COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

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

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ABSTRACT: Sodium is an essential nutrient with important functions in regulating extracellular fluid volume and the active transport of molecules across cell membranes. However, recent estimates from NHANES III (Third National Health and Nutrition Examination Survey) data show that over 95% of men and over 75% of women exceed the recommended daily tolerable upper intake of sodium. Since these high levels of dietary sodium are associated with a high prevalence of hypertension, prehypertension and, possibly, other adverse effects on health, many national and international health organizations recommend that sodium intake be significantly decreased. Traditionally, salt (sodium chloride) has been used as a food preservative that kills or limits the growth of foodborne pathogens and spoilage organisms by decreasing water activity. Salt also performs other important functions in foods by adding flavor and masking bitter tastes, controlling growth of yeast and fermentative bacteria, and promoting binding of proteins and other components in foods to achieve desired textures. Many processed foods contain high levels of salt and several countries have developed national programs for significantly reducing the sodium chloride content in many processed foods and encouraging a decrease in discretionary salt use. This review considers published data on the apparent adverse health effects of excess salt intake as well as the important functions of salt in different foods and possible strategies for reducing sodium levels in processed foods while still producing safe foods that consumers find acceptable.

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, by some, to be a potential health threat. The Inst. of Medicine of the Natl. Academy of Sciences has established adequate daily intakes (AIs) for sodium and potassium and a tolerable upper intake level (UL) for sodium, based on its effects on blood pressure (Table 1; IOM 2004). Persons with a greater risk for hypertension (adults who are Black, over 40 y old, or already have hypertension or prehypertension) have been urged to consume no more than the AI level of sodium each day (CDCP 2009).

Natural sodium levels in foods generally account for only about 10% of dietary intake. Most dietary sodium is ingested in the form of sodium chloride (table salt). In European and North American countries, approximately 5% to 10% of intake is due to the discretionary addition of salt at the table and during cooking, whereas processed foods and foods served in restaurants are estimated to contribute over 75% of dietary sodium (Mattes and Donnelly 1991). A recent study in Denmark used lithium-tagged salt to replace normal salt used by 87 people in the home for a 10-d period. Analyses of 24-h urine samples revealed that 8.7% (for women) and 10.2% (for men) of salt consumed was added to foods by the subjects. Approximately, 90% of sodium chloride intake came from sodium naturally present in foods or added to processed and manufactured foods (Andersen and others 2009). In Asian countries, salt added in home cooking and at the table accounts for an estimated 72% to 76% of dietary intake. Soy sauce, miso, salted vegetables, fruits, and fish contribute significantly to dietary sodium (Brown and others 2009).

In addition to obviously salty foods, such as certain snacks, sodium content is quite high in many packaged dinners, soups, sauces, and processed meats and cheeses. Cured meats, for example, are estimated to contribute 20.5% of the sodium in the Irish diet (Desmond 2007). Although salt levels in breads and cereals

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Table 1 — Daily sodium and potassium intakes and recommended intakes in the U.S. (IOM 2004).

	Sodium	Sodium chloride	Potassium
AI (adequate intake): 19 to 50 y	1.5 g/d (65 mmol)	3.8 g	4.7 g/d (120 mmol)
AI: 51 to 70 y	1.3 g/d (55 mmol)	3.3 g	4.7 g/d (120 mmol)
AI: > 71 y	1.2 g/d (50 mmol)	3 g	4.7 g/d (120 mmol)
UL: tolerable upper intake level	2.3 g/d (95 mmol)	5.8 g	Not established
Median intake (males)	4.2 g (183 mmol)	10.6 g	2.9 to 3.2 g/d (74 to 82 mmol)
Median intake (females)	3.3 g (142 mmol)	8.3 g	2.1 to 2.3 g/d (54 to 59 mmol)

are relatively low, people generally consume more of this food group and therefore breads and cereals contribute an estimated 35% to 50% to sodium intake in some countries (Beer-Borst and others 2009; Brown and others 2009; Thomson 2009).

Some foods, for example, 8 oz of some commercial tomato soups and 4 oz of some types of pizza, may contain nearly an entire day's adequate intake of sodium. This has led the American Public Health Assn. and the American Medical Assn. to call for a 50% reduction in sodium in processed and restaurant foods over a 10-y period. Revocation of the generally recognized as safe (GRAS) status of salt has also been proposed to make food processors justify the amount of salt added to foods (Dickinson and Havas 2007). FDA held a hearing on this proposal and on possible changes to labeling regulations in November 2007.

Sodium reduction is also a topic of intense international interest. 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. Various initiatives to reduce population-wide salt intake and the cost and effectiveness of these programs were evaluated (WHO 2007). An international organization of experts from 80 countries, WASH (World Action on Salt and Health), was established in 2005 to publicize adverse effects of sodium chloride on health and to work with governments and industry to reduce salt levels in catered, restaurant, and processed foods, as well as salt added during cooking and at the table (http://www.worldactiononsalt.com/). Several countries, including Japan, Finland, Australia, and the U.K., have developed strategies for significantly reducing the sodium chloride content in many processed foods and encouraging a decrease in discretionary salt use (Cobcroft and others 2008; He and MacGregor 2009).

It is critical to note that efforts to reduce salt in processed foods must be balanced with the original purpose of salting many foods—prevention of the growth of pathogenic and spoilage organisms. Salt- and sodium-containing ingredients also serve other functions in foods including producing and maintaining characteristic textures, controlling yeast growth during breadmaking, and masking bitter tastes. When salt and sodium levels in foods are reduced, then other preservatives may be needed to ensure food safety and flavoring agents, other additives, and different processing techniques may be required to preserve quality and texture of foods.

Health Effects of Salt

General

Humans can survive on diets with a wide range of sodium concentrations. Results from the 1985–1987 INTERSALT study of blood pressure and electrolyte excretion in 32 countries indicated that median urinary excretion of sodium ranged from 0.2 mmol/d in Yanomamo Indians in Brazil to 242 mmol/d in residents of Tianjin, China. This corresponds to a range of daily intakes of approximately 0.0046 g to 5.6 g of sodium. In European and North American countries, median daily sodium intakes ranged from 2.3 g (100 mmol) to 4.3 g (187 mmol) (ICRG 1988). More than 100 publications documenting sodium intake in adults and children in countries around the world were recently reviewed, including data from the 1996–1999 INTERMAP study (Brown and others 2009).

Approximately 98% of dietary sodium is absorbed in the intestine. Excess sodium is excreted mainly by the kidneys and some is lost with perspiration. 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 (Adrogué and Madias 2008).

Several hormones and the sympathetic nervous system enable healthy humans to adapt 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 changes in dietary sodium intake. However, as people age or develop certain chronic diseases, kidney function may decline thereby affecting 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 correlated with higher risk for coronary heart disease, stroke, and end-stage renal disease (He and MacGregor 2007).

