was associated with the lowest rates of different diseases as documented by the already quoted Russian epidemiological studies.

Regulatory requirements for drinking water calcium and magnesium

The World Health Organization in the *Guidelines for drinking water quality* (WHO, 1993) evaluated calcium and magnesium from the point of view of water hardness but did not set any either minimum or maximum recommended limits. A reasonable requirement for the minimum required concentration of hardness (calcium or equivalent cations) for softened and desalinated water, set up in Council Directive 80/778/EEC (EC, 1980) appeared obligatorily in national legislation of all EEC members. Nevertheless, this Directive remains in force to December 2003, since Directive 98/83/EC newly entered in force since 1998 (EU, 1998). The latter directive does not present any requirement for the Ca and Mg levels or water hardness (apart from the lower limit for $pH \geq 6.5$ which requires indirectly a certain level of dissolved solids); on the other hand, it does not prevent the member states from implementing such a requirement, if needed, into their national legislation. What is the position of the central European countries in this regard? None of the EU member states (Austria, Germany) has this indicator included in their provisions. In contrast, all of the four candidate countries (Czech Republic, Hungary, Poland, Slovakia) have certain requirements for the minimum Ca and Mg levels in their respective provisions, obligatory at different degrees. The recommendations or requirements as presented by the WHO, EU and Central European countries are reviewed in Table 1 (see Annex 1).

What development is to be expected in the EU countries? If these indicators are not reintroduced into the Directive (to be revised every 5 years on an obligatory basis) the requirements for water Ca and Mg levels – if kept at all – will move in most countries from the level of regulatory measures to a lower level of unbinding regulations such as technical standards (different measures for reduction of water corrosivity can be taken as an example) or different methodical recommendations for both the water supply sector and the public. The approach applied in the UK can be taken as an example of health education. The Committee on Medical Aspects of Food Policy of the Department of Health concluded: "…in view of the consistency of the epidemiological evidence of a weak inverse association between natural hardness and cardiovascular disease mortality, it remains prudent not to undertake softening of drinking water supplies…" (Department of Health, 1994). This conclusion confirmed the advice that had been in place for many years and that continue to be given by the Drinking Water Inspectorate as the drinking water authority of the country in the leaflets for the public: „if you do install a water softener you should make sure that you have a supply of unsoftened water for drinking and cooking“ (Drinking Water Inspectorate, 1999).

This recommendation reflects that the cation exchange process called sodium cycle softening is most commonly used in households today. As part of this process, undesirable sodium is released into water while the calcium and magnesium salts are captured. American studies showed higher incidence of hypertension, which together with consequent lower magnesium intake are important risk factors for CVD, among the population, including children, using sodium cycle softening for drinking water treatment (20 to 40 % of households in the USA did so in the late 1980's) (Das, 1988).

Discussion

Most of the existing studies show that higher water hardness (i.e. drinking water calcium and magnesium) is related to decreased risks for CVD and especially for sudden death from CVD. This relationship has been independently described in epidemiological studies with different

study designs, performed in different areas (with different populations), and at different times. Consistent epidemiological observations are supported by the data coming from autopsy, clinical, and animal studies. The biological plausibility is high, but the specificity is less evident due to the multifactorial aetiology of CVD. The values of the relative risks were rather moderate or weak, but mostly statistically significant. It can be summarized that the relationship between the calcium and magnesium intake with drinking water and CVD stands up to most of the criteria for causality.
In spite of that, some recent papers either prudently adopt an ambiguous attitude („to date... causality is still not proven, but there are many potential arguments in favour...“ (Sauvant *et al*, 2002)) or condition possible preventive actions by the need for further investigation or intervention studies. Intervention studies with drinking water, which for statistical reasons would have to include very large numbers of subjects, are not easily feasible. But are not there relevant studies carried out in the areas where the water source has changed and where the change in water hardness was associated with a change in mortality from CVD as reported by the already quoted British study (Crawford *et al*, 1971) or a more recent Italian study focused on comparison of mortality from CVD between two areas supplied with water with different magnesium levels. The area supplied with water with a low magnesium level (0.7 mg/l) showed a markedly higher CVD mortality as compared to the area supplied with water richer in magnesium (27 mg/l). Nevertheless, later when the water source changed in the latter area and the water Mg level decreased to less than 1 mg/l the CVD mortality increased and became close to that of the former area (Menotti *et al*, 1979).

