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Magnesium Level in Drinking Water and Cardiovascular Risk Factor: A Hypothesis

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Abstract. Water hardness can no longer be considered as the most reliable 'water factor' with regard to the cardiovascular risk observed in epidemiologic studies. Only two out of three studies have shown a reverse correlation between cardiovascular mortality and water hardness. But studies carried out on the water Mg level alone, as opposed to those on water hardness (Ca + Mg) have all shown a reverse correlation between cardiovascular mortality and the Mg level.

In developed countries, the Mg intake is often marginal and the Mg intake coming from drinking water represents the critical factor through which the Mg intake is deficient or satisfactory. Thus, Mg deficiency, either experimental or in man facilitates cardiovascular pathology.

The importance of the Mg intake in drinking water is both quantitative and qualitative. Water containing Mg is better and more quickly absorbed than dietary Mg. This particular availability might help to understand why an adequate water Mg level may determine a better state of health, even without any Mg deficiency. Epidemiological data in man and experimental data in rats have demonstrated that the intake of water containing a sufficient amount of Mg may prevent arterial hypertension and correlated ionic and nervous disturbances.

Indirectly the water Mg level also interferes in the leakage of food-borne Mg during cooking. There is an inverse correlation between the Mg loss in the cooked food and the Mg level of the cooking water itself. Mg appears to be an antagonist of noxious polluting agents (e.g. in the human amnion, Mg is a competitive inhibitor of Pb and Cd). It is not advisable to enrich water in Mg in the course of the processing since its corrosivity index would also increase. The best pathway is probably to neutralize corrosive water by filtration on calibrated grains of earth–alkaline metals (Neutralite or Magno or Akdolit) to ensure the highest possible Mg/Ca ratio, with the best anticorrosive power.

Introduction

In 1957, *Kobayashi* [58] pointed out the possible relationship between the composition of drinking water and cardiovascular diseases after observing a geographical correlation between stroke mortality and the water acidity of the rivers. *Schroeder* [96] statistically checked the validity of the Japanese data, and then examined the epidemiological implications of this phenomenon in the United States. He suggested an inverse correlation between various types of heart diseases and total drinking water hardness: drinking soft water increases the cardiovascular risk which is reciprocally reduced by hard water consumption.

In all continents, numerous studies have been devoted to this inverse correlation through a large number of statistical units of observations (states, towns, districts), diversification of the causes of mortality (general, cardiac, vascular) and multiplication of observed parameters (analytical data on water, climatic and geological factors) [27, 49, 54, 71–78, 86]. The inverse correlation has been confirmed in the majority of the studies and, in particular, when the geographical scale of the epidemiological study is larger, i.e. when the cultural, climatic and professional parameters vary widely. However, the inverse relationship between the hardness of the water and cardiovascular mortality is not always found [26, 27, 51]. Consequently, the water parameter cannot be considered a major risk since it may be completely missing; but studies on the water factor have shown the frequency of the relationship between cardiovascular diseases and drinking water. Other etiological and atmospheric cofactors, associated with hardness (i.e. pluviosity [49] or salt-consumption [28]) might have possible roles, but the main question concerns the relationship between drinking water and a satisfactory condition of the cardiovascular apparatus. Two types of research have attempted to determine either the cardiovascular protecting factors in protective water, or the cardiovascular toxic factors in noxious water. These water factors are only to be taken into consideration when they represent a notable part of the recommended dietary allowances or qualitatively, if they constitute a higher bioavailability intake.