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 prehypertension with SBP 120 to 139 mm or DBP 80 to 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 (Dickinson and Havas 2007). Age, body mass index, activity levels, and dietary sodium and potassium are all known to affect blood pressure. However, some analysts question the importance of dietary sodium, relative to other factors, as a cause of hypertension in the general population (Hollenberg 2006).

Some individuals appear to be "salt-sensitive" and experience a very significant drop in blood pressure when consuming a low-salt diet, while others are "salt-resistant" and do not see a significant change. A high prevalence of salt sensitivity occurs among persons with hypertension, diabetes, chronic kidney disease, and metabolic syndrome as well as among persons over 40 and African-Americans (Dickinson and Havas 2007; He and MacGregor 2007; Chen and others 2009). U.S. Dept. of Agriculture (USDA) estimates that these at-risk individuals constitute nearly 70% of the adult population in the U.S. (CDCP 2009).

Gender differences in salt sensitivity have also been reported with females experiencing greater decreases in blood pressure in response to dietary sodium reduction (He and others 2009b). Salt sensitivity may be related to changes in physiological processes during aging, body mass index, or dietary and lifestyle variables (Hoffmann and others 2008).

Mechanisms by which sodium affects blood pressure and the circulatory system are not completely understood. It has been suggested that, in response to high salt intake, persons with salt-sensitive hypertension do not excrete as much sodium in urine as salt-resistant individuals. Higher serum sodium levels would be followed by an expansion of plasma volume, an increase in cardiac output, and a sustained increase in systemic vascular resistance. This may occur in some people. However, a trial with healthy Black adults demonstrated that salt-loading induced similar serum sodium concentrations and similar increases in plasma volume and cardiac output in salt-sensitive and salt-resistant individuals. However, blood vessels of salt-resistant persons dilated in response to high salt intake and blood pressure did not increase significantly. This vasodilation did not occur in the salt-sensitive subjects (Schmidlin and others 2007).

Data from numerous studies indicate that higher intakes of salt or sodium are associated with elevated blood pressure in populations overall and in many individuals. The INTERSALT study found that 4 groups of people in nonindustrialized areas with very low sodium intakes had low blood pressure readings that did not increase with age. Data from over 45 other groups indicated that urinary sodium excretion was significantly correlated with blood pressure and age-related increases in blood pressure. A negative association was observed between potassium excretion and blood pressure at most centers (ICRG 1988). The INTERMAP study of blood pressure, dietary recall data, and urinary sodium levels for over 4600 adults in the U.S., U.K., Japan, and China revealed that several dietary variables, including sodium, were correlated with blood pressure measurements (Brown and others 2009).

People living in nonindustrial societies are, of course, more physically active, seldom overweight, and may differ genetically in some ways from more industrialized populations. However, several studies of people who migrated from low-salt, isolated areas to urban centers demonstrated that these people were not protected by their genetics but developed hypertension as they adapted to city life, became more sedentary, and increased their intake of salt and consumed less dietary potassium (He and MacGregor 2007).

Following publication of data in the late 1960s showing that Finnish men had a very high rate of coronary heart disease mortality, Finland initiated major efforts to reduce cardiovascular disease and promote health. These included public information campaigns and collaborations with the food industry to develop lower-salt foods. Dietary salt intake among Finnish men declined from 12 to 13.2 g/d in 1979 to 8.6 to 9.5 g/d in 2002. During this time, mean SBP in males declined by an average of 8 mm despite an increase in mean body mass index (Laatikainen and others 2006). Other population intervention programs involving thousands of people in Japan, China, and Portugal also demonstrated decreases in population blood pressure in response to a reduction in dietary sodium (He and MacGregor 2007).

Numerous treatment trials have been conducted with hypertensive and normotensive individuals examining the effects of increased/reduced dietary sodium on blood pressure. Inconsistent results have been reported from studies employing acute salt-loading or depletion for a very short term (1 wk or less). These results have been cited by those who are skeptical of programs to reduce dietary sodium (Taubes 1998). However, these trials may not reliably predict results of currently recommended long-term, modest decreases in dietary sodium. A recently published randomized crossover trial of low and high sodium diets (50 and 250 mmol/d for 7 d each) reported significant reductions of SBP and DBP of 22.7 and 9.1 mm Hg in patients with resistant hypertension (blood pressure remains elevated despite the use of 3 antihypertensive medications) (Pimenta and others 2009).

A meta-analysis of 28 dietary interventions that lasted for at least 1 mo demonstrated that reductions in dietary sodium significantly decreased blood pressure in both normotensive and hypertensive individuals. A weighted linear regression of the data indicated a significant dose response between sodium reduction and blood pressure such that a reduction of 6 g salt/d resulted in mean decreases of 7 mm Hg in SBC for hypertensive and 4 mm Hg in normotensive subjects (He and MacGregor 2002). A randomized double-blind crossover trial of a modest reduction of salt (diets with 9.7 and 6.5 g salt/d) demonstrated that the lower sodium diet was associated with significant reductions in blood pressure in white, black, and Asian subjects with mildly raised blood pressure in the U.K. A significant decrease in arterial stiffness, measured by pulse wave velocity, was observed in some subjects (He and others 2009a).

Other dietary constituents, including potassium, affect blood pressure. The DASH (Dietary Approaches to Stop Hypertension) diet, which provides a significant amount of potassium from fruits, vegetables, and low-fat dairy products, has been shown to reduce blood pressure (IOM 2004; Adrogué and Madias 2008). In a study comparing consumption of control "typical American" diets and DASH diets each containing several sodium levels (1.15 to 3.44 g sodium/d), average SBP was significantly lower on the DASH diet compared to the control diet at all salt levels. SBP also decreased significantly with a decrease in dietary sodium on both the "typical" diet (–6.7 mm) and the DASH diet (–3 mm). The combination of the DASH diet and reduced dietary sodium appeared to have an additive effect in reducing SBP. Greater mean reductions in blood pressure were observed in persons with hypertension and in African-Americans consuming the "typical" diet with the lowest levels of sodium than in other subgroups (Sacks and others 2001).

Experimental studies with several species of animals, in which dietary intake can be more strictly controlled, documented increases in blood pressure with higher salt intakes (He and MacGregor 2007). Chimpanzees fed diets with high levels of potassium and high or low levels of sodium had significantly lower SBP and DBP on the lower sodium diets (Elliott and others 2007). A review of long-term experiments on salt and hypertension in animals noted that salt has 2 distinct effects: (1) a rapid rise in blood pressure in response to increased salt occurring over days or weeks and (2) a slow, progressive increase in blood pressure during a significant portion of the lifetime of normal individuals. In some species, this long-term increase in blood pressure appeared irreversible and may correspond to the age-related increase in blood pressure observed in human populations (van Vliet and Montani 2008).

