FRI BRIEFINGS

Sodium Reduction and Its Effects on Food Safety, Food Quality, and Human Health

A Brief Review of the Literature

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INTRODUCTION

Traditionally salt (sodium chloride) has been viewed as a food preservative that enhances human health by killing or limiting growth of foodborne pathogens and spoilage organisms. However, in recent decades with increasing consumption of many different processed foods containing high levels of sodium, the perception of dietary salt has evolved to a point where it is now considered a potential health threat. The Institute of Medicine has established adequate daily intakes (AI) for sodium and potassium and a tolerable upper intake level (UL) for sodium based on its effects on blood pressure (Table 1). According to data from NHANES III, over 95% of men and over 75% of women in the U.S. exceed the recommended daily tolerable upper intake of sodium. This has led to recommendations by many health organizations that Americans significantly decrease sodium and salt intake.

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http://fri.wisc.edu/docs/pdf/FRI_Brief_Sodium_Reduction_11_08.pdf

Table 1. Sodium and potassium intakes and recommendations in the U.S. (*32*)

	Sodium	Sodium chloride	Potassium
AI (adequate intake): 19–50 years	1.5 g/day (65 mmol)	3.8 g	4.7 g/day (120 mmol)
AI: 51–70 years	1.3 g/day (55 mmol)	3.3 g	4.7 g/day
AI: >71 years	1.2 g/day (50 mmol)	3.0 g	4.7 g/day
UL (tolerable upper intake level): all ages	2.3 g/day (95 mmol)	5.8 g	not established
Median intake (males)	4.2 g (183 mmol)	10.6 g	2.9–3.2 g/day (74–82 mmol)
Median intake (females)	3.3 g (142 mmol)	8.3 g	2.1–2.3 g/day (54–59 mmol)

Natural sodium levels in foods vary but generally account for only about 10% of dietary intake. Dietary sodium is ingested primarily in the form of sodium chloride, table salt. Approximately 5–10% of intake is related to the discretionary addition of salt at the table and during cooking. Processed foods and foods served in restaurants contribute over 75% of dietary sodium in industrialized countries. (*61*) In addition to obviously salty foods, such as snacks, sodium content in processed meats and cheeses, some breads and breakfast cereals, and many soups, sauces, and packaged dinners is quite high. Some foods, including 8 oz of some commercial tomato soup and 4 oz of some types of pizza, may contain nearly an entire day's adequate intake of sodium. This led the American Public Health Association and the American Medical Association to call for a 50% reduction in sodium in processed and restaurants foods over a ten-year period. Revocation of the GRAS status of salt has also been proposed in order to have food processors justify the amounts of salt added to foods (*20*). FDA held a hearing on this proposal and on possible changes to labeling regulations in November 2007 and accepted public comments on these issues through August 2008.

WHO (World Health Organization), as part of its Global Strategy on Diet, Physical Activity and Health, organized a forum and technical meeting in 2006 to review and discuss the link between high salt consumption and health and various initiatives to reduce population-wide salt intake and the cost and effectiveness of these programs. Several countries, including Finland, Australia, and the UK, have developed strategies for significantly reducing the sodium chloride content of many processed foods (*14*). An international organization of experts on the health effects of salt in 80 countries, WASH (World Action on Salt and Health) began in 2005 to publicize the adverse effects of sodium chloride on health and work with governments and industry to reduce salt levels in processed foods, catered foods and restaurant food, as well as salt added during cooking, and at the table (www.worldactiononsalt.com/).

In our efforts to reduce salt in processed foods, we must remember that the original purpose of salting many foods was to prevent the growth of pathogenic and spoilage organisms. Salt also serves other functions in foods, including maintaining texture, controlling yeast growth during bread-making, and masking bitter tastes. If salt levels in foods are reduced, then other preservatives, flavoring agents, additives, or processing techniques may be needed to preserve quality and microbial safety.

HEALTH EFFECTS OF SALT

General

Approximately 98% of dietary sodium is absorbed in the intestine, and excess sodium is excreted mainly by the kidneys with some loss occurring in sweat. In healthy adult humans at steady state conditions, urinary sodium excretion roughly equals intake. Sodium is an essential nutrient, the cation mainly responsible for regulating extracellular fluid volume and plasma volume. It also determines membrane potential of cells and participates in the active transport of some molecules across cell membranes. Other cations, including potassium and calcium, interact with sodium and influence its physiological effects.