Accessory Protective Factors in Drinking Water

A significant inverse correlation has been irregularly found between cardiovascular mortality and natural water elements: K^+ [98], Ca^{2+} [98], Li^+ [71], CO_3H^- [98], F^- [67], I^- [77, 78], Ni [71], Cr, Fe, Zn, Cu, Se [47, 77, 78, 80], perhaps Va [44, 96], Si [99] and As [89]. It is obvious that if the importance of dietary K intake (particularly the K/Na ratio [69, 85, 105] is critical, the quantitative part of water K is rarely important. This observation is identical with that made on Ca. Its dietary intake has an important cardiovascular protective role [10, 12, 68, 89, 94], but Ca in drinking water, which is often poorly assimilated, represents a negligible element of the Ca intake. The importance of the Ca level in drinking water can be presented to the consumer as an anticorrosive substrate of the protective coating deposited on the pipes by nonaggressive waters. The inverse correlation between Li^+ and mortality is low and becomes inverse when the partial correlations are calculated [71]. Nevertheless, the lowered bicarbonate and carbonate levels are essential elements of the corrosivity [7, 8, 99]. The water contribution of various trace elements, the minimum requirements of which are known (F, I, Cr, Fe, Zn, Cu), may be important, but it is difficult to appreciate this contribution when the requirements have not yet been defined (As, Si ...).

Magnesium: The Major Protective Water Factor

Of all the factors studied in drinking water, the highest inverse correlation has been observed between Mg and cardiovascular mortality [2–4, 54, 71–76, 100, 108a, 109]. Moreover, in Canada, the myocardial Mg level is significantly lower in soft-water districts than in hard-water districts. The same is found in the hearts of the subjects who died from sudden heart attacks or myocardial infarcts (even outside necrosed tissue areas where the leak also depends on tissue lysis [3, 5, 6, 23–25, 71–75, 106]). Quantitatively, the water Mg contribution may represent the amount of Mg required to bring an insufficient dietary Mg level to a correct level [3, 42, 54, 71–75, 77, 78, 102, 109]. In fact, in developed countries, the adult Mg intake is marginal as compared to the 'recommendable' dietary allowance [6 mg/kg/day; 36, 100, 101] and even to the slightly lower recommended dietary allowance (5 mg/kg/day) proposed by the US National Academy of Sciences in adults. The inadequacy of the Mg intake is even worse in anabolic phases such as growth, pregnancy, lactation ...

According to its Mg content (from 10 to 100 mg/l), 2 liters of water (drinking water, tea, coffee, soups) increase the Mg intake from 20 to 200 mg/day. A higher water Mg intake is even observed with some bottled mineral waters, i.e. Vittel Hépar: 130 mg/l [83].

The Mg level of cooking water also interferes in the Mg dietary intake. A nutrient in the cooking water, always loses an important part of its Mg [95], but the Mg loss is lower when the food is cooked in a water with high Mg content. There is an inverse correlation between the Mg loss in the cooked food and the Mg level of the cooking water [28, 36, 47, 77]. Nowadays, housewives often cook with softened water. They would do better to use unsoftened drinking water.

Thus, quantitatively, the magnesium of drinking water represents an appreciable part of the overall dietary intake. As a risk index, the Mg level in water is more satisfactory than hardness. According to a number of reports, its participation in hardness ranges from 10 to 89% [75, 76]. One should distinguish between hard waters with low Mg content in Great Britain [74] and France [29, 108], uncorrelated with cardiovascular mortality and the US hard waters with high Mg contents [75, 76] and reversely correlated with cardiac diseases [46]. It is to be hoped that in water, as well as in the overall diet [47], the Mg/Ca ratio is not too low. As a matter of fact, in France and Great Britain, the Mg/Ca ratio amounts on the average to a few hundredths, while in the US, it ranges from 1 to 5.

The water Mg intake may quantitatively represent the critical contribution allowing the control of an Mg deficiency whose physiological effects on the cardiovascular apparatus are perfectly well known [2–4, 11, 100].

But, the contribution of Mg in drinking water is also interesting qualitatively.

Studies conducted by *Lowik* et al. [66] and *Binnerts* et al. [13] with diets poor, normal and rich in Mg show that with an absolute equivalent Mg intake, Mg in drinking water is much better absorbed than dietary Mg.

This particular bioavailability of water Mg can be proven experimentally. The mortality rate of mice in which Mg deficiency had been induced by a diet with a very low Mg content could be controlled by the mere intake of water containing 30 mg Mg/l [54, 109]. This Mg level is found in various hard waters of the distribution system. The boiling of water, decreases the Ca level, but has little effect on the Mg level.