Cardiovascular disease (CVD)

Hypertension is a recognized risk factor for CVD and is often associated with other cardiovascular risk factors, such as obesity, insulin resistance, and elevated blood lipids, in a condition called the metabolic syndrome. A comparison of 24-h urinary sodium excretion, in more than 700 people with and without symptoms of the metabolic syndrome, found that higher levels of sodium excretion were significantly related to elevated blood pressure and to obesity (Hoffmann and Cubeddu 2009). Higher sodium intakes also impair relaxation of smooth muscles in the endothelium of arteries, in response to shear stress of flowing blood. This is another known risk for cardiovascular disease. Consumption of a diet containing 50 mmol or 1.15 g sodium/d (slightly lower than the recommended intake for adults up to 50 y old) improved flow-mediated dilation in arteries in a group of overweight/obese individuals as compared to that observed in persons consuming diets containing 150 mmol or 3.46 g sodium/d (approximately the current median intake in the U.S.). These changes were independent of effects on blood pressure (Dickinson and others 2009).

Correlations between sodium intake and cardiovascular disease and mortality are difficult to establish because this disease develops over many years and is affected by several dietary variables as well as lifestyle factors. Reviews have generally concluded that epidemiological evidence for a positive correlation between sodium intake and CVD is not strong (Alderman 2006; Walker and others 2007). Results from some recently published studies illustrate this.

- Data from an 18-mo study on 2275 adults with prehypertension 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 (Cook and others 2009).
- Analysis of data on a cohort from the Rotterdam Study found that there was no consistent association of urinary sodium, potassium, or sodium/potassium ratio with CVD in 387 subjects with an incident stroke or myocardial infarction compared to 1448 randomly selected subjects (Geleijnse and others 2007).
- A recent analysis of data from NHANES III found an inverse relationship between dietary sodium values, reported by 8699 persons, and the 754 deaths from CVD that occurred during an average follow-up of 8.7 y. However, in most subgroups, this relationship was not statistically significant (Cohen and others 2008).
- A recent analysis of data from participants in the TOHP I and II studies (Trials of Hypertension Prevention) indicated that risk of a cardiovascular event was 25% less, during 10 to 15 y of follow-up, in the intervention groups that had received comprehensive education and counseling on reduction of dietary sodium. Initially, participants in this study were prehypertensive and were aged 30 to 54 y (Cook and others 2007).
- A follow-up study compared incidence of coronary heart disease and stroke with consumption of a DASH-style diet by participants in the Nurses' Health Study. Diet was assessed 7 times during 24 y of follow-up. Nurses who consumed diets most similar to the DASH diet (which included lower sodium levels) had a significantly lower risk for stroke and coronary heart disease (Fung and others 2008). Several components of the DASH diet, including lower salt and higher potassium intakes, may be responsible for this protective effect.

Bone disease

Normally the body absorbs about 27% of dietary calcium but intestinal absorption of calcium can change in response to suboptimal or excess serum calcium levels and the presence of vitamin D and other nutrients. Metabolism and intercellular transport of sodium and calcium are linked and, therefore, high-salt diets may affect calcium retention and bone density. Data from several studies have demonstrated that a higher sodium intake is correlated with greater urinary losses of calcium (Carbone and others 2003; Lin and others 2003; Frings-Meuthen and others 2008). For example, a diet containing 11.2 g salt/d significantly increased urinary calcium excretion in postmenopausal women as compared to a diet with 3.9 g salt/d (Teucher and others 2008). Other factors, including age, gender, menopausal status, and other dietary constituents are known to affect the extent of calciuria.

Elevated urinary calcium levels are not necessarily directly related to bone mineral density or bone turnover. Persons consuming the currently recommended amount of calcium (1200 mg/d for women past age 50) may be able to compensate for increased calciuria caused by an additional 2.3 g sodium/d. But with a calcium intake of 600 mg/d or less, the body most likely will not be able to increase calcium absorption enough to compensate for increased calcium excretion (Heaney 2006). A recent study with postmenopausal women found that bone calcium balance was negative on low-calcium diets (518 mg/d) regardless of sodium intake. On moderate calcium diets (1284 g/d), bone calcium balance was positive when sodium levels were low (1.54 g/d), but not when they were high (4.42 g/d) (Teucher and others 2008).

Other dietary constituents affect sodium and calcium metabolism. Consumption of the DASH diet, which contains approximately 3 times the amount of calcium, magnesium, and potassium in a "typical" American diet is associated with significantly reduced markers of bone turnover in adults as compared to the typical American diet (Lin and others 2003). Fruits and vegetables are not only good sources of potassium but also are rich in compounds, such as citrate, that generate basic ions like bicarbonate during metabolism (Sebastian and others 2002). Sodium-loading studies demonstrated that sodium bicarbonate does not induce the same increases in urinary calcium that are seen with sodium chloride (Schoppen and others 2008).

A comparison of the net endogenous acid production of different diets revealed that typical American diets produce a low-grade metabolic acidosis (average of +48 mEq/d), while diets of preagricultural humans were net base-producing (average of –88 mEq/d). Cereal grains, the most commonly consumed foods in modern diets, yield net acid when metabolized (Sebastian and others 2002). Human clinical studies revealed that an elevated intake of sodium chloride also results in low-grade metabolic acidosis (Frassetto and others 2007; Frings-Meuthen and others 2008). Low-grade metabolic acidosis, caused by diets deficient in fruits and vegetables and containing excess sodium chloride, may cause increased bone resorption and calcium excretion (Morris and others 2006).

Other health effects of salt

Some studies suggest that high dietary sodium levels are associated with other health issues including gastric cancer, kidney stones, and severity of asthma. Data supporting these connections are not definitive, but a high dietary intake of sodium may affect development or severity of some of these conditions (He and MacGregor 2009). For example, the increased urinary calcium in persons on high-salt diets may contribute to formation of calcium oxalate stones (Obligado and Goldfarb 2008).

Functions of Sodium Compounds in Foods

Flavor

Saltiness is one of the basic tastes perceived by humans. Newborns appear indifferent to salt, although they do react to sweet, sour, and bitter tastes. Positive responses to salt increase during the first 4 to 6 mo of life and have been associated with birth weight. Lower birth weights are correlated with more positive responses to salt during childhood and with risk for hypertension later in life (Stein and others 2006; Beauchamp and Mennella 2009).

Sodium and lithium are the only cations with a taste that is primarily salty. Potassium and calcium, have some component of saltiness to their taste but they have other flavors, 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. Rats fed a low-potassium or low-calcium diet, 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 (McCaughey 2007).