Humans can survive on diets with a wide range of sodium concentrations. Results from the Intersalt Study of blood pressure and electrolyte secretion in 32 countries reported that median urinary excretion of sodium ranged from 0.2 mmol/day in Yanomamo Indians in Brazil to 242 mmol/day in residents of Tianjin, China. This corresponds to daily intakes of approximately 0.0046 g and 5.6 g of sodium, respectively. In European and North American countries, median daily sodium intakes range from 2.3 g (100 mmol) to 4.3 g (187 mmol) (*35*). Several hormones and the sympathetic nervous system in healthy humans enable adaptation to different dietary salt levels and maintain plasma levels of sodium within an optimal range by altering the excretion of sodium in sweat and urine in response to dietary sodium intake. However, as people age or develop some chronic diseases, kidney function may decline thereby affecting the homeostatic regulation of electrolytes. As the efficiency of excretion of excess sodium diminishes, plasma volume may increase and stress the cardiovascular system by inducing hypertension. Hypertension, in turn, is directly related to coronary heart disease, stroke, and end-stage renal disease.

Hypertension

Approximately two-thirds of adults in the U.S. have either hypertension, defined as untreated systolic blood pressure (SBP) >139 mm or diastolic blood pressure (DBP) >89 mm, or pre-hypertension with SBP 120–139 mm or DBP 80–89 mm. Untreated hypertension is associated with increased incidences of diabetes, heart disease, stroke, and kidney disease. Therefore, there is universal agreement that interventions that reduce or prevent development of high blood pressure would significantly improve health (*20*). Body mass index, activity levels, and diet are known to affect blood pressure. Evidence has accumulated from epidemiological, migration, population intervention, treatment, genetic, and animal studies that higher intakes of salt or sodium are directly correlated with elevated blood pressure in populations overall and in many individuals.

The Intersalt Study collected data on blood pressure and urinary electrolytes in over 10,000 men and women in 52 centers in 32 countries. Data from four groups of non-industrialized people with very low sodium intakes revealed that blood pressure was low and did not increase with age. Data from other groups indicated that within centers, urinary sodium excretion was significantly correlated with blood pressure. Across centers, age-related increases in blood pressure were significantly related to sodium excretion. A negative association was observed between potassium excretion and blood pressure at most centers (*35*).

People living in traditional societies are, of course, also more physically active, are rarely overweight, and may be genetically different in some ways from more industrialized populations. However, data from a nomadic Iranian group with easy access to salt demonstrated that a high salt intake was associated with a higher incidence of hypertension and an increase in blood pressure as people aged, in spite of an active lifestyle and no overweight individuals (*46*). In addition, several studies of people who migrate from low salt, isolated areas to urban centers demonstrated that these people are not protected by their genetics but develop hypertension as they adapt to city life and increase their intake of salt and reduce dietary potassium (*31*).

Correlations between dietary constituents and blood pressure can be difficult to establish definitively from observational studies because data may include dietary recall of foods eaten only during the past 24 hours or analysis of a single urine specimen. These may or may not be representative of a person's usual diet. Other dietary and life style factors also impact blood pressure. This has led some to question the importance of dietary sodium as a cause of hypertension in the general population (*33;57*).

Following publication of data in the late 1960s showing that Finnish men had a very high rate of coronary heart disease mortality, Finland expended major efforts to prevent cardiovascular disease and promote health. This included collaboration with the food industry to develop lower salt foods. Dietary salt intake among men has declined from 12–13.2 g/d in 1979 to 8.6–9.5 g/d in 2002. For women, salt intakes declined from 9.4–10.2 g/d to 6.9–7.4 g/d. During this time, SBP declined by an average of 8 mm despite an increase in body mass index (*37*). Other population intervention programs in Japan, China, and Portugal also demonstrated a decrease in population blood pressure in response to a reduction in dietary sodium (*31*).

Numerous treatment trials have been conducted with hypertensive and normotensive individuals, examining the effects of reduced dietary sodium on blood pressure. Some were of short duration and/or involved acute salt restriction. These are considered less useful in predicting potential results of the recommended long-term, modest decrease in dietary sodium. A meta-analysis of investigations that lasted for at least one month demonstrated that reductions in dietary sodium significantly decreased blood pressure in both normotensive and hypertensive individuals and that a dose-response was evident between 3 and 12 g salt/day. Some individuals appear to be "salt sensitive" and experience a very significant drop in blood pressure when consuming a low salt diet while others may not see a significant change. A high prevalence of salt sensitivity occurs among persons with hypertension, diabetes, and chronic kidney disease as well as among the elderly and African-Americans. This sensitivity may have a genetic basis or may be related to body mass index or other dietary and life style variables (*20;31*).