Breakfast should provide an intake of water Mg since the Mg requirements increase when people resume their activities. Suppressing breakfast and/or the coffee break induces massive reduction of magnesuria [13, 66].

Accordingly, the urinary Mg/Ca ratio is higher than it is in the ingested water [61, 62].

These particular absorption qualities of water Mg [65] suggest an interpretation of the investigations of *Novikov* et al. [84]. The study of various cardiovascular, nervous and ionic parameters in Siberian populations, comparable in all respects except for the hardness of their drinking water, shows an inverse correlation between soft water with a low Mg content and arterial hypertension as well as K-Na, P-Ca and neuroendocrine alterations which may cause vascular pathology.

Rats were administered a balanced diet, namely with an adequate Mg level: blood and tissue Mg was normal in all these animals. But the Mg and Ca levels of their drinking water were different in each group. The results showed similar correlations between the Mg water level and vascular impairments with similar ionic and neuroendocrine disorders in the rats and the Siberian populations. This suggests that an insufficient Mg level in drinking water can induce hypertension together with neuroendocrine and humoral disorders in both animals and man. Recently, *Altura and Altura* [3a] have indeed demonstrated that alterations in dietary and water-borne Mg intake can produce hypertension in rats; they found an inverse correlation between serum Mg level and elevation in arterial blood pressure which was linked to microvascular changes.

The effect of Mg contained in drinking water could be explained by its particular bioavailability. In awakening periods, when the metabolic Mg requirements are increased, an adequate intake of quickly and well-absorbed water Mg would avoid solicitation of the neuroendocrine controls of the Mg homeostasis (vegetative, adrenal, thyroparathyroid and pancreatic [34, 35]). When the water Mg intake is too low, the necessity of maintaining the Mg homeostasis might induce, in the long run, a dysfunction of these regulations. Since the diverse regulatory mechanisms of Mg homeostasis are the same as those which control the K-Na and P-Ca balance [34, 35], it is conceivable that their dysfunction might induce nervous hyperexcitability and arterial hypertension.

Drinking water containing Mg as a specific element of Mg intake, qualitatively and quantitatively, is particularly beneficial to the cardiovascular and nervous functions. This is probably due to the fact that dietary Mg intake acts as an antagonist of certain noxious factors of the water.

Noxious Factors of the Water: 'Natural' and 'Polluting' Factors; Advantage of the Ryznar Corrosivity Index

'Natural' Elements: Na and Na/K Ratio

The noxious effects of Na on blood vessels have been known for over 4,500 years [37]. The industrial civilization consumes too much Na [81] and not enough K [41, 69, 81, 85, 93, 105]. Numerous studies have considered Na as a major risk factor in drinking water [14, 20, 21, 112]. In the majority of the epidemiological studies [39], a direct correlation between hypertension and the Na level in drinking water has been observed. However, this relation is not consistent [39, 98]. It is obvious that the Na of drinking water is not a major element of the Na intake, but it can easily be modified. It is difficult to cut down by 50% the Na intake which is provided in meat and dairy products! People are more reluctant to reduce their usual consumption of salt. But one should avoid the consumption and use of cooking water which is very rich in Na^+ such as artificially softened waters [39], whose Na levels can be as high as 500 mg/l. It should be mentioned that the use of soft waters seems to involve an increased consumption of salt, as demonstrated by a direct correlation with natriuria [28].

Water intake represents only a small part of the total Na level and of the Na/K ratio in the general intake. Still, its importance should not be overlooked in cases of specific backgrounds such as hypertension and of consumption of soft waters with high Na contents which result in increased consumption of salt.

Corrosivity and 'Polluting' Metals

As early as 1974, *Schroeder and Kraemer* [99] thought that the noxious cardiovascular effects of certain soft waters might be due to the presence of toxic metals solubilized in the geological layers or in the pipes.

Kobayashi [cited by *Schroeder,* 96] gives a prominent position to the direct correlation between the SO_4^{2-}/CO_3^{2-} ratio – related to the water acidity (X 3–5) – and diseases such as hypertension and strokes in Japan.