Sodium compounds, such as sodium chloride and monosodium glutamate, enhance the flavor of some other ingredients in foods. Salt affects the flavor of cheeses and appears to have a greater impact in low-fat products (Johnson and others 2009; Saint-Eve and others 2009). Salt also suppresses or masks bitter flavors. It has been estimated that about 25% of the population are nontasters (insensitive to ordinary levels of bitter compounds) and about 25% are supertasters (very sensitive to bitter compounds) (Kilcast and den Ridder 2007). Therefore, significantly decreasing the salt in some foods may make them unpalatable to as many as a fourth of consumers, while an equal number may not even notice the change.

Sodium chloride levels in different natural cheeses vary from 0.7% to 6%. Salt significantly affects growth of starter cultures and activities of lipolytic and proteolytic enzymes that produce important characteristic flavor compounds or bitter compounds during ripening of cheese (Guinee and O'Kennedy 2007; Johnson and others 2009). Growth and metabolic activities of cheese starter cultures and yeast and sourdough starters for bread are stimulated or depressed depending on sodium chloride levels. In addition to their other functions in foods, these microbes synthesize important flavor and aroma compounds (Man 2007).

Texture/processing

Sodium chloride interacts with other major components in foods thereby affecting the texture of foods. For example, salt increases hydration of proteins and enhances the binding of proteins to each other and to fat. These properties stabilize emulsions of ground meat mixed with fat and promote development of a network of gluten proteins in yeast breads.

In meat, 1.5% to 2.5% (w/w) added salt enables proteins to bind more water, thereby increasing tenderness and decreasing fluid loss in heat-processed products. Actin and myosin in meat proteins swell in the presence of salt, binding water and fat and allowing formation of heat-stable emulsions of comminuted meats, such as frankfurters. These myosin proteins bind to each other thereby improving the texture of processed meats (Man 2007; Xiong 2007) and also restructured fish products (Pedro and Nunes 2007).

Solubility of proteins and the water content of cheese are also affected by salt. These, in turn, determine rheology, texture, and changes that occur during cooking. Low concentrations of NaCl (5% to 6%, w/w, salt-in-moisture) increase the solubilization of casein or para-casein in natural cheeses. In pasteurized process cheeses, emulsifying salts (sodium citrate, orthophosphates, polyphosphates) are added to aid in the hydration of para-casein, emulsification of fats, and stability. Content and composition of emulsifying salts vary in different products, but a level of about 1.5% is typically used (Guinee and O'Kennedy 2007; Johnson and others 2009).

Yeast bread and some other baked goods require some salt to control growth of yeast and develop an extensible gluten network. Salt helps control hydration of glutenin and gliadin proteins which is critical for the development of enough gluten to trap small air bubbles in the 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 oversized bread with poor texture. Bakers 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" (Cauvain 2007; Lynch and others 2009).

Salt also affects color development in baked products by influencing Maillard reactions. It has been shown that salt has a plasticizing effect during heating of cereal products which improves mobility of reactants and enhances Maillard reactions, producing a darker colored product (Moreau and others 2009).

In cakes and quick (nonyeast) breads, salt does not have such a critical technological function and is added primarily for flavor. However, sodium carbonate and sodium bicarbonate, used for leavening in these products, contribute to the total sodium content. Some published data indicate that salt concentrations are in the range of 1 to 1.34 g per 100 g in breads and rolls and 0.32 to 0.52 g/100 g in cakes (Cauvain 2007).

Preservation and microbial safety

Controlling growth of pathogens in foods is essential to public health, particularly for high-risk populations including very young children, pregnant women, the elderly, and people whose immune systems are weakened by chronic illnesses, immunosuppressive therapy, or chemotherapy. According to the website of the Centers for Disease Control and Prevention (http://www.cdc.gov; accessed in 2009), there are an estimated 76 million cases of foodborne illnesses annually in the U.S. Although many cases involve mild to moderate gastrointestinal symptoms, it is estimated that over 300000 people require hospitalization and approximately 5000 deaths occur annually from foodborne illnesses (Mead and others 1999).

Microbes are also an important cause of food spoilage. USDA Economic Research Service estimates that billions of pounds of food in the U.S. are lost annually by retailers, foodservice, and consumers (Buzby and others 2009). A significant amount of this loss is caused by microbes that alter the odor, taste, texture, or appearance of foods causing them to be rejected for human consumption.

Salt (sodium chloride) and drying have been used for thousands of years to decrease water activity (a_w) in meat, fish, vegetables, eggs, and some fruit, such as olives and dried plums, thereby preserving these fresh foods for later consumption. Available water is a critical factor affecting microbial growth on and in foods. Fresh foods, process cheese, and low-salt bacon have a high a_w (0.95 to 1), as do highly perishable foods such as fresh meat and fish ($a_w > 0.99$) (Christian 2000). Consequently, there is sufficient water to support growth of most bacterial pathogens and spoilage organisms if other conditions do not limit growth. Salt is added to meat and fish, particularly as a deterrent to growth of *C. botulinum* (Desmond 2007; Pedro and Nunes 2007).

Shelf-stable sauces, processed meats, and cheeses rely, in part, on salt for safety and preservation. In addition to sodium chloride, other salts, sugars, proteins, and humectants in foods decrease a_w. Examples of foods with reduced a_w include: hard cheeses, ham, and bacon with a water activity of 0.90 to 0.95; jams and heavily salted fish (0.75 to 0.80); and dried fruits (0.60 to 0.75) (Christian 2000; Nummer and Andress 2002). Water lost during processing/cooking increases sodium concentrations on a finished product basis. For example, 100-g samples of fresh raw pork belly, raw cured bacon, and cooked bacon contain, respectively, 0.032 g, 0.833 g, and 2.3 g sodium (Data from USDA Natl. Nutrient Database, http://www.nal.usda.gov/fnic/foodcomp/search/). Salt also inhibits spoilage microbes while allowing growth of lactic acid bacteria in fermentations producing sauerkraut and pickles.

On the most basic level, salt preserves food by exerting a drying effect, drawing water out of cells of both the food and microorganisms through the process of osmosis. Salt concentrations

Table 2—Approximate minimum water activity values for growth of some foodborne microbes.