Both sodium and other dietary constituents affect blood pressure. The DASH (Dietary Approaches to Stop Hypertension) diet, which is high in fruits, vegetables, and low-fat dairy products, has been demonstrated to reduce blood pressure. In a study comparing consumption of "typical American" diets and DASH diets each containing several sodium levels (150 to 50 mmol/d), average SBP decreased significantly with the decrease in dietary sodium on both the "typical" diet (–6.7 mm) and the DASH diet (–3 mm). Greater mean reductions in blood pressure were observed in persons with hypertension and in African-Americans than in other subjects consuming the "typical" diet with the lowest compared to the highest levels of sodium (*53*).

The DASH diet also provides higher levels of dietary potassium which have been shown to decrease blood pressure (*1;34*). Data from an 18 month study on 2275 adults with pre-hypertension found that the urinary sodium to potassium ratio, rather than urinary sodium or urinary potassium concentrations alone, was the strongest predictor of cardiovascular disease events. According the Institute of Medicine, most American adults consume only about half the recommended intake of potassium (4.7 g/day) (*17*).

Experimental studies with several species of animals, including rodents, rabbits, baboons, and chimpanzees, where dietary intake can be more strictly controlled, have demonstrated that higher salt intakes do increase blood pressure (*31*). In a review of long-term experimental studies with animals on the effects of salt on hypertension, it is evident that salt has two distinct effects: (*i*) an acute or rapid increase in blood pressure in response to increased salt occurring over days or weeks and (*ii*) a slow, progressive response to salt that occurs over a long time (a significant portion of the lifetime of normal individuals). In some species this long term increase in blood pressure appears to be irreversible. This long term response may correspond to the age-related increase in blood pressure observed in many human societies (*59*).

Cardiovascular Disease (CVD)

Dietary sodium intake has been linked to hypertension, and hypertension is considered a risk factor for CVD. Mechanisms by which sodium affects blood pressure and heart disease are not completely understood. Impaired relaxation of smooth muscles in the endothelium of arteries in response to shear stress of flowing blood is a known risk for cardiovascular disease. Consumption of a diet containing 50 mmol sodium/day (a little less than the recommended intake of 65 mmol/day for adults up to 50 years old) improved flow-mediated dilation in arteries as compared to that observed in persons consuming diets containing 150 mmol sodium/day (approximately the current median intake in the U.S.). These changes were independent of effects on blood pressure (*21*).

However, correlations between sodium intake and cardiovascular disease and mortality are more difficult to establish because disease and mortality may develop over many years following assessment of dietary intakes and several other dietary variables as well as lifestyle factors also impact cardiovascular health. Reviews have generally concluded that evidence for a positive correlation between sodium intake and CVD is not strong (*2;60*).

A recent analysis of dietary data from NHANES III found an inverse relationship between dietary sodium values calculated from 24-hour dietary recall data from 8,699 persons and the 754 deaths from CVD that occurred in an average follow-up of 8.7 years. In most comparison groups, this relationship was not statistically significant (*15*). In another recent analysis, follow-up data (for 10–15 years) on CVD from participants in the TOHP I and II studies (Trials of Hypertension Prevention) demonstrated that risk of a cardiovascular event was 25% less among those in the intervention groups that had received comprehensive education and counseling on reduction of dietary sodium. Initially, participants in this study were aged 30–54 years and prehypertensive (*16*). In yet another recently published study, the association between coronary heart disease and stroke and consumption of a DASH-style diet was evaluated in participants of the Nurses' Health Study. Diet was assessed 7 times during 24 years of follow-up. Women who consumed diets most similar to the DASH diet with reduced sodium levels had a significantly lower risk for stroke and coronary heart disease (*25*). Several components of the DASH diet were likely responsible for this protective effect, and a lower salt intake may have been one of them.

Bone Disease

Sodium and calcium metabolism and intercellular transport are linked, and it has been suggested that high salt diets may adversely affect calcium retention and bone density. Data from numerous studies have demonstrated that higher sodium intakes are correlated with greater urinary losses of calcium. For every 2300 mg sodium ingested, an additional 20–60 mg calcium are excreted in urine (*58*). This increased calciuria varies somewhat with age, gender, menopausal status, and levels of other dietary constituents, such as potassium and protein.