Water alkalinity (bicarbonate CO_3H [99] and CO_3^{2-} level [7, 8]) might be a protective factor. One should distinguish between two physical factors of water: aggressivity towards Ca carbonate and corrosivity to metals. A nonaggressive water may be corrosive. These two notions can, however, be connected because of the occurrence of a calcium deposit which protects the pipes from corrosion. Corrosivity decreases together with aggressivity [30, 56]. The Langelier index [63] determines whether a water is encrusting ($I_L > 0$) or aggressive ($I_L < 0$); a positive response of I_L is a sign of anti-aggressivity.

Ryznar [92] has proposed an empirical index (I_R), which appears to be more representative of the corrosive or scaling characteristics of the water: $I_R < 6$: scaling water; $6 < I_R < 7$: balanced water; $I_R > 7$: corrosive water.

The Ryznar index should be systematically used in epidemiological studies on the relationship between drinking water and health. It is obvious that a very corrosive water can be contaminated by metals classified into 'essential' elements and 'toxic' polluting factors. But this classification is unsatisfactory since high levels of 'essential' elements become toxic and conversely low levels of 'toxic' elements appear to be essential [109]. For example, a negative correlation is found between cardiovascular mortality and low levels of Fe, Cu, Cr, Mn, Zn, As intake, but high levels of Ca [67, 70, 71, 88, 99, 102], Cr [71, 99], Mn [70, 71, 99], V [45], Zn (57), and As [111] have polluting, toxic effects. The noxiousness of corrosive waters is mainly due to two toxic heavy metals: Pb and Cd [17, 18, 39, 102]. Water Pb does not have a geological origin. Unlike Cd, it has a pseudocolloidal form which, in the course of further processing, easily flocculates and is eventually absorbed. The lead loading occurs in the distribution system [17, 18, 39, 102]. A short portion of lead water pipe, lead solders, stagnation in the pipes (therefore high Pb levels in the early morning, heating of the water, earth plugging of an electrical appliance) make the problem even worse and can bring about elevated levels of Pb in the water [32, 33, 114]. Attempts have been made to replace lead pipes with galvanized iron pipes. However, Zn which is used for galvanization always contains Cd, which is released when corrosive water stagnates in the pipes [17, 18]. The use of polyvinyl chloride (PVC) pipes does not always solve the water pollution problem, as PVC may contain lead salts as stabilizing agents and, consequently may contaminate the water [16].

The effects of water-polluting agents cumulated with those from digestive and pulmonary sources are greatly to be feared, beause cation absorption is increased when the cations are water soluble [109]. Besides, even low levels [59, 107] of Cd and Pb have detrimental cumulative effects on the cardiovascular system [80, 90], as they increase tissue Na and Ca levels and decrease the K and Mg levels. These effects, which are comparable to those of Mg deficiency, can be controlled by Mg intake. Indeed, Cd intoxication decreases the Mg level in bone, teeth and soft tissues [52, 53, 59, 113]. Conversely, Mg reduces Cd absorption [109, 110] and is a competitive inhibitor of Cd in the isolated amnion (unpublished data). Mg, partly, antagonizes the carcinogenic effects of Cd [87] and antagonizes the uncoupling of oxidative phosphorylation induced by Cd in hepatic mitochondria but not in renal mitochondria [48]. The increase in Mg intake reduces Pb retention and increases Pb excretion [79, 104]. But a decrease of Pb absorption due to the described Mg intake [38] has not been confirmed [109, 110], and is ancillary because the increase in the urinary Pb level observed in the course of parenteral Mg loading cannot be easily explained through this mechanism [60]. Conversely, Mg deficiency increases Pb retention, both in the mother and in the fetus [22]. Also, all the available studies [except for two: ref. 40, 82] show an antagonism between Mg and Pb. For example, Pb and Cd cross animal [1, 31, 89] and human [19, 50, 64] placental barriers, and Mg is a competitive inhibitor of Pb and Cd in the isolated human amnion [9, 43, 44].