Relevant is also a large Indian food intervention study (Singh, 1990) that divided a group of 400 individuals with CVD risk into two subgroups: one strived to consume diet rich in magnesium and the other (controls) ate normal diet. Within 10 years the intervention group showed a statistically significantly lower rates of myocardial infarction, sudden cardiac death and total complications in the cardiovascular system. The effect observed may not have been specific of magnesium, other diet components may also have played a role. Successful interventions (with drinking water or diet supplementation) were also carried out in experiments on animals (Durlach *et al*, 1985; Sherer *et al*, 1999).

Apart from the relationship between the drinking water Ca and Mg levels and risk for CVD which is best studied and is the most relevant from the public health point of view, it is possible that other beneficial effects of high water Ca and Mg against some other diseases (e.g. neurological) may manifest themselves, as documented by the above quoted recent studies. This all offers promising prospects for preventive measures.

Several studies dealing with the relationship between magnesium deficiency and CVD incidence also raised the question of whether Mg supplementation could be used for the primary prevention of these diseases and their sequelae. Several methods of supplementation have been proposed, including: fortification of food, public education to change dietary habits, oral supplementation, and addition of Mg to community water supplies (Eisenberg, 1992; Durlach *et al*, 1985; Durlach, 1989; Rylander, 1996; Bar-Dayan *et al*, 1997). Several questions related to possible supplementation were posed by Eisenberg: (1) Will Mg supplementation reduce the risk of sudden death? (2) How much time is required before the effects of such supplementation are evident? (3) What is the optimal method of supplementation? (4) Is supplementation technically and financially feasible? (Eisenberg, 1992).

In agreement with the focus of this article and the commonly known fact that the preventive measures which do not require behavioural changes have always been the most effective in public health attention will be paid to the ways of drinking water supplementation. And we have to be serious about this question. In the light of the high incidence and seriousness of CVD which are the leading cause of mortality in most industrialized countries, potential effective measures even if reducing mortality from myocardial infarction or other CVD by a small percentage only (not to speak of the hypothetical 30% reported by some studies) could save thousands of human lives (Rylander, 1996; Marx *et al*, 1997). Such an incredible number would mean incomparable higher efficiency among any of the measures on chemical quality of drinking water (lowering any of toxic substances below the limit values) applied up to know.

If anybody drinks low magnesium or low calcium water, it means that he/she is at higher risk for some diseases but it does not mean that he/she will certainly develop the disease. This situation is easily comparable with drinking water containing a contaminant in amounts let's say by 300% higher than the limit allowed – a man drinking such water may not develop the disease possibly caused by the given contaminant, since the limits are established to cover a sufficient safety factor. Nevertheless, the man is at higher risk for the pollutant-related disease. Although the risks are comparable, if the risk from low magnesium water is not higher, the regulatory and enforcement mechanisms for undesirable contaminants are very strong, while those for naturally present beneficial elements such as Mg and Ca are very weak, if any at all.

Let's say that never in the past so much background data and knowledge were available at time of establishing a limit for chemicals in drinking water as they are now for magnesium and calcium. Even if such an intervention measure as drinking water fluoridation, continued in some countries to date, is taken into account.

Conclusions and recommendations

Calcium and magnesium are important parts of drinking water and are of both direct and indirect health significance. A certain minimum amount of these elements in drinking water is desirable since their deficiency poses at least comparable health risk as exceedance of the limit for some toxic substances does.

Based on the available data, the desirable minimum of magnesium and calcium can be estimated to be > 10 mg/l and > 20-30 mg/l, respectively. Nevertheless, this does not mean that if low levels of these elements were increased to remain below the minimum mentioned above (e.g. if the magnesium level were increased from 2 to 5 mg/l), it would be of no importance. It seems that any increase, even by several mg/l, could have a health effect. Although a certain minimum quantity of these elements is desirable, it definitely does not mean the more the better. While considering higher levels of magnesium and calcium in drinking water, not only the absolute content of these elements but also the fact that higher water Mg and Ca levels are mostly associated with higher levels of the other dissolved solids that may not be beneficial to health should be taken into account.

What can be called the optimum Mg and Ca levels in drinking water ranges from 20 to 30 mg/l (for magnesium) and from 40 to 80 mg/l (for calcium), respectively, and for water hardness as Σ Ca+Mg from about 2 to 4 mmol/l.