However, urinary calcium excretion is not necessarily directly related to bone mineral density or bone turnover. The body normally absorbs only about 27% of dietary calcium but can adapt to less than optimal serum calcium levels by increasing the absorption of calcium in the intestine. Persons consuming the currently recommended amount of calcium (1200 mg/day for women past age 50) may be able to compensate for the urinary loss of calcium caused by high dietary sodium levels. But if dietary calcium totals 600 mg/day or less, the body will most likely not be able to compensate, by increased dietary absorption, for the calciuria caused by an additional 2.3 g sodium/day (*32*). A recent study with post-menopausal women found that bone calcium balance was negative on low calcium diets (518 mg/d) whether they were high (4.42 g/d) or low (1.54 g/d) in sodium. Bone calcium balance was positive on moderate calcium diets (1284 g/d) when sodium levels were low but not when they were high (*58*).

The anion associated with sodium also affects calcium metabolism. High sodium diets contain high levels of table salt (sodium chloride), and most studies on the physiological effects of sodium use high salt diets. But sodium loading studies have demonstrated that sodium bicarbonate does not induce the same increases in urinary calcium that are seen with sodium chloride (*54*). Some studies have demonstrated that an elevated intake of salt results in a decrease in blood pH and propose that this low-grade metabolic acidosis increases bone resorption and calcium excretion (*24*). Consumption of the DASH diet, which contains approximately three times the amount of calcium, magnesium, and potassium as a "typical" American diet and is low in acid, is associated with significantly reduced markers of bone turnover in adults as compared to the typical American diet (*39*). Minerals, and probably other constituents in fruits and vegetables, may counteract the acidity of current Western diets and help preserve bone structure.

Some research suggests that high dietary sodium levels are associated with other health issues, including gastric cancer, kidney stones, and asthma. Data supporting these connections are not as definitive but a high dietary intake of sodium may affect development or severity of some of these conditions. For example, the increased urinary calcium occurring in persons on high salt diets may contribute to formation of calcium oxalate stones (*45*).

FUNCTIONS OF SODIUM COMPOUNDS IN FOODS

Flavor

Saltiness is one of the basic tastes perceived by humans and is likely a trait that evolved in order to identify foods containing the salt required for normal physiological functions. Sodium and lithium are the only cations with a taste that is primarily salty. Some other minerals, such as potassium and calcium, have some component of saltiness to their taste but there are other flavors as well, sometimes described as "metallic" or "bitter." Sodium chloride is the saltiest sodium compound. As the size of the anion associated with sodium increases, perceived saltiness decreases. Interactions among minerals with respect to taste are not well understood. When rats are placed on low potassium or low calcium diets, they consume more sodium chloride. It is well known that many diets in industrialized countries are deficient in calcium and potassium. However, it is not known whether this deficiency increases the appetite for salt in humans (*41*).

Salt has other effects on the flavor of foods by enhancing the taste of some other ingredients and suppressing or masking bitter flavors. Perception of bitterness is genetically controlled. It has been estimated that about 25% of the population are non-tasters (insensitive to ordinary levels of bitter compounds) and about 25% are supertasters (very sensitive to bitter compounds) (*36*). This presents difficulties in formulating low-salt foods. Significantly decreasing the salt in some foods may make these foods unpalatable to as many as a fourth of consumers while an equal number may not even notice it.

Sodium chloride also affects flavor by regulating the growth of certain microbes and the activity of particular enzymes. Salt concentrations significantly impact activities of proteolytic and lipolytic enzymes that produce important, characteristic flavor compounds or bitter compounds during ripening of cheese. Growth and metabolic activities of cheese starter cultures and yeast and sourdough starters for bread are stimulated or depressed by specific sodium chloride levels. These microbes, besides contributing to important structural characteristics of these foods and aiding in preservation, also synthesize important flavor and aroma compounds (*40*).

Texture/Processing

Sodium chloride interacts with other major components in foods, thereby affecting the texture of foods and reactions occurring during processing. In particular, salt enhances hydration of proteins and enhances binding of proteins to each other and to fat. These reactions stabilize emulsions of ground meat mixed with fat and promote development of a network of gluten proteins in yeast breads.

In meat, added salt activates proteins to bind more water molecules. This increases tenderness of the meat and decreases fluid loss in heat-processed vacuum-packaged products. In the presence of salt, myofibrillar proteins are loosened, and this enhances their ability to bind more fat thereby increasing viscosity and forming more stable emulsions of comminuted meats. Salt facilitates binding of myosin proteins to each other, improving the texture of processed meats (*40*). Salt performs a similar function in restructured fish products (*47*). Salt may also stabilize the red pigment in meat.