Practical Conclusions on the Processing of Drinking Waters

Drinking water containing Mg is, qualitatively and quantitatively, useful, and therefore drinking and cooking water should not be softened. In the case of Mg-poor water, the problem of the best processing technique can be discussed. It is tempting to have it enriched in order to get 30 mg/l Mg.

Simpson [103] suggests that one should increase the Mg level of tap water after it has been collected from the tap. *Marier* et al. [71] and *Anderson* et al. [5] do not agree with the idea of adding Mg to the water in processing stations. This increase in the Mg level, in processing stations, might impair the balance due to super saturation of CO_3Ca and increase corrosivity.

Two methods have been proposed to reduce the corrosivity: *Richards and Moore* [91] increase the pH and precipitate the metals by adjunction of lime, but this method is inadequate because the decrease of Pb is insufficient; besides, Na orthophosphate which is used as a corrosivity inhibitor increases the already excessive intake of P in our diet.

Neutralization by filtration on calibrated grains of earth-alkaline metals reduces the Pb level in water. Marble has long been used, but the reaction is too low. Neutralite (CO_3Ca + CO_3Mg) or Magno or Akdolit (CO_3Ca + MgO) [15, 30] have also been used. With the best anticorrosive power the best filter should induce the highest Mg/Ca ratio.

Taux de magnésium de l'eau de boisson et facteur de risque cardiovasculaire

La dureté de l'eau ne peut représenter la caractéristique correspondant fidèlement avec la donnée épidémiologique définissant un «facteur eau» de risque cardiovasculaire. La notion selon laquelle la mortalité cardiovasculaire est en relation inverse avec la dureté de l'eau ne se retrouve que dans 2 enquêtes sur 3. Par contre, la corrélation inverse se retrouve toujours lorsqu'on remplace l'étude de la dureté (somme de taux de Ca et Mg) par celle du taux isolé de Mg. La ration alimentaire des pays développés étant très souvent marginale, l'apport du Mg de l'eau de boisson constitue le facteur critique laissant la ration déficiente si l'eau est pauvre en Mg et la faisant passer à un taux non carencé lorsqu'elle est riche en Mg. Or la carence magnésique expérimentale et clinique favorise la pathologie cardiovasculaire. L'importance de l'apport du Mg de l'eau de boisson ne se réduit pas à cette donnée quantitative directe. Elle est aussi qualitative car le Mg de l'eau semble être absorbé mieux et plus rapidement que celui des aliments. Cette particularité pourrait peut-être permettre de comprendre que – même avec un apport magnésique suffisant – une eau riche en Mg soit plus saine: des données épidémiologiques et expérimentales vérifient en effet que même en l'absence de carence magnésique, la prise d'une eau riche en Mg prévient l'hypertension artérielle, les troubles sodopotassiques, phosphocalciques et nerveux observés tant chez l'homme que chez l'animal d'expérience. Le taux de Mg de l'eau intervient aussi indirectement sur les apports en Mg par ses effets au cours de la cuisson des aliments: une eau douce appauvrit les aliments en Mg tandis qu'une eau dure les enrichit. Le taux de Mg de la ration intervient enfin pour antagoniser les polluants cardiovasculo-nocifs (par exemple, dans l'amnios humain, Mg est un inhibiteur compétitif de Pb et Cd). Aux effets propres du Mg sur l'appareil cardiovasculaire, il convient donc d'adjoindre ses propriétés antagonistes des métaux cardiovasculotoxiques dont les eaux corrosives favorisent l'apport. Comme il ne paraît pas possible d'enrichir artificiellement en Mg les eaux de boisson sans en accroître «l'indice de corrosivité», cette pratique apparemment séduisante, ne semble donc pas recommandable dans les stations de traitement des eaux. Il convient d'y neutraliser les eaux corrosives par filtration sur des grains calibrés d'alcalino-terreux (Neutralite, Magno ou Akdolit), en s'efforçant d'obtenir à pouvoir anti-corrosif égal le rapport Mg/Ca hydrique le plus élevé.

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