How to ensure the minimum and optimum calcium and magnesium levels in drinking water?

1) To select an adequate water source. If several water sources are available or can be mixed, preference should be given to the sources (as a rule, to the underground sources) containing the optimum, or at least the minimum, Mg and Ca levels, as considered in the context of general water composition. These sources should be in priority exploited for the drinking (nutritional) purpose than for other, technical purposes.

2) To set strict rules for water treatment technology decreasing the amount of Ca or Mg in drinking water (distillation, membrane technologies such as RO, ion exchange, precipitation, etc.) or to keep some minimum content of Mg and Ca in case of water softening or desalination. To soften drinking water only if needed for health reasons, i.e. not for technical reasons. In the light of rapid growth in membrane technologies and their applicability to drinking water treatment, such rules will be more and more urgently needed.

3) To promote stabilization of soft water sources. This procedure is often used to reduce water corrosivity either by passing the water through calcium carbonate filter (sometimes preceded by dosing with carbon dioxide) or by adding a calcium compound such as lime milk directly to water. Unfortunately, this results only in a negligible increase in the magnesium level. Nevertheless, this procedure can be at least partly optimised, on the one hand, by means of improvement of the treatment design, and on the other hand, by selection of an adequate filtration material with a higher magnesium content, e.g. material on a basis of $CaCO_3$ + $MgCO_3$ or $CaCO_3$ + MgO.

4) To address the issue of increasing the magnesium level by addition of magnesium salts directly to water while treated which has not been much tested in practice. Some authors expressed their fears that it could do more harm than good since it might disturb seriously the balance between elements or the balance due to super saturation of $CaCO_3$ and increase corrosivity (Durlach *et al*, 1985). Although the first objection can be justified to some extent (the Mg to Ca ratio of about 1:2 should be observed), the other one is not justified from the point of view of water supply, if the resulting Mg level reaches about 10-20 mg/l.

   A recent case from the Czech Republic (Kyncl, 2002) has shown that central fortification with magnesium is technically feasible: A North-Moravian water supply company was made an offer to supply drinking water to a large Polish city of about 100 000 population situated near the Czech-Polish border. The Polish customer wanted the water supplied to meet the Polish decree requirement for the indicator water hardness (60 – 500 mg/l; hardness expressed as $CaCO_3$). Initial hardness of the water originating from a surface source was 50 mg/l and had to be increased to reach the minimum level required. For time and financial reasons, the classical technology of dosing with carbon dioxide followed by dosing with lime was not applicable and therefore addition of some soluble magnesium or calcium salt directly to water appeared to be the only way to meet the requirement. Four salts (magnesium chloride, calcium chloride, magnesium sulphate, calcium sulphate) were tested in laboratory for chemical purity, solubility and effect on pH and sensorial characteristics of water. All of the salts tested showed acceptable results for all parameters studied up to the dose of 20 mg/l. Finally, technical grade crystalline magnesium chloride $MgCl_2.6H_2O$ was selected because of its good solubility and lower cost. The magnesium content was increased by about 50%, i.e. from the mean level of 3 mg/l to 4,5 (4,2-4,8) mg/l, which was sufficient to meet the minimum water hardness required of 60 mg (equivalent $CaCO_3$)/l. The water was supplemented at the main supply line to the Polish city (at a flow of about 100 l/sec) for almost one year (2001-2002). The supplementation was stopped, but not for technical reasons: the Polish health authorities changed their position and did not require the limit to be met any more. Mg supplementation increased the cost of water production by about 5%. Reaching a magnesium level of 10 mg/l would increase the cost of water production by about 20 %.

Although artificial fortification of drinking water with calcium and magnesium to a certain level is technically feasible, before its possible regulation it would be reasonable to address the following questions: (a) Cost/benefit assessment; (b) Is fortification of drinking water an effective way if only about 1% of tap water is used for drinking and cooking, and bottled water consumption is continuously increasing? (c) Is this form of water Ca and Mg equally bioavailable as the same elements of natural origin? (We do not know, but magnesium chloride is the most common form of therapeutical oral Mg supplementation.) (d) Environmental impact on aquasystems (Probably no impact); (e) To fortify to the minimum or optimum level (and what are the minimum and optimum levels)?

Since the solution of these questions may seem too complicated, it should be noted that artificial fluoridation of community water supply had been applied in many countries all over the world without addressing these issues, which were of the same relevance in the case of fluorides.