In natural cheeses, sodium chloride levels generally vary from 0.7% to 6% and play important roles in ensuring the quality, texture, and flavor of different types of cheese (*29*). Salt concentration is a major factor controlling microbial growth and therefore affects the growth and activity of cheese starter cultures as well as the growth of spoilage and pathogenic microorganisms (to be considered in the next section). Starter cultures vary somewhat in their sensitivity to salt; generally high sodium chloride concentrations are inhibitory while lower concentrations stimulate growth of the starter bacteria. Salt inhibits the growth of many potential contaminant microbes that could interfere with starter cultures.

Solubility of proteins and the water content of cheese are also affected by salt, and this, in turn, determines rheology, texture, and changes occurring during cooking. Low concentrations of NaCl (5–6%, w/w, salt:moisture) increase the solubilization of casein or para-casein in natural cheeses. In pasteurized process cheeses, emulsifying salts (sodium citrates, orthophosphates, polyphosphates) aid in hydration of para-casein, emulsification of fats, and production of a stable product. Content and composition of emulsifying salts vary somewhat in different products but a level of about 1.5% is typically used (*29*).

Yeast bread and some other baked goods require a certain amount of salt for controlling growth of yeast and for development of an extensible gluten network. Salt helps control hydration of glutenin and gliadin proteins in development of enough gluten to trap small air bubbles in dough to produce a high quality bread. Optimal salt concentrations stabilize gluten and prevent stickiness in dough. Too little salt allows excessive growth of yeast, resulting in an oversized bread with poor texture. Bakers are careful to add specific amounts of salt that have been determined to allow sufficient yeast growth so that dough will increase in volume slowly and uniformly, producing loaves of bread with good grain (*10*).

In cakes and quick (non-yeast) breads, salt does not have such a critical technological function and is added mainly for flavor. Sodium carbonate and sodium bicarbonate are used for leavening in these products and contribute to the total sodium content.

Preservation

Salt has been used to preserve meat, fish, vegetables, eggs, and even some fruit, such as olives, for thousands of years. Its primary effect is to reduce water activity of foods so that there is not enough water available for growth of pathogenic or spoilage organisms. Most foodborne bacteria, including *Clostridium botulinum, E. coli, Listeria monocytogenes, Salmonella* spp., and the spoilage bacteria *Pseudomonas* spp., cannot grow below a water activity of 0.92. However, there are some species that tolerate lower minimum water activities: spoilage lactic acid bacteria (0.90), *Staphylococcus aureus* (0.83), and some spoilage yeasts (0.62). Molds (*Aspergillus* and *Penicillium*) tolerate lower water activities than most bacteria, ranging from 0.80 to 0.83 (*6;13*). It should be noted that these limiting water activity levels are valid only when other growth conditions are favorable. If pH, oxygen levels, or temperature are below optimum, microbes may not tolerate these minimum water activity levels because of other stressful conditions. Some microbes, including *L. monocytogenes*, synthesize specific stress proteins in response to high salt levels (*23*). In addition, some toxin-producing bacteria may be able to grow at relatively low water activity levels but can only synthesize toxins with a greater amount of available water.

Meat naturally contains 50–70 mg sodium/100 g but salt added to some processed meats may increase this by ten- to thirty-fold. Cooked bacon (100 g), for example, contains 2.3 g sodium while bologna and frankfurters contain more than one gram sodium/100 g meat (Table 2). Sodium chloride along with sodium nitrite remain essential for preventing growth of *C. botulinum* in cured meats. Sodium chloride (3.5%) is also an important deterrent to *C. botulinum* in vacuum-packed fish products (*47*). Spoilage bacteria on fresh vegetables are inhibited by salt during production of sauerkraut, olives, and various pickles while the fermenting lactic acid bacteria thrive. Shelf-stable sauces also rely, in part, on salt and vinegar for preservation.

Currently, other barriers to microbial growth, such as refrigeration and heat treatment along with appropriate packaging to prevent recontamination and microbial growth, have reduced the use of salt as a preservative for many foods. Other preservatives, including sodium salts of organic acids (benzoate, diacetate, lactate, propionate, sorbate), sodium nitrite, and several sodium phosphate compounds, are often added to foods singly or in combination to prevent microbial growth and improve texture (Table 3). These compounds also reduce water activity, for example 3% sodium lactate reduces water activity more than 3% sodium chloride. In addition, organic acids reduce pH and otherwise interfere with microbial metabolism.