Microbe	Minimum water activity	Reference
Campylobacter jejuni	0.98	Doyle and Roman (1982)
Clostridium botulinum B	0.94	Ohye and Christian (1967)
Clostridium botulinum E	0.97	Ohye and Christian (1967)
Escherichia coli	0.95	Marshall and others (1971)
Listeria monocytogenes	0.92	Tapia De Daza and others (1991)
Pseudomonas fluorescens	0.97	Marshall and others (1971)
Salmonella spp.	0.95	Christian (2000)
Staphylococcus aureus	0.86	Scott (1953)
Aspergillus flavus	0.80	Pitt and Miscamble (1995)
Saccharomyces cerevisiae	0.90	Christian (2000)
Zygosaccharomyces bailii	0.80	Pitt and Richardson (1973)

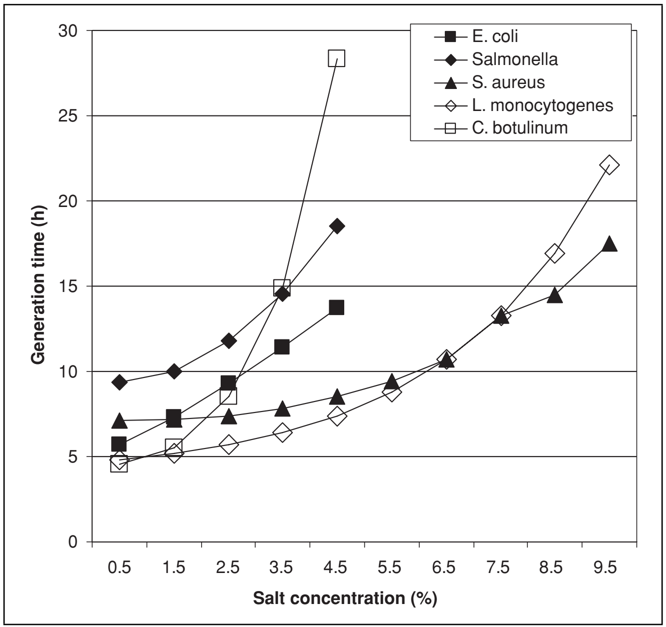

Figure 1—Effect of sodium chloride on growth of foodborne pathogens in broth culture, pH 6, 10°C, as estimated by Pathogen Modeling Program (www.ars.usda.gov/Services/docs.htm?docid=6786) and ComBase (www.combase.cc/).

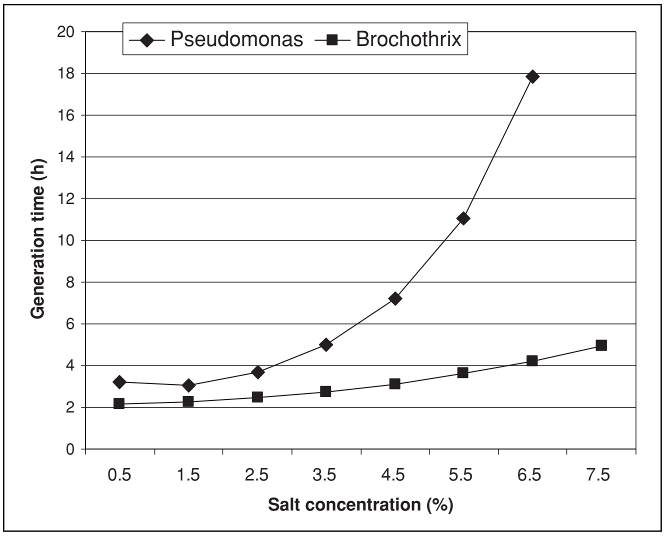

Figure 2—Effect of sodium chloride on growth of food spoilage bacteria in broth culture, pH 6, 10°C, as estimated by COMBASE (www.combase.cc/).

required to inhibit microbes vary with species. Campylobacters are highly sensitive to salt, with 0.5% NaCl being optimal for growth (Doyle and Roman 1982). On the other hand, proteolytic *C. botulinum* tolerate up to 10% NaCl and, when other growth conditions are favorable, *S. aureus* can grow in the presence of > 20% NaCl. Minimum water activity levels allowing growth of some important foodborne microbes, when other growth conditions are near optimal, are listed in Table 2. At some a_w levels, bacteria are capable of growth but not toxin production. For example, *S. aureus* can grow aerobically at 37°C at an a_w of 0.86, but only produces enterotoxin if a_w is at least 0.90 (Baird-Parker 1990).

Figure 1 illustrates the inhibitory effect of salt on growth of several foodborne pathogens at 10°C (slight temperature abuse) in broth culture. While sodium chloride concentrations of 0.5% and 1.5% do not significantly affect any of the pathogens, higher salt levels significantly increase time required for one generation of growth of some pathogens including *E. coli*, *Salmonella*, and nonproteolytic *C. botulinum*. Other microbes, including *S. aureus* and *L. monocytogenes* and the spoilage bacteria *Brochothrix* and *Pseudomonas* (Figure 2), are more resistant to salt. In the absence of salt or other preservatives, these bacteria could multiply under conditions of temperature abuse to spoil foods or cause foodborne illness.

Microbes can adapt to elevated salt levels in foods. They may accumulate potassium, amino acids, or sugars to prevent a large influx of sodium and outflow of water from cells. Other strategies include increased activity of sodium efflux systems, changes in cell morphology and membrane fatty acids (Christian 2000; Lado and Yousef 2007), and production of specific stress proteins that enable survival (Cheville and others 1996; Duché and others 2002). Microbes can also survive in very high salt concentrations even when they cannot grow. Although *Salmonella* and *E. coli* require an a_w of at least 0.95 for growth, both species survived for 8 to 10 d at 20°C in natural sheep casings at an a_w of 0.85 (Wijnker and others 2006). The more salt-tolerant *Listeria monocytogenes*, which grows at an a_w as low as 0.92, remained viable for 259 d at 4°C commercial cheese brine (23.8% NaCl, a_w approximately 0.80) (Larson and others 1999).

Other properties of foods, such as pH, temperature, oxygen, fat, and other additives, affect the sensitivity of microbes to salt in specific foods. Table 3 demonstrates some of these effects

Table 3—Influence of pH, temperature, and atmosphere on the minimal a_w (maximal sodium chloride concentration) permitting growth of selected foodborne pathogens.

Pathogen	[NaCl]	pH	Temperature	Atmosphere	Reference
Clostridium botulinum	3%	6.5	10°C	10 H_2:90 N_2	Gibson and others (2000)
(B & E non-proteolytic)	3.5%	6.5	10°C	10 H_2:85 N_2:5 CO_2	
	0.5%	6 to 6.5	5°C	100% CO_2	
	2.5%	5.5 to 6	10°C		
	0.5%	6	5°C		
Escherichia coli	6%	5.6 to 6.8	15°C	Air	Gibson and Roberts (1986)
(10 strains)	4%	5.6 to 6.8	10°C		
Listeria monocytogenes	3%	4.5	25°C	Air	McClure and others (1989)
	10%	5 to 8			
Salmonella spp.	2%	5.6 to 6.8	10°C	Air	Gibson and Roberts (1986)
(3 serotypes)	4%	5.6 to 6.8	15°C		
	6%	6.8	15°C		
	6%	5.6 to 6.2	17.5°C		

for pathogens grown in laboratory media. At lower temperatures, *E. coli* grows only at low salt concentrations (Gibson and Roberts 1986). Similarly, in more acidic environments, *L. monocytogenes* is less tolerant of salt (McClure and others 1989). Data for salmonellae demonstrate both of these effects. An atmosphere of 100% CO_2, compared to other anaerobic atmospheres, limits the growth of *C. botulinum* at higher salt levels (Gibson and Roberts 1986).