5) Public health education seems to be a quite easily applicable measure for the moment. The public, in particular that living in the areas supplied with water low in Ca and Mg, should be discouraged from using water softeners or other home water treatment units removing Ca or Mg from water intended for drinking and cooking. At the same time, the consumption of Ca/Mg-rich water (e.g. bottled natural mineral water) could be encouraged to replace at least partly tap (well) water low in the minerals. However, this solution is not easily applicable to water for cooking.

Introduction of regulatory measures concerning the minimum levels of Ca and Mg in drinking water seems to be justified and highly desirable. They should be based on the fact that it is much simpler and much more effective to keep the existing Ca and Mg drinking water levels than to add these minerals to water artificially. Practically, this means restricting the use of technologies leading to removal of Ca and Mg from water only to the cases where the Mg and Ca levels are too high (i.e. of hundreds of mg/l or more) provided that the required minimum of Σ Ca+Mg is kept in the water after treatment. Nevertheless, apart from this „negative“ regulation, a positive approach should be adopted. And if Directive 98/83/EC contains some general instructions concerning e.g. the disinfection by-products: *„where possible, without compromising disinfection, Member States should strive for a lower value”*, why could not it give a general instruction that drinking water should contain certain minimum Mg and Ca levels and that the member states should strive to reach these levels?

Anyway, further studies are needed to address not only the traditional issues such as the Mg and Ca levels but also water treatment technologies (e.g. magnetic treatment or phosphate dosing) which do not modify the absolute levels of these elements in water but may mask the presence or may limit the effect of these elements through different mechanisms.

ANNEX 1

Table 1: Requirements on calcium, magnesium, or hardness in drinking water

Country/ Organization	**Regulation**	**Validity from**	**Requirement**			**Note**
			Parameter	**Unit**	**Limit value**	
WHO	Guidelines for DW quality (2nd ed.)	1993	Hardness	-	-	WHO concl epidem. stud significant i hardness of disease, the permit the c causal. No h water hardn
EC	CD 80/778/EEC	1980 (-2003)	calcium	mg/l	≤ 100	
			magnesium	mg/l	≤ 50 (GL ≤ 30)	GL…guide
			total hardness	mg/l Ca	≥ 60	Minimum re and desalina cations.
EU	CD 98/83/EC	1998	-	-	-	These param requirement value of 6.5
Austria	Ord. 304/2001 (TWV)	2001	-	-	-	No limit val among the p in drinking
Czech Republic	Decree 376/2000	2001	calcium	mg/l	≥ 30	Exceptions
			magnesium	mg/l	≥ 10	Exceptions
			Ca + Mg	mmol/l	GL 0.9 – 5.0	GL…guide
Germany	Ord. TrinkwV 2000	2003	-	-	-	These param requirement value. Indire Article 4 (1)
Hungary	Ord. 201/2001	2001	hardness	mg/l CaO	50 – 350	Minimum re is to be met sources, and
Poland	Decree 937/2000	2000	hardness	mg/l $CaCO_3$	60 – 500	Hardness ex
Slovakia	Decree 29/2002	2002	calcium	mg/l	GL > 30	GL…guide
			magnesium	mg/l	GL 10 – 30	GL…guide
					≤ 125	
			Ca + Mg	mmol/l	GL 1.1 – 5.0	GL…guide
Czech Republic	*Decree revision draft*	*2003 ?*	*calcium*	*mg/l*	*^{3} 30*	*For softene*
					GL 40 – 80	*Guide level.*
			magnesium	*mg/l*	*^{3} 10*	*For softene*
					GL 20 – 30	*Guide level.*
			Ca + Mg	*mmol/l*	*GL 2.0 – 3.5*	*GL…guide*

⊕ TrinkwV 2000

TrinkwV 2000 in Article 4, Clause 1 („Water … has to be fit for consumption and clean. This requirement is considered as met, if … the generally recognized technical rules are observed…“) refers among others to DIN 2000, which is a recognized technical rule, and general instructions given in DIN 2000, e.g. „requirements on drinking water quality shall be based on the characteristics of safe underground water drawn from a sufficient depth and through sufficiently effective filter layers“ (section 5.1) or „undesirable changes in water quality caused by water treatment should be minimized in agreement with technical rules“ (section 4.6), and thus guarantees certain minimum levels of calcium and magnesium in drinking water.

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