Sodium concentrations required to inhibit pathogens vary somewhat with the species but also with pH, temperature, oxygen levels, and other components in foods, including moisture and fat as well as other additives. Numerous models have been developed to describe the effects of various combinations of environmental factors on the growth of pathogenic bacteria. ComBase (www.combase.cc/) is a collaborative project among the USDA, Food Standards Agency and Institute of Food Research in the UK, and the Australian Food Safety Centre of Excellence. These groups have contributed large amounts of data on effects of factors, such as sodium chloride concentrations, on growth of pathogens and spoilage organisms. Their modeling toolbox provides a quantitative method for predicting microbial responses to changes in three or more environmental factors. Some of the basic data are based on growth of microbes in laboratory cultures. Therefore, these models cannot predict exact results in particular foods, but they can provide estimates of interactions among various factors that should be tested in real foods.

Table 2. Sodium levels (mg/100 g) in standard and reduced salt foods
(Data from www.nal.usda.gov/fnic/foodcomp/search/)

Food	Standard	Reduced sodium
Frankfurter	1090	311
Beef Bologna	1080	682
Salami, pork and beef	2010	623
Bacon, cooked	2310	1030
Ham, extra lean, roasted	1385	681
Bread, commercial white	681	27
Soup, condensed tomato (Campbell’s)	573	427
Cheese, Swiss	192	14
Cheese, Parmesan	1602	63
Soy sauce	5637	3333

Table 3. Amount of sodium contributed by some common sodium-containing additives as compared to that contributed by sodium chloride

Sodium compounds	Typical use	% sodium in compound	Grams of Na/100g food
Chloride	1.5–2%	39.34%	0.59–0.79 g
Benzoate	0.1%	15.95%	0.016 g
Diacetate	0.1–0.4%	16.18%	0.016–0.065 g
Lactate	1.5–3%	20.51%	0.31–0.62 g
Propionate	0.3%	23.93%	0.07 g
Sorbate	0.3%	17.14%	0.05 g
Nitrite	0.012%	33.32%	0.004 g
Acid Pyrophosphate (SAPP)	0.35%	20.72%	0.10 g
Tripolyphosphate (STPP)	0.35%	31.24%	0.16 g
Pyrophosphate (TSPP)	0.35%	34.57%	0.17 g
Hexametaphosphate (SHMP)	0.35%	22.55%	0.11 g

STRATEGIES IN FORMULATION OF REDUCED SODIUM FOODS

Flavors

Sodium chloride affects the taste of specific foods by providing the flavor of saltiness, by enhancing or masking other flavors, and by controlling growth of microbes that produce flavorful compounds. Slight stepwise reductions, by 5–10%, in levels of sodium chloride in foods may not be noticed by consumers, and if this occurs over time in a number of processed foods it may result in significantly decreased sodium intake. Successful examples include: (*i*) a 33% reduction in salt levels in cereals in the UK during a 7-year period; (*ii*) a 33% sodium reduction in Kraft processed cheese; and (*iii*) a reformulation of Heinz products that resulted in an 11–18% decrease in sodium levels (*36*). These reductions in salt content may be not only tolerated but even better liked. People who start consuming low-salt diets for health reasons usually come to prefer less salt in their food within a few months and then rate salty foods as bad tasting.

Currently there are no compounds that can effectively substitute for the flavor of sodium chloride in foods. Lithium compounds are salty but are toxic in amounts that would be needed as salt substitutes. Calcium and potassium compounds have some salty flavor but they also have off-flavors, such as a metallic or bitter taste. Potassium chloride, for example, can replace up to 30% of sodium chloride in many foods. Beyond that concentration, foods become unpalatable. Some ammonium compounds taste salty but can impart an undesirable smell and may be unstable in processed foods. Magnesium sulfate has been suggested as a partial salt replacement but it does have a bitter taste at some concentrations. Some amino acids (arginine and lysine) and dipeptides also have a salty taste but, again, it is not a "pure" salt taste so that other additives must be used to mask off-flavors and bitter tastes (*36*).

Discovery and formulation of "bitter blockers" to reduce objectionable flavors in salt substitutes and low salt foods are currently the focus of much research. Sweeteners, such as sucrose and the intensely sweet protein thaumatin, have been used to interfere with the perception of bitter compounds. Dihydroxybenzoic acid and its salts have been reported to effectively counteract metallic aftertastes without affecting sweetness (*42*).