Large amounts of data on the effects of environmental factors on growth of pathogens and spoilage organisms have been published and numerous predictive models have been developed to describe the combined effects of sodium chloride concentrations, acidity, temperature, and other factors on microbial growth. Programs available on the internet have integrated data from several sources to produce interactive models predicting microbial growth under different conditions. The Pathogen Modeling Program (PMP) (http://www.ars.usda.gov/Services/docs.htm?docid=6786), from USDA, includes models for spoilage organisms and pathogens in broth and some foods. ComBase (http://www.combase.cc/) is a collaborative project among the USDA, Food Standards Agency, and Inst. of Food Research in the U.K., and the Australian Food Safety Centre of Excellence. Its modeling toolbox provides a quantitative method for predicting microbial responses to changes in 3 or more environmental factors. Much of the data used in these models are derived from growth experiments in defined laboratory media not food. But they do provide estimates of effective concentrations and illustrate important interactions among various factors that can be tested in real foods. Foods are very complex systems and some natural and added constituents may have unexpected effects on viability and growth of microbes (van Boekel 2008).

Added salt may be insufficient to completely inhibit growth of pathogens, but may depress microbial growth rates and work with other preservatives, strict refrigeration (below 4°C), or heat treatment combined with appropriate packaging, to prevent growth and toxin production. This is multiple hurdle technology to ensure safety of foods and extend shelf life.

Other sodium-containing compounds are also used for food preservation. For example, disodium phosphate is a critical component for safety of shelf-stable pasteurized process cheese products (Tanaka and others 1986) and sodium nitrite is important for preventing growth and toxin production of *C. botulinum* in cured meats (Davidson and Taylor 2007). Predictive models can estimate effective combinations of sodium chloride and sodium nitrite on *L. monocytogenes* and *Salmonella* (Betts and others 2007). Figure 3 illustrates the combined effects of these compounds on growth of *L. monocytogenes* in broth at slight temperature abuse conditions. In the absence of nitrite, 5.5% NaCl is required to prolong generation time to about 11 h. Combinations of 120 ppm nitrite plus 0.5% NaCl and of 100 ppm nitrite plus 3% NaCl have approximately the same growth inhibitory effect.

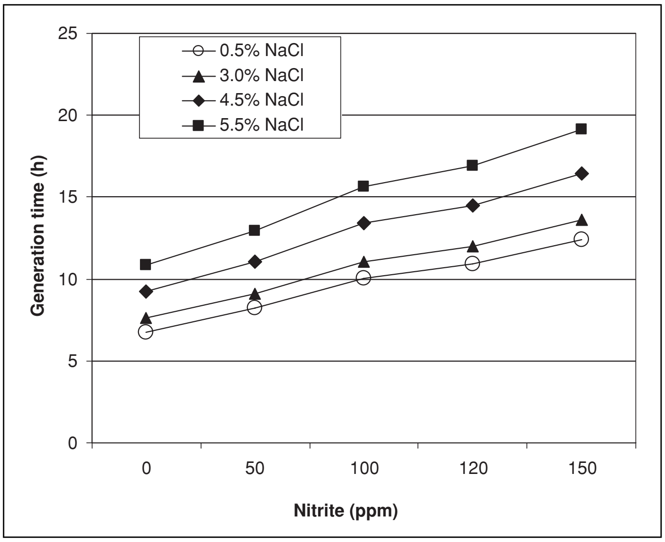

Figure 3—Effects of combinations of sodium chloride and nitrite on growth of *Listeria monocytogenes* in broth culture, pH 6, 10°C, as estimated by COMBASE (www.combase.cc/).

In a model system representative of a deli-style turkey with 65% moisture and pH 6, a predictive model suggests that without sodium salts, *L. monocytogenes* can grow within 12 d storage at 4°C (OptiForm Listeria Control Model 2007; www.purac.com). In contrast, the addition of 100 ppm sodium nitrite and 2% sodium chloride (together contributing 393 mg sodium per 50-g serving) will delay growth of the pathogen through 24 d, which provides a significant increase in the margin of safety to the consumer (Seman and others 2002).

Effective 2003, the USDA-FSIS mandated that processors incorporate strategies, such as the use of growth inhibitors, to control *L. monocytogenes* in ready-to-eat meat and poultry products (Anonymous 2003). In response to these regulations, many U.S. manufacturers add other sodium-based inhibitors such as sodium

Table 4—Amount of sodium contributed by some common sodium-containing additives as compared to that contributed by sodium chloride.

Sodium compound	Typical use	% sodium in compound	mg of Na/100 g food
Chloride	1.5% to 2%	39.34%	590 to 790
Benzoate	0.1%	15.95%	16
Diacetate	0.1% to 0.4%	16.18%	16 to 65
Lactate	1.5% to 3%	20.51%	310 to 620
Propionate	0.3%	23.93%	70
Sorbate	0.3%	17.14%	50
Nitrite	0.012%	33.32%	4
Acid pyrophosphate (SAPP)	0.35%	20.72%	100
Tripolyphosphate (STPP)	0.35%	31.24%	160
Pyrophosphate (TSPP)	0.35%	34.57%	170
Hexametaphosphate (SHMP)	0.35%	22.55%	110

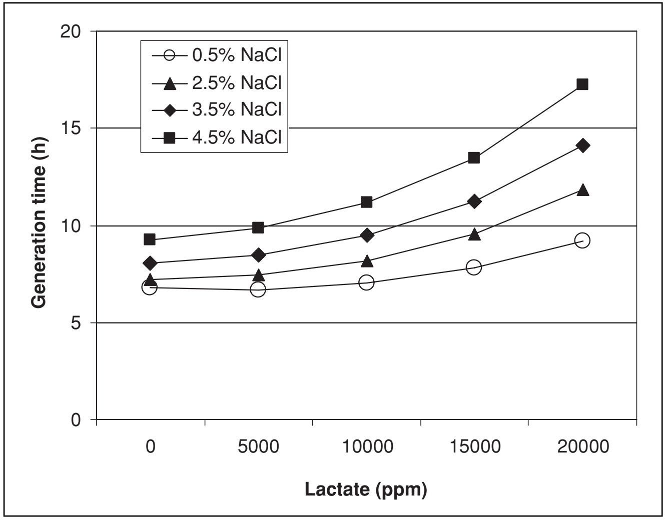

Figure 4—Effects of combinations of sodium chloride and lactate on growth of *Listeria monocytogenes* in broth culture, pH 6, 10°C, as estimated by COMBASE (www.combase.cc/).

lactate (maximum 4.8% of formulation weight) and sodium diacetate (maximum 0.25%), in addition to sodium chloride, to deli-style meat and poultry products and frankfurters to inhibit growth of this pathogen (Anonymous 2000). These compounds may reduce water activity and otherwise interfere with microbial metabolism and transport across cell membranes (Doores 2005).