Many herbs and spices add flavor to foods, allowing for the reduction of sodium chloride content. A wide variety of "sea salt" preparations are now sold as alternatives to refined salt. Sea salts contain several calcium, potassium, and magnesium compounds and sometimes other compounds that contribute to flavor. These non-sodium compounds constitute nearly 60% of some varieties of sea salt, with the result that significantly less sodium may be consumed (*36;48*).

Enhancing saltiness of foods may be accomplished by physical or chemical means. Sodium chloride interacts with taste receptors only when it is in solution. Therefore, physical processes that reduce the size or change the form of salt crystals to increase their solubility will increase the sensation of saltiness for a given amount of salt. This could be useful in designing lower salt snack foods with finer salt crystals on the surface that deliver sufficient saltiness with a lower amount of sodium. Some peptides from a variety of hydrolyzed proteins and the sweeteners trehalose and thaumatin enhance the salty taste of foods and permit reduction of sodium chloride levels without significantly altering taste. There are also some drugs and detergents that increase the saltiness of foods by enhancing the passage of sodium across membranes to taste receptors. However, these compounds are not recommended for general use.

In summary, there is no single compound that can simply and completely replace the flavor of sodium chloride in foods without adding some undesirable taste that must be masked with other compounds. However, salt replacers at certain concentrations can be used in some foods depending on the other ingredients naturally in the foods and on additives that mask off flavors. Herbs and spices can add flavor to foods, reducing the need for as much salt. In addition, it is possible for people to become accustomed to the taste of lower salt levels in foods and even come to prefer them over a period of a few months.

Texture and Other Quality Characteristics

Although sodium chloride performs important technological functions during production of many meat, fish, dairy, and bakery products, some of these foods probably contain more salt than is necessary for high quality characteristics. However, many factors affect quality of these foods, including starter cultures, moisture levels, fat content, pH, other additives, and processing conditions. Reducing sodium chloride levels may require alterations in other parameters to ensure that foods retain acceptable flavors and textures.

In meat products, a reduction in sodium chloride levels requires replacement of the water-holding, protein-binding, and fat-binding functions of the salt that is eliminated. One strategy that does not involve addition of other compounds is the use of different physical forms of salt. Flake salt and salts with dendritic crystals, as compared to the usual granular salt, have been reported to promote superior water and fat binding in some meat batters and emulsions. It may be possible to use lower amounts of such salts and still produce high quality products with reduced cook losses (*18*). Salt substitutes used in reduced sodium meats include potassium, calcium, and magnesium chloride compounds. KCl appears to be the best chloride substitute in terms of water retention. Immersion of cod fillets in NaCl or KCl solutions of equal molar volume had similar effects on water uptake and losses of free amino acids but the fillets in KCl had significantly lower drip loss (*38*). Several polyphosphate compounds also effectively bind water and improve the stability of meat emulsions. Potassium phosphates can perform these functions as well as their sodium counterparts, but high levels of potassium compounds may adversely alter taste. Other binding agents used in low-salt meat products increase viscosity. These include non-meat proteins (soy, milk), starches from several plant sources, and gums and alginates (*18*).

In breads, lower salt concentrations would allow more rapid yeast growth, thereby adversely affecting texture, but this may be addressed by reducing the amount of yeast added to the batter or by changing other processing conditions. A reduction in sodium concentrations also affects rheological properties of doughs but it may be possible to compensate somewhat by adjusting mixing and other mechanical processes in plants. KCl has been found to have similar effects on yeast growth and rheological properties of dough as that of NaCl. The primary limitation to this substitution is the metallic taste of KCl (*10*). A brown bread with 32% less sodium with acceptable baking properties, appearance, texture and flavor was formulated using KCl, calcium carbonate, magnesium chloride and magnesium sulfate (*11*).

Commercial cheddar cheeses in the U.S. vary significantly in sodium chloride levels, and it may be possible to reduce salt levels in some cheeses significantly by improving production methods, e.g. better mixing of salt in with cheese curd or production of more uniform sized curd chips. Reductions of up to 0.5% salt in cheddar cheese and up to 35% in cottage cheese have been judged acceptable by consumers. Partial substitution of KCl for NaCl does not adversely affect starter culture activity or texture although there are flavor issues with higher potassium concentrations (*52*). Magnesium chloride and calcium chloride do not appear to be good substitutes for NaCl in cheeses because texture becomes crumbly, soft or greasy. Protein enrichment, by addition of ultrafiltered whole milk retentate to milk used for cheese-making, produces good quality low sodium cheeses with a good texture. This may be a result of the higher calcium and phosphate content in these cheeses.

Salt levels in pasteurized processed cheeses can be reduced by starting with a reduced sodium cheese and by using different combinations of potassium emulsifying salts. Complete elimination of emulsifying salts can reduce sodium levels by 20–40%. However the result is a gummy cheese product with separation of oil and water. However, a careful blending of different cheese ingredients and optimization of processing conditions can produce a more stable product. Other ingredients such as starches and gums can also be used to maintain an acceptable cheese spread texture (*29*).

Preservation

Salt reduces water activity in foods thereby acting as a critical hurdle to control growth of pathogens and spoilage organisms. If sodium chloride levels are decreased, it may be necessary to increase concentrations of some other preservatives or more carefully control cooking or storage temperatures to ensure safe foods with a reasonable shelf life. Other processing techniques such as high pressure and packaging strategies such as different modified atmospheres may inhibit growth of pathogens and spoilage organisms and extend shelf life of low salt foods. Any changes in ingredients or processes, of course, need to be tested to ensure that they do not render a food organoleptically unacceptable.

If salt levels are reduced, it may be necessary to substitute other compounds to maintain safety of foods. Substitution of potassium chloride for sodium chloride is acceptable to consumers for many foods as long as no more than 30% of the NaCl is replaced. KCl appears to affect microbes in foods in a similar fashion to NaCl (*3;28;51*). Recent experiments with *L. monocytogenes* (*8*) and *S. aureus* (*7*) demonstrated that KCl could directly replace NaCl at the same molar ratio with the same antimicrobial effects on these foodborne pathogens in laboratory media. Further challenge studies in actual foods should be done to confirm these findings but these experiments indicate that KCl can be safely used to replace NaCl.

Organic acids are used as chemical preservatives to reduce pH and can be used to ensure microbiological safety (*22*). Concentrations of these compounds customarily used are listed in Table 3 along with the amount of sodium contributed by sodium salts of these compounds. Except for sodium lactate, the other compounds contribute much less sodium than NaCl at the concentrations used. Sodium chloride levels in packaged cooked meats were reduced by 40% by using a combination of potassium lactate and sodium diacetate (Purasal® Opto.Form PD 4 from

PURAC) without compromising sensory qualities or reducing shelf life (*19*). Sorbate, benzoate, propionate and diacetate inhibit *L. monocytogenes* in cured and uncured meat products (*26;27;55*). However, with the exception of lactate and diacetate, many of the salts of organic acids are awaiting regulatory approval in the U.S. In contrast, sorbates and benzoates are approved in many other food applications and are widely used to inhibit yeasts and molds in bakery products, cheese, and fruit products. It is also effective against some important bacteria such as *E. coli*, *Salmonella*, and *Staphylococcus* (*12;56*). These preservatives have flavors of their own that limit their use in certain products or above certain concentrations in other products.

Natural and organic foods are becoming increasingly popular and, to support this trend, there is great interest in natural antimicrobials. Active components from several plants or essential oils have exhibited antimicrobial activity against molds and bacterial pathogens in numerous laboratory experiments (*9*). These include thymol, eugenol, and cinnamaldehyde as well as compounds from onion, garlic and mustard (*5;43;44;50*). However, these compounds are generally not as effective in foods where fats or other food components may inactivate or sequester these antimicrobials (*30*). In addition these compounds have their own flavors, and products must be tested to determine whether concentrations that are effective antimicrobially are also acceptable to consumers.

Nitrite also has significant antimicrobial effects and is often used in cured and fermented meats along with sodium chloride. The maximum input level, 150 mg/kg, along with 3.5% sodium chloride is used to prevent growth of *C. botulinum*. Some predictive models have been developed to determine effective levels of different combinations of these two compounds on *L. monocytogenes* and *Salmonella* (*6*).

One factor of importance to food processors that has not yet been discussed is the relative cost of salt substitutes in relation to NaCl. Salt is very cheap and any substitute used will increase the cost of the product. Producers and their marketing departments will consider relative costs of various salt substitutes in addition to their effects on flavor, texture and safety of food products. This issue is put forth by advocates of governmental directives or regulations for lower-salt foods. For example, if all bakers must reduce salt levels in their bread, then no one company that is trying to produce a healthier food is at a disadvantage for using a more expensive salt substitute (*49*). Others point out that widespread sodium reduction by food processors will have a positive economic benefit for society by reducing health care costs (*4*).

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