Combined effects of lactate and sodium chloride on growth of *L. monocytogenes* in broth at slight temperature abuse conditions are illustrated in Figure 4. In the absence of lactate, 4.5% NaCl is required to depress growth to a generation time of 9 to 10 h. Addition of 1% or 2% lactate permits reduced NaCl concentrations of 3.5% and 0.5%, respectively. All of these organic acids, 1.6% lactate and 0.1% diacetate, 0.3% sorbate, 0.1% benzoate, and 0.2% propionate, can suppress growth of *Listeria* at 4°C for 12 wk on ham containing 2.2% NaCl and 156 ppm nitrite (Glass and others 2007b).

Since sodium salts of organic acids, sodium nitrite, and sodium phosphate compounds are added to foods to prevent microbial growth and improve texture, sodium reduction strategies must also consider these sources of added sodium. As noted in Table 4, sodium lactate is the largest potential contributor to sodium content, after sodium chloride. Formulating certain foods with reduced amounts of these compounds may have a negative effect on food safety.

Strategies in Formulation of Reduced-Sodium Foods

General

A comprehensive strategy to reduce salt intake to 6 g/d (from around 8.6 g/d) has been undertaken in the U.K. in an effort to reduce rates of hypertension and cardiovascular disease. Voluntary salt reduction targets for different categories of manufactured foods were first proposed in 2006. Information on current target values can be found at the Food Standards Agency web site (http://www.food.gov.uk/multimedia/pdfs/consultation/consultsalttargets.pdf). Target levels were set with an eye on effects related to flavor, texture, and safety of foods and are periodically reconsidered in light of experiences to date with these reformulations. The overall strategy also includes a public education campaign with television commercials and an informative web site (http://www.salt.gov.uk/).

Food manufacturers and processors have reduced salt levels in some foods. A comparison of sodium levels in standard and reduced-salt foods available in the U.S. is presented in Table 5. However, a 2009 survey by WASH (http://www.worldactiononsalt.com/) found large differences in the salt content of foods produced by global companies and sold in different countries. Kellogg's cornflakes, for example, contains 1.75, 1.8, or 2.8 g salt/100 g, depending on whether it is sold in Spain, England, or the Middle East, respectively. A KFC Fillet Burger has 3.7 g salt/100 g in New Zealand and only 2.4 g/100 g in Australia. Such

Table 5—Sodium levels (mg/100 g) in standard and reduced-salt foods (data from http://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

differences indicate that it is possible to reduce salt levels in many foods and still produce popular products.

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. Small stepwise reductions, of 5% to 10%, in levels of sodium chloride in foods are often not even noticed by consumers. If this occurs over time in a number of processed foods, it may result in significantly decreased sodium intake. Successful examples include: (1) a 33% reduction in salt levels in cereals in the U.K. during a 7-y period; (2) a 33% sodium reduction in Kraft processed cheese; and (3) a reformulation of Heinz products that resulted in an 11% to 18% decrease in sodium levels (Kilcast and den Ridder 2007). These reductions in salt content may be not only tolerated but even better liked than the original food formulation.

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 increase the solubility of salt crystals will increase the sensation of saltiness for a given amount of salt. For example, finer salt crystals could be used to coat snack foods to deliver sufficient saltiness with less sodium. Electrostatic coating of chips improves adhesion of small salt particles and can give a more even coating (Buck and Barringer 2007).

Many herbs and spices add flavor to foods allowing for the reduction of sodium chloride content. 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. One recommended additive that allows reduction of sodium content of foods is monosodium glutamate that provides an umami flavor (Kilcast and den Ridder 2007). Salad dressings, soup, and stir-fried pork, produced with less salt and added naturally brewed soy sauce were judged acceptable by consumers (Kremer and others 2009). Dried bonito (fish) enhances the saltiness and palatability of steamed egg custard thereby allowing a reduction in sodium content (Manabe 2008).

Odors of foods also affect perceptions of taste. A recent European study found that salt-associated odors could enhance perception of saltiness. Panelists presented with a series of solutions containing a standard, small amount of salt rated those with aromas such as bacon, ham, peanuts, and anchovy as saltier than solutions with no added aroma or those that smelled like tomatoes. Solutions with a carrot odor were rated as less salty than the no-aroma solution (Lawrence and others 2009). Certain well-selected odors may effectively compensate for changes in taste of low-sodium foods.

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 impart off-flavors, described as metallic or bitter. Potassium chloride, for example, can replace up to about 30% of sodium chloride in many foods. Beyond that concentration, foods become unpalatable (Charlton and others 2007; Park and others 2009). Magnesium sulfate, some ammonium compounds, amino acids, and dipeptides also have a salty taste but, again, it is not a "pure" salt taste so that other additives are required to mask off-flavors and bitter tastes (Kilcast and den Ridder 2007).

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 nonsodium compounds constitute nearly 60% of some varieties of sea salt and their use may significantly reduce sodium intake (Kilcast and den Ridder 2007; Pszczola 2007). A mineral salt containing 50% sodium chloride and 44.5% potassium chloride, along with calcium and magnesium carbonates and magnesium sulfate was used in the formulation of several meat products. Although it significantly decreased sodium content, these meats were ranked lower than the standard products by a taste panel because of differences in odor, taste, and consistency (Schoene and others 2009).

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 (McGregor 2007). A review on bitter-masking molecules describes recent advances in the discovery and development of these compounds (Ley 2008).

Texture and other quality characteristics

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

Formulation of low-salt meat batters is technologically challenging because a reduction in sodium chloride levels requires other ionic compounds to replace the water-holding, protein-binding, and fat-binding functions of the salt that is eliminated. Comminuted meat products containing less than 1.5% salt form unstable emulsions with poor texture (Xiong 2007). One proposed strategy that does not involve addition of other compounds, is the use of different physical forms of salt. Salt companies, such as Morton and Cargill, produce fine flake and dendritic salts whose crystals have a larger surface area and dissolve more rapidly. There have been reports that such salts have the potential to improve water and fat binding in some meat batters and emulsions at lower salt concentrations. Further research is needed to substantiate this claim (Desmond 2007).

Potassium, calcium, and magnesium chlorides and several polyphosphate compounds can be used to stabilize meat emulsions in reduced-sodium meats. KCl and NaCl, at equal ionic strengths, interact identically with meat proteins, but calcium and magnesium chlorides are not as effective (Gordon and Barbut 1992; Aliño and others 2009). 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 (Larsen and Elvevoll 2008). Potassium phosphates can bind water and improve stability as well as their sodium counterparts, but high levels of potassium compounds may adversely alter taste. Other binding agents, such as nonmeat proteins (soy, milk), starches from several plant sources, and gums and alginates, increase viscosity in low-salt meat products (Desmond 2007).

Sodium chloride controls growth of yeast and promotes the development of gluten structure in bread. Therefore, a reduction in salt may permit more rapid yeast growth and adversely affect texture. These effects may be mitigated to some extent by decreasing the amount of yeast used and by adjusting mixing and other mechanical processes during manufacture (Cauvain 2007).

In a series of experiments to evaluate characteristics of wheat bread formulated with 0.6%, 0.3%, and 0% salt compared to the customary level of 1.2%, reduced salt levels did not significantly impact the rheological properties of the dough, baking quality, or sensory attributes. However, omission of salt completely produced unpleasant flavors and a significant reduction in structural quality of dough and bread (Lynch and others 2009). The U.K. Food Standards Agency has recommended reducing salt levels in bread to a target of 0.9 g salt/100 g (Cauvain 2007).

KCl has similar effects on yeast growth and rheological properties of dough as that of NaCl but its use is limited by its metallic off-flavor (Cauvain 2007). A brown bread containing 32% less sodium and formulated with a combination of KCl, calcium carbonate, magnesium chloride, and magnesium sulfate was judged to have acceptable baking properties, appearance, texture, and flavor (Charlton and others 2007).

Cheeses, including commercial Cheddar cheeses in the U.S., vary in sodium chloride levels and it may be possible to reduce salt levels in some cheeses. Reducing sodium chloride in cheese presents many challenges as described in a recent review (Johnson and others 2009). 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 (Reddy and Marth 1995). 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 during 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 (Guinee and O'Kennedy 2007).

Salt levels in pasteurized process cheeses can be reduced by starting with a reduced-sodium cheese and using some potassium emulsifying salts. Complete elimination of emulsifying salts can reduce sodium levels by 20% to 40%. However, the result is a gummy cheese product with separation of oil and water. 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 (Guinee and O'Kennedy 2007).

Salt is added to a concentration of 2% to 2.25% to cabbage in making sauerkraut to suppress the growth of spoilage bacteria and select for growth of fermentative lactic acid bacteria. Addition of a starter culture of *Leuconostoc mesenteroides* to cabbage consistently produced sauerkraut with a firm texture and good flavor with salt concentrations of 0.5% or 1% (Johanningsmeier and others 2007).

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, packaging, and storage temperatures to ensure safe foods with a reasonable shelf life. Any changes in ingredients or processes must be tested to ensure that they do not render a food organoleptically unacceptable or permit growth of pathogens (Fulladosa and others 2009).

Substitution of potassium chloride for sodium chloride is acceptable to consumers for many foods as long as no more than 30% to 40% of the NaCl is replaced. KCl appears to affect microbes in foods in a similar fashion to NaCl (Reddy and Marth 1991; Askar and others 1993; Guardia and others 2006). Preliminary experiments with *L. monocytogenes* (Boziaris and others 2007) and *S. aureus* (Bidlas and Lambert 2008) in laboratory media demonstrated that KCl, at the same molar ratio, could directly replace NaCl as an antimicrobial agent. Further challenge studies in real foods must be done to confirm that KCl can safely replace NaCl.

Organic acids are used as chemical preservatives in some foods (Doores 2005). Table 4 lists concentrations of those compounds that are typically used along with the amount of sodium contributed by sodium salts of these compounds. Most sodium salts of organic acids contribute much less sodium than NaCl at the concentrations used. However, sodium lactate is used at relatively high concentrations and can contribute a significant amount of sodium.

Potassium, sodium, and calcium lactates are equally effective in controlling growth of bacteria in meat packaged in modified atmospheres (Devlieghere and others 2001). A combination of potassium lactate and sodium diacetate (Purasal® Opto.Form PD 4 from PURAC) in packaged cooked meats maintained sensory quality and shelf life, while reducing sodium chloride levels by 40% (Devlieghere and others 2009). Sorbate, benzoate, propionate, and diacetate inhibit *L. monocytogenes* in cured and uncured meat products (Glass and others 2007a, 2007b; Seman and others 2008). With the exception of lactate and diacetate, many salts of organic acids are awaiting regulatory approval for use in meats in the U.S. In contrast, sorbates, propionates, and benzoates are approved in many other food applications and are widely used to inhibit yeasts and molds in baked goods, cheeses, and fruit products. They also effectively inhibit some important pathogens such as *E. coli, Salmonella*, and *Staphylococcus* (Chipley 2005; Stopforth and others 2005). These preservatives have flavors of their own which 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 exhibit antimicrobial activity against molds and bacterial pathogens in numerous laboratory experiments (Burt 2004). These include thymol, eugenol, and cinnamaldehyde, as well as compounds from onion, garlic, and mustard (Benkeblia 2004; Nadarajah and others 2005a, 2005b; Raybaudi-Massilia and others 2006). However, these compounds are generally not as effective in foods where fats or other food components may inactivate or sequester these antimicrobials (Gupta and Ravishankar 2005). In addition, many of these compounds have their own strong flavor profiles and may not be acceptable to consumers.

Perspectives

Sodium chloride is an important nutrient and an essential ingredient in producing safe foods with acceptable sensory characteristics and structures. However, population surveys indicate that a great majority of people in industrialized societies consume much more than the current recommended amount of sodium chloride. This includes over 95% of men and over 75% of women in the U.S. according to data from NHANES III (Third National Health and Nutrition Examination Survey). Reduction of sodium levels in the diet is considered to be one important strategy for reducing prevalence of hypertension and cardiovascular diseases. Other dietary and lifestyle changes, including increased exercise and intake of fruits and vegetables with high potassium levels and reduced intakes of saturated fats, are also important for good health.

In North American and European countries, processed foods and restaurant foods account for over 70% of dietary intake of sodium. Food processors face the challenge of reducing salt content in their foods while still producing safe, palatable, and economical foods. It is probably not necessary, for improving health, to lower salt concentrations in every food if the overall dietary intake is reduced. Individuals, particularly those who are salt-sensitive, also need to control discretionary use of salt during cooking and at meals. However, it is difficult to reduce sodium intake for those who frequently eat restaurant meals and processed foods.

In addition to processing and safety challenges involved in producing low sodium foods, there is also an economic consideration. Sodium chloride is very cheap and any substitute used will increase the cost of the product. Production of foods with a reduced sodium content will require reformulation and additional associated costs of consumer testing and pilot plant tests. This economic issue is emphasized 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 cost disadvantage for using a more expensive salt substitute (Purdy and Armstrong 2007).

Several recent analyses have described the significant positive economic benefit for society that widespread reduction in dietary sodium would achieve. Millions fewer people would develop hypertension and its associated diseases and this could save billions of dollars in health care expenditures as well as improving productivity and quality of life (Beaglehole and others 2007; Dall and others 2009a, 2009b; Palar and Sturm 2009